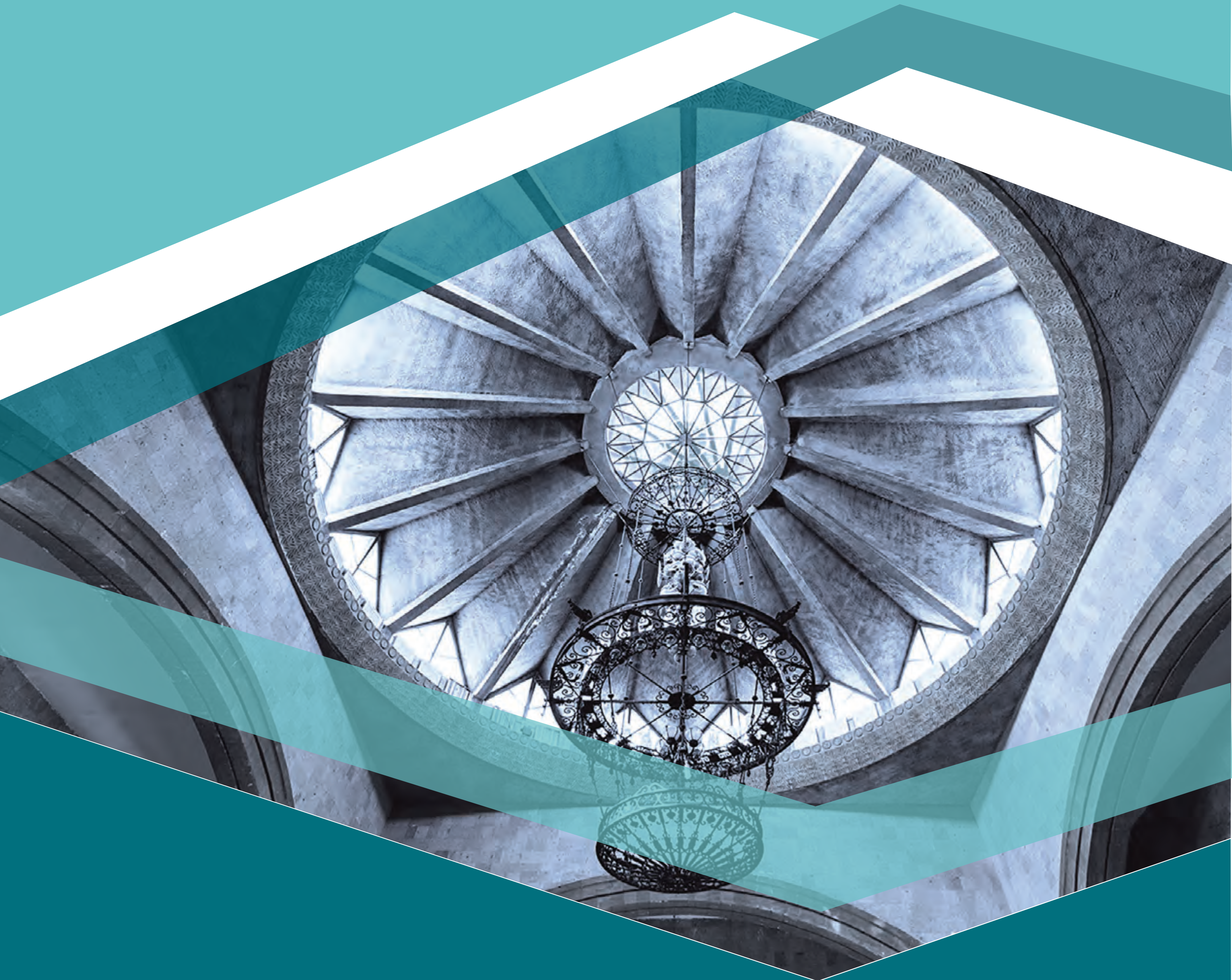
ISSN 2738-2656

2026-10



JOURNAL OF ARCHITECTURAL AND ENGINEERING RESEARCH

The Scientific Council of National University of Architecture and Constraction of Armenia approve the journal for publication

THE MINISTRY OF EDUCATION, SCIENCE, CULTURE AND SPORTS OF THE REPUBLIC OF ARMENIA

JOURNAL OF ARCHITECTURAL AND ENGINEERING RESEARCH

2 0 2 6 - 10

YEREVAN 2026

CONTENT

DEVELOPMENT OF THE METHODOLOGY FOR CREATING A DATABASE OF MULTI-APARTMENT RESIDENTIAL BUILDING DATA BASED ON THE EXAMPLE OF A SEPARATE RESIDENTIAL SECTION IN THE REPUBLIC OF ARMENIA

Mesrop Sahakyan[1], Mariam Kocharyan[1], Lusine Yeghiyan[1]*, Arevik Nazaryan, Sargis Tovmasyan[1]

[1] *National University of Architecture and Construction of Armenia, Yerevan, RA*

Abstract: *This article analyzes the existing challenges in the management and data coordination of multi-apartment residential buildings in Armenia. Special emphasis is placed on the absence of a comprehensive, digital, unified database on multi-apartment buildings, which creates significant obstacles to urban planning, socio-economic development, and the improvement of quality of life. The seismic resistance of buildings is a primary concern, a fact underscored by the 1988 Spitak earthquake. Yet, no information source exists in Armenia that documents the seismic resilience of each building. The lack of technical monitoring of the housing stock, as well as insufficient cooperation and fragmented data among relevant authorities, further complicates the effective management of the housing sector. Under these circumstances, the collection and centralization of comprehensive digital information in a single repository has become especially urgent. The primary aim of this research is to develop a scientifically grounded methodology for the creation of an architectural and technical database of multi-apartment buildings in Armenia. To achieve this, the study examines international experience and synthesizes both local and global approaches to collecting spatial and technical data on multi-apartment buildings. The current state of residential buildings is analyzed, unique challenges are identified and classified, and principles and patterns for architectural and technical analysis in the database are proposed. The methodology is further elaborated through the modeling of the database based on a case study of a distinct residential segment. The article employs methods such as the collection and summarization of archival materials and documents, systemic and situational analyses, and the study of government decisions related to the topic. The proposed methodology can serve as a foundation for creating a unified and digital repository of architectural and technical data on multi-apartment buildings in Armenia, with wide application in urban planning, technical assessment of the building stock, and the enhancement of public safety.*

Keywords: *multi-apartment building, architectural and technical database, Armenia, digital inventory, mapping, data collection methodology.*

Lusine Yeghiyan*
E-mail: lusineyeghyan@gmail.com

Received: 19.12.2025
Revised: 11.01.2026
Accepted: 24.02.2026

Introduction

The management of residential buildings in Armenia continues to face substantial challenges due to the absence of a unified, digital building database. Fragmented responsibilities among government agencies, insufficient monitoring, and the lack of technical documentation undermine effective decision-making in housing policy. As highlighted in recent research, the Armenian housing stock reflects both the legacy of Soviet-era standardized construction and the urgent need for modernization, yet no centralized mechanism exists to document structural conditions, energy efficiency, or seismic resilience.

The importance of creating such a repository is underscored by historical precedents: the catastrophic 1988 Spitak earthquake revealed the vulnerability of Armenia's multi-apartment stock, yet more than three decades later, no comprehensive registry tracks seismic resistance or building condition on a nationwide scale. Current housing management remains reactive rather than proactive, relying on partial surveys or scattered municipal archives.

Against this backdrop, the present study aims to develop a scientifically grounded methodology for the establishment of a unified architectural and technical database of multi-apartment residential buildings in Armenia. The research focuses on the following key objectives: to examine international experience and identify effective models for the management of multi-apartment residential buildings, to synthesize international and local practices in the collection and systematization of spatial and technical data on residential building stocks, to analyze the current state of multi-apartment buildings in Armenia, identify existing challenges, and develop a classification based on their defining characteristics, to establish principles and regularities for the architectural and technical analysis of residential buildings within a unified database, to develop a scientifically grounded methodology for the creation of a comprehensive residential building database, to model and test the proposed methodology through a pilot case study using a selected residential area as an example. Drawing on international experience and through the comparative analysis of residential building databases from nine countries: Germany, Spain, the Netherlands, Russia, the United States, France, Estonia, Kazakhstan, and Japan [1-41], local research addressing the necessity of residential building modernization [42-45], and the analysis of sector-specific legal acts and regulations, this research aims to define the structure, scope, and functional framework of comprehensive residential building data. The methodology is demonstrated through a pilot case study in Yerevan's Davtashen district, where a digital inventory and mapping exercise illustrate how centralized data collection could serve urban planning, technical assessment, and public safety.

Materials and Methods

The study was conducted through a comprehensive analysis of published and archival sources related to both international and Armenian experience. It examined scientific articles, reports, legal acts, regulations, and records of realized and unrealized projects, complemented by original research data. Using scientific methods of analysis and generalization, the research applied a systemic approach and situational analysis, synthesizing archival materials and evaluating relevant government decisions of the Republic of Armenia concerning housing management and building stock modernization. Furthermore, remote-sensing and LiDAR data were employed to identify potential building footprints, while geospatial (GIS) technologies supported spatial analysis, data integration, and visualization. The classification scheme for building information was developed to ensure the consistency and interoperability of the collected data.

Armenian Experience in Residential Building Databases

Standard-design residential construction in Armenia began to develop in the 1950s, amid a severe housing shortage throughout the Soviet Union. During this period, large-scale mass housing programs were launched based on pre-designed standard projects, aiming to provide affordable dwellings rapidly and efficiently. In Armenia, early standardized housing primarily consisted of five-story buildings constructed from stone and monolithic structures, widely implemented not only in Yerevan but also in regional cities. The largest segment of Armenia's multi-apartment housing stock was created during the Soviet decades, particularly between the 1950s and 1980s, when thousands of panel buildings were erected in Yerevan and other cities to accommodate the rapidly growing population [42]. Following independence, new housing construction nearly came to a halt due to the economic crisis. Over the past two decades, especially in Yerevan, modern multi-apartment residential complexes have emerged, reflecting a shift toward new architectural typologies and investment-driven urban development. Today, multi-apartment buildings in Armenia represent not only functional housing units but also the material expression of the country's social and historical transformations, embodying both the legacy of the past and the challenges of the future.

Despite the absence of a unified residential building database, several legal acts and government regulations have been adopted in Armenia to govern housing management, building maintenance, and urban development. These documents collectively define the institutional and legal framework for the sector and can serve as the foundation for developing an integrated building information system[1,2,3,4,5].

In various normative legal documents of the Government of the Republic of Armenia, there are both direct and indirect references to multi-apartment residential buildings, their management, and control mechanisms. However, these references are at times inconsistent and, from a technical and programmatic perspective, lack clarity. In addition, multiple data-exchange systems exist between various public and private institutions. Nevertheless, information related to multi-apartment residential buildings, including data formats, storage practices, and standards, differs across governmental bodies and is not uniformly regulated by sector-specific normative and legal acts.

International Experience in Residential Building Databases

Germany

Germany has led the creation of standardized, methodologically robust building-stock databases, beginning with TABULA/EPISCOPE's European typology framework that included Germany as a key case [4], later expanded with cadastral integration, machine-learning methods, and life-cycle benchmarks [1-5]. A nationwide set of ~29 million buildings (≈19 million residential) was function- and type-classified from OpenStreetMap and auxiliaries with only 3.6% deviation from official stats [1]. Using census grids plus morphological/socio-economic features, XGBoost predicted building size and construction year, mapping each to a TABULA archetype with 97.4% and 73.9% accuracy [2]. By harmonizing cadastral building footprints (HU-DE), address registers, and land-use data, researchers generated a nationwide dataset comprising approximately 51 million building polygons in its raw form, reduced to about 48 million polygons after preprocessing (removal of overlaps, small and atypical objects). Based on the classified residential buildings, around 62% were identified as detached houses [3]. TABULA/EPISCOPE groups dwellings into representative model buildings by size, age band, and energy parameters for consistent European comparison [4]. Using DGNB certification data, researchers proposed LCA benchmarks and stressed standardization with automated quality checks [5]. Openness varies: TABULA and archetype resources are open [4], ML datasets appear in academic repositories [1,2], while cadastral access is partly license-bound [3] and DGNB-based LCA remains proprietary [5]. Overall, Germany's databases show high rigor, national coverage, and validation [1,2], with TABULA enabling cross-country comparability [4], but fragmentation persists and access to cadastral and DGNB-based datasets is limited [3,5].

---

[1] Law of the Republic of Armenia "On State Registration of Rights to Property", HO-295. Available at: https://www.arlis.am/hy/acts/109181

[2] Order of the Minister of Urban Development of the Republic of Armenia dated 31 March 2014 "On Approval of Construction Norms RA CN 31-01-2014 'Residential Buildings. Part I. Multi-Apartment Residential Buildings'", No. 93-N. Available at: https://www.arlis.am/hy/acts/90112

[3] Decision of the Government of the Republic of Armenia dated 8 April 2021 "On Approval of the Strategic Program for the Establishment of an Integrated Cadastre", No. 505-L. Available at: https://www.arlis.am/hy/acts/151578

[4] Order of the Chairman of the Urban Development Committee of the Republic of Armenia dated 31 January 2022 "On Approval of the Rules for the Maintenance, Operation, and Modernization of Multi-Apartment Buildings (Including Energy Efficiency and Energy Saving)", No. 02-N. Available at: https://www.arlis.am/hy/acts/159909

[5] Decision of the Government of the Republic of Armenia dated 6 October 2022 "On Approval of the List of Basic and Thematic Spatial Data and Guidelines for Their Standardization within the Framework of the National Spatial Data Infrastructure of the Republic of Armenia", No. 1569-N. Available at: https://www.arlis.am/hy/acts/169336

Spain

Spain has developed residential building stock datasets mainly from Energy Performance Certificates (EPCs) and cadastral or open geospatial data. Early studies used EPC samples to define national energy baselines and identify inefficiencies [6], later integrating EPC, cadastral, and socio-economic data for urban-scale analyses and decision-making [8-10]. EPC data characterize national energy performance patterns and inform retrofit policy design [6]. A typological and climate-based framework defines representative dwelling archetypes (1980-2007), and tests retrofit scenarios across 13 climate zones, showing major energy-demand reductions from envelope upgrades [7]. At the city scale, EPC indicators linked with socio-economic data in Valencia reveal spatial inequalities and retrofit priorities [8]. In Barcelona, cadaster and field diagnostics identify priority neighborhoods such as Raval, Carmel, and Besòs-Maresme for rehabilitation [9], while Bilbao applies a QGIS-based workflow using open cadastral data to extract building-envelope geometry and thermal parameters by construction year, supporting energy modelling [10]. Cadastral and open-data layers in Barcelona and Bilbao are publicly accessible and GIS-compatible, enabling reproducible stock characterization [9,10], whereas EPC data remain aggregated and regionally incomplete [6,8]. Overall, Spain's EPC-based research provides a strong national evidence base for building-energy analysis [6-8], and the cases of Barcelona and Bilbao show advanced integration of cadastral, EPC, and socio-economic data through open-GIS workflows for efficient diagnosis and prioritization [9,10].

Netherlands

The Netherlands operates one of Europe's most comprehensive national building and address registries, Basisregistratie Adressen en Gebouwen (BAG), managed by Kadaster, the national Cadastre, Land Registry, and Mapping Agency. Established by law in 2009 as part of the Dutch Base Registries, BAG integrates data collected by municipalities and maintained nationally by Kadaster, ensuring consistency and legal reliability [11]. Over time, it has become a core element of the national Spatial Data Infrastructure, supporting urban planning and public administration [11-13]. BAG's governance model includes municipalities as primary data providers, Kadaster as the central coordinator, and the Ministry of the Interior overseeing the framework. It records key attributes such as building footprints, official addresses, construction year, and functional use [11]. Kadaster applies Linked Data and semantic web principles to connect BAG with other national datasets, enabling automated data exchange and analysis [12]. The Kadaster Knowledge Graph (KKG) links BAG with cadastral, demographic, and topographic data, creating a unified semantic structure for research and innovation [13]. All BAG data are publicly accessible via the PDOK platform, compliant with the INSPIRE Directive, and promoting transparency and reuse [12]. Overall, the BAG system provides nationwide coverage, legal authority, and continuous updates under a strong governance model. Its integration into semantic web and open-data infrastructures makes it one of Europe's most advanced building data systems, though effective use still demands technical expertise and interoperability management [11-13].

Russia

Russia operates several large-scale information systems for managing the residential building stock. The core platform, the State Housing and Utilities Information System (ГИС ЖКХ), consolidates data on multi-apartment buildings, utilities, and management companies, while the "Reform of Housing and Utilities" (Реформа ЖКХ) platform and regional programs collect information on building conditions, renovation needs, and funding for capital repairs [14,15]. These systems aim to centralize housing data and enhance transparency for both authorities and residents. Both ГИС ЖКХ and Реформа ЖКХ register construction year, number of apartments, ownership type, management company details, service contracts, tariffs, and repair schedules, functioning as nationwide housing registries [14,15]. Russian legislation also requires technical building passports containing structural and engineering characteristics and condition assessments, crucial for renovation planning [16,17]. Research introduces models for capital repair fund monitoring, linking financial flows with building registers to improve accountability [18]. Recent studies highlight BIM-based monitoring for continuous condition tracking and digital twin creation, enhancing maintenance and safety management [19]. Other works connect building data to risk management systems, aligning with national GOST and international ISO 31000/14001 standards [20]. While ГИС ЖКХ provides open access to basic building information such as address, construction year, and management company, detailed technical and financial data are restricted to registered users [15]. Building passports remain accessible mainly to municipal and housing authorities, limiting transparency. Overall, Russia achieves nationwide housing coverage through ГИС ЖКХ and Реформа ЖКХ [14,15], with legally mandated technical passports ensuring documentation of all multi-apartment buildings [16,17]. The integration of financial monitoring enhances transparency [18], and the adoption of BIM enables modern digital monitoring tools [19], though openness, interoperability, and regional data quality remain limited, and risk management systems are still developing [17,20].

United States

In the United States, residential building data systems are shaped by federal, state, and city initiatives. The U.S. Department of Energy (DOE) Buildings Performance Database (BPD) is the largest open dataset of empirical building energy performance and characteristics, supporting market analytics and retrofit decision-making [21,22]. Complementing it, the Standard Energy Efficiency Data (SEED) Platform is an open-source tool enabling jurisdictions to manage benchmarking and Building Performance Standards programs through consistent taxonomies and cross-source data alignment [23]. At the city level, open-data portals and benchmarking ordinances, such as those in New York City and Chicago, provide localized datasets for policy analysis and building-stock characterization [24-26]. The BPD aggregates over 750,000 anonymized building records, harmonizing descriptors and energy-use data for benchmarking and savings estimation, with peer-group analytics, quality control, and validation [21,22]. The SEED platform supports consistent data taxonomies, cross-dataset matching, and audit trails, addressing local governments' staffing and data-quality challenges [23]. Comparative studies using open data from ten U.S. cities show that open-data models outperform national baselines (CBECS) in predicting building energy performance, with building area, property type, conditioned area, and water use as key predictors [24]. Analysis of six years of NYC benchmarking data (2011-2016) identifies two performance clusters, one improving in energy intensity and another stagnating or increasing, revealing varied policy outcomes and the need for targeted measures [25]. The ZoLa platform integrates zoning, land-use, and tax-lot data, offering regulatory and spatial context for linking with energy datasets to enhance urban-scale modeling [26]. The BPD provides open, anonymized records and analysis tools [21,22], SEED is fully open-source for adoption by cities and states [23], and many city benchmarking datasets (e.g., NYC, Chicago) are publicly available, while platforms like ZoLa provide authoritative geospatial layers for integration and policy applications [24-26]. Overall, the United States has built a multi-layered data ecosystem that combines federal big-data infrastructures (BPD), jurisdictional frameworks (SEED), and city-level open benchmarking systems [21-26], enabling empirical analysis, compliance tracking, and policy design, though data completeness, uneven coverage, and linkage issues between buildings and tax parcels remain challenges that SEED continues to address [23,24].

France

France has developed the national buildings database BDNB by merging multiple official sources, land-tax "fichiers fonciers," IGN BD-TOPO, and ADEME EPC/DPE records into a unified, building-centric schema to support stock analysis and policy design [28]. A recent study links geolocated EPC data in BDNB to "Danube" archetypes to quantify renovation levels by age band and housing type, showing post-war dwellings with the highest activity and single-family houses undergoing more extensive roof works than collective housing [27]. The same study outlines BDNB fields such as construction year, height, use, and location, and notes biases in EPC data (e.g., certificates tied to transactions) that may overestimate renovation rates when used independently [27]. In Île-de-France, a component-based “TyPy” workflow enriches BDNB to estimate material stocks and demolition waste at the building level, supporting circular economy planning and designed for replication across French regions [28]. France also participates in the ECCABS archetype-aggregation framework, enabling European-level comparability, national energy demand modeled within this framework differs from statistics by only -6% to +2% [29]. The BDNB integrates public datasets and EPCs into an interoperable, updatable system suitable for building-level analysis, while EPC microdata remain partially restricted, though the methods and regional applications are publicly documented [28,27]. Overall, BDNB offers an integrated foundation for EPC-archetype renovation analysis with known limitations, component-level material and waste modeling in Île-de-France, and harmonized archetype modeling within a European framework [27-29].

Estonia

Estonia maintains a centralized Estonian Building Registry (EHR)**,** one of Europe’s first national 3D building databases, covering all registered buildings and supporting national energy modeling, digital twin development, and decarbonization strategies [33]. However, several studies highlight data incompleteness, particularly for technical attributes such as wall materials and thermal properties, prompting efforts toward registry enrichment and quality improvement [30-32]. Analyses of the EHR revealed extensive missing data fields, a combined enrichment approach using rule-based expert systems and machine learning models successfully reconstructed attributes like external wall materials, improving completeness and analytical usability [30]. Using EHR and Level of Detail geometry data, researchers developed neighborhood-scale digital twins for energy simulations, showing the potential of registry-based datasets for urban-scale energy and emissions modeling [31]. Comparative studies indicate that both expert-rule and machine-learning enrichment improve EHR data quality, with machine learning offering automation and scalability, while expert methods ensure interpretability and contextual reliability [32]. National-scale decarbonization modeling combined EHR-based archetypes with energy scenarios to estimate life-cycle greenhouse gas mitigation potential, projecting up to a 95% reduction in annual emissions by 2050 if renovation and energy-supply decarbonization progress as planned [33]. The EHR is a publicly maintained national database with open access to basic information (address, year, footprint), while detailed data are restricted to authorized users, academic collaborations have enabled extended access for developing enrichment and digital-twin methodologies [30-33]. Overall, the EHR forms the foundation of Estonia’s building-stock research and decarbonization modeling. Ongoing enrichment efforts [30-32] and integration into life-cycle frameworks [33] underscore its scientific and policy significance, though incomplete technical data and limited public accessibility remain major challenges.

Kazakhstan

Kazakhstan does not have a unified national open building register comparable to those in Western Europe. Instead, building stock data are incorporated into regional exposure databases for Central Asia and national statistical reports. International projects (NHESS studies 2021-2024) have produced harmonized, high-resolution datasets on residential building distribution and population exposure, while recent architectural research addresses the legacy and modernization challenges of Soviet-era housing [34-37]. A 2021 seismic risk exposure database compiled by Patel et al. integrated census and housing statistics at 500 m resolution, generating spatialized estimates of residential building counts and population distribution essential for seismic risk modeling [34]. Scaini et al. (2024) refined this approach by combining population density, building typologies, and structural replacement costs, improving regional comparability across Kazakhstan and neighboring countries [35]. Complementary research expanded coverage to infrastructure and non-residential assets, creating a comprehensive framework for regional exposure assessment [36]. In parallel, Sarzhanov and Schurch [2023] analyzed Soviet-era housing typologies, construction methods, and modernization issues, adding a qualitative socio-technical perspective to the statistical datasets [37]. Most Kazakhstan-related building data originate from international collaborations rather than national open registries [34-36]. These datasets are available through open-access scientific publications but not as official government-maintained databases, while national statistics remain aggregated and lack spatial detail. The Soviet housing analysis [37] is openly published yet qualitative. Integration into regional harmonized exposure databases has enabled cross-country comparability and high-resolution spatialized data at 500 m grid scale, supporting disaster risk and urban planning [34-36]. However, Kazakhstan still lacks a dedicated open building register and depends on external projects. Existing exposure datasets primarily serve disaster risk modeling rather than energy or renovation analysis, and no public GIS interface currently provides nationwide building-level accessibility for researchers or citizens.

Japan

Japan has developed multiple building databases and monitoring systems, ranging from official GIS-based inventories in Tokyo to high-resolution 3D city models under Project PLATEAU, as well as specialized registries for historical housing in Kyoto. These initiatives combine advanced digital technologies such as 3D and LiDAR with efforts to document and preserve traditional housing, reflecting Japan's integration of building data into urban planning, disaster risk reduction, and heritage conservation [38-41]. In Tokyo, the official GIS building database includes floor plans, story counts, total floor area, and usage classifications; these attributes were used to estimate station-area population and employment, demonstrating the value of detailed building data for transport-oriented planning [38]. Project PLATEAU, launched in 2020, created standardized 3D city models in CityGML format covering about 18 million buildings across 150 cities. Supporting applications in planning, disaster preparedness, and public engagement, it stands as one of the most comprehensive open digital building inventories globally [39]. In Kyoto, research on Kyo-machiya (traditional wooden townhouses) established a GIS-based monitoring system using PDA mobile GIS tools to georeference, photograph, and assess each house's condition and features, producing a longitudinal database for conservation and heritage-sensitive planning [40]. Earlier studies in Tokyo proposed LiDAR-based updating of urban building inventories to overcome photogrammetric limitations in dense areas, automating updates of building footprints and heights, especially in the Roppongi district, an essential step for seismic risk and damage assessments [41]. Japan's building data systems vary in accessibility: Project PLATEAU is fully open and standardized [39], Tokyo's administrative GIS data are research-accessible but not public [38], Kyoto's heritage GIS serves mainly local authorities [40], and LiDAR datasets require technical processing for broader use [41]. Overall, Japan's building data ecosystem is technologically advanced, integrating 3D and LiDAR systems with both modern and historical housing records. While Project PLATEAU exemplifies national-scale openness, fragmentation persists between municipal, national, and heritage datasets, and technical barriers still limit the full public application of LiDAR-based methods.

Comparative Summary of Country Analyses through Tables

Based on the preceding country analyses, the following comparative table has been compiled. It summarizes which key attributes are included in residential building databases across different countries, such as address, year of construction, building use type, number of apartments, technical data, renovation information, and ownership details. The table provides a structured overview of the findings from all examined cases (Table 1).

Table 2 summarizes the main systems and tools used to manage residential building databases in different countries. It provides an overview of whether building footprints are available, which national databases are in place, what mapping tools are applied, the primary data sources, and the general level of openness. This comparative perspective complements the attribute-based analysis by focusing on institutional and technical infrastructures.

Table 1. Availability of Key Attributes in Residential Building Databases by Country

Country	**Address**	**Year of Contraction**	**Building use type**	**Number of Apartments**	**Technical data**	**Renovation data**	**Ownership info**
Germany	+	partial	+	-	partial	partial	-
Spain	+	+	+	Partly via tex registers	partial	-	-
Netherlands	+	+	+	-	partial	-	-
Russia	+	+	+	-	partial	-	-
USA	+	+	+	Partial (e. g. NYC PLUTO dataset)	partial	-	-
France	+	+	+	-	partial	-	-
Estonia	+	+	+	-	partial	-	-
Kazakhstan	+	+	+	+ (aggregate only)	-	-	-
Japan	+	+	+		- (only footprints and year)	-	-

Table 2. Main Systems, Tools, and Data Sources for Residential Building Databases by Country

Country	**Building footprint**	**Main database/ system**	**Mapping tools**	**Data sources**	**Openness**
Germany	(GeoBasis-DE, INSPIRE)	TABULA / DE typology + national building inventory	GIS (ArcGIS, QGIS), national statistics	EPC data, census, cadastre	Partial
Spain	(Catastro)	*Catastro Inmobiliario* (national cadastre)	Cadastre GIS viewer, ArcGIS	Parcel and building registry, tax databases	Portal
Netherlands	(BAG viewer)-	BAG (*Basisregistratie Adressen en Gebouwen*) + Kadaster	BAG viewer (PDOK), 3D BAG model	Municipal data, national cadastre, GIS	Open
Russia	(Rosreestr map)	Rosreestr (EGRN) - Unified State Register	Public cadastral map	Parcel and building registry, technical passports	Restricted
USA	(city open data)	Buildings Performance Database (BPD), state and city-level databases (e.g., NYC PLUTO, LA GeoHub)	GIS (ArcGIS/QGIS), city open-data portals	Building permits, tax data, EPC	Partial
France	(IGN Geoportail, BatiParis)	BDNB (*Base de Données Nationale des Bâtiments*) + IGN BDTOPO	Geoportail, BatiParis map	Integration of 30+ government registries, national statistics, EPC	Partial
Estonia	(xGIS Maaamet, EBR)	EHR / Estonian Building Registry + ADS (Address Data System)	xGIS Maaamet viewer, QGIS	Cadastre, building permits, energy certificates	Partial
Kazakhstan	(no public map)	Housing Stock Statistics (National Bureau of Statistics)	Statistical reporting (no public map)	Census, national statistics	Restricted
Japan	(NLNI datasets, shapefiles)	National Land Numerical Information (Building Data)	GIS datasets (shapefiles), e-Stat Japan	Local government building data, census	Partial

Taken together, comparative work highlights that effective international benchmarking must consider more than "which parameters are present or absent." Equally important are the institutional settings**,** data governance frameworks**,** technological approaches **(**e.g., GIS, digital twins, LiDAR), and accessibility conditions (open, restricted, or partially aggregated). By situating Armenia's case within such a comparative framework, the present study not only identifies missing data categories but also clarifies which methodological and institutional choices may be most transferable. This provides the basis for a nuanced comparative table in the following section.

Summary of Lessons for Armenia

The comparative review of international experiences highlights a set of transferable principles that are directly relevant to the Armenian context. Although Armenia currently lacks a unified building database, the synthesis of lessons from Germany, Spain, the Netherlands, Russia, the United States, France, Estonia, Kazakhstan, and Japan provides a structured pathway for designing such a system.

A first recurring insight concerns the importance of standardized typologies and archetype models. Germany has shown how layering cadastral data with archetype frameworks and machine learning enrichment can provide reliable and comprehensive stock characterizations [1-5]. Spain has demonstrated the potential of combining EPC datasets with cadastral registers and simulating retrofit potential across climatic zones using archetype models [6-10]. France further illustrated how EPC-archetype linkages can be expanded to monitor renovation progress, while standardized archetype frameworks ensure comparability across European contexts [27-29]. These cases emphasize that Armenia should establish a typology-based framework for its residential stock, which will form the backbone of the proposed national database.

Secondly, the governance and institutional framework is critical. The Netherlands' BAG register illustrates how a centralized, authoritative system can serve as the backbone of national spatial data infrastructures, with local authorities responsible for updates and validation [11-13]. Russia underscores the importance of legal mandates such as technical passports for multi-apartment buildings, ensuring that documentation is systematically produced and maintained [14-20]. Armenia can draw on these models by establishing clear legal requirements and institutional responsibilities for maintaining the database, supported by mechanisms of accountability.

Third, data quality, enrichment, and integration with advanced technologies emerged as another common theme. Estonia provides a clear example of using expert rules, machine learning, and digital twins to enrich incomplete registry data and to support neighborhood-level energy and decarbonization modeling [30-33]. Japan offers longer-term perspectives through Project PLATEAU, demonstrating the added value of 3D city models and LiDAR for continuously updating inventories [38-41]. Armenia can adopt a phased approach, beginning with GIS-based registries, then progressively integrating enrichment techniques and advanced modeling as institutional and technical capacities grow.

Fourth**,** transparency, openness, and usability are indispensable. Open-access platforms such as BAG in the Netherlands [11-13], BPD in the United States [21,22], and Project PLATEAU in Japan [39] have shown that accessible datasets stimulate innovation, academic research, and civic participation. At the same time, countries like Russia illustrate the drawbacks of limited openness, which constrains research and reduces the potential for broad policy uptake [14-20]. Armenia should balance openness with necessary restrictions, ensuring accessibility for research and planning while protecting sensitive information.

Finally, contextual and historical dimensions should not be overlooked. Kazakhstan highlights the importance of documenting Soviet-era mass housing typologies and their modernization challenges [37]. This resonates directly with Armenia's own housing legacy, where much of the stock consists of standardized series requiring systematic evaluation and renewal. Armenia should therefore integrate historical documentation with forward-looking data collection, ensuring both preservation of context and planning for modernization [34-37].

Beyond these lessons, the comparative analysis highlights emerging opportunities for a national residential-building database in Armenia. Rapid advances in open-data technologies and international cooperation in spatial and building information systems can be leveraged. Partnerships with European and Asian actors, participation in regional data-harmonization efforts, and adaptation of open-source tools (e.g., SEED, BAG-inspired models) provide a practical basis to accelerate digitalization of the housing sector. Armenia's compact urban structure also enables phased rollouts and pilot testing to refine methods before nationwide deployment.

Concurrently, several risks must be addressed to ensure long-term sustainability. Institutional fragmentation, limited technical capacity, and scarce financial resources could impede implementation and inter-agency coordination. The absence of a legal mandate for technical building passports threatens data completeness and continuity. Privacy and cybersecurity constraints may curtail openness, limiting research and policy utility. Without sustained government support, strong data governance, and long-term funding, the initiative risks remaining a short-lived project rather than a durable national platform.

Results and Discussion

The proposal of a phased approach to database implementation is driven by the need to reduce risks associated with database development and to ensure system stability.

The proposed phased implementation approach consists of five consecutive stages, each with clearly defined objectives and outcomes.

Phase 1. Selection of a pilot residential area and boundary definition

- Select a representative residential area (neighborhood or microdistrict), taking into account building typology, construction period, and urban planning characteristics.
- Define the boundaries of the area and identify the buildings within it.
- Outcome: a spatially defined pilot zone and a list of database objects.

Phase 2. Development of the data system and model

- Develop a unified system of building characteristics (technical, spatial, functional, and operational indicators).
- Establish the logical structure of the database (tables, attributes, and relationships).
- Outcome: an approved data model and a defined set of indicators.

Phase 3. Initial data collection and verification

- Collect available archival, cadastral, and design documentation.
- Conduct field surveys to verify missing or unreliable data.
- Perform cross-validation of data across different sources.
- Outcome: a verified and reliable dataset for the pilot area.

Phase 4. Database population and functional testing

- Enter the verified data into the database.
- Test data retrieval, updating, and analysis functionalities.
- Identify methodological and technical shortcomings.
- Outcome: an operational pilot database and a refined methodology.

Phase 5. Dissemination and scaling

- Refine the methodology based on pilot results.
- Develop normative and methodological guidelines for nationwide implementation.
- Gradually extend the database to other residential areas, municipalities, and regions.
- Outcome: a scalable framework for a national multi-apartment residential building database.

The proposed multi-stage methodology enables incremental improvement, reduces the likelihood of errors, and ensures alignment of the database with the institutional and information environment.

Within the framework of this research, a methodology for creating a database of multi-apartment residential buildings was developed and proposed (Appendix 1). Although formulated using multi-apartment housing as the primary example, the methodology can also be applied to the creation or integration of databases for public and industrial buildings in different cities or individual urban areas.

The methodology comprises the following main stages:

I. Data collection
II. Multi-factor data analysis
III. Data classification
IV. Data integration
V. Application of results

I. Data Collection

The primary data sources include the Cadastre Committee of the Republic of Armenia, municipal or local authorities, up-to-date cartographic and topographic datasets, and residential building management companies. Data collected from these official sources are complemented by resident surveys and observations using Google Earth Street View.

The data collection methods include field (in-situ) surveys, analysis of online sources, automated data acquisition via a GIS platform, and structured questionnaires.

During the collection and examination of multi-apartment building data through the GIS platform, the following processes are carried out: address classification, cadastral linkage, building identification, and geometric delineation. Based on building geometry, standard-design residential buildings are detected and classified. Through the analysis of address data and cadastral maps alone, it is possible to identify the building's location, address, land parcel information (functional and designated land use), and geographic coordinates. The determination of building coordinates is essential for the verification stage, as it enables field-based validation and correction of inaccurately delineated or misclassified buildings.

II. Multi-Factor Data Analysis

During data validation and filtering, the completeness and accuracy of the collected information are verified. Duplicate or unreliable entries are removed, while missing data are supplemented using alternative verified sources.

To enhance the quality of results obtained through the GIS platform, datasets are cross-referenced with satellite imagery, and clearly low-quality or non-applicable images are excluded from the analysis. Comparative analyses are conducted between data obtained from official sources and GIS-derived results. In cases of inconsistency, data verified through field surveys serve as the primary basis for validation.
Analytical reports may be generated to assess data completeness and interlinkages. The final validated datasets are confirmed through expert discussions and agreements with relevant institutions.

III. Data Classification

The collected data are classified into the following main groups:

General information: address, year of construction, building type, cadastral number, identification code, land parcel area, managing authority.

Architectural and spatial data: number of floors, number of apartments by type, number of entrances, staircases, elevators, building footprint area, basement area, attic area, technical floor area, total residential floor area, area of public or commercial spaces, total floor area, floor height, maximum elevation point, site coverage ratio, and floor area ratio (density coefficient).

Structural system: type of structural system, external wall type, foundation type, roof type, thermal insulation of external walls, and overall technical condition.

Engineering systems: roof drainage, sewage, cold and hot water supply, ventilation, gas supply, heating, electrical supply, fire protection systems, and their technical condition.

Main renovations: information on the type, scope, and year of implementation of renovation or reconstruction works (Appendix 2).

IV. Data Integration

Based on the validated datasets, the systemic structure of the database is formed. Data are standardized into a unified format and organized by region, city, administrative district, and building series.

V. Application of Results

The structured and systematized data on multi-apartment residential buildings can serve as a foundation for urban planning and policy-making, public awareness and information dissemination, strategic planning of renovation and reconstruction programs, risk assessments (including seismic resilience and energy efficiency), socio-economic analyses, preparation of investment programs, and modeling of spatial development strategies.

Example of Residential Building Database Mapping in the Davtashen Administrative District

This study includes a pilot application conducted in the Davtashen administrative district of Yerevan, which contains multi-apartment buildings of diverse typologies, from Soviet-era prefabricated panel structures to newly built residential complexes. Each multi-apartment building was identified based on orthophoto boundaries, address data, and cadastral information. Identification through address databases alone often leads to inconsistencies related to property registration and population records. Therefore, to minimize these discrepancies, the research team developed a combined dataset integrating cadastral and address data, ensuring higher accuracy and completeness.

The addresses were linked to cadastral data (Fig.1), enabling geometric delineation and spatial verification of buildings. During the study, buildings were classified, geocoded, and verified through multiple stages, address classification, cadastral linkage, geometric isolation, and analytical verification.

Fig. 1. *The address has been linked with cadastral data*

As a result, several non-residential structures were filtered out, and a total of 334 buildings were identified within the Davtashen district, 195 of which were classified as multi-apartment residential buildings (Fig. 2).

Field verification and satellite imagery were used to validate the data and eliminate errors. Low-quality or outdated images were excluded, and site visits were performed when necessary to confirm building typologies.

This mapping allowed for the creation of a pilot residential building database map for the district, which visually illustrates the distribution and typological diversity of multi-apartment buildings. The spatial analysis confirms that many of these buildings, despite architectural variations, can be categorized as standard-design residential buildings based on their geometric and functional characteristics. Figure 3 presents an illustrative map of residential buildings in Davtashen, demonstrating how cadastral and address data integration can support the development of a comprehensive urban database.

Figure 4 illustrates the detailed information displayed for an individual building when selected on the database map. The interface shows key architectural, structural, and technical attributes, such as the building's address, construction year, number of floors and apartments, structural type, and condition, demonstrating how the proposed system enables building-level data visualization.

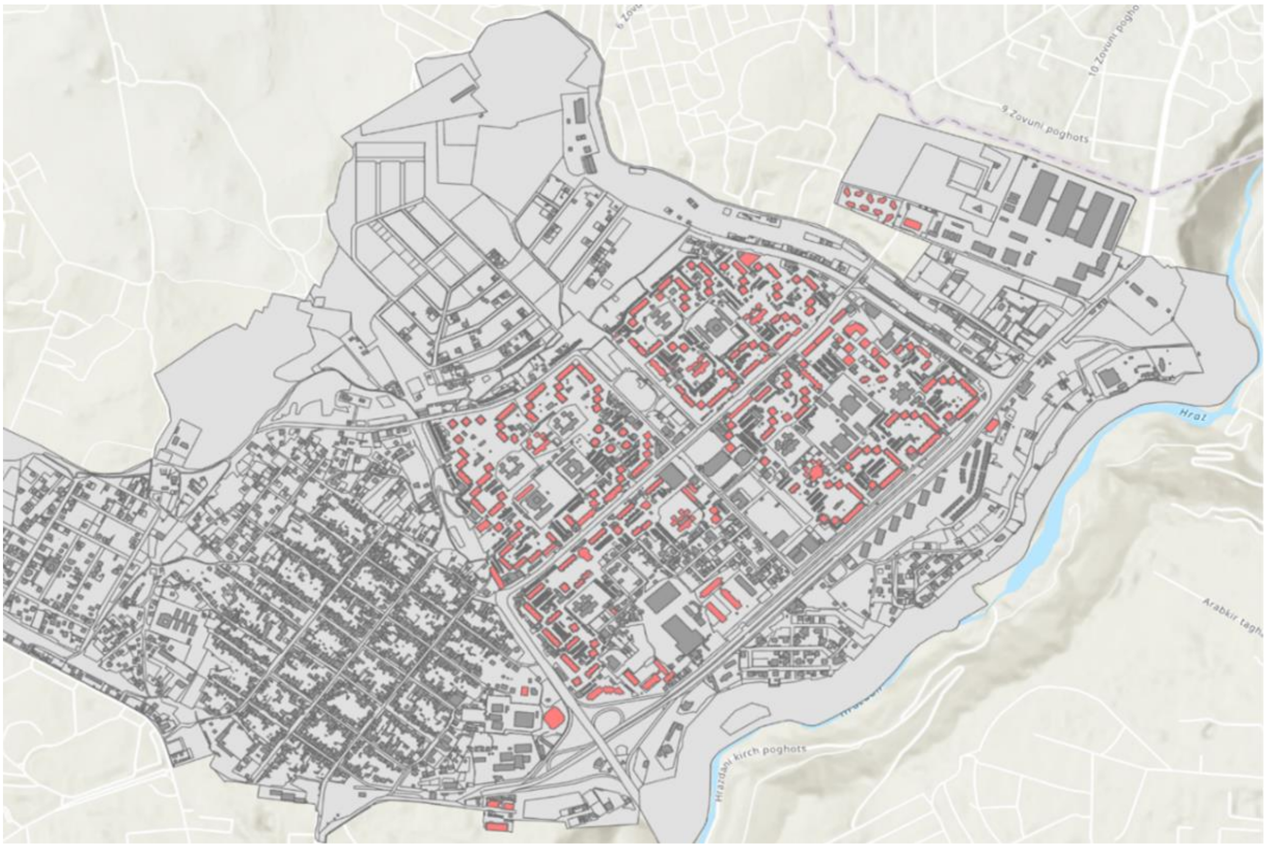


Fig. 2. *Isolated multi-apartment residential buildings*

Fig. 3. *Characteristic data of a multi-apartment building according to the proposed residential building database*

Fig. 4. *Preliminary example of the characteristic data and map of the residential building database map of the Davtashen administrative district*

Conclusion

As the study has shown, there exist a number of normative legal documents and scientific-practical projects developed at different periods concerning the collection of data on multi-apartment residential buildings, which reflect their management and control mechanisms. At the same time, a comprehensive and accurate dataset on the architectural and technical condition of buildings is still lacking in the form of a unified platform.

The analysis makes it possible to identify the main prerequisites for developing a database creation methodology for the Republic of Armenia. These include:

- A typological system of multi-apartment residential buildings, which will serve as the foundation of the database.
- Clearly defined legal requirements and institutional responsibilities for maintaining the database.
- Data quality, enrichment, and integration with advanced technologies, starting from a GIS platform and gradually incorporating enrichment techniques and advanced modeling.
- Limited data accessibility, ensuring availability for research and project development while protecting confidential information.
- A combination of historical documentation and ongoing data collection, maintaining contextual integrity while allowing for modernization.

As a result of the research, a methodology for the creation of a database of multi-apartment residential buildings has been developed and proposed, reflecting the fundamental principles and approaches underlying the database design. The methodology consists of the following main stages: data collection, analysis, classification, integration, and application of results.

The outcomes of this work can be applied in the formation or integration processes of databases for multi-apartment residential buildings, as well as for public and industrial buildings, both in various cities and in separate urban sectors.

Acknowledgment

The authors express their sincere gratitude to the National University of Architecture and Construction of Armenia for providing the opportunity to the Young Researchers' Union to participate in the internal grant program.

Conflict of Interest

The authors declare no conflicts of interest.

Funding

The research was funded by the internal grant program of the National University of Architecture and Construction of Armenia.

DATABASE CREATION METHODOLOGY

APPENDIX 1

PHASES	STEPS	
1. DATA COLLECTION	**RECEIVING SOURCES** • Cadastre Committee of the RA • Municipality or local authorities • Up-to-date cartographic and topographic datasets • building management companies • Resident surveys • Google Earth Street View observations	**COLLECTION METHODS** • Field (in-situ) surveys • Analysis of online sources • Automated data capture through a GIS platform
2. MULTI-FACTOR DATA ANALYSIS	**VALIDATION AND FILTERING** • Verify the completeness and accuracy of the data • Removal of unreliable data • Missing data are completed using alternative verified sources	**CONFIRMATION** • Expert discussions • Agreements with relevant institutions
3. DATA CLASSIFICATION	**CLASSIFICATION OF GROUPS** • General information • Architectural and spatial data • Structural system • Engineering systems • Technical condition of structural and engineering systems • Main renovations	
4. DATA INTEGRATION	**STANDARDISATION** • The collected and approved data are standardized in a unified format	**SEPARATION** • By region • By city • By administrative district • By building series
5. APPLICATION OF RESULTS	**DEFINING THE APPLIED AND PROSPECTIVE FRAMEWORKS** • Urban planning and policy-making • Public awareness and information-sharing • Strategic development of renovation and reconstruction programs • Risk assessments (including seismic resilience and energy efficiency) • Socio-economic and demographic analyses • Preparation of investment programs • Modeling of spatial development strategies	

ARRAGEMENT OF INCLUDED DATA

APPENDIX 2

SECTIONS	ITEMS			
1 DATA GROUPS	GENERAL INFORMATION	ARCHITECTURAL AND SPATIAL DATA	STRUCTURAL SYSTEM	ENGINEERING SYSTEMS
	• Address • Year of construction • Building type • Cadastral number • Identification code • Land area • Governing body	• Number of floors • Number of apartments by type • Number of entrances • Number of staircases • Number of elevators • Construction area • Basement area • Mansard area • Technical floor area • Total area of residential units • Area of public or commercial areas • Total area • Floor height • Maximum elevation point • Construction percentage and density coefficient	• Structural type • External wall type • Foundation type • Roof type • Thermal insulation of outer walls	• Roof drainage • Sewage • Cold water supply • Hot water supply • Ventilation • Gas supply • Heating • Electrical supply • Fire protection system
2 MAIN RENOVATIONS	TYPE OF WORK	SCOPE OF WORK	YEAR OF IMPLEMENTATION	
3 LOCATION ON THE MAP				
4 ASSESSMENTS / REPORTS				

References

[1]. A. Bandam, E. Busari, C. Syranidou, J. Linssen, D. Stolten, Classification of Building Types in Germany: A Data-Driven Modeling Approach. Data, 7 (4), 2022, 45. Doi: https://doi.org/10.3390/data7040045

[2]. K. Dabrock, J. Ulken, N. Pflugradt, J. M. Welnand, D. Stolten, Generating a Nationwide Residential Building Types Dataset Using Machine Learning. Building and Environment, 274, 2025, 112782. Doi: https://doi.org/10.1016/j.buildenv.2025.112782

[3]. A. Hartmann, G. Meinel, R. Hecht, M. Behnisch, A Workflow for Automatic Quantification of Structure and Dynamics of the German Building Stock Using Official Spatial Data. ISPRS International Journal of Geo-Information, 5 (8), 142, 2016. Doi: https://doi.org/10.3390/ijgi5080142

[4]. T. Loga, B. Stein, N. Diefenbach, TABULA Building Typologies in 20 European Countries—Making Energy-Related Features of Residential Building Stocks Comparable. Energy and Buildings, 132, 2016, 4-12. Doi: https://doi.org/10.1016/j.enbuild.2016.06.094

[5]. F. Schlegl, J. Gantner, R. Traunspurger, S. Albrecht, P. Leistner, LCA of Buildings in Germany: Proposal for a Future Benchmark Based on existing Databases. Energy and Buildings, 194, 2019, 342-350. Doi: https://doi.org/10.1016/j.enbuild.2019.04.038

[6]. M. Gangolells, M. Casals, N. Forcada, M. Macarulla, E. Cuerva, Energy Mapping of Existing Building Stock in Spain. Journal of Cleaner Production, 112 (5), 2016, 3895-3904. Doi: https://doi.org/10.1016/j.jclepro.2015.05.105

[7]. J.M. Gonzalez-Caballin Sanchez, A. Meana-Fernandez, J.C. Rios-Fernandez, A.J. Gutierrez Trashorres, Characterization of Housing Stock for Energy Retrofitting Purposes in Spain. Building Simulation, 16, 2023, 947-962. Doi: https://doi.org/10.1007/s12273-022-0964-2

[8]. Á. Manso Burgos, D. Ribó-Pérez, J. Van As, C. Montagud-Montalvá, R. Royo-Pastor, Diagnosis of the building stock Using Energy Performance Certificates for urban energy planning in Mediterranean compact cities. Case of study The city of València in Spain. Energy Conversion and Management, 20, 2023, 100450. Doi: https://doi.org/10.1016/j.ecmx.2023.100450

[9]. C. Cornado, S. Vima-Grau, P. Garcia-Almirall, A. Uzqueda, M. de la Asuncion, Decision-Making Tool for the Selection of Priority Areas for Building Rehabilitation in Barcelona. Buildings, 12 (2), 2022, 247. Doi: https://doi.org/10.3390/buildings12020247

[10]. C. Villanueva-Díaz, M. Álvarez-Sanz, Á. Campos-Celador, J. Terés-Zubiaga, The Open Data Potential for the Geospatial Characterisation of Building Stock on an Urban Scale: Methodology and Implementation in a Case Study. Sustainability, 16 (2), 2024, 652. Doi: https://doi.org/10.3390/su16020652

[11]. S. Coetzee, M. Odijk, B. van Loenen, J. Storm, J. Stoter, Stakeholder analysis of the governance framework of a national SDI dataset - whose needs are met in the buildings and address register of the Netherlands? International Journal of Digital Earth, 13 (3), 2018, 355-373. Doi: https://doi.org/10.1080/17538947.2018.1520930

[12]. A. Rowland, E. Folmer, W. Beek, R. Wenneker, Interoperability and Integration: An Updated Approach to Linked Data Publication at the Dutch Land Registry. ISPRS International Journal of Geo-Information, 11 (1), 2022, 51. Doi: https://doi.org/10.3390/ijgi11010051

[13]. S. Ronzhin, E. Folmer, P. Maria, M. Brattinga, W. Beek, R. Lemmens, R.V.Veer, Kadaster Knowledge Graph: Beyond the Fifth Star of Open Data. Information, 10 (10), 2019, 310. Doi: https://doi.org/10.3390/info10100310

[14]. P.A. Chernova, L.G. Shobey, Aktual'nyye problemy gosudarstvennoy informatsionnoy sistemy zhilishchno-kommunal'nogo khozyaystva. Education and Low, 6, 2022, 127-130 (in Russian). Doi: https://doi.org/10.24412/2076-1503-2022-6-127-130

[15]. A.N. Pavlov, "GIS ZHKKH" i "Reforma ZHKKH" — novyye shagi k informatizatsii otrasli zhilishchno-kommunal'nogo khozyaystva Rossii. VI International Scientific Conference on Problems and Prospects of Economics and Management. Svoye Izdatel'stvo, Saint Petersburg, December-2017, 222-225 (in Russian).

[16]. I.M. Utrobin, Otsenka i pasportizatsiya zhilykh zdaniy pri rekonstruktsii. Molodoy uchenyy, 19 (205), 2018, 170-171 (in Russian).

[17]. A.O. Khubaev, B.R. Dolov, Development of a Method for Improving Scientific and Technical Support of Construction (NTSS) on the Basis of Neural Modeling. Proceedings of Tula State University. Technical Sciences, 7, 2023, 625–628 (in Russian).

[18]. I. Davletov, E. Kurbanov, N. Rakhimov, Sh. Zhuraev, Model of Information System for Control of Funds Aimed for Repair of Apartment Buildings. Bulletin of Science and Practice, 7 (6), 2021, 329-335. Doi: https://doi.org/10.33619/2414-2948/67/36
[19]. N.S. Bolshakov, Monitoring of the Structural Health of Buildings and Facilities Using Information Modeling Methods. The Eurasian Scientific Journal, 16 (6), 2024, 1-13 (in Russian).
[20]. E.E. Smirnova, Y. Larionova, A. Mukhammedov, Risk Modeling in Safety Standards for the Housing of Russia. AIP Conference Proceedings, October 06, 2022. Doi: https://doi.org/10.1063/5.0106719
[21]. P.A. Mathew, L.N. Dunn, M.D. Sohn, A.C. Mercado, C.Y. Custodio, T. Walter, Big-Data for Building Energy Performance: Lessons from Assembling a Very Large National Database of Building Energy Use. Applied Energy, 140, 2015, 85-93. Doi: https://doi.org/10.1016/j.apenergy.2014.11.042
[22]. R.E. Brown, T.Walter, L.N. Dunn, C.Y. Custodio, P.A. Mathew, Getting Real with Energy Data: Using the Buildings Performance Database to Support Data-Driven Analyses and Decision-Making. Lawrence Berkeley National Laboratory, 2014.
[23]. N. Long, B. Anderson, J. Robertson, K. Huber, J. Huggins, J. Dean, et al., Advances in Building Data Management for Building Performance Standards Using the SEED Platform. Energy and Built Environment, 2024 (in press).
[24]. J. Roth, B. Lim, R. Jain, D. Grueneich, Examining the Feasibility of Using Open Data to Benchmark Building Energy Usage in Cities: A Data Science and Policy Perspective. Energy Policy, 139, 2020, 111327. Doi: https://doi.org/10.1016/j.enpol.2020.111327
[25]. C. Kontokosta, B. Hong, N. Johnson, D. Starobin, Using Machine Learning and Small Area Estimation to Predict Building-Level Municipal Solid Waste Generation in Cities. Computers, Environment and Urban Systems, 70, 2018, 151-162. Doi: https://doi.org/10.1016/j.compenvurbsys.2018.03.004
[26]. U. Bera, Zoning and Land Use (ZoLa): One Stop Shop for Zoning Information. New York City Department of City Planning, New York, USA, 2011.
[27]. L. de Carvalho Araujo, M. Bonhomme, S. Faraut, N. Tornay, Unveiling Renovation Patterns in the French Building Stock Using Archetype Classification and Energy Performance Certificates Data. Energy and Buildings, 336, 2025, 115647. Doi: https://doi.org/10.1016/j.enbuild.2025.115647
[28]. R. Tirado, A. Aublet, S. Laurenceau, M. Thorel, M. Louërat, G. Habert, Component-based Model for Building Material Stock and Waste-Flow Characterization: A Case in the Île-De-France Region. Sustainability, 13 (23), 2021, 13159. Doi: https://doi.org/10.3390/su132313159
[29]. É. Mata, A.S. Kalagasidis, F. Johnsson, Building-Stock Aggregation through Archetype Buildings: France, Germany, Spain and the UK. Building and Environment, 81, 2014, 270-282. Doi: http://dx.doi.org/10.1016/j.buildenv.2014.06.013
[30]. A. Ferrantelli, J. Kurnitski, Energy Performance Certificate Classes Rating Methods Tested with Data: How Does the Application of Minimum Energy Performance Standards toWorst-Performing Buildings Affect Renovation Rates, Costs, Emissions, Energy Consumption?. Energies, 15 (20), 2022, 7552. Doi: https://doi.org/10.3390/en15207552
[31]. E-R. Parts, E. Pikas, T.M. Parts, E. Arumägi, I. Liiv, T. Kalamees, Quality and Accuracy of Digital Twin Models for the Neighbourhood Level Building Energy Performance Calculations. E3S Web of Conferences, 396, 2023, 04021. Doi: http://dx.doi.org/10.1051/e3sconf/202339604021
[32]. A. Torim, E. Iliste, E. Pikas, I. Liiv, T. Robal, T. Kalamees, Comparing Domain Expert and Machine Learning Data Enrichment of Building Registry. Buildings, 15 (11), 2025, 1798. Doi: http://dx.doi.org/10.3390/buildings15111798
[33]. K. Lylykangas, K. Kertsmik, K. Aule, P. Pruuli, R. Habeek, T. Kalamees, Decarbonisation of Estonia’s Residential Building Stock. Energy and Buildings, 346, 2025, 116193. Doi: http://dx.doi.org/10.1016/j.enbuild.2025.116193
[34]. M. Wieland, M. Pittore, S. Parolai, U. Begaliev, P. Yasunov, S. Tyagunov, B. Moldobekov, S. Saidiy, I. Ilyasov, T. Abakanov, A Multiscale Exposure Model for Seismic Risk Assessment in Central Asia. Seismological Research Letters, 86 (1), 2025, 210-222. Doi: http://dx.doi.org/10.1785/0220140130
[35]. C. Scaini, A. Tamaro, B. Adilkhan, S. Sarzhanov, V. Ismailov, R. Umaraliev, M. Safarov, V. Belikov, J. Karayev, E. Faga, A New Regionally Consistent Exposure Database for Central Asia: Population and Residential Buildings. Natural Hazards and Earth System Sciences, 24 (3), 2024, 929-945. Doi: https://doi.org/10.5194/nhess-24-929-2024
[36]. C. Scaini, A. Tamaro, B. Adilkhan, S. Sarzhanov, Z. Ergashev, R. Umaraliev, M. Safarov, V. Belikov, J. Karayev, E. Faga, A Regional-Scale Approach to Assessing Non-Residential Building, Transportation and Cropland Exposure in Central Asia. Natural Hazards and Earth System Sciences, 24 (2), 2024, 355-373. Doi: https://doi.org/10.5194/nhess-24-355-2024

[37]. N. Sarzhanov, T. Schurch. Rethinking Soviet Era Mass Housing in Kazakhstan. Spatium, 49, 2023, 42-50. Doi: https://doi.org/10.2298/SPAT221002001S

[38]. B. Tsong Teh, M. Shinozaki, L. Wai Chau, Ch. Siong Ho, Using Building Floor Space for Station Area Population and Employment Estimation. Urban Science, 3 (1), 2019, 12. Doi: https://doi.org/10.3390/urbansci3010012

[39]. T. Seto, T. Furuhashi, Y. Uchiyama, Role of 3D City Model Data as Open Digital Commons: A Case Study of Openness in Japan's Digital Twin "Project PLATEAU". The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLVIII-4/W7, 2023, 201-208. Doi: https://doi.org/10.5194/isprs-archives-XLVIII-4-W7-2023-201-2023

[40]. T. Iizuka A. Matsumoto, T. Seto, K. Yano, GIS-Based Monitoring Systems for Kyo-Machiya in Kyoto City. 22nd CIPA Symposium Proceedings, Kyoto, Japan, October 11-15, 2009, 1-6.

[41]. T.T. Vu, M. Matsuoka, F. Yamazaki. LiDAR Signatures to Update Japanese Building Inventory Database. 25th Asian Conference on Remote Sensing, November-2004.

[42]. K. Azatyan, K. Rashidyants, M. Kocharyan, A. Ohanyan, The Importance of Modernization in the Perspective of the City's Housing Stock Development: Yerevan Specifics. E3S Web of Conferences, 458, 2023, 07012. Doi: https://doi.org/10.1051/e3sconf/202345807012

[43]. K. Azatyan, K. Rashidyants, M. Kocharyan, Tasks of Ensuring the Operating Life of Standard Housing Blocks Built in Yerevan: Strategy. Scientific Papers of National University of Architecture and Construction of Armenia, 85, 2023, 17-26. Doi: https://doi.org/10.54338/18294200-2023.1-02

[44]. K. Azatyan, K. Rashidyants, A. Ohanyan, Summarising the Seismic Risk Reduction Processes in Standard Residential Buildings of Yerevan: Why Don't We Have Real Results?. Budownictwo i Architektura / Civil and Architectural Engineering, 23 (2), 2024, 15-36. Doi: https://doi.org/10.35784/bud-arch.5546

[45]. K. Azatyan, M. Igitkhanyan, A. Ohanyan, Challenges to Residential Quarter Reconstruction: The Case of the Center of Yerevan City. Journal of Architectural and Engineering Research, 2022, 3, 10-31. Doi: https://doi.org/10.54338/27382656-2022.3-002

***Mesrop Sahakyan, Doctor of Philosophy (PhD) in Architecture** (RA, Yerevan) - National University of Architecture and Construction of Armenia, Junior Resercher at the "Maintenance and Development of the Research Laboratory of Construction and Architecture", sahakyan0707@gmail.com*

***Mariam Kocharyan, Resercher** (RA, Yerevan) - National University of Architecture and Construction of Armenia, mariamkocharyan95@gmail.com*

***Lusine Yeghiyan, Resercher** (RA, Yerevan) - Yerevan State University, Lecturer at the Chair of Cartography and Geomorphology, Centre of Geospatial Technologies (LLC, GIS), Engineer, lusineyeghyan@gmail.com*

***Arevik Nazaryan, Master Student** (RA, Yerevan) - National University of Architecture and Construction of Armenia, revik3540@gmail.com.*

***Sargis Tovmasyan, Doctor of Science (Architecture), Associate Professor** (RA, Yerevan) - National University of Architecture and Construction of Armenia, Head of the ScienceDepartment, tosar@mail.ru*

INTERDISCIPLINARY ANALYSIS OF FORTRESSES IN THE CONTEXT OF FOLKLORE AND ARCHITECTURE

Davit Nahatakyan[1,2], **Ashot Grigoryan**[1,3], **Hasmik Matikyan**[2,4]*

[1] *National University of Architecture and Construction of Armenia, Yerevan, RA*

[2] *Shirak Center for Armenological Studies NAS, Gyumri, RA*

[3] *National Museum-Institute of Architecture after Alexander Tamanyan, Yerevan, RA*

[4]*Armenian State University of Economics, GB, Gyumri, RA*

Abstract: *The 'fortress' or 'castle' of the Armenian Highlands (the terms are used interchangeably here) has not been comprehensively studied from the interdisciplinary perspectives of folklore and architecture. Historically, among humanity's most significant achievements, fortresses and fortification systems encompass both tangible and intangible dimensions. While the fortresses of the Armenian Highland have been extensively studied from architectural and design perspectives, their intangible aspects remain relatively underexplored. This article proposes an interdisciplinary approach integrating material analysis with intangible cultural data. It does so by drawing together studies from the province of Tayk, where well-preserved fortifications enable spatial and typological analysis, and from the Shirak region, which is rich in folklore and ethnographic material but has only a limited number of surviving structures. By combining these complementary datasets, the research interprets Tayk's material heritage through Shirak's intangible traditions and reconstructs Shirak's fragmented fortification systems by comparing them with Tayk's. This reciprocal model offers a more comprehensive understanding of Armenian fortification heritage, linking physical remains with symbolic and cultural meanings and viewing fortresses as carriers of collective memory. The approach taken is: a) To analyze Tayk's fortification systems using typological and spatial classification; b) To collect and present folklore and ethnographic materials from Shirak related to fortifications, supplemented with written and scholarly sources; and c) To examine interactions between fortification realities and their representation in folklore, and the influence of intangible culture on perception of the material environment. The study used a combined methodology, including fieldwork, comparative analysis, and analytical synthesis. Field research in the Shirak region involved collecting folkloric data through interviews, oral histories, and ethnographic observations, which were later thematically classified with a focus on fortifications. These data were supplemented by scholarly literature, historical sources, and written traditions, including religious texts.*

Keywords: *Fortress, architecture, folklore, fieldwork, narrator, Shirak, Tayk, ethnography.*

Hasmik Matikyan*

E-mail: hasvrej2024@gmail.com

Received: 25.04.2026
Revised: 19.05.2026
Accepted: 15.07.2026

Introduction

In the Armenian Highlands, castles/fortresses occupy a distinctive and multifaceted role in both material and spiritual cultural heritage, spheres that are often closely intertwined. This study seeks to identify, extract, and analyze representations of castles and fortresses in Armenian folklore and literary traditions, with particular attention to how their symbolic meanings correspond to their architectural forms and material structures. By situating literary and folkloric narratives within fortress architecture, the research aims to reveal how physical structures function not only as defensive or strategic structures but also as carriers of cultural memory, identity, and ideological significance.

From an architectural point of view, these interdisciplinary analyses are especially important for presenting examples of fortresses from the historical Tayk province, since the main settlement solutions known in the Armenian Highlands, with their fortresses, are well preserved there. In addition, significant geopolitical events in medieval Tayk affected the region's material culture [1].

Fortification complexes that are truly considered the province's distinctive features have been preserved in Tayk. Their relatively good state of preservation allows us to classify them as of provincial (Arsis, Berdagarak, etc.) or local significance (Nikhagh, Vorjnhag, Vzhanget, etc.), and to recreate the province's general fortification system [2]. On the other hand, in the literary environment and folklore of Shirak, significant manifestations of the fortress's spiritual and allegorical use have been preserved, which, when complemented by architectural solutions, yield intertwined results in Armenology. As a result of the fieldwork carried out in 2016-2021 and 2022 to the present day[1], regularly and canonically, several fortresses have also been documented and discussed.

In this respect, the best-preserved Armenian fortification systems are located in two historical regions: Cilicia and Tayk. Furthermore, within folklore and literary studies, there is a notable gap in specialized works devoted specifically to fortresses.

What is a fortress? What material and spiritual value did it represent? What did it give to native Armenians? What deep consciousness and feelings did Armenians carry, having such a powerful fortress behind them? To answer this question, we want to integrate existing ideas from the Armenian literary environment and intangible folklore with tangible architectural studies.

Systematic fortress-fortification in the Armenian Highlands has an ancient history. Dating back to the Stone Age, it is based on the tendency to protect settlements and ensure the safety of their inhabitants (which, in turn, is connected to human perceptions of nature). The cult of the peak, mountain, and stone had its own place in the system of naturalistic perceptions: "You will burn the stone. And you will eat the stone, and you will build a hill..." [3].

In the urban planning of the Armenian Highlands, since ancient times, it has been customary to consider the settlement and the fortress as one whole. Armen Zaryan, based on the comments made by Strabo and N. Adonts, confirms that "the Urartians organized the country with the concept of 'settlement-fort systems'." Three groups of systems arise:

1. One fortress with villages located around it,
2. Groupings of two or more fortress cities and villages,
3. Groupings of fortress cities [4].

This approach could change due to the influence of the geographical and climatic conditions of the Armenian Highlands. Within this section, the situation arising from the area's "impenetrable" river valleys was considered important and predetermining. In general, in medieval Armenia, it was customary to use a tricentric system to organize the construction of cities (towns) and their "protective" fortresses (for example, Shirakavan-Argina-Tignis or Yervandashat-Yervandakert-Bagaran, etc.) [4].

The work of S. Petrosyan is of fundamental importance for the semantic study of fortresses, as he thoroughly addressed the issues of classes and triads. According to him, "the idea of society consisting of three equal classes had taken such deep roots in the Armenian consciousness that it had even conditioned the tripartite system of the economic and social structure of Armenian settlements" [5]. The works of Ashot Grigoryan are valuable for their insights into the origins and principles of Armenian fortress construction and its theory [6]. There are some studies of the architecture of Armenian fortresses. Mikael V. Hovhannisyan

[1] Fieldwork is being carried out with the support of the Land and Culture organization.

documented valuable materials related to the Armenian fortresses of Cilicia [7]. In Kirkyasharyan's work, the history of the cities of ancient Armenia and Asia Minor is discussed, which naturally also includes references to fortresses and fortified cities [8]. H. Manandyan, in his work “The Cities of Armenia in the 10th-11th Centuries”, partially touched upon the Armenian medieval fortified cities [9].

L. Kirakosyan, in several works, refers to the fortresses and fortification systems built in different eras of Armenia and Artsakh[2] [10]. Varazdat Harutyunyan [11] and Stepan Mnatsakanyan [12] have descriptive and documentary materials about the fortresses of Syunik. A valuable source about the provinces, regional centers, and settlements of Tayk from the early Christian period is the “Ashkharsuyts” [13] (a world atlas with 15 maps). There is some information on the Tayk fortresses in the works of N. Marr, E. Takaishvili [14], and others. There is an illustrated catalog of the fortresses of some of Tayk’s provinces in the works of Buba Kudava [15]. We have touched upon the Tayk fortresses in our two monographs and several articles [2,16]. This scientific work thus marks the first attempt to consider the fortress in both spiritual and physical terms through interdisciplinary analyses to reveal its role and significance in Armenian culture.

The results of long-term field expeditions indicate that the fortification system of the historical province of Tayk was formed under the direct influence of Armenian principles of traditional settlement planning and spatial organization. The patterns observed in the spatial organization of settlements were systematically reproduced in fortification construction, forming the foundation for its spatial and functional organization. In this regard, fortresses appear not only as defensive structures but also as expressions of continuity in settlement and territorial organization.

Materials and Methods

The study's methodology can be divided into three main components. First, an analysis and synthesis of primary sources on fortresses from both architectural and folkloric traditions has been conducted. Second, the research is based on the compilation and integration of materials gathered through numerous architectural and folkloric field studies conducted and ongoing by the authors. Third, the study involves identifying and interpreting intangible inherited values and concepts—such as folklore, fairy tales, legends, and related narratives—within the material domain —in this case, architecture.

Davit Nahatakyan was responsible for the study of the architectural component, Ashot Grigoryan for the analysis of historical primary sources and symbolism, and Hasmik Matikyan for the study of the folkloric and ethnographic components. The analyses and conclusions were developed collaboratively by all participants.

Results and Discussion

Based on field studies and comparative analysis of fortification systems within the current territory of the Republic of Armenia, as well as other historical provinces (Turuberan, Vaspurakan, Syunik, Ayrarat, Gugark, etc.), three main spatial-typological groups of fortresses can be distinguished in Tayk. These groups are closely interconnected with the logic of settlement placement and development.

The first group consists of riverbed fortresses, located along major rivers or in adjacent lowland areas. They were formed to control strategic communication routes, since historical road networks largely coincided with river systems. Functionally, these fortresses served as primary defensive nodes, absorbing the enemy's first blow and ensuring the safety of nearby settlements. Within this typological group, both local fortresses (such as Nikhagh, Vorjnhagh, Chordvank in the Arsatspor district; Inkuzeq, Asparashen in Azordatspor, etc.) and regional centers can be distinguished, which coordinated the defense of broader territories (for example, the Tortum fortress, the Bolkha district center fortress—Oltu or Ughtik, etc.) (Figs. 1,2).

[2] The newly discovered fortress near Tigranakert, Artsakh, Armenian Studies, Stepanakert, 2014, 14-22.

Fig. 1. *The Castles of the Boy and Girl of Parnak*

Fig. 2. *The Cave Fortress-Dwelling of Berdunk*

The second group includes mid-river fortresses located along typical sections of tributaries that feed major rivers. These represent the next level of the defensive system. Depending on the length of the tributary and the abundance of arable lands along it—which in turn determined the number of medium and large settlements—multiple fortresses could exist within a single sub-valley. Good examples are the several fortresses of Hovak and Aspak in the Bolkha district. These fortresses are typically situated at elevations of 1400–1700 meters above sea level. They were intended for situations in which the enemy managed to break through the primary river line defense. In such cases, the invasion would continue upstream along tributaries, where each sub-valley formed a new local center of resistance. This type of fortress is numerous in Tayk and played an important role in the depth organization of the defense system, ensuring a mechanism of gradual resistance (Fig. 3).

Fig. 3. *Aspak and Arsis/Arsyats fortresses*

The third group consists of high-mountain fortresses, located at elevations of approximately 1800–2200 meters above sea level, mainly on plateaus, often built on hills within these plateaus. These form the third, deepest defensive line and are characterized by wide visibility and high strategic control. Examples include the fortresses of Vorduli in Berdatspor, Geghik, and Vardishen in Okaghe, and Chordvank and Turkashen in Kogh. Notably, this zone contains the oldest layers of fortification, including Bronze Age and Iron Age structures, which indicates the early strategic importance of these areas.

The combination of these three types constitutes the complete defensive structure of the Tayk fortification system, grounded in spatial hierarchy and the purposeful use of natural landscapes. In its fundamental principles, this system is comparable to fortification models found both in the present-day territory of the Republic of Armenia and in other historical provinces of Armenia, demonstrating a unified military-architectural approach.

At the same time, it should be noted that Armenian fortification typology also includes a group conventionally referred to as "plain fortresses," which, however, are absent from Tayk due to the region's mountainous, gorge-dominated landscape. Plain fortresses are typical of relatively flat environments and are constructed on low hills. Despite topographical differences, certain structural features of these fortresses are comparable to those of highland fortresses. According to our observations, such fortresses are located at elevations of approximately 800–1000 meters above sea level. Examples include several well-known fortresses of the Ararat plain, such as Erebuni, Karmir Blur, and Oshakan, as well as the ancient Armenian capitals Artashat and Armavir.

The long-standing and stable traditions of fortification in Tayk indicate that fortresses possess not only architectural and spatial significance but also carry deeper semantic meaning. They function as multilayered systems in which material, functional, and ideological components are intertwined. In this context, an important theoretical question arises: should fortresses be considered exclusively as physical and spatial structures, or do they also possess intangible cultural, spiritual, and symbolic dimensions? In other words, it is necessary to determine whether fortification is limited to military-defensive functions or also includes processes related to collective memory, folklore, and identity formation.

Research shows that the fortification tradition of Tayk, shaped over millennia, has had a significant cultural impact. Through their continuous use, reconstruction, and spatial role, fortresses became integrated into local cultural systems, acquiring symbolic and sometimes spiritual significance. Thus, the fortification system of Tayk can be characterized as a complex phenomenon in which architectural, spatial, and cultural layers are interwoven. It represents not only a material heritage but also a multifaceted system suitable for further in-depth and sub-typological scientific study.

Armenian authors have consistently accorded castles and fortresses significant importance in their historical novels and literary works, most notably in the works of Gevorg Marzpetuni (Muratsan) and Derenik Demirchyan. They depict castles not merely as architectural structures but as embodiments of historical experience and human resilience in the face of external threats. In their narratives, castles function as both strategic defensive sites and symbolic representations of continuity, protection, and the endurance of Armenian socio-political and cultural life. Castles are prominently featured in biblical texts, often depicted as instruments of defense. God is frequently metaphorically associated with castles, symbolizing protection and security.

The Word "Castle" from the Point of View of Semantics

To emphasize the semantic comprehensiveness of the word castle/fortress, it is important to study the Armenian lexical use of it as a unit in various collocations and metaphorical combinations. In its basic form, the word castle/fortress appears at different linguistic levels. We will particularly address its word-forming possibilities as a lexical unit in a linguistic context. As a root, a *fortress* can actively participate in the formation of both word complexes and word derivations, often becoming a complex derivational word: Fortress, fortalice [17].

The word “castle” is equivalent to the word *Berd* (fortress) – “Berdatsunts” - in the sense of extremely strong, thunderous [18].

We often notice that the word *tower* (berd) is used as a synonym for fortress. According to the “Dictionary of the Modern Armenian”[3] a *fortress* is a fortified structure serving defensive purposes, such as a tower. S. Malkhasiants' Armenian Explanatory Dictionary [17] emphasizes the following semantic layers of the word fortress:

1. *Strong place, strong.*
   - Inaccessible mountains are sometimes fortresses.
2. *An artificially fortified position or structure for defense against the enemy.*
   - To build a fortress,
   - To destroy a fortress,
   - They remained besieged in the fortress for two years.
3. *A strong bolt or lock.*
   - A lock for the house makes it a fortress.
4. *A conical mound of dung.*
   - How many fortresses of dung do you have?
   - They plant a broom tree at the edge of the castle.

This last version of this word, in the meaning of a dung heap, is particularly noteworthy. One of the narrators from Shirak, Aregnazan Mkhitaryan (H. Matikyan’s fieldwork, Shirak region, 2025), mentioned in a private conversation with us: “We call a dung heap a ‘ghalakh.’ We do not use the word *fortress*. We will make a dung heap, cover it with manure, which will resemble a dome, a real fortress. We make it wider at the bottom, then crush it from above. The appearance is that of a fortress”.

In another source, the word ‘fortress’ is also used to mean a dung heap, a place to store dung [19]. The dung cone, or tower, is cattle dung, which, after some processing, is divided into rectangular pieces and stacked in a circular cone shape to dry, so that it becomes winter fuel. This old tradition is still used in Armenian villages, and some skill is needed to stack it correctly, so the "stack" has sufficient strength and is as open as possible from all sides, allowing the dung to dry. This stack, seen from above, resembles a truncated cone and a tower, like the conical towers of a castle.

In the early architecture of the Armenian highlands, T. Toramanyan discovered tower-shaped structures built atop hills, preserved as truncated cones without covers (Fig. 4). Their purpose remains unknown; for example, the "Oyugh" tower [20] near the village of Aghavnadzor. The tradition of building towers from dung probably dates back thousands of years and can be linked to the tower-shaped structures of the Armenian Highlands.



Fig. 4. *Megalithic period tower-shaped structure of Aghavnadzor ‘Oyugh’ according to T. Toramanyan, Dung Tower, fortress. Traditional Armenian residential house in the village of Tsaghkunk*

[3] Dictionary of Modern Armenian. Language Institute Named After H. Acharyan, NAS RA, Yerevan, 1969 (in Armenian). Available at: https://surl.li/qzfrvp (accessed on June 30, 2026).

The synonymic paradigm indicates the following synonyms for the word fortress: fortress, fort, castle, stronghold, military base [21].

The word *castle* has an idiomatic use, where popular ideas are revealed, for example: *air castle / unreal, unrealizable dreams /, building air castles/weaving unrealizable plans /, castle in the air / unreal dream /, castle made of paper* [22] – all having the meaning of an unreal dream.

All of these idioms have a **negative or ironic assessment**:

- "building air castles" → frivolous plans,
- "castle made of paper" → quickly collapsing hope.

This shows that Armenian folk thinking values practicality, moderation, and realism.

The idiomatic uses of the word "castle" reveal the language's figurative thinking. The following elements are also deployed in the cited idioms:

- **air** - emptiness, instability
- **paper** - fragility, temporality

These are contrasted with the castle's traditional material, **stone**, which is a criterion of stability in linguistic thinking.

In parallel, we have encountered a phraseological unit with the same meaning in English-speaking culture: "castle in the air". In some cases, the expression "building castles in the sand" is common. A rich series of idioms is formed with *air* and expresses uncertainty in Armenian:

- Thrown into the air- empty,
- To shoot into the air – to express oneself in an empty place,
- Being in the air – not stable,
- Living in the air – to live a life detached from life and reality.

In Armenian and English reinterpreted structures, the castle serves as a metaphor for strength, imagination, dreams, and security, and, by linking it to fragile materials (*air, paper, sand*), irony is created. Thus, *the air castle, the paper castle,* and the English *castle in the air* give an idea of the imagination of the human mind, while at the same time emphasizing the real components of the castle's construction – the stone that gives it strength.

The meanings of *house* and *castle* are sometimes identified in English figurative expressions, particularly in proverbs and sayings: "An Englishman's home is his castle", "A man's home is his castle", "My home is my castle". The house is compared to a *castle* because, by law and tradition, it provides the Englishman with protection, power, and freedom, as a castle provides to a king.

The word-formation possibilities of *castle* and the diversity of reinterpreted structures it forms can be explained by its central role in a person's social and personal life. In all cases, the examination of dictionary material allows us to conclude that the words formed with this component predominantly emphasize the dominance of the concept of castle, which acquires its semantic authority during word-compounding and word-derivation. The concept of the *castle* becomes a word-root, a word-pole, around which folk phraseological thinking is also vibrantly formed.

Consider the general architecture of a traditional Armenian residential house in the village of Tsaghkunq, Gegharkunik Province, Republic of Armenia, which has been preserved since the 19th century. We see a rectangular structure, part of whose aisle has the form of a truncated cone. The main halls of the houses had no other windows, and the only window was above. If we compare it with the tower-shaped structure, the tower of the dung (Armenian: atar), we will see similar dimensional commonalities. In other words, the term house-fortress shares commonalities in both physical and spiritual senses (Fig. 4).

The Symbolic Meaning of Castles in Biblical Texts

In biblical texts, the concept of "castle" often symbolizes reliability, protection, and strength, emphasizing divine or human protection. It is associated with mountains. Let us cite examples: Mountains are extraordinary places with unique environments. They are the threshold of calm and chaos, life and death. Historically, mountains have been places of seclusion, retreat, and sanctuary, places of voluntary spiritual contemplation, meditation, and refuge, or places of involuntary escape from enemies. The Bible makes extensive references to mountains and hills as places of protection: "I will say of the Lord, my refuge and my fortress, my God, in him I will trust". **Daniel 11:19** "After this, he will turn back towards the fortresses of his own land, but he will stumble and fall and be no more". This is about a king or general who leans on the **fortresses of his land**, but is ultimately defeated. Physical fortresses do not provide salvation without the will of God.

God is the only fortress where man can find true security—not material, but spiritual and eternal. Human-built fortresses may collapse, but no danger can destroy God's fortress, because it is founded on faith, righteousness, and the name of the Lord.

These literary and folkloric manifestations are not accidental, since the fortress was vital to both the physical and spiritual protection of human identity. In the Armenian Highlands, we know of numerous natural *hill/mountain/ mountain fortresses* that, due to their difficult access, served as natural strongholds for the surrounding population. In this case, we should not only consider physical but also spiritual protection. In general, the choice of the location of the fortresses, the construction approach, the spatial connection between the settlement and the fortress, the role of the fortress citadel and the harmony with nature, the secular and the spiritual, and the essence and manifestations of the interconnectedness with the higher are seen in the examples of Tayk Geghik, Enkuzek, Erknis, Hovak and several dozen other fortresses (Fig. 5).


Fig. 5. *The Early-Period Fortress of Geghik Village in the Voqaghe Province, and the Megalithic Fortress of Chordvank Village in the Kogh Province*

A manifestation of Tayk fortress construction, which we labeled "God Ahead" during fieldwork, was probably also found elsewhere in the Armenian Highlands, but was particularly evident in the relatively well-preserved Tayk fortresses. All the fortresses have or had cult structures. Following the example of medieval Tayk fortresses, these have been preserved as churches, mostly modest single-nave churches with halls, lined up like the fortress walls. However, the other regularity is more remarkable, namely the location of the churches within the fortresses. The fortresses are naturally built on heights, and the entrance is usually from the rear. The most protected part of the front is inaccessible, and an enemy approaching through the gorge sees only this aspect of the fortress. Churches within the fortresses are placed near the main facades or, if the facade faces east, are generally integrated into the walls. That is, the enemy is initially "met" by the cult structure. This phenomenon is widespread in Tayk Arsiatspor, Vokaghe, Azordatspor, Boghkha, Partizatspor, and other provinces, as recorded by us in Odik, Enkuzek, Arsis/Arsits, Berdagrak, Oshkidzor, Barnak, Aspak, and Berdus (probably Berdunk) Cave-Fortress 2, the third fortress of the village of Hovak, etc. This emphasizes that a person who is physically protected must first and foremost be spiritually protected. In a private conversation with us, Kaps teller Vrezh Margaryan (H. Matikyan's fieldwork, 2024) compared the cave to a fortress: "In ancient times, the cave was considered an auxiliary defensive place to the fortress. The kingdom of canyons and caves protected the people. They built a wall in front of the cave. There was such a cave-fortress in the territory of the Kaps village".

Shirak teller Katya Khachatryan (Fieldwork, 2025, Shirak region, settlement Horom) mentioned in conversation: "We had our own fortress, our mountain, which was a fortress city".

The mention of a cave-fortress preserved in Shirak folklore is also interesting. It turns out we really do have cave-fortresses. One of the cave-fortresses discovered during our fieldwork this year was Berdus/ Berdunk, which also serves as the gateway to the Partez settlement, the provincial center of Partizatspor. The road leading to the provincial center of Partez passes through the gorge past the Berdus/Berdunk settlement, near which it narrows considerably, where it also joins the narrow gorge coming from Berdazpor province. That intersection was mostly protected by three cave-fortresses, the front walls of which have been preserved. Berdus/Berdunk cave-fortress 2 is a complex fortification system-labyrinth with three- to four-story-high caves, the front parts of which were enclosed by a wall (Fig. 2). On the first floor, the entrance junction, lined with high towers, has been preserved. The eastern facade of a single-nave hall church is integrated into the third-floor wall, and about 800 meters to the north, along the fourth floor, the cave leads to another single-nave hall church standing separately on a platform. About 50 meters north of that last church, a small square-shaped lime-mortar fortress has been preserved. This probably enclosed the complex's northern entrance. About 500 meters north of the last fortress, on a high cliff in the gorge, another small fortress is located. In general, cave-fortress settlements are found throughout the Armenian Highlands and adjacent regions, including Ani, Vardzunik, and Khndzoresk.

The Functional Significance of the Castle/Fortress in the Folklore Environment

The castle or fortress has not only physical but also symbolic significance in Armenian folklore. In fairy tales, the fortress often serves as a closed world in which the king's daughter is imprisoned or a magical object is kept.

It symbolizes a test for the hero, who must cross the border and enter another world.

The word *fortress* recurs in several Armenian folk tales. The king's fortress is emphasized, for example, in the fairy tale "Kiko", while the devil's fortress is prominent in the fairy tale "Khipilik's headwear". In the "Bald Man's Tale", the fortress is described as a structure on the top of a mountain: "… a long way, a short way, against a barren mountain, they saw that small mountain at the top of a mountain fortress…".

This "A long way, a short way" means not only a physical process but also **a test, a hero's path.** "A long way, a short way"–a folk phrase created by the repetition of movement–indicates covering a long distance, which is characteristic of the fairy tale environment. As we have discussed, the means of defense is sometimes manifested in the folklore environment as a fortress. This is depicted not only as a physical structure but also as a place endowed with spiritual, social, and cultural functions, associated with heroism, testing, unity, and preservation of tradition. Many heroes in folk tales must overcome a fortress's walls to prove their strength.

Considering the fortress as a form of test, we first find fortresses where the act of climbing, let alone building, itself constitutes a challenge and a test. For example, the fortresses of Tayk Vordis/Vordik, Aspak, Kitsporut, Vzhjanget, Erakhani, and others are built on inaccessible, remote rocky outcrops, and one cannot help but imagine the challenges the builders must have overcome. The result was a real, psychologically oppressive effect on the opponents and a great psychological advantage for the defenders, who had accomplished a feat simply by building it. They lived proudly below the fortress and always felt protected by it (Fig. 3).

The Castle in the Artistic Environment

In literary contexts, the castle is identified with the mother, the cradle, and the motherland. All this takes a particular form in the folk art of Hovhannes Shiraz:

Whether I am a swaddled baby, life is a cradle, you are the child in my arms,

Whether I am an army, you're my fortress; you are the tent I put up.

Or:

Our mother is our ***cradle,***

Our mother is our home's ***fortress***.

In these lines, with musicality, the word "mother" is repeated: she is both the cradle, the beginning, and the source, and she ensures the home's protection.

In folk thinking, the mother is also a fortress, a rock. The idea of remaining defenseless is sometimes emphasized in the expression of being an orphan without a mother, that is, being defenseless.

In this parallel of motherhood/motherland, it hardly seems a coincidence to find the fortress of VORDJNHAGH in the Arsyatspor province of Tayk, or the NIKHAGH located next to it. Fortresses are mentioned there, dating back to the early Middle Ages, when they were known as the cradle of the Mamikonians [21]. The names of the fortress are composed of the roots "VORDJ" and "Khagh", as well as "NI" and "Khagh". If we consider, for example, the Oshkidzor settlement and the fortress of Tayk, we will see that the fortress, with its location and majestic appearance, leaves an impression of protection and a cradle, or of protecting the "infant" like a mother, physically and especially spiritually. Almost all large villages in Tayk have their own local fortresses, while the provincial ones are even larger. In other words, for the natives, the builders were psychologically associated with security and warmth. In one of the Shirakian love rhyme songs, the beloved considers his beloved a fortress:

The water has gone its own way,
The dew has gone to the rose,
My beloved brave boy,
Is a fortress among a thousand.

(Hasmik Matikyan's Fieldwork, 2025).

The expression "*Is a fortress among a thousand*" shows that he stands out from all others, like a fortress in a plain: high, unshakable, unique. In musical folklore, especially in songs containing clear local coordinates, the fortress is emphasized by using a clear place name:

Under the destroyed fortress of Kars,
My beloved girl was sleeping,
I called her name, but no response,
I guess she was aching.

The terms "beloved fortress", "paired fortresses", and "girls' and boys' fortresses" are again widespread in Armenian fortification practice. According to the memoirs of Atrpet [23] and others, the Parnak twin fortresses of the Berdacpor province are known, one of which has an emphasized cult orientation—"GIRL", with "BOY" behind it, leaning on an inaccessible rock mass (Fig. 1). Fortresses with such names have been preserved, for example, in the present-day Tavush region of Armenia, etc. In the context of folklore games, the "Fortress game" deserves attention. V. Bdoyan, referring to "Fortress game", notes that this "Armenian game was written down in the period from the end of the 19th century to the middle of the 20th century. The collected games are the remains of medieval fragments; they are important both in terms of form and content".

The traditional game known as "Fortress" derives its name from the concept of a fortress and reflects symbolic notions of defense, territory, and social organization. The central object of the game, representing the fortress, may be constructed from various materials, such as a flag, a large stone, or another selected marker. Participants are divided into two groups of equal strength: one assumes the role of defenders of the fort, while the other attempts to capture it. The defenders protect the symbolic structure, with the most agile participants placing one foot on the fort or holding a stake or pillar established within it. The opposing team captures the fort by touching the object or placing a foot upon it, followed by a verbal declaration announcing the successful capture. Due to its representation of military strategies, defensive practices, and territorial competition, the game is traditionally classified as a military game [24].

Although the fundamental structure of the game remains consistent, fortress is practiced according to diverse regional variations throughout Armenia. These localized adaptations demonstrate the dynamic nature of folk traditions, in which cultural practices are continuously reproduced and transformed through community participation. A particularly significant element in some versions of the game is the inclusion of an “architect” role. The presence of this figure indicates that the fortress's symbolic meaning extends beyond the physical structure itself, reflecting cultural recognition of the social function of the builder or designer who created and organized defensive space.

This interpretation corresponds with S. Bronner’s concept of **cultural praxis**, introduced in *Explaining Traditions: Folk Behavior in Modern Culture* (2011). Bronner argues that traditions should not be understood simply as fixed cultural forms inherited from the past; rather, they acquire meaning through performance, repetition, and local enactment. Through practice, traditions become active expressions of social structures, collective concerns, and cultural systems of knowledge [25].

From this perspective, the game of Fortress represents more than a recreational activity; it functions as a performative model through which participants negotiate symbolic space, authority, and social roles. The acts of defending and capturing the fort reproduce concepts associated with the construction and protection of physical structures, while the designation of an architect introduces a figure of organization and authority. By imitating the social processes involved in creating and managing defensive spaces, the game operates as a mechanism of folk transmission, preserving and communicating cultural knowledge through embodied experience and participation.

Following Bronner’s approach to folk architecture, buildings and built environments can likewise be examined as cultural expressions that both reflect and shape traditional practices. Architectural forms are not merely material objects but also representations of social behavior, collective memory, and systems of informal learning. Researchers studying folk buildings typically examine their form, construction methods, use, and decoration. Among these elements, form—particularly elevation, façade, floor plan, and decorative features—is often prioritized because it is visible, measurable, relatively stable, and suitable for comparative analysis across different cultural contexts [26].

A further example of the fortress's symbolic and performative significance in Armenian culture is evident in the traditional group dance known as “Berd” (“Fortress”). Similar to the game of Fortress, the dance transforms the concept of the fort into a collective cultural expression. Through the formation of a human tower, in which participants support one another to create a symbolic defensive structure, the dance represents unity, cooperation, and the community's collective strength.

From the perspective of cultural praxis, the “Berd” dance demonstrates how architectural concepts can be transformed into embodied cultural practice. The fortress is no longer understood only as a physical structure or military object; rather, it becomes a symbolic form reproduced through movement, coordination, and collective participation. Through their bodies, performers recreate ideas of construction, stability, and defense, transforming architectural knowledge into an intangible cultural expression.

However, a folkloristic analysis of architecture extends beyond physical appearance. The social and behavioral processes associated with constructing, entering, and using buildings provide essential evidence of cultural transmission. The selection of materials, organization of labor, and practical use of enclosed spaces reveal systems of knowledge transmitted through imitation, observation, and participation. In this sense, both folk architecture and the Armenian game of Fortress demonstrate how communities communicate concepts of space, protection, authority, and social organization through lived practice.

Within this broader framework, medieval Armenian fortifications can be understood not only as physical structures but also as components of larger cultural, spatial, and communicative systems. Ara Zarean's recently published study on the medieval Armenian fortresses of historical Syunik examines the relationship between fortifications and broader networks of mobility and communication, interpreting them as interconnected elements within a regional infrastructural system. The study explores the spatial and functional relationships among roads, bridges, caravanserais, fortresses, and watchtowers, emphasizing their integrated role in the organization of medieval territories and the functioning of defensive, economic, and communication networks.

A significant contribution of A. Zarean's work lies in its systematic analysis of historical and textual sources, which provides a comprehensive framework for understanding the architectural, historical, and functional characteristics of these fortifications. The study also introduces a concise illustrated glossary of fortress components and related terminology, offering a valuable methodological resource for the classification, interpretation, and comparative study of medieval Armenian fortification architecture [27].

Castle/fortress in the Context of Paremiology

The concept of a *fortress*, entrenched in popular consciousness, also appears in folklore, in blessings and wishes, and in curses. Blessings-wishes, curses, oath formulas, both in general and in Armenian linguistics, are considered words of desire. Wish formulas/blessings/ composed of the words "mountain" and "fortress": sometimes these word combinations are used in parallel. Our fieldwork across various settlements in the Shirak region provides evidence of this:

- Be as strong as a fortress,
- Be as strong as a mountain,
- Be my rock,
- Stand tall like a mountain,
- If you have a parent, your parent stands behind you like a rock/fortress/,
- As firm as a mountain, as upright as a tower.

In several reinterpreted folk structures, especially in blessings, the nouns "mountain" and "fortress" sometimes become equivalent.

Armenian wishing texts demonstrate a marked prevalence of the lexical root associated with "fortress". Formulas that invoke a castle or fortress occur throughout the full range of cultural expressions, from children's nursery rhymes to adult ritualized wishes, reflecting the enduring symbolic significance of fortification in Armenian cultural consciousness. For instance, the Armenian word **«ամուր» (amur)**—the root of **«ամրոց»** (amrots) (castle or fortress)—is explicitly described as signifying strength, stability, and protection, further emphasizing the conceptual association between fortresses and resilience in both linguistic and cultural contexts. 'May your teeth be strong', 'May your back be strong', 'May your feet and hands be strong', 'May you have a strong family', 'May your arms be strong', etc.

The meaning of strength is sometimes expressed in the word combinations "wall" and "back":

A piece of *wall* – a giant, or standing like a wall,

To have someone's *back* – to protect someone,

Back someone up – to give strength.

In literary sources, we find terms such as "mountain" and "rock". These are logical formulations, since it is no secret that, physically, the fortresses are located on a hill. In this regard, in addition to the ancient traditions adopted across the Armenian Highlands, we also encounter in Tayk a specific fortification principle that the citadel of the fortress was not built on the highest point, but in the middle of the gorge, on a naturally isolated island-shaped rock massif, usually close to a settlement of the same name: Enkuzek, Norberd, Erakhani, Oshkidzor, Nikagh, etc. It is not that we do not encounter the mentioned principle in other provinces of Armenia, but it is much more widespread here.

Conclusion

During field studies, the question often arises: “Where are the people who built such fortresses?” That question not only suggests a loss of hereditary continuity, but it also emphasizes the need to restore cultural self-awareness as a condition for national vitality and self-preservation. The construction of the cities of settlement and their physical and moral-psychological guardians was based on our ancestors' systematic ideas about the fourfold division of the world and the three-class division of society, which were part of natural philosophy. The urban planning creations of Tayk discussed here were also built using this general approach, which naturally combined with local worldview peculiarities over time.

The comparative approach adopted here revealed that, in Armenian cultural perception, the fortress is not only a material defensive structure. It is also a semantic and symbolic system in which physical reality and folk imaginative thinking are interconnected and mutually shape one another. Fortresses are not only built environments but also narrative spaces where architecture and folklore mutually construct meaning. Grounded in the parallel examination of material structures and intangible cultural expressions, this approach enabled a more comprehensive understanding of fortifications as both built environments and culturally constructed meanings. The authors note that the existing scholarship predominantly comprises historiographical, source-critical, and topographical studies, as well as descriptive analyses of individual fortresses. Systematic and theoretically grounded studies remain rare, and only a limited number of works address issues of spatial organization and territorial distribution. Two main factors can explain this situation. The first is geopolitical: the present territory of the Republic of Armenia is distinctly surrounded by its historical regions, and, due to geopolitical constraints, the physical investigation of fortresses has long been inaccessible to many researchers. The second factor concerns the poor state of physical preservation of fortresses within the current borders of Armenia, where most survive primarily as archaeological remains.

The typological analysis of Tayk fortifications reveals a coherent hierarchical system consisting of riverine, mid-valley, and high-mountain fortresses. This spatial structure reflects not only defensive logic and adaptation to geography but also a deeper principle of territorial organization embedded in the settlement culture of the Armenian Highlands. The recurrence of similar organizational patterns across regions confirms a long-term, stable tradition of integrated settlement–fortress planning. At the same time, analysis of architectural materials, folklore, literary texts, oral testimonies, and Biblical texts demonstrates that the fortress occupies a central position in Armenian cultural consciousness. It is consistently reinterpreted as a symbol of protection, endurance, identity, and moral strength. Metaphorical structures such as fortress-mother, fortress-homeland, and fortress-cradle reveal how architectural space is transformed into a cultural model of collective security and belonging. Idiomatic and semantic extensions of the term “fortress” itself further confirm its deep integration in an Armenian linguistic worldview, where concepts of stability and protection are anchored in both material and symbolic dimensions.

The convergence of architectural evidence and folkloristic interpretation indicates that Armenian fortresses function as memory-bearing structures, linking physical space with narrative tradition and collective identity. They are not isolated monuments but active components of a cultural system in which the built environment, language, and belief mutually reinforce one another. The methodology applied here demonstrates that the fortress, as a form of tangible cultural heritage, cannot be fully understood outside the framework of intangible cultural memory. While fortresses are materially present as architectural and archaeological structures—defined by walls, spatial organization, topography, and defensive logic—they simultaneously exist in cultural consciousness as vehicles of collective memory, transmitted through folklore, oral narratives, linguistic expressions, and symbolic representations.

From this perspective, the semantic field of "fortress" is directly conditioned by architectural form and function. Key physical characteristics of fortifications—such as elevated placement, enclosure, defensive systems, and visual and spatial dominance—are consistently mapped onto linguistic and conceptual structures that denote strength, protection, stability, and security. Consequently, any semantic analysis of the lexical unit "castle/fortress" must be firmly anchored in its architectural and spatial foundations, since the built environment constitutes the primary experiential source shaping its cultural, metaphorical, and linguistic meanings. In biblical discourse, fortresses symbolize a human security that is insufficient unless grounded in spiritual protection and faith in God.

This is further supported by folkloric evidence, where the concept of the fortress, deeply embedded in popular consciousness, is widely reflected in blessings, wishes, curses, and oath formulas. In Armenian linguistic and ethnographic tradition, such verbal expressions are generally classified as "words of desire", functioning as culturally codified forms of aspiration, protection, and moral evaluation. Fieldwork in various settlements of the Shirak region demonstrates that wish formulas frequently incorporate the lexical fields of "mountain", "fortress", and "rock", which are often used in parallel or in interchangeable configurations. These expressions reveal a shared metaphorical system in which physical elevation, stability, and structural strength are transferred into ethical and emotional domains. Many stories preserved in folklore come from ancient times and are directly related to male-female, earth-sky, stone-mountain, guardian, and tripartite structures (father/mother/child; Father/Son/Holy Spirit in the era of Christianity), a strong guardian, and many other philosophical ideas. In literary contexts, we find the fortress compared to the mother, the cradle, and the motherland, among other metaphors, as well as to the mountain and the rock. In song folklore, parallels are sometimes drawn, such as fortress-wall strength and beloved fortress. In epic folklore, building or appearing in a fortress is associated with trials and heroism. The mention of a cave-fortress preserved in Shirak folklore is also interesting, revealing a conceptual understanding and also pointing to a material history. Fortress games also place particular emphasis on social construction through the mandatory role of an architect-game maker.

These literary and folkloric manifestations are not accidental, since the fortress was of vital importance to the physical and spiritual protection of human identity. Armenian medieval fortresses are monuments of multi-layered cultural and spiritual value that, by their nature, go beyond the boundaries of purely defensive or constructional structures. The fortress in the Armenian cultural system acts not only as a material heritage—walls, towers, and defensive systems—but also as a symbol of spiritual security, collective self-awareness, and an inner connection with the native land. The study of folklore and ethnographic sources, particularly those from the Shirak region, shows that Armenians also perceived the fortress as a spiritual refuge associated with higher powers, the maternal image, the cradle, and protection.

In contemporary culture, the paucity of such structures surviving in Armenia, along with the historical realities of centuries of migration and displacement, has led to a gradual erosion of awareness of spiritual and physical protection. As a result, a certain weakening of national identity, of land ties, and of psychological tendencies toward adaptation has been observed. A combined interdisciplinary approach incorporating the folklore and intangible heritage of a region may therefore help to fill out our broader understanding of the partial record of a historical, tangible region or settlement.

Acknowledgements

The authors gratefully acknowledge the financial support of the Higher Education and Science Committee of the Ministry of Education, Science, Culture and Sports of the Republic of Armenia (RA MoESCS) for funding the two research projects underpinning this study.

The authors sincerely thank **Francesco Augelli** (Politecnico di Milano) and **Paul Cowdell** (University of Bristol) for their valuable guidance and academic support. They also acknowledge the Shirak Center for Armenological Studies (NAS RA), the National University of Architecture and Construction of Armenia, and the Land and Culture National Organization for their institutional support.

Conflict of Interest

The authors declare no conflicts of interest.

Funding

The research was supported within the two projects financed by the Higher Education and Science Committee of MESCS RA (1. Research project № 25RG-6B114; 2. Research project № 25RG-6A091).

References

[1] L. Nazaryan, D. Nahatakyan, A. Hayrapetyan, H. Muradyan, H. Matikyan, A. Akopov, The Spread of Chalcedonism in Tayk and its Influence on the Formation of the Historical and Cultural Environment. Proceedings in Archaeology and History of Ancient and Medieval Black Sea Region, 15, 2023, 736-744. Doi: https://doi.org/10.53737/2284.2023.77.54.028

[2] A. Akopov, D. Nahatakyan, S. Hakobyan, A. Hayrapetyan, Tayk, Historical and Architectural Research, part 1 (Azordatspor and Chakq). SCAS NAS RA, Gyumri, 2023.

[3] Gh. Alishan, Hayots Hin Havatke kam Hetanosakan Kronë. Hrazdan Publishing House, Yerevan, 2002 (in Armenian).

[4] A. Zaryan, Aknarkner Hin yev Mijnadaryan Hayastani Kaghakashinutyan Patmutyan. Academy of Sciences of the Armenian SSR, Yerevan, 1986 (in Armenian).

[5] S. Petrosyan, Daserë yev Eṙadasutyan Drsevornery Hin Hayastanum. Institute of History Publishing House, Yerevan, 2006 (in Armenian).

[6] A. Grigoryan, Armenian Christian Architecture and the Influence of Pre-Christian Culture, Yerevan, ATJATI Publishing, 2023 (in Armenian).

[7] M.V. Hovhannesyan, Haykakan Kilikio Berdern u Berdakaghaknery. San Lazzaro degli Armeni, Venice, 1989 (in Armenian).

[8] S.M. Krkyasharyan, Hin Hayastani yev Pokr Asiayi Kaghakneri Patmutyan Drvagner. Yerevan, 1970 (in Armenian). Available at: https://surl.li/snzwvh Accessed on June 20, 2026.

[9] H. Manandyan, Hayastani Kaghaknery 10-11 Darerum. Institute of History and Archaeology, Academy of Sciences of the USSR, Yerevan, 1940 (in Armenian).

[10] L. Kirakosyan, A. Aghajanyan, The Fortress-Settlements of Ghazaravan and Orgov (on the Defensive System and Architecture). Monument, 8, Yerevan, 2013.

[11] V. Harutyunyan, Haykakan Chartarapetutyan Patmutyun. Luys Publishing House, Yerevan, 1992 (in Armenian).

[12] S. Mnatsakanyan, Hay Chartarapetutyan Syuniki Dprotsë. Yerevan, 1960 (in Armenian). Available at: https://surl.li/zhdejr Accessed on June 28, 2026.

[13] S. Yeremyan, Hayastanë ëst Ashkharhatsuytsi (Pordz VII Dari Kartezi Verakazmutyan Zhamanakakits Karteghagrman Himki Vra). Academy of Sciences of the Armenian SSR, Yerevan, 1963 (in Armenian).

[14] E. Takaishvili, Arkheologicheskaya Ekspeditsiya 1917 g. v Yuzhnye Provintsii Gruzii. Academy of Sciences of the Georgian SSR, Tbilisi, 1952 (in Russian).

[15] Tao-Klarjeti, Istoriisa da Kulturis Dzeglebis Katalogi. Artanuji Publishing House, Tbilisi, 2017 (in Georgian).

[16] D. Nahatakyan, A. Akopov, A. Hayrapetyan, Tayk, Historical and Architectural Research, part 2 (Arsiatspor), SCAS NAS RA publ., Gyumri, 2024.

[17] S. Malkhasiants, Armenian Explanatory Dictionary (vol. 1). Armenian SSR State Publishing House, Yerevan, 1944 (in Armenian).

[18] S. Eloyan, Dictionary of Neologisms in Modern Armenian. Nairi, Yerevan, 2002 (in Armenian).

[19] A.M. Sukiasyan. Explanatory Dictionary of Synonyms of the Armenian Language. Yerevan State University, Yerevan, 2009 (in Armenian). Available at: https://surl.li/awcfem. Accessed on February 13, 2026.

[20] T. Toramanyan, Nyuter Haykakan Chartarapetutyan. Armfan Publishing House, Yerevan, 1942 (in Armenian).

[21] P. Bediryan, Extensive Explanatory Dictionary of Armenian Idioms. Yerevan State University Publishing House, Yerevan, 2011 (in Armenian).

[22] Leo, Hayots Patmutyun (vol. 2). Academy of Sciences of the Armenian SSR, Yerevan, 1947 (in Armenian).

[23] Atrpet, Chorokhi Avazanë. Mekhitarist Printing House, Vienna, 1929 (in Armenian).
[24] V. Bdoyan, Traditional Armenian Games. Academy of Sciences of the Armenian SSR, Yerevan, 1980 (in Armenian).
[25] S. Bronner, Explaining Traditions: Folk Behaviour in Modern Culture, The University Press of Kentucky, 2011.
[26] S. Bronner, American Folk Buildings, Constructions, and Landscapes. The Oxford Handbook of American Folklore and Folklife. Oxford University Press, 2019.
[27] A. Zarian, The Fortifications of the Syunik Region of the 9th-14th centuries, Vahram Abtalian Cultural Foundation of the Armenian General Benevolent Union (AGBU), Yerevan, 2026 (in Armenian).

Davit Nahatakyan, Doctor of Philosophy (PhD) in Architecture *(RA, Yerevan) - National University of Architecture and Construction of Armenia, Assistant Professor at the Chair of Theory, History and Heritage of Architecture; (RA Gyumri) - Researcher at Shirak Center for Armenological Studies NAS, e-mail:dnahatakyan@nuaca.am*

Ashot Grigoryan, Doctor of Science (Architecture) *(RA, Yerevan) - National University of Architecture and Construction of Armenia, Professor at the Chair of Theory, History and Heritage of Architecture; (RA, Yerevan) - Scientific Secretary of the National Museum-Institute of Architecture after Alexander Tamanyan, e-mail:ashothaykazun@gmail.com*

Hasmik Matikyan**, **Doctor of Philosophy (PhD) in Philology, Associate Professor *(RA, Gyumri) - Shirak Center for Armenological Studies, NAS, Researcher at the Department of Folklore Studies; (RA, Gyumri) - Senior lecturer at the Armenian State University of Economics, GB, hasvrej2024@gmail.com*

IRON-DECORATED GRAPHENE NANOPLATELETS PRODUCED BY ATMOSPHERIC-PRESSURE FERROCENE PYROLYSIS AS NANO-ADDITIVES FOR CEMENT MORTARS

Harutyun Gyulasaryan[1], Manoj Chhetri[2], Karen Martirosyan[2], Nelli Muradyan[3], Hovsep Hoveyan[3,4], Manuk Barseghyan[3]*, Aram Manukyan[1]

[1] *Institute for Physical Research, NAS RA, Ashtarak, RA*

[2] *University of Texas Rio Grande Valley, Texas, USA*

[3] *National University of Architecture and Construction of Armenia, Yerevan, RA*

[4] *Urban Development Committee, Yerevan, RA*

Abstract: *This study examines iron-based graphene nanoplatelets (Fe-GNPs), synthesized through a modified ferrocene pyrolysis route, as hybrid nano-additives for cement mortars. The nanomaterial was characterized by scanning electron microscopy, X-ray diffraction, Brunauer–Emmett–Teller surface area analysis, and thermogravimetric analysis, confirming a graphitic carbon network decorated with crystalline α-Fe nanoparticles. Mortars containing 0.001, 0.01, 0.05, and 0.1 wt.% Fe-GNPs, with and without surfactant-assisted ultrasonication, were tested in flexure and compression after 7 and 28 days of curing. The results showed a clear concentration-dependent response, with 0.01 wt.% yielding the highest strength gains. At 28 days, this dosage increased flexural strength by 14.5% without surfactant and by 21.2% with surfactant, while compressive strength rose by 17.8% and 22.5%, respectively, relative to the control mortar. Higher dosages reduced the reinforcing effect, mainly because agglomeration limited efficient stress transfer and matrix densification. The findings indicate that Fe-GNPs synthesized by a continuous atmospheric-pressure route are promising hybrid nano-additives for improving the mechanical performance of cement mortars, provided that dosage and dispersion are carefully controlled.*

Keywords: *iron-based graphene nanoplatelets, cement mortars, nano-reinforcement, dispersion, flexural strength, compressive strength.*

Manuk Barseghyan*
E-mail: manuk.barseghyan@nuaca.am

Received: 27.04.2026
Revised: 29.06.2026
Accepted: 14.07.2026

Introduction

Cement mortars are among the most widely used construction materials due to their cost-effectiveness and relatively high compressive strength. Despite these advantages, conventional cement mortars exhibit comparatively low tensile and flexural strength and limited fracture toughness, making them susceptible to crack initiation and propagation under tensile stresses, shrinkage, and environmental loading. These microcracks can significantly compromise long-term durability by facilitating the ingress of water, chlorides, and other aggressive agents that accelerate deterioration processes such as corrosion and chemical attack [1].

To overcome these limitations, significant research efforts have focused on reinforcing cementitious materials by incorporating micro- and nanoscale additives. Traditional reinforcement approaches include steel fibers, polymer fibers, and other macro-scale fillers that improve crack resistance and energy absorption [2-4]. More recently, nanomaterials such as carbon nanotubes (CNTs), graphene oxide, graphene-based nanostructures, nanosilica, and metal or metal-oxide nanoparticles have attracted considerable attention due to their exceptionally high surface area, mechanical strength, and ability to interact with the cement hydration products [5-7]. These nanomaterials can act as nucleation sites for hydration, promote the formation of additional calcium silicate hydrate (C–S–H) phases, and refine the pore structure of the cement matrix. Each class of nanomaterial contributes differently to mechanical enhancement, depending on its morphology, optimal concentration, and interaction with the cement hydration process.

In particular, CNTs and other carbon-based nanomaterials offer unique advantages due to their high aspect ratio and extremely high mechanical strength [8]. When properly dispersed within the cement matrix, they can enhance load transfer, bridge microcracks, and improve both mechanical and functional properties of cement-based composites. Consequently, integrating nanostructured reinforcements into cement mortars represents a promising strategy for developing next-generation, high-performance, multifunctional construction materials. In mortar matrices, the addition of CNTs has been shown to increase compressive strength by up to 35% and flexural strength by 28% compared to control mixes at optimal dosages (ranging from 0.02 to 0.5 wt.% of cement) under standard curing conditions [9]. Field-specific investigations also demonstrate peak enhancements in both compressive and flexural strengths at around 0.3 wt.% CNTs, with up to ~32–36% improvements after 28 days of curing [10].

Graphene nanoplatelets (GNPs), thin, plate-like stacks of graphene sheets with thicknesses of a few nanometers, provide a two-dimensional reinforcement morphology that can be even more effective under certain conditions. GNPs improve the mechanical properties of cementitious composites primarily through nanofiller effects, enhanced hydration, and crack bridging, thereby reducing porosity and creating a more compact microstructure [9,11].

Experimental studies have demonstrated that incorporating GNPs can significantly influence the mechanical performance of cementitious materials. For example, when GNPs are added at an optimal concentration of ~0.04 wt.% relative to cement, flexural strength has been reported to increase by up to 12.8%. Compressive strength increases by up to 33.9% after 28 days of curing compared with plain mortar [5]. In study [11], the addition of surface-modified GNPs at ~0.05 wt.% resulted in flexural strength increases of ~15-24% and compressive strength increases of ~3-8% in cement paste specimens. These findings highlight the strong dependence of reinforcement efficiency on nanoplatelet dispersion, surface modification, and concentration within the cement matrix.

The degree of strength enhancement depends strongly on the dispersion of GNPs, their concentration in the matrix, and their interactions with other components of the mortar. Excessively high concentrations of GNPs can lead to agglomeration, diminishing reinforcement efficiency, and potentially reducing the resulting strength gains. Effective dispersion methods, such as ultrasonication in the presence of surfactants or polymers (e.g., PVP), have been shown to significantly improve the uniformity of nanoplatelet distribution, thereby enhancing the mechanical performance of the composites [12,13].

In the present study, iron-based graphene nanoplatelets (Fe-GNPs) synthesized by a modified ferrocene pyrolysis route were evaluated as nano-reinforcements for cement mortars. Unlike conventional graphene-based additives, the present material combines graphitic nanoplatelets with iron nanoparticles generated via a single synthesis route, making it relevant from both functional and processing perspectives. The study focuses on two questions: first, whether Fe-GNPs can improve flexural and compressive performance at very low dosages; and second, how strongly the resulting behavior depends on dispersion quality. Special attention is therefore given to the combined influence of Fe-GNPs dosage and surfactant-assisted ultrasonication, as well as to the structural characterization of the synthesized nanomaterial. The aim is not only to identify an optimum dosage window, but also to clarify the practical conditions under which this hybrid additive can act efficiently in a cementitious matrix.

Materials and Methods

Raw materials

Ordinary Portland cement (OPC, CEM I 52.5 N) conforming to GOST 31108-2020 and supplied by Araratcement Factory (Yerevan, Armenia) was used as the binder. Its chemical composition and key physical properties, determined in accordance with GOST EN 196-1-2002 to GOST EN 196-3-2002, are summarized in Table 1. These parameters govern hydration kinetics, setting behavior, and the mechanical response of the reference mortar against which the effect of Fe-GNPs incorporation is evaluated.

Table 1. Chemical composition and key physical properties of the cement used in this study

Characteristics	Units		Results Obtained
Al_2O_3	Content wt. %		3.11
SiO_2			24.4
Fe_2O_3			1.1
CaO			56.9
MgO			4.8
SO_3			2.7
Free CaO			1.2
Insol. Resid.			1.79
Loss of Ignition			4.0
Specific gravity	g/cm^3		3.1
Blaine's fineness	m^2/kg		430
Standard consistency	%		29
Setting time	min	Initial	50
		Final	300
Flexural strength	MPa	7 days	4.4
		28 days	4.8
Compressive strength	MPa	7 days	44.4
		28 days	51.1

DISPERBYK-199, a commercial wetting and dispersing agent, was used to improve nanoparticle dispersion in the aqueous phase before mixing. According to the manufacturer, the recommended dosage is 0.2–1.0 wt.% of the total binder content. In the present study, the dispersant amount was adjusted in proportion to the Fe-GNPs content to promote nanoparticle wetting and reduce agglomeration during ultrasonication. This step was introduced because uniform dispersion is essential for effective reinforcement, whereas poorly dispersed nanomaterials may behave as defects rather than as strengthening inclusions.

Natural river sand was used as the fine aggregate. Its main physical properties are listed in Table 2. Before mixing, the sand was washed to remove impurities and oven-dried at (105 ± 5)°C for 24 h to constant mass. These precautions were taken to reduce unintended variations in moisture content and effective water-to-cement ratio. The use of well-characterized, clean, and dry fine aggregate was necessary to ensure that the observed changes in mechanical performance could be interpreted primarily in relation to Fe-GNPs incorporation rather than variability in aggregate condition.

The selected raw materials provided a stable basis for mortar production. They ensured that the measured changes in mechanical performance could be attributed primarily to the incorporation of Fe-GNPs rather than to uncontrolled variation in the constituent materials.

Table 2. Key physical properties of the fine aggregate (natural river sand) used in mortar preparation are presented as average values

Characteristics		Units	Results Obtained
Specific Gravity		g/cm^3	2.54
Bulk density in the loose state		kg/m^3	1650
Bulk density in compact state		kg/m^3	1790
Sieve Residue			
		Partial	Total
Sieve size (mm)	2.5	13.80	13.80
	1.25	21.05	34.85
	0.63	28.14	60.99
	0.315	19.94	89.13
	0.16	10.58	99.71
Particle content of < 0.16 mm		0.29	
Fineness modulus		-	2.98

Synthesis of Fe–GNPs

Iron-based graphene nanoplatelets were synthesized by a modified ferrocene pyrolysis method using a two-zone horizontal tube furnace. Ferrocene served as the organometallic precursor, while nitrogen-bearing benzene vapor transported it and provided an additional carbon source. The first heating zone was maintained at 180 °C to promote ferrocene sublimation, whereas the second zone was held at 1000 °C to induce thermal decomposition and formation of iron–carbon nanostructures. Compared with sealed high-pressure ferrocene pyrolysis, this atmospheric-pressure configuration offers better process continuity and greater practical relevance for scale-up. The presence of iron species formed during decomposition promotes catalytic graphitization, leading predominantly to graphene nanoplatelets together with a minor fraction of other carbon nanostructures (Fig. 1).

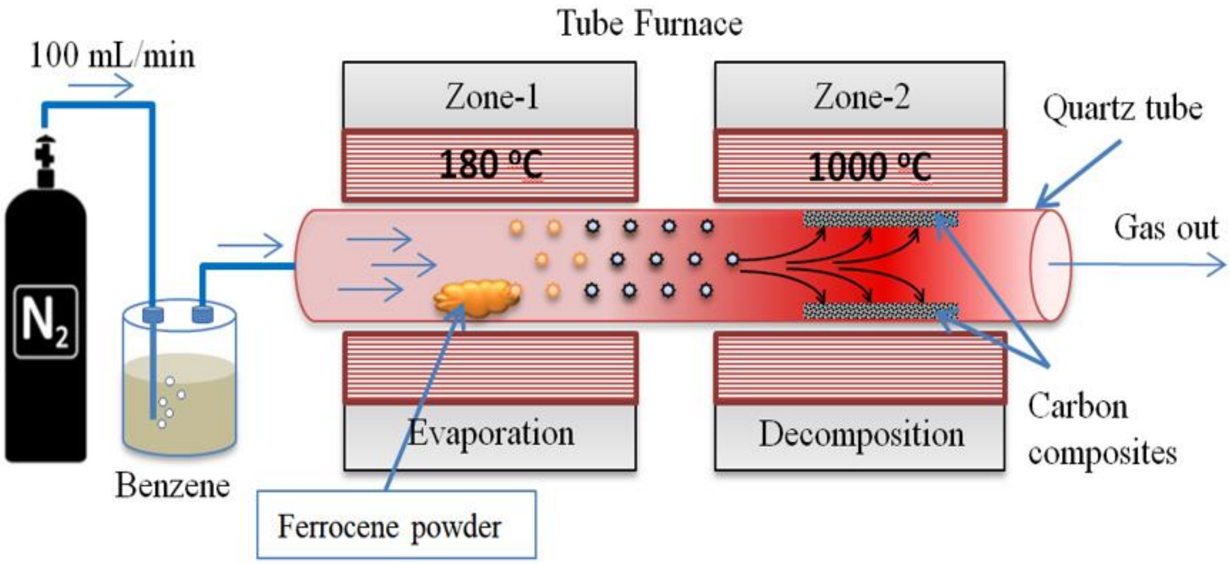


Fig. 1. *Schematic illustration of the ferrocene decomposition process and production of Fe–GNPs*

The first zone of the furnace is maintained at 180 °C to sublimate ferrocene, while the second zone reaches 1000 °C to induce thermal decomposition and formation of iron–carbon nanocomposites. Nitrogen flow enriched with benzene transports the ferrocene vapors between the zones, promoting the growth of graphene nanoplatelets. This setup enables continuous operation, controlled particle morphology, and scalable production of Fe–GNPs.

Mixing and Specimen Preparation

Cement mortars incorporating Fe-GNPs were prepared by a controlled multi-step procedure designed to improve nanoparticle dispersion and mixture reproducibility. First, cement and sand were dry-mixed for 3 min to obtain a homogeneous powder blend. In parallel, the mixing water was ultrasonicated for 40 min using a Hielscher UP400St digital sonicator (400 W, 24 kHz) to facilitate nanoparticle deagglomeration and dispersion. For Fe-GNPs-containing mixtures, the nanomaterial was gradually introduced into the water during sonication. In mixtures containing DISPERBYK-199, the dispersant was added to the same aqueous phase before mixing with the dry constituents. The liquid phase was then introduced gradually into the cement–sand blend, followed by controlled mechanical mixing. This sequence was selected to improve nanoparticle distribution and to limit the persistence of coarse agglomerates in the fresh mortar. The detailed mixing proportions of all mortar compositions are presented in Table 3.

Table 3. Mix proportions of cement mortars with varying Fe-GNPs content, with and without dispersant

Mix design	Sand (g)	Cement (g)	W/C	Fe-GNPs (wt.% of cement)	Dispersant (Disperbuk-199 wt.% of cement)
Without DISPERBYK-199					
C0	2200	880	0.47	0	0
C1	2200	880	0.47	0.001	0
C2	2200	880	0.47	0.01	0
C3	2200	880	0.47	0.05	0
C4	2200	880	0.47	0.10	0
With DISPERBYK-199					
C0	2200	880	0.47	0	0
C1	2200	880	0.47	0.001	0.001
C2	2200	880	0.47	0.01	0.01
C3	2200	880	0.47	0.05	0.05
C4	2200	880	0.47	0.10	0.10

For each composition, six prismatic specimens (40×40×160 mm) were cast for mechanical testing at 7 and 28 days. The mortar was placed in two layers and compacted on a vibrating table (C278, Matest, Brugherio, Italy) to reduce entrapped air and improve packing density. After 24 h, the specimens were demolded and cured at (20 ± 2) °C and 98% relative humidity. This procedure was adopted to maintain consistent curing conditions across all mixtures and to ensure that differences in mechanical response reflected material design rather than curing variability (Fig. 2).

The diagram illustrates the sequential steps, including ultrasonic dispersion of nanoparticles, incorporation of dispersant, dry mixing of cement and sand, gradual addition of the liquid phase, and layerwise casting with compaction. This procedure ensures uniform nanoparticle distribution, improved workability, and reproducible mechanical performance of the resulting mortars.

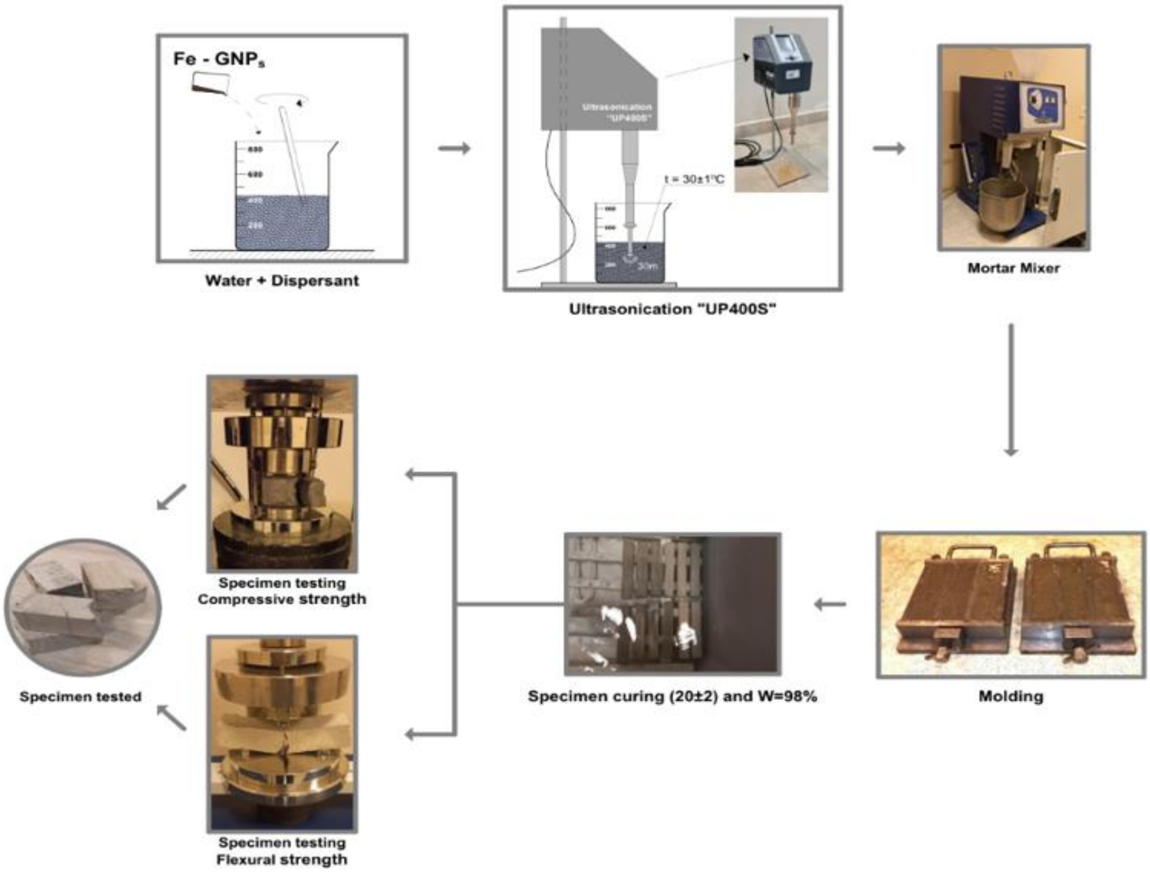


Fig. 2. *Schematic representation of the experimental procedure for Fe-GNPs-modified mortar mixtures*

Characterization Methods

Microstructural and Phase Analysis (SEM, XRD, TGA)

The synthesized Fe-GNPs were characterized for morphology, phase composition, and thermal behavior using scanning electron microscopy (SEM), X-ray diffraction (XRD), and thermogravimetric analysis (TGA/DSC). SEM observations were carried out on a LEO 1530 microscope operated at 30 kV with a field-emission gun, enabling direct visualization of graphene nanoplatelet morphology and the spatial distribution of iron nanoparticles. Phase analysis was performed using an X'PERT PRO diffractometer with Cu Kα radiation (λ = 1.5418 Å), enabling identification of the graphitic carbon and α-Fe phases present in the hybrid material.

Thermogravimetric analyses were performed on an SDT Q600 thermal analyzer to assess thermal stability and oxidation behavior. Approximately 11.4 mg of sample was heated from room temperature to 1000 °C at 20 °C min^{-1} under flowing air. The combined mass-loss and heat-flow data were used to distinguish carbon fractions of different structural order and to evaluate the contribution of the iron-containing phase during oxidation.

The specific surface area of the graphene-based nanomaterial was determined by nitrogen adsorption using a Micromeritics ASAP-2020M analyzer. The isotherms were interpreted using the Brunauer–Emmett–Teller method. Because surface area strongly affects interactions with hydration products and the nanomaterial's ability to act as a nucleation substrate, this parameter is relevant to interpreting subsequent mortar results.

Mechanical testing (Flexural and Compressive Strength)

The mechanical performance of the mortars was evaluated by flexural and compressive strength testing. Flexural strength was determined on 40×40×160 mm prismatic specimens using a Unitronic 50 kN machine under three-point bending in accordance with EN 196-1-2002, clause 9.2. Compressive strength was measured on 40×40×40 mm specimens using a Matest 2000 kN automatic testing machine in accordance with EN 196-1-2002, clause 9.3. Six specimens were tested for each composition, and average values were used for comparison. This testing program was selected to capture the influence of Fe-GNPs incorporation on both crack-sensitive flexural behavior and bulk load-bearing capacity.

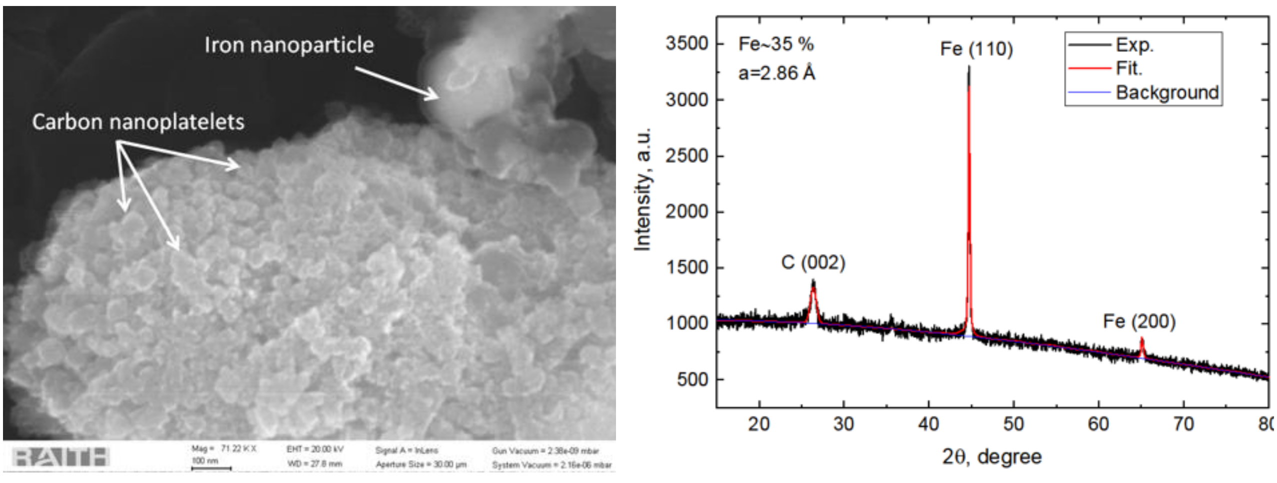
Results and Discussion

Structural Characterization of Fe-GNPs

Figure 3a shows the morphology of the synthesized Fe-GNPs. The SEM image reveals thin graphene nanoplatelets together with iron nanoparticles distributed across the carbonaceous matrix. In addition to platelet-like graphitic structures, a minor fraction of tubular carbon species is also visible, indicating that the pyrolysis process generated a mixed carbon nanostructure rather than a strictly single-morphology product. Such a hybrid architecture is relevant because platelet-like carbon structures can contribute to pore filling and crack deflection, whereas the iron particles may influence both graphitization during synthesis and interfacial behavior after incorporation into cementitious systems.

Figure 3b presents the XRD pattern of the synthesized nanocomposite. Rietveld refinement indicates the presence of two main phases: graphitic carbon and α-Fe. The reflection at $2\theta \approx 26°$ corresponds to the (002) planes of graphitic carbon, while the peaks near 45° and 65° are assigned to body-centered cubic α-Fe. The carbon reflection is relatively broad, which is consistent with limited stacking order and the presence of few-layer graphitic structures rather than bulk graphite. The sharpness of the iron peaks indicates that the metallic phase is comparatively well crystallized.

Quantitative phase analysis estimated the iron content of the nanocomposite to be approximately 35 wt.%, confirming the formation of a hybrid carbon–metal system. This result is important because the present additive is not a simple graphene powder modified after synthesis, but a material in which graphitic carbon and iron are generated together under the same pyrolytic conditions. That hybrid character is likely to influence both the powder's dispersion behavior and its interaction with the cementitious matrix.



a. b.

Fig. 3. a. *SEM micrograph*, **b.** *X-ray diffraction (XRD) pattern of Fe–GNPs*

The SEM and XRD results together confirm that the synthesized product is a hybrid nanocomposite composed predominantly of graphitic nanoplatelets and crystalline α-Fe nanoparticles, with a minor fraction of carbon nanotubes. This mixed nanostructure is potentially advantageous for cement reinforcement because it provides multiple interfaces for nucleation, stress transfer, and crack interaction.

Thermogravimetric analysis is widely used to assess the structural quality of graphene-based materials because the oxidation temperature depends strongly on graphitic order [14]. More ordered carbon structures generally oxidize at higher temperatures than defective or amorphous fractions. Accordingly, the TGA/DSC response of Fe-GNPs provides indirect evidence of the coexistence of carbon species with different structural organizations in the synthesized material.

Figure 4 shows the TGA/DSC response of Fe-GNPs in air. The curves reveal a multi-step oxidation profile, indicating the coexistence of carbon species with varying degrees of structural order and iron-containing phases. Rather than a single oxidation event, the thermal behavior reflects the heterogeneous nature of the synthesized nanocomposite [14].

The first oxidation stage, observed at approximately 300–350 °C, is associated with the combustion of amorphous and highly defective carbon. A smaller mass change in the range of 400–500 °C, accompanied by an exothermic feature, can be linked to iron-containing regions that are less effectively protected by graphitic carbon. This behavior suggests that the metallic phase is not uniformly encapsulated throughout the sample, consistent with the morphology observed by SEM.

The dominant mass loss, about 52%, occurs between 500 and 700 °C and is accompanied by a sharp exothermic peak. This stage is assigned to the oxidation of the more ordered graphitic carbon fraction, including graphene nanoplatelets and related graphitized structures. Its higher oxidation temperature, relative to the defective carbon fraction, is consistent with stronger structural order and greater thermal stability.

Above approximately 780 °C, only a weak thermal feature is observed, with negligible additional mass loss. The final residue, around 52 wt.%, consists predominantly of iron oxides and is consistent with the iron content estimated from XRD. Overall, the thermal analysis supports the interpretation that the Fe-GNPs material is a heterogeneous hybrid system comprising graphitic carbon, more defective carbon domains, and iron-containing particles.

This behavior can be further explained by considering the mechanism of nanomaterial formation and subsequent interaction with the cement matrix. During synthesis, iron nanoparticles act as catalytic centers that promote the decomposition of ferrocene and the graphitization of carbon species, thereby forming graphene nanosheets and small carbon nanotubes [15,16]. Thus, the presence of α-Fe is directly related to the mechanism of hybrid nanostructure formation.

Second, after incorporation into the cement matrix, iron nanoparticles are embedded within the graphitic carbon network. These iron-containing particles may enhance interfacial interactions between the nanomaterial and hydration products and may serve as additional nucleation sites for the formation of calcium silicate hydrate (C–S–H), thereby contributing to matrix densification [16].

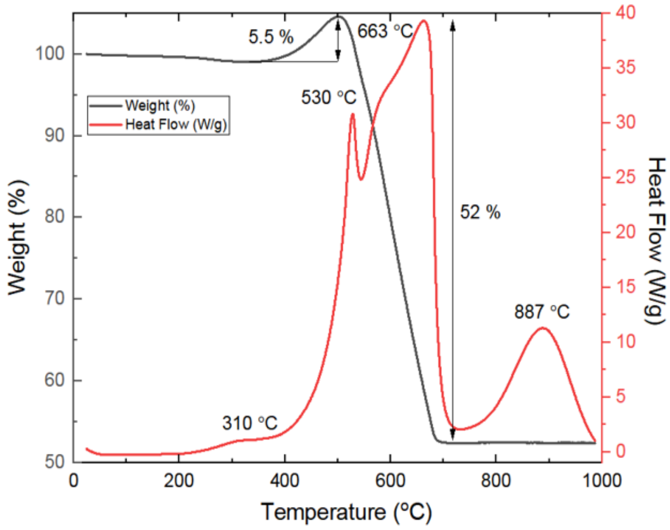


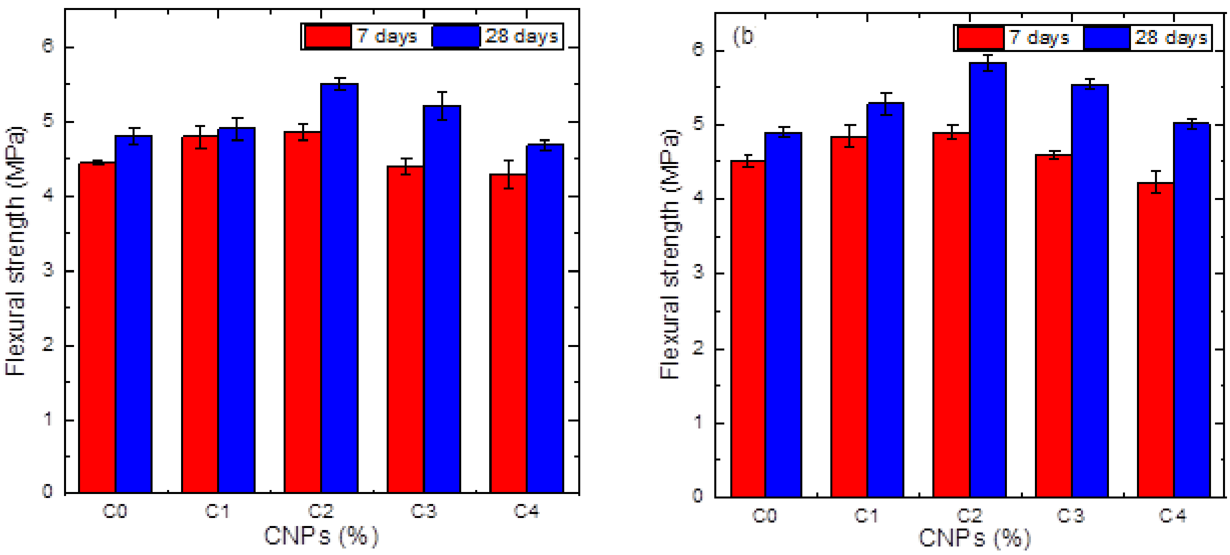
Fig. 4. *TGA and DSC curves of Fe-GNPs*

Flexural and Compressive Strength

The synthesized Fe-GNPs were incorporated into cement mortars as nano-additives to evaluate their influence on mechanical performance. Mortar compositions containing 0.001, 0.01, 0.05, and 0.1 wt.% Fe-GNPs relative to cement were prepared to identify a dosage range within which reinforcement could be achieved without severe agglomeration. Flexural and compressive strengths were determined after 7 and 28 days of curing, and the role of surfactant-assisted dispersion was examined in parallel.

In addition to the Fe-GNPs dosage, the effect of the dispersing agent DISPERBYK-199 was also examined. Before mixing with cement, the nanocomposites were ultrasonically dispersed in water for 40 min to improve distribution within the fresh mortar. In the surfactant-containing mixtures, the dispersant was introduced at this stage to stabilize the suspension and reduce re-agglomeration. This comparative design makes it possible to distinguish between the effect of the nanomaterial itself and the effect of improved dispersion quality.

Figures 5 and 6 summarize the flexural and compressive strength results for mortars containing different Fe-GNPs dosages, with and without surfactant. The designations C0, C1, C2, C3, and C4 correspond to Fe-GNPs contents of 0, 0.001, 0.01, 0.05, and 0.1 wt.% of cement, respectively. The reference composition C0 serves as the baseline against which the effect of Fe-GNPs incorporation is assessed.



a. **b.**

Fig. 5. *Flexural strength of cement mortars containing different wt.% concentrations of graphene nanoplatelets (GNPs).* **a.** *Mixtures without surfactant,* **b.** *Mixtures with the addition of surfactant*

The results are presented for specimens cured for 7 and 28 days, illustrating the influence of nanoplatelet concentration and dispersion conditions on the flexural performance of the mortar composites. The comparison highlights the role of surfactant-assisted dispersion in improving the effectiveness of GNPs reinforcement.

The experimental results show that both flexural and compressive strengths increased with curing age for all mixtures, as expected from continued cement hydration. The incorporation of Fe-GNPs further improved mechanical performance, but the magnitude of the improvement depended strongly on dosage and dispersion condition. Among the investigated mixtures, composition C2 containing 0.01 wt.% Fe-GNPs produced the highest strength values at both curing ages. After 28 days, the flexural strength of C2 increased by 14.5% without surfactant and by 21.2% with surfactant relative to the control mortar. Under the same conditions, compressive strength increased by 17.8% without surfactant and by 22.5% with surfactant. These results indicate that a low Fe-GNPs dosage can be effective when the nanomaterial is sufficiently dispersed within the cementitious matrix.

When the Fe-GNPs dosage exceeded the optimum level, both flexural and compressive strengths decreased. This behavior is attributed mainly to nanoparticle agglomeration, which reduces the effective surface area available for interaction with hydration products and creates locally weak regions in the matrix. The results therefore underline that the reinforcing effect is governed not only by the presence of the nanomaterial but also by the balance between dosage and dispersion quality.

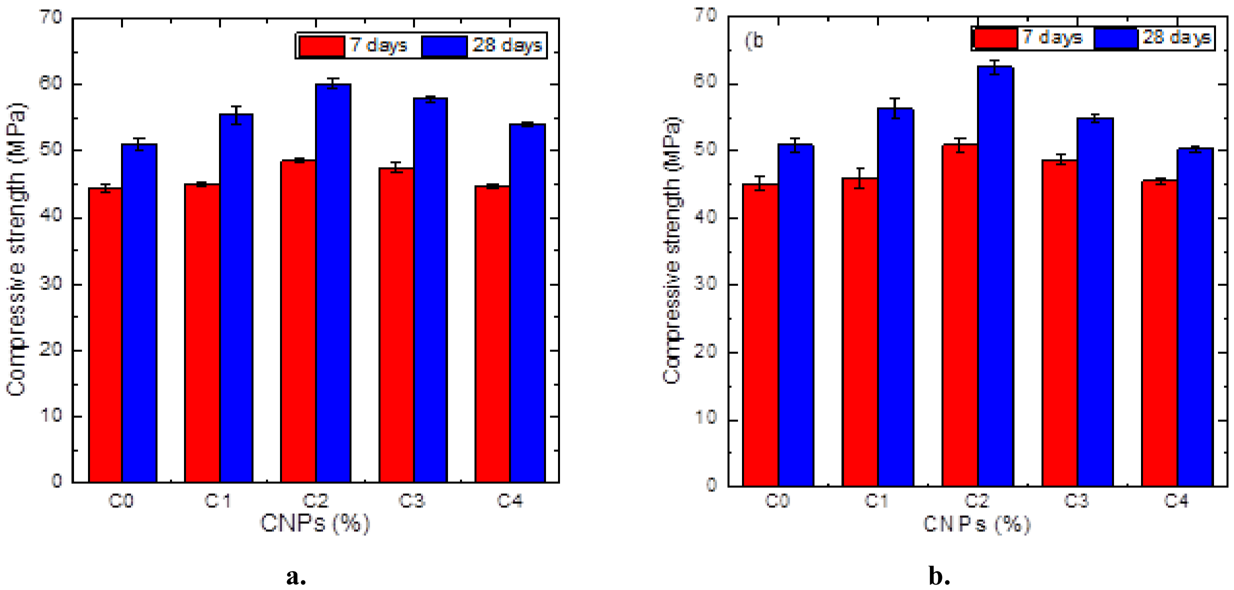


Fig. 6. *Compressive strength of cement mortars containing different wt.% concentrations of graphene nanoplatelets (GNPs).* **a.** *Mixtures without surfactant*, **b**. *Mixtures with the addition of surfactant*

The results correspond to specimens cured for 7 and 28 days and illustrate the influence of nanoplatelet concentration and dispersion conditions on the compressive performance of the mortar composites. The comparison highlights the role of surfactant-assisted dispersion in improving nanoparticle distribution and enhancing the load-bearing capacity of the cement matrix.

The strength enhancement observed in the optimized Fe-GNPs mixtures can be explained by several complementary mechanisms. First, the platelet-like carbon phase may act as a nanofiller, contributing to matrix densification and reducing fine voids [15-17]. Second, graphitic nanostructures can hinder the propagation of microcracks by promoting crack deflection and local bridging. Third, the high surface area of the Fe-GNPs system may facilitate the nucleation of hydration products, particularly in the vicinity of the dispersed nanomaterial [16,18]. These mechanisms should be understood as mutually reinforcing rather than mutually exclusive, and their relative contribution is expected to depend strongly on the quality of dispersion achieved in the fresh mixture [19,20].

The use of DISPERBYK-199 substantially improved nanoparticle dispersion and, consequently, the mechanical performance of the mortars. Better dispersion reduces the likelihood of coarse agglomerates acting as stress concentrators and allows a larger fraction of the Fe-GNPs surface to participate in matrix modification. The fact that the surfactant-bearing mixtures outperformed their unsurfacted counterparts at the same Fe-GNPs dosage supports the interpretation that dispersion quality is a decisive factor in the effectiveness of this nano-additive system [19,21].

At dosages above 0.01 wt.%, the reduction in strength indicates that the negative effect of agglomeration outweighs the potential benefits of additional nanomaterial [22-24]. This concentration-sensitive behavior is consistent with the broader literature on graphene-based cementitious composites, where reinforcement efficiency typically decreases beyond an optimal dosage window.

The structural characterization results help explain the mechanical response of the Fe-GNPs-modified mortars. The combined SEM, XRD, BET, and TGA/DSC analyses confirmed that the synthesized additive is a hybrid carbon–metal nanomaterial with graphitic nanoplatelets, crystalline α-Fe, and a high specific surface area. These features are compatible with the observed strengthening effect, particularly at low dosage and under improved dispersion conditions. At the same time, the present results suggest that structural quality alone is insufficient. Without adequate distribution within the cementitious phase, the potential benefit of the nanomaterial cannot be fully translated into mechanical gain.

Overall, the results demonstrate that Fe-GNPs can serve as effective nano-reinforcements for cement mortars when used at low dosage and with adequate dispersion. The combination of measurable strength enhancement, low optimum content, and an atmospheric-pressure synthesis route makes the system technically promising. However, further work on matrix-level microstructure and durability would be useful for broader practical validation.

Fe-GNPs: Scalable Synthesis for Cementitious Applications

In addition to mechanical performance, the practical relevance of the synthesis route is an important consideration for potential application in cement-based materials. From this perspective, the Fe-GNPs used in the present study were obtained via a modified ferrocene pyrolysis process at atmospheric pressure in a continuous two-zone furnace, which differs from more restrictive, closed, high-pressure routes [25].

Compared with sealed high-pressure solid-phase pyrolysis, the present synthesis route offers two practical advantages: continuous operation and a less demanding pressure regime. These features are relevant because they simplify process control and improve the prospects for scaling the synthesis beyond laboratory batch production. At the same time, the present study does not attempt a full techno-economic analysis; therefore, the practical significance of the route should be interpreted as indicative rather than definitive [19,26].

From a processing standpoint, the proposed route is attractive because it combines continuous operation with moderate process complexity. In addition, the optimal Fe-GNPs dosage identified in this study is low, which limits the amount of nanomaterial needed to achieve measurable mechanical improvement. This point is important in cementitious systems, where even technically effective nano-additives may become impractical at high required dosages [26].

The optimum incorporation level identified in this study, 0.01 wt.% of cement (C2 mix in Table 3), corresponds to approximately 0.1 kg of Fe-GNPs per ton of cement. In the present work, all mortar mixtures were prepared at a laboratory scale using 880 g of cement per batch. This confirms that only a small amount of additive is required to achieve a measurable strengthening effect under the investigated conditions.

Energy demand is also an important consideration. Atmospheric-pressure continuous systems avoid the use of reinforced high-pressure equipment and reduce the repeated heating–cooling cycles characteristic of strictly batch-based closed processes. For this reason, the proposed method may be more attractive for further scale-up studies than synthesis routes that rely on more restrictive pressure conditions [27,28].

Taken together, the low optimum dosage, the continuous atmospheric-pressure synthesis route, and the demonstrated mechanical benefits suggest that Fe-GNPs warrant further consideration as hybrid nano-additives for cementitious materials. However, any claim regarding large-scale implementation should remain provisional until supported by dedicated analyses of production, durability, and cost.

Comparative Assessment of Nano-Additives

A comparative evaluation of Fe-GNPs with other widely investigated nano-additives, particularly multi-walled carbon nanotubes (CNTs) and graphene oxide (GO), is useful for positioning the present results within the broader field of cement nanomodification. Such a comparison must be interpreted cautiously because performance reported in the literature depends strongly on matrix composition, water-to-cement ratio, dispersion protocol, curing conditions, and specimen geometry.

CNTs are well known for their crack-bridging ability and for their potential to improve compressive, flexural, and tensile performance [2,24,29]. However, their effectiveness strongly depends on dispersion, and relatively high dosages are often associated with loss of workability and agglomeration. These limitations do not diminish their importance, but they do highlight the practical challenge of consistently translating intrinsic nanomaterial properties into composite-level gains.

Graphene oxide is highly reactive due to its oxygen-containing functional groups and can enhance hydration kinetics and matrix refinement. At the same time, GO performance is sensitive to the synthesis route, degree of oxidation, and dispersion protocol. In some systems, its strong chemical activity is beneficial; in others, it complicates reproducibility or control of the fresh state [30,31].

In the present study, the Fe-GNPs system achieved a compressive strength increase of about 22% at a low optimum dosage of 0.01 wt.% when surfactant-assisted dispersion was used. On this basis, Fe-GNPs may be viewed as a technically promising compromise between mechanical benefit, dosage efficiency, and synthesis practicality. The comparison does not suggest that Fe-GNPs are universally superior to CNTs or GO; rather, it indicates that they represent a competitive hybrid alternative worthy of further investigation [32-34].

The comparison in Table 4 should therefore be considered indicative rather than absolute. Its purpose is to position the present Fe-GNPs system within the current landscape of carbon-based nano-additives for cementitious composites, not to establish a definitive ranking across studies conducted under different experimental conditions.

Table 4. Comparative analysis of nano-additives used in cementitious composites, highlighting mechanical performance improvements, production complexity, and relative cost considerations

Nano-Additive	Typical Optimum Dosage (wt.%)	Compressive Strength Increase (%)	Production Complexity	Relative Cost Level	Key References
CNTs	0.2–0.3	30–35	High (CVD + purification)	High	[2,29]
GO	0.03–0.05	15–25	Moderate–High (chemical oxidation)	Moderate	[30,32]
Fe–GNPs (this work)	0.01	~22	Moderate (continuous pyrolysis, atmospheric pressure)	Low–Moderate	Present study

As shown in Table 3, CNTs- and GO-based systems can yield substantial performance gains, but the present Fe-GNPs system is notable for combining a low optimum dosage, meaningful mechanical improvement, and a synthesis route that is potentially compatible with continuous production. This combination is one of the main practical strengths of the present study [30,34].

Although the comparative assessment is encouraging, direct comparisons among nano-additive systems remain difficult because published studies vary in matrix design, curing conditions, dispersion strategies, and testing methodologies. Accordingly, broader validation of the Fe-GNPs concept should include durability, rheological behavior, and matrix-scale microstructural analysis in future work.

Conclusion

Iron-based graphene nanoplatelets (Fe-GNPs) were successfully synthesized by a modified ferrocene pyrolysis route operating under continuous atmospheric-pressure conditions. Structural characterization confirmed the formation of a hybrid graphitic carbon–iron nanomaterial composed of graphene-based nanoplatelets, crystalline α-Fe, and a minor fraction of additional carbon nanostructures.

When incorporated into cement mortars, Fe-GNPs produced a clear reinforcing effect that depended strongly on dosage and dispersion quality. Among the concentrations evaluated in this study, 0.01 wt.% of cement was identified as the optimal Fe-GNPs dosage, yielding the highest flexural and compressive strengths. The use of surfactant-assisted ultrasonication further increased the measured gains relative to the control mortar.

The observed improvement in mechanical performance is consistent with a combination of matrix densification, crack-growth restraint, and enhanced interaction between the nanomaterial and hydration products. At higher dosages, the reinforcing effect declined, indicating that agglomeration and dispersion limitations outweighed the potential benefits of additional Fe-GNPs content.

From a practical perspective, the study suggests that Fe-GNPs synthesized by an atmospheric-pressure route deserve further consideration as hybrid nano-additives for cementitious materials. Their low optimum dosage and measurable strengthening effect are encouraging, but broader validation should include hardened-matrix microstructure, durability-related properties, and process-scale assessment before making strong application claims.

Acknowledgments

The authors acknowledge the use of research facilities and technical support provided by the Republic of Armenia (RA) state budget within the framework of the programs "Maintenance and Development of the Research Laboratory of Construction and Architecture" and "Maintenance and Development of the Research Laboratory for Construction Problems Modeling".

Conflict of Interest

The authors declare no conflicts of interest.

Funding

The authors would like to acknowledge the financial support of the Higher Education and Science Committee of the Republic of Armenia (Project No. 21AG-1C008).

References

[1]. G. Huang, Y. Liu, T. Benn, L. Luo, T. Xie, Y. Zhuge, A Comprehensive Framework for the Design and Optimization of Limestone-Calcined Clay Cement: Integrating Mechanical, Environmental, and Financial Performance. Journal of Composites Science, 8 (12), 2024, 524. Doi: https://doi.org/10.3390/jcs8120524

[2]. M. Ru, W. Zedong, W. Xiaowei, Q. Longbang, L. Hui, Experimental Study on Shear Properties of Aligned Steel Fiber Reinforced Cement-Based Composites. Construction and Building Materials, 184, 2018, 27-33. Doi: https://doi.org/10.1016/j.conbuildmat.2018.06.026

[3]. M.S. Konsta-Gdoutos, Z.S. Metaxa, S.P. Shah, Highly Dispersed Carbon Nanotube Reinforced Cement-Based Materials. Cement and Concrete Research, 40 (7), 2010, 1052–1059. Doi: https://doi.org/10.1016/j.cemconres.2010.02.015

[4]. M. Heikal, H.A. Abdel-Gawwad, F.A. Ababneh, Positive Impact Performance of Hybrid Effect of Nano-Clay and Silica Nano-Particles on Composite Cements. Construction and Building Materials, 190, 2018, 508–516. Doi: https://doi.org/10.1016/j.conbuildmat.2018.09.163

[5]. Y. Chen, X. Li, C. Li, N. Zhang, R. Liu, C. Lu, Improvement of Flexural and Compressive Strength of Cement Mortar by Graphene Nanoplatelets. The Open Civil Engineering Journal, 15, 2021, 165–171. Doi: https://doi.org/10.2174/1874149502115010165

[6]. P.T. Dalla, I.K. Tragazikis, G. Trakakis, C. Galiotis, K.G. Dassios, T.E. Matikas, Multifunctional Cement Mortars Enhanced with Graphene Nanoplatelets and Carbon Nanotubes. Sensors, 21 (3), 2021, 933. Doi: https://doi.org/10.3390/s21030933

[7]. S. Lv, Y. Ma, C. Qiu, T. Sun, J. Liu, Q. Zhou, Effect of Graphene Oxide Nanosheets of Microstructure and Mechanical Properties of Cement Composites. Construction and Building Materials, 49, 2013, 121–127. Doi: https://doi.org/10.1016/j.conbuildmat.2013.08.022

[8]. L. Silvestro, P. Jean Paul Gleize, Effect of carbon nanotubes on compressive, flexural and tensile strengths of Portland cement-based materials: A systematic literature review. Construction and Building Materials, 264, 2020, 120237. Doi: https://doi.org/10.1016/j.conbuildmat.2020.120237

[9]. Z.S. Metaxa, A.K. Tolkou, S. Efstathiou, A. Rahdar, E.P. Favvas, A.C. Mitropoulos, G.Z. Kyzas, Nanomaterials in Cementitious Composites: An Update. Molecules, 26 (5), 2021, 1430. Doi: https://doi.org/10.3390/molecules26051430

[10]. S. Malumyan, Influence of Carbon Nanotubes Concentration on the Mechanical Properties of Cement Mortars. Journal of Architectural and Engineering Research, 5, 2023, 47-52. Doi: https://doi.org/10.54338/27382656-2023.5-006

[11]. W. Baomin, D. Shuang, Effect and Mechanism of Graphene Nanoplatelets on Hydration Reaction, Mechanical Properties and Microstructure of Cement Composites. Construction and Building Materials, 228, 2019, 116720. Doi: https://doi.org/10.1016/j.conbuildmat.2019.116720

[12]. B. Wang, R. Jiang, Z. Wu, Investigation of the Mechanical Properties and Microstructure of Graphene Nanoplatelet-Cement Composite. Nanomaterials, 6 (11), 2016, 200. Doi: https://doi.org/10.3390/nano6110200

[13]. Y. Zhou, Y. Wang, T. Gao, Y. Ling, N. Jiang, A.M. Tawfek, H. Yuan, Optimization of Graphene Nanoplatelets Dispersion and its Performance in Cement Mortars. Materials, 15 (20), 2022, 7308. Doi: https://doi.org/10.3390/ma15207308

[14]. F. Farivar, P. Lay Yap, R.U. Karunagaran, D. Losic, Thermogravimetric Analysis (TGA) of Graphene Materials: Effect of Particle Size of Graphene, Graphene Oxide and Graphite on Thermal Parameters. C, 7 (2), 2021, 41. Doi: https://doi.org/10.3390/c7020041

[15]. Y. Zhang, M. Cui, Zh. Bi, Z. Shi, J. Hou, Q. Fang, G. Chen. Experimental Investigation of the Effects of Graphene Nanoplatelets on the Microstructure and Compressive Performance of Concrete under Changing Climate Conditions. Construction and Building Materials, 482, 2025, 141654. Doi: https://doi.org/10.1016/j.conbuildmat.2025.141654

[16]. Z. Hang, Y. Fan, J. Yang, Ch. Feng, J. Yang, Sh. Wang, Improved Compressive and Flexural Performances of Functionally Graded Graphene Nanoplatelet Reinforced Cement Composites: Experiments and Modelling. Construction and Building Materials, 391, 2023, 131828. Doi: https://doi.org/10.1016/j.conbuildmat.2023.131828

[17]. K.Y. Eayal Awwad, B.F. Yousif, K. Fallahnezhad, K. Saleh, Xu. Zeng, Influence of Graphene Nanoplatelets on Mechanical Properties and Adhesive Wear Performance of Epoxy-Based Composites. Friction, 9, 2021, 856–875. Doi: https://doi.org/10.1007/s40544-020-0453-5

[18]. P.T. Dalla, I.K. Tragazikis, G. Trakakis, C. Galiotis, K.G. Dassios, T.E. Matikas, Multifunctional Cement Mortars Enhanced with Graphene Nanoplatelets and Carbon Nanotubes. Sensors, 21 (3), 2021, 933. Doi: https://doi.org/10.3390/s21030933

[19]. N.G. Muradyan, H. Gyulasaryan, A.A. Arzumanyan, M.M. Badalyan, M.A. Kalantaryan, Y.V. Vardanyan, D. Laroze, A.Manukyan, M.G. Barseghyan, The Effect of Multi-Walled Carbon Nanotubes on the Compressive Strength of Cement Mortars. Coatings, 12 (12), 2022, 1933. Doi: https://doi.org/10.3390/coatings12121933

[20]. S.A. Malumyan, N.G. Muradyan, M.A. Kalantaryan, A.A. Arzumanyan, Y. Melikyan, D. Laroze, M.G. Barseghyan, Simultaneous Effect of Diameter and Concentration of Multi-Walled Carbon Nanotubes on Mechanical and Electrical Properties of Cement Mortars: With and without Biosilica. Nanomaterials, 14 (15), 2024, 1271. Doi: https://doi.org/10.3390/nano14151271

[21]. S. Saravanan, L. Huang, A. Babaahmadi, Effect of Graphene Oxide Dispersion on Hydration and Carbonation Performance of Low-Clinker Cement. Construction and Building Materials, 508, 2026, 1444950. Doi: https://doi.org/10.1016/j.conbuildmat.2025.144950

[22]. L.J. Jaramillo, R. Kalfat, Evaluation of Mechanical Properties and Water Resistance Performance of Concrete Modified with Graphene Nanoplatelets (GNP). International Journal of Concrete Structures and Materials, 19 (39), 2025. Doi: https://doi.org/10.1186/s40069-025-00778-0

[23]. I. Prudente, H. Santos, J. Fonseca, J. Oliveira, A. Shibutani, I. de Fátima Gimenez, E. Santos, L. Barreto, Highlights on the Effects of Graphene-Family Materials Dispersion on Hydration and Mechanical Properties of Cement-Based Materials. ACS Omega 10 (46), 2025, 55161-55184. Doi: https://doi.org/10.1021/acsomega.5c07530

[24]. S. Malumyan, N. Muradyan, The Effect of Different Multi-Walled Carbon Nanotubes Aspect Ratio on the Compressive Strength of the Cement-Based Concrete. Journal of Architectural and Engineering Research, 8, 2025, 62–68. Doi: https://doi.org/10.54338/27382656-2025.8-06

[25]. Y. Sargam, K. Wang, Influence of Dispersants and Dispersion on Properties of Nanosilica Modified Cement-Based Materials. Cement and Concrete Composites, 118, 2021, 103969. Doi: https://doi.org/10.1016/j.cemconcomp.2021.103969.

[26]. L. Silvestro, P. Jean Paul Gleize, Effect of Carbon Nanotubes on Compressive, Flexural and Tensile Strengths of Portland Cement-Based Materials: A Systematic Literature Review. Construction and Building Materials 264, 2020, 120237. Doi: https://doi.org/10.1016/j.conbuildmat.2020.120237

[27]. W. Baomin, D. Shuang, Effect and Mechanism of Graphene Nanoplatelets on Hydration Reaction, Mechanical Properties and Microstructure of Cement Composites. Construction and Building Materials, 228, 2019, 116720. Doi: https://doi.org/10.1016/j.conbuildmat.2019.116720

[28]. Z. Hang, Y. Fan, J. Yang, Ch. Feng, J. Yang, Sh. Wang, Improved Compressive and Flexural Performances of Functionally Graded Graphene Nanoplatelet Reinforced Cement Composites: Experiments and Modelling. Construction and Building Materials, 391, 2023, 131828. Doi: https://doi.org/10.1016/j.conbuildmat.2023.131828

[29]. S. Saravanan, L. Huang, A. Babaahmadi, Effect of Graphene Oxide Dispersion on Hydration and Carbonation Performance of Low-Clinker Cement. Construction and Building Materials, 508, 2026, 144950. Doi: https://doi.org/10.1016/j.conbuildmat.2025.144950

[30]. Z.S. Metaxa, J-W.T. Seo, M.S. Konsta-Gdoutos, M.C. Hersam, S.P. Shah, Highly Concentrated Carbon Nanotube Admixture For Nano-Fiber Reinforced Cementitious Materials. Cement and Concrete Composites, 34 (5), 2012, 612-617. Doi: https://doi.org/10.1016/j.cemconcomp.2012.01.006

[31]. J. Yang, S. Han, Q. Wang, Ch. Wu, M. An, Z. Yu, Y. Wang, P. Yan, The Influence of Graphene Oxide on the Hydration and Mechanical Properties of Cement-Based Materials with Low Water-Binder Ratio. Cement and Concrete Composites, 152, 2024, 105640. Doi: https://doi.org/10.1016/j.cemconcomp.2024.105640

[32]. N. Muradyan, A. Arzumanyan, M. Kalantaryan, K. Khachatryan, E. Zendri, A. Arzumanyan, Geopolymer Mortars from Tuff Waste: A Circular Approach. Civil Engineering Journal, 11 (10), 2025, 4092-4107. Doi: https://doi.org/10.28991/CEJ-2025-011-10-07

[33]. D.C. Marcano, D.V. Kosynkin, J.M. Berlin, A. Sinitskii, Z. Sun, A. Slesarev, L.B. Alemany, W. Lu, J.M. Tour, Improved Synthesis of Graphene Oxide. ACS Nano, 4 (8), 2010, 4806-4814. Doi: https://doi.org/10.1021/nn1006368

[34]. Yu Zhang, Ch. Li, Sh. Wang, J. Zhong, Size Effects of Graphene Oxide Nanosheets on the Mechanical Property of Cement Pastes: Packing of C-S-H nanoparticles and mechanism. Cement and Concrete Research, 199, 2026, 108044. Doi: https://doi.org/10.1016/j.cemconres.2025.108044

Harutyun Gyulasaryan, Doctor of Philosophy (PhD) in Physics and Mathematics *(RA, Ashtarak) - Institute for Physical Research (IPR), Republic of Armenia, Researcher at the Solid-State Physics Laboratory, gharut1989@gmail.com*

Manoj Chhetri, MS (Physics/Interdisciplinary Studies), Graduate Researcher *(USA, Brownsville) - University of Texas Rio Grande Valley (UTRGV), Former Graduate Teaching Assistant; Researcher at the Department of Physics and Astronomy, chhetrimanoj1992@gmail.com*

Karen Martirosyan, Doctor of Science (Physics), Full Professor *(USA, Edinburg/Brownsville) - University of Texas Rio Grande Valley (UTRGV), Houston Endowed Chair in Science, Math and Technology; Director of the Advanced Nanoscience Laboratory; Associate Vice President for Research Enhancement, karen.martirosyan@utrgv.edu*

Nelli Muradyan, Doctor of Philosophy (PhD) in Engineering *(RA, Yerevan) – National University of Architecture and Construction of Armenia, Senior Researcher at the Maintenance and Development of the Research Laboratory of Construction and Architecture, nmuradyan@nuaca.am*

Hovsep Hoveyan, Doctor of Philosophy (PhD) in Engineering *(RA, Yerevan) – Urban Development Committee; National University of Architecture and Construction of Armenia, Researcher at the Maintenance and Development of the Research Laboratory of Construction and Architecture, Hoveyan.shin@gmail.com*

Manuk Barseghyan, Doctor of science (Physics) *(RA, Yerevan) – National University of Architecture and Construction of Armenia, Rector, manuk.barseghyan@nuaca.am*

Aram Manukyan, Doctor of Philosophy (PhD) in Physics and Mathematics *(RA, Ashtarak) - Institute for Physical Research (IPR), Republic of Armenia, Researcher, Head of the Solid-State Physics Laboratory, manukyan.ipr@gmail.com*

SUSTAINABLE PLANNING INDICATORS: NORTH KAZAKHSTAN CASE

Nailya Appassova
Kazakh Agrotechnical Research University named after S. Seifullin, Astana, Republic of Kazakhstan

Abstract: *This study develops and tests a quantitative indicator system to assess sustainable development in small urban districts in Kazakhstan. The research addresses the lack of measurable tools for small settlements, although they are important for sustainable territorial planning. Its novelty lies in using official socio-economic passport data to build a reproducible system of 18 indicators grouped into demographic, economic and resource-pressure, social-infrastructure, and spatial blocks. The study applied a quantitative case study method using the Bulaevo Urban District in the North Kazakhstan Region as of January 1, 2025. Standardized indicators were compared with regulatory benchmarks, and block and integrated sustainability indices were calculated. The integrated index was 0.19, indicating a low level of sustainability. The main deficits concerned preschool education, employment structure, and agricultural land use. The proposed system can support local authorities in monitoring sustainability, setting planning priorities, expanding preschool infrastructure, diversifying employment, and reducing pressure on agricultural land.*
Keywords: *economic sustainability, planning, small cities, social infrastructure, sustainable architecture.*

Nailya Appassova
E-mail: appassova@mymail.academy

Received: 29.05.2026
Revised: 18.06.2026
Accepted: 13.07.2026

Introduction

Over the past two decades, the issue of the sustainability of small towns and rural settlements has ceased to be a purely regional problem. With the adoption of the Sustainable Development Agenda 2030 in 2015, it was elevated to a global priority. SDG 11 explicitly prescribes making cities and towns of all sizes "inclusive, safe, resilient, and sustainable"[1]. A year later, the New Urban Agenda adopted at the Habitat III conference in Quito consolidated this principle as applied to the "urban-rural continuum" and thereby included small settlements in the priorities of the urban agenda[2].

In 2024, the OECD explicitly stated that small and remote rural areas worldwide face sustained population decline, aging, and service shortages [1]. The gap does not stem from a lack of data, as many countries, including Kazakhstan, collect information regularly and in sufficient detail. In actuality, the gap arises because the collected data is not translated into measurable sustainable development indicators (SDIs) that align with recognized international regulations [2]. Such assessment methodologies have been developed for buildings [3] and large municipal systems [4,5]. However, in our opinion, no such tools have yet been developed for small urban districts, especially in Central Asian countries that emerged after the collapse of the USSR and possess unique socio-economic, cultural, historical, environmental, and climatic features [6]. Individual works on Kazakhstani settlements treat socio-economic factors as a context for architectural and planning solutions [7]. Broader architectural studies also show that future-oriented concepts, including futurism, have influenced the design and architectural solutions of the twentieth and early twenty-first centuries [8]. However, these studies remain primarily conceptual and design-oriented and do not offer a standardized system of measurable indicators for assessing sustainability at the level of small urban districts.

[1] United Nations General Assembly. Resolution adopted by the General Assembly on 25 September 2015, "Transforming Our World: The 2030 Agenda for Sustainable Development". Available at: https://sdgs.un.org/2030agenda (accessed on July 15, 2026).
[2] UN-Habitat. The new urban agenda. Habitat III. 2016. Available at: https://habitat3.org/the-new-urban-agenda/ (accessed on July 15, 2026).

Background

According to the General scheme of organization of the territory of the Republic of Kazakhstan, the North Kazakhstan Region (NKR) has experienced a steady population decline over the past three decades. Between 1999 and 2019, small towns in the region lost 13% to 25% of their inhabitants [9], making the demographic dimension a priority for assessing a settlement's sustainability. At the same time, the region retains a pronounced agricultural specialization. Agricultural production is the backbone of the local economy and therefore dictates the structure of employment and the nature of the load on land resources [10, 11]. The social infrastructure of small districts was established in the 20th century and has virtually not been updated since then [9].

The northern regions of Kazakhstan have a special place in demographic literature. Here, the spatial and demographic transformation of the 1990s took the form of a massive population flow from small cities to large centers, on a scale unparalleled in any other territory of Central Asia that had gained independence after the collapse of the USSR. The trend of population outflow from small towns persists to this day [12]. As recently as 2024, the annual outflow of migrants from the northern regions reached 1-2%. If the trend continues, the NKR population will decline by 20-25% by 2050. In 2024, the rural population deficit across Kazakhstan reached 111,000 people, marking an all-time record since observations began in 2000. In NKR specifically, mortality consistently exceeds the birth rate [13].

Appasova and Kornilova [7] have observed this pattern at the level of specific settlements, reporting that four small cities in the NKR lost between 5% and 25% of their inhabitants between 1999 and 2025. The researchers associate the population decline with the state of social and communal infrastructure, the results of a sociological survey, and the architectural and planning features of development.

The research goal of the present study was to propose a system of quantitative indicators of sustainable development for the small urban districts of Kazakhstan and to test it using data from the Bulaevo Urban District in the North Kazakhstan Region.

The set goal was achieved through the following objectives: (1) to extract measurable indicators of sustainable development from the data of the district passport; (2) to compare the obtained values with verified regulatory benchmarks; (3) to calculate block and integrated sustainability indices; (4) to conduct a comparative analysis of the two district settlements in relative terms; (5) to identify structural deficits and formulate planning priorities.

Research question: To what extent do the data of the socio-economic passport of the small urban district make it possible to assess the compliance of the settlement with the principles of sustainable development enshrined in international documents?

Literature Review

The transition from descriptive to quantitative approaches to assessing the sustainability of settlements was first marked in scientific literature in the mid-2010s and has since gained significant momentum. Balgarina et al. [14] proposed a conceptual classification of indicators across three dimensions – economic, social, and environmental – emphasizing that there were both synergies and trade-offs among them. The key thesis was that a simple weighted aggregation of indicators without accounting for these relationships distorts the final estimate. An alternative approach focused on buildings and individual facilities was implemented by Hasnash et al. [3]. The researchers extracted indicators from international standards (ASHRAE, LEED, BREEAM), measured them using standard formulas, and compared them with global benchmarks. The results showed a strong position of the assessed object in thermal and energy indicators, with a pronounced deficit in environmental and spatial indicators [15]. Fundamentally, both studies use the same methodological strategy: a fixed set of indicators, verified thresholds, and aggregation into a block index. This exact strategy served as a foundation of our work, although applied to an object with a fundamentally different scale and type of data.

Nurlanova et al. [16] have tested an integrated indicator for the regions of Kazakhstan that relied solely on official statistics, abandoning expert weights. The indicators were grouped into three areas: economy, ecology, and standard of living. The approach was proven to be reproducible for any region of the country without additional data collection.

Quantitative assessment of the sustainability of Kazakhstani cities focuses mainly on large centers. Nyussupova et al. [4] developed an integrated index of sustainable urban development (SUDI) for cities of national importance based on 2007-2019 data, structuring 30 indicators across five blocks. The results suggested a moderate level of sustainability of most of the cities examined, the demographic and environmental blocks being the most problematic [17]. Using a rating methodology with risk analysis, the Eurasian Research Institute[3] and Rozhdestvenskaya and Stroev [18] found that large cities are more sustainable than medium and single-industry ones, mainly by virtue of the economic block.

Both works share a common limitation: the lower limit of the samples included cities with a population of 100,000 or more. Thus, small towns of district significance with a population of up to 15,000 were not included in the systematic estimates. Meanwhile, Kazakhstan has 48 such cities, more than half of the total number of urban settlements in the country[4]. This scale is typical of most NKR administrative centers and is the subject of the present study. At the same time, the above research does not offer a formalized system of measurable indicators that would allow settlements to be compared with one another or their dynamics to be tracked on a single scale.

Thus, research in the field has a methodological gap: tools for quantitative sustainability assessment have been developed only for large cities, individual objects, and the regional level [19]. The urban district, as the minimal planning unit with unified passport documentation, is not represented in these systems [20]. Recent studies also confirm the need to shift from descriptive regional analysis to reproducible quantitative tools to assess economic sustainability at the meso level. Safiullin et al. [21], for example, developed a methodological framework for identifying risks to sustainable regional economic development under the transformation of foreign economic supply chains, combining qualitative and quantitative analysis, cluster analysis, and regression modeling. Although their study focuses on a large regional economy rather than on a small urban district, it supports the broader methodological argument that territorial sustainability requires measurable indicators and transparent analytical procedures.

Without measurable indicators at the district level, SDG 11 remains unattainable in practice, as urban planners lack the information on which parameters do not meet standards and to what extent. This means that the challenge of adopting the SDGs in planning lies in planners' inability to justify development priorities with quantitative indicators.

Methods

The study employed a quantitative case study design with an internal comparison of two subjects. The main subject of research was Bulaevo Urban District as a whole, for which block indices and an integrated sustainability index were calculated. The subjects of comparison were two settlements comprising the district: the central town of Bulaevo and the satellite village of Medvezhka. Their infrastructure profiles were compared in relative terms to reveal intra-district asymmetry. The urban district was selected on three interrelated grounds. Firstly, it represents the most common type of administrative unit in NKR: a small district center with one satellite rural settlement, a combined population of about 9,000, and a pronounced agricultural specialization. Secondly, the district exhibits dynamics typical of the region as a whole, with a population

[3] Eurasian Research Institute. Urbanization and spatial demographic trends in Kazakhstan. Available at: https://surl.lu/vykgco (accessed on July 15, 2026).

[4] Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (BNS RK). Administrative-territorial units of the Republic of Kazakhstan (as of January 1, 2026). Available at: https://surl.lu/dnqrch (accessed on July 15, 2026).

decrease from 9,638 to 9,117 over the period 1999-2025 [7]. Thirdly, the district's socio-economic passport provides a complete set of indicators across all sections, without gaps, which is a crucial condition for building a single-source indicator system. Given that the urban district is the smallest unit of Kazakhstan's settlement network for which such documentation is prepared uniformly, the tested method applies to other districts without additional field research.

The district has a pronounced agrarian spatial structure, as shown in Figure 1. Agricultural land accounts for 88.3% of the district territory, while arable land accounts for 54.1% of agricultural land. In addition, the livestock load coefficient reaches 24.8 head per 100 ha, exceeding the regulatory benchmark of 10.8 head per 100 ha. These parameters show that the environmental dimension of the case is expressed primarily through land-use intensity and resource-pressure indicators rather than through direct measurements of environmental quality.

To clarify this context, Figure 1 combines the regional location of Bulaevo Urban District with a schematic planning profile of the study area. The figure shows the centre – satellite settlement structure of Bulaevo and Medvezhka, transport accessibility, social-infrastructure markers, agricultural land-use context, the integrated sustainability index, and key resource/environmental proxy indicators. It serves as a spatial framework for interpreting passport-based indicators and linking socio-economic, planning, and environmental aspects of the assessment.

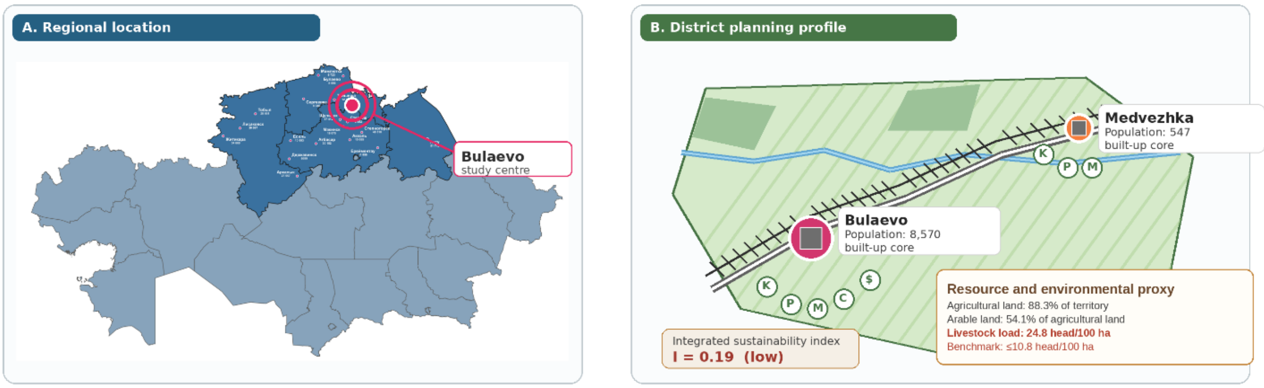


Fig. 1. *Spatial context of Bulaevo Urban District, North Kazakhstan Region: regional location and schematic district planning profile*

Data Sources

The empirical basis of the study was the Socio-economic passport of Bulaevo Urban District, Magzhan Zhumabayev district, North Kazakhstan region, dated January 1, 2025. The passport is formed by the akimat in accordance with a unified form provided by the Ministry of National Economy of the Republic of Kazakhstan. It contains information on eight sections: demographics, labor resources, ethnic composition, land resources, economic entities, livestock, social infrastructure, and employment structure. For the study, 58 primary numerical indicators were extracted from the passport, and calculated indicators were obtained by normalizing them to population size or to the respective age groups.

Benchmark Selection Rationale

Benchmark selection was based on a hierarchical and reproducible procedure. Since the purpose of the study was not to construct an expert rating but to test whether routine district-level passport data can be translated into measurable sustainability indicators, only benchmarks that met four criteria were used. First, the benchmark had to be expressed as a quantitative threshold or normative value. Second, it had to apply to small urban or rural settlements rather than only to large metropolitan systems. Third, the benchmark had to be derived from an official, regulatory, or internationally recognized source. Fourth, the corresponding indicator had to be available in the socio-economic passport without additional field measurement.

Three groups of benchmarks were used. The first group includes national planning and construction standards of the Republic of Kazakhstan, which were applied to social infrastructure indicators such as preschool education, school coverage, hospital provision, and cultural institutions. These benchmarks are directly relevant to settlement planning because they define minimum or recommended levels of service provision for urban and rural communities. The second group includes national statistical reference values from the Bureau of National Statistics of the Republic of Kazakhstan. These values were used for indicators where the benchmark is not a planning norm but a country-level socio-economic reference point, such as unemployment, self-employment, and average household size. The third group includes sectoral environmental and agricultural norms, primarily the maximum permissible livestock load on pasture areas established by the Ministry of Agriculture of the Republic of Kazakhstan. International benchmarks were used only where national planning norms did not provide an equivalent reference value and where the indicator is widely used in comparative rural and demographic studies, such as population aging.

Indicators for which no verified benchmark was available were not excluded from the system. Instead, they were treated as descriptive indicators. This decision was methodologically important because descriptive indicators provide the spatial and socio-economic context of sustainability deficits, whereas their exclusion would have narrowed the analysis to only those aspects already regulated. However, descriptive indicators were not included in the calculation of the integrated index. This avoids pseudo-precision and prevents the arbitrary standardization of indicators for which no reliable threshold exists.

Indicator System

The indicator system was structured around four operational dimensions of sustainable human settlement development: demographic sustainability, economic sustainability and resource pressure, social infrastructure, and spatial sustainability. These dimensions align with the Sustainable Development Goals and the New Urban Agenda but have been adapted to the scale of a small urban district and the structure of Kazakhstan's socio-economic passport data. Demographic indicators correspond mainly to SDGs 3 and 10; economic indicators to SDG 8; social infrastructure indicators to SDGs 3, 4, and 11; and spatial indicators to SDG 11 and SDG 11.a. The resource-use and environmental dimension, linked to SDGs 2 and 15, is represented through land-use and livestock-load indicators in Block II.

The inclusion of indicators was based on two criteria. First, the indicator had to be available in numerical form in the socio-economic passport or be directly calculable from passport data. Second, it had to be relevant for assessing sustainability at the scale of a small urban district, where demographic decline, infrastructure provision, agricultural specialization, and centre–satellite asymmetry are closely interrelated. Indicators were standardized only when a verified quantitative benchmark or reference value was available. Indicators without a verified benchmark were retained as descriptive variables because they characterize the district's spatial and socio-economic context but were not included in the integrated index calculation.

The final indicator set, including the thematic blocks, benchmarks, benchmark sources, assessment type, and SDG alignment, is presented in Table 1. The environmental component is not treated as a separate block of direct ecological quality indicators because the passport lacks data on soil conditions, vegetation cover, pasture degradation, air quality, or water quality. Instead, it is represented by resource-use proxies: the share of arable and agricultural land, land transferred to economic entities, and livestock load. This approach preserves the method's reproducibility while making the environmental relevance of the agrarian land-use structure explicit.

Of the 18 indicators, 9 are standardized because their values can be compared with verified quantitative thresholds or reference values. The remaining 9 indicators are descriptive. They are used to characterize the district's socio-economic, spatial, and land-use context. Still, they are not included in the integrated index due to the lack of verified regional or sectoral benchmarks. This distinction avoids arbitrary normalization and keeps the assessment reproducible for other small urban districts using the same type of passport data.

Table 1. System of SDIs for Bulaevo Urban District

Block	No.	Indicator	Benchmark	Benchmark source	Type of assessment	SDG
I. Demographic sustainability	1	Share of pensioners in the population	~15%	OECD [1]	standardized	3, 10
	2	Proportion of vulnerable groups (pensioners + people with disabilities + low-income)	–	–	descriptive	3, 10
	3	Share of large families in households	–	–	descriptive	3, 10
	4	Average household size	2.5 people	BNS RK[5]	standardized	3, 10
II. Economic sustainability and resource pressure	5	Official unemployment rate	4.7%	BNS RK[6]	standardized	8
	6	Share of self-employed in the working population	23.4%	BNS RK[7]	standardized	8
	7	Business density per 1,000 inhabitants	–	–	descriptive	8
	8	Arable land share in agricultural land as a land-use intensity proxy	–	–	descriptive	2
	9	Livestock load coefficient, head per 100 ha, as a pasture-pressure proxy	≤10.8 head/100 ha	Zootechnical norm for the steppe zone[8]	standardized	2, 15
	10	Agricultural land share in the district territory as an agrarian land-use dominance proxy	–	–	descriptive	15
	11	Share of agricultural land transferred to economic entities as an economic land-use pressure proxy	–	–	descriptive	15
III. Social infrastructure	12	Preschool education coverage	70–80%	SP RK 3.02-110-2012[9]	standardized	4
	13	School education coverage	≥95%	SP RK 3.01-101-2013[10]	standardized	4
	14	Hospital facilities per 10,000 inhabitants	1.0	SP RK 3.01-101-2013[11]	standardized	3
	15	Cultural institutions per 1,000 inhabitants	1.0	SP RK 3.01-101-2013[12]	standardized	11
IV. Spatial sustainability	16	Population density, people/km^2	–	–	descriptive	11
	17	Concentration coefficient (share of central settlement inhabitants)	–	–	descriptive	11
	18	Center/satellite infrastructure asymmetry	–	–	descriptive	11.a

Note: Indicators 8–11 are interpreted as resource-use and environmental proxy indicators. They do not measure environmental quality directly, but characterize land-use intensity, pasture pressure, agrarian land-use dominance, and economic pressure on land resources. Only indicators with verified quantitative benchmarks were standardized and included in the integrated index calculation

[5] Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (BNS RK). Sample survey of households. 2025. Available at: https://stat.gov.kz (accessed on July 17, 2026).

[6] Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (BNS RK). Employment and unemployment. 2025. Available at: https://surl.li/ywevun (accessed on July 17, 2026).

[7] Ibid.

[8] Order of the Minister of Agriculture of the Republic of Kazakhstan of April 14, 2015, No. 3-3/332 "On approval of the maximum allowable load on the total area of pastures" (rev. 2024).
Available at: https://adilet.zan.kz/rus/docs/V1500011064 (accessed on July 17, 2026).

[9] Construction Committee of the Republic of Kazakhstan. SP RK 3.02-110-2012. Preschool education institutions. 2012, rev. 2025. Available at: https://prg.kz/document/?doc_id=32203098 (accessed on July 17, 2026).

[10] Construction Committee of the Republic of Kazakhstan. SP RK 3.01-101-2013. Urban planning. Layout and development of urban and rural communities. 2013, rev. 2025.
Available at: https://prg.kz/document/?doc_id=39214714&pos=6;234 (accessed on July 17, 2026).

[11] Ibid.

[12] Ibid.

Analytical Procedures

The analysis was carried out in three stages. At the first stage, the actual value and the deviation from the benchmark, in both absolute and percentage terms, were calculated for each standardized indicator. According to the obtained deviation, each indicator was assigned one of three statuses: "corresponds" (value within the benchmark or better), "borderline" (deviation does not exceed 5 percentage points or 5% of the benchmark), and "does not correspond" (deviation exceeds the specified threshold). Descriptive indicators were interpreted contextually against regional data and results from related studies.

At the second stage, a block sustainability index I_k was calculated for each of the three blocks of standardized indicators:

$$I_k = \frac{n_{corr}}{n_{st}}, \tag{1}$$

where n_{st} – number of standardized indicators in the block, n_{corr} – number of indicators with the "corresponds" status. The value of I_k ranges from 0 to 1. Block IV, "Spatial sustainability", was not included in the calculation due to the lack of verified benchmarks and was analyzed separately by comparing the infrastructure profiles of two district settlements.

At the third stage, the integrated sustainability index was calculated as the arithmetic mean of the three block indices:

$$I = \frac{1}{3}\sum_{k=1}^{3} I_k\,. \tag{2}$$

The blocks were not weighted, as assigning weights would have required an expert assessment procedure beyond the scope of the present study. The integrated index was interpreted using a three-level scale: 0.75–1.00 – high sustainability, 0.50–0.74 – moderate, 0.00–0.49 – low. All calculations were performed using primary data from the socio-economic passport, without inferential statistical methods, in line with the design of a single case study.

Thus, the study consisted of two levels of analysis as described in Table 2.

Table 2. Study design

Level	Subject	Method	Results
District in total	Bulaevo Urban District	Calculation of block indices and the integrated index for 9 standardized indicators	Integrated sustainability index I
District settlements	Bulaevo town and Medvezhka village	Comparison of infrastructure profiles in relative terms (per 1,000 inhabitants)	Intra-district asymmetry profile

The comparison of settlements was carried out without normative benchmarks – by direct comparison of relative indicators. This approach eliminates the effect of the 15-fold difference in population size and enables determination of whether the infrastructure is evenly distributed throughout the district.

Statistical methods (correlation and regression analysis) were not used to test the hypothesis, since the design of a single case study does not imply sample-based conclusions, and the number of observations ($n = 1$) makes such tests methodologically improper.

Results

Block indices based on the 9 standardized indicators indicate that none of the three evaluated blocks meets the threshold for moderate sustainability (Table 3). Block I, "Demographic sustainability", received an index of 0.00 – neither standardized indicator corresponds to the benchmark. Block II, "Economic sustainability and resource pressure," has an index of 0.33: of the three standardized indicators, only the official unemployment rate meets the benchmark. The index value for Block III, "Social infrastructure", is 0.25: of the four standardized indicators, only the availability of hospital facilities meets the standard. Block IV was excluded from the calculation of the integrated index due to the lack of verified benchmarks and is discussed separately through the comparative settlement profile.

The integrated sustainability index based on the three blocks amounted to:

$$I = \frac{0.00 + 0.33 + 0.25}{3} = 0.19. \quad (3)$$

The obtained value corresponds to a low level of sustainability on the adopted scale (0.00-0.49). The district meets standard requirements in only 2 of the 9 standardized indicators – the unemployment rate (2.8%, with a benchmark of 4.7%) and the availability of hospital facilities (1.17 per 10,000 inhabitants, against a standard of 1.0).

Table 3. Block SDIs of Bulaevo Urban District

Block	Standardized indicators	Match benchmark	I_k index	Level
I. Demographic sustainability	2	0	0.00	low
II. Economic sustainability and resource pressure	3	1	0.33	low
III. Social infrastructure	4	1	0.25	low
IV. Spatial sustainability	–	–	–	descriptive
Integrated index	**9**	**2**	**0.19**	**low**

The detailed profile demonstrates not only the status of each indicator but also the extent of its deviation from the standard (Table 4).

Table 4. Standardized indicator profile

No.	Indicator	Fact	Benchmark	d_i, %	Status
1.	Share of pensioners, %	18.3	15.0	+ 22.0	does not correspond
4.	Average household size, people	3.34	2.5	+ 33.6	does not correspond
5.	Unemployment rate, %	2.8	4.7	− 40.4	**corresponds**
6.	Share of self-employed, %	45.1	23.4	+ 92.7	does not correspond
9.	Agricultural load, head/100 ha	24.8	10.8	+ 129.6	does not correspond
12.	Preschool education coverage, %	53.0	75.0	− 29.3	does not correspond
13.	School education coverage, %	92.0	95.0	− 3.2	borderline
14.	Hospitals per 10,000 inhabitants	1.17	1.0	+ 17.0	**corresponds**
15.	Cultural institutions per 1,000 inhabitants	0.55	1.0	− 45.0	does not correspond

Note: $d_i = (x_i - b_i) / b_i \times 100\%$. *For indicators 5 and 14, a negative value means surpassing the standard in the desired direction; for the rest, a deficit relative to the benchmark.*

The most critical deviations are found in three indicators. The share of self-employed exceeds the republican benchmark by 92.7%, indicating a predominance of informal and secondary employment over the formal labor market. The agricultural load on land exceeds the maximum permissible norm by 129.6%. Preschool coverage lags 29.3% below the standard's lower limit, indicating a shortage of places for at least 95 preschool children.

The descriptive land-use indicators clarify the environmental meaning of the resource-pressure block. As visualized in Figure 1, agricultural land occupies 88.3% of the district territory, while arable land accounts for 54.1% of agricultural land. This indicates a highly transformed agrarian landscape with limited non-agricultural buffer areas. The livestock load coefficient is the only resource-use indicator with a verified regulatory benchmark and therefore was included in the standardized part of the assessment. Its value, 24.8 head per 100 ha, exceeds the benchmark of 10.8 head per 100 ha by 129.6%. This result should be interpreted not as a direct measurement of pasture degradation, but as a proxy for potential pressure on land resources.

The nine descriptive indicators reveal the context in which the identified deviations from standards exist.

In the demographic block, vulnerable population groups, including pensioners, people with disabilities, and people with low income, make up 22.8% of district residents. The share of large families is low at 1.5% of households.

In the economic block, business density is 4.7 per 1,000 inhabitants – a low value indicating poor development of small businesses. Only 54.1% of agricultural land is arable. At the same time, 88.3% of the district's territory is covered by agricultural land, resulting in a virtual lack of natural buffer areas [22, 23]. The share of land transferred to economic entities reaches 58.7% of the total agricultural land area.

In the social infrastructure block, school education coverage (92.0%) falls in the borderline zone: technically below the standard, but only slightly. Six preschool institutions have an average group size of 48 children, exceeding the recommended norm (25–30 children), indicating not only low coverage but also overcrowding in existing institutions.

The comparison of the two district settlements in relative terms demonstrates sectoral rather than unidirectional asymmetry (Table 5). With a 15-fold population difference, Medvezhka surpasses Bulaevo in the number of schools, medical facilities, and preschool education coverage. On the other hand, Bulaevo has five cultural institutions, which are completely absent in Medvezhka. The share of pensioners is noticeably higher in the district center, while the proportion of people with disabilities is practically the same.

Table 5. Comparative profile of Bulaevo and Medvezhka (relative indicators)

Indicator	Bulaevo	Medvezhka
Population, people	8,570	547
Households	2,535	193
Average household size, people	3.38	2.83
Schools per 1,000 inhabitants	0.58	1.83
Students per school	231	85
Preschool education coverage, % of estimated preschool-age population	51.5	76.2
Cultural institutions per 1,000 inhabitants	0.58	0.00
Medical facilities per 1,000 inhabitants	0.117	1.828
Share of pensioners, %	18.7	13.0
Share of people with disabilities, %	4.0	4.8

Discussion

The obtained integral index (I = 0.19) corresponds to low sustainability on the accepted scale. Of the nine standardized indicators, only two meet their benchmarks: the official unemployment rate and the provision of hospital facilities. These results are at odds with the picture painted by official statistics. Formally, unemployment in the district is below the republican average, which is traditionally interpreted as a sign of economic well-being. The II-6 indicator, however, suggests otherwise. Self-employed people account for 45.1% of the working-age population in the district, against 23.4% across the Republic of Kazakhstan as a whole. It appears that a significant part of this category consists of subsidiary farming and informal agricultural labor, which, statistically, appears to be employment without creating either a tax base or sustainable income [24]. The OECD [1] reports a similar pattern in small rural districts in different countries, indicating that low official unemployment with high self-employment is not a sign of a sustainable settlement economy [25].

An insightful comparison can be drawn with the results of Nyussupova et al. [4]. With a similar aggregation methodology, large cities in Kazakhstan received moderate sustainability indices (0.5 and higher). Nurlanova et al. [16] confirmed the hypothesis regarding the sustainability of large cities, although small settlements were excluded from the analysis. The index of 0.19 obtained for a small district in our study fits well into this logic: the smaller the settlement, the fewer resources there are to meet standards in several blocks simultaneously.

Block I received an index of zero. The share of pensioners (18.3%) exceeds the OECD benchmark by 22.0% (di = +22.0%), and the average household size (3.34 people) is significantly higher than the NKR regional indicator (2.5 people). The latter fact, however, needs to be interpreted with caution. Large households can reflect both a traditional lifestyle and forced cohabitation for economic reasons. The available passport data are clearly insufficient to distinguish between these reasons.

The most critical deviations are concentrated in Block II. Agricultural load on land exceeds the maximum permissible norm as per the Order of the Ministry of Agriculture of the Republic of Kazakhstan No. 3-3/332[13] by 129.6% ($d_i = +129.6\%$): 24.8 head of cattle per 100 ha against the norm of 10.8 head/100 ha. It is worth noting, however, that the passport provides only the total number of livestock, whereas the standard is calculated relative to pastureland. Since the share of pastures in the total area of agricultural land in the district is unknown to us, we are inclined to believe that the real load on pastures is likely higher than the estimate. Researchers have already cautioned about this exact risk [14, 26, 27], arguing that environmental indicators derived indirectly from aggregated data tend to underestimate the burden on natural resources.

Block III is rather heterogeneous. Coverage with preschool education is 53%, while the lower limit, as per SP RK 3.02-110-2012[14], is 70%. Six institutions have an average group size of 48 children, nearly twice the recommended number. This data indicates not simply a deficit of coverage but an overcrowding of existing institutions. Provision with cultural institutions (0.55 per 1,000 inhabitants) lags behind the standard by 45.0% ($d_i = -45.0\%$). This result is consistent with data from Nyussupova et al. [4], which highlight the cultural block as a systematically weak link in Kazakhstani cities, regardless of their size. At the same time, the present assessment treats educational infrastructure only as basic physical service provision; future versions of the indicator system could supplement school and preschool coverage with qualitative indicators of digital capacity and learning environment, which are becoming increasingly relevant for Kazakhstan's school system [28].

The comparative analysis of Bulaevo and Medvezhka yielded a result different from intuitive expectations. In several respects, the satellite settlement is better provided for than the district center. Medvezhka surpasses the district center in terms of the number of schools, medical facilities, and preschool education coverage per 1,000 inhabitants. In our view, the explanation lies in the historically established logic of standards: the minimum set of objects (as confirmed by other studies – schools, medical centers, kindergartens) was determined for each settlement regardless of its size. The town of Bulaevo later received additional facilities in proportion to population growth and its administrative role. As a result, when infrastructure is normalized by population, the smaller settlement appears to be relatively well provided with basic facilities. This result, however, should be interpreted as a passport-based indicator of service provision rather than as a full assessment of spatial accessibility; such an assessment would require mobility or accessibility modeling [29]. At the same time, Medvezhka is completely devoid of a cultural component, which shows that intra-district asymmetry is sectoral rather than purely quantitative.

This observation echoes the concept of "infrastructural asymmetry" highlighted in OECD documents [1]. The problem of small settlements is often not the absolute absence of facilities, but their sectoral incompleteness. For example, even where basic educational infrastructure exists, the long-term stability of local services may depend on whether the settlement can provide an adequate professional and technological environment for education-sector specialists [30]. The lack of cultural institutions in Medvezhka, despite the availability of a school and a medical center, creates a functionally incomplete environment that keeps residents physically present but fails to provide the quality of life necessary for long-term retention. Appasova and Kornilova [7] reported a similar situation based on a sociological survey. Respondents in the study named the lack of "basic comfortable conditions" as one of the key motives for migration.

Limitations and Further Research Prospects

Three limitations merit separate discussion. The first limitation concerns the time cross-section of the data.

---

[13] Order of the Minister of Agriculture of the Republic of Kazakhstan of April 14, 2015, No. 3-3/332 "On approval of the maximum allowable load on the total area of pastures" (rev. 2024). Available at: https://adilet.zan.kz/rus/docs/V1500011064 (accessed on July 17, 2026).

[14] Construction Committee of the Republic of Kazakhstan. SP RK 3.02-110-2012. Preschool education institutions. 2012, rev. 2025. Available at: https://prg.kz/document/?doc_id=32203098 (accessed on July 17, 2026).

The socio-economic passport presents indicators at a single point in time, which makes it impossible to analyze dynamics. The calculated integrated index, I = 0.19, reflects the state of Bulaevo Urban District as of January 1, 2025, but does not show whether the sustainability level is improving or deteriorating. This limitation can be overcome either by accessing archival socio-economic passports for previous years or by comparing the passport data with the results of the 2021 national census.

The second limitation concerns the environmental dimension of the assessment. In the revised indicator system, four passport-derived variables are interpreted as proxies for resource use and the environment: arable land share, agricultural land share, land transferred to economic entities, and livestock load. These indicators characterize potential pressure on land resources, but they do not directly measure environmental quality. In particular, they do not show the actual condition of pastures, soil contamination, vegetation cover, water quality, or air quality; these aspects require direct ecological measurements, geobotanical surveys, or specialized modeling approaches [31, 32, 33]. A similar difficulty was noted by Balgarina et al. [14] when developing a regional sustainability index for Kazakhstan: aggregated official data can identify potential sustainability risks, but it should be supplemented by more detailed environmental monitoring. Therefore, the environmental results of the present study should be interpreted as planning signals rather than as a full ecological diagnosis. Future research can overcome this limitation by combining passport data with geobotanical surveys, pasture monitoring, remote-sensing indicators, and local environmental measurements.

The third limitation concerns scalability. The system of 18 indicators was tested on one urban district; therefore, its reproducibility for other districts of North Kazakhstan Region depends on the completeness and comparability of their socio-economic passports. According to our preliminary observations, passport data are not always equally detailed across districts, which may limit direct comparison. A logical next step would be to test the proposed system on a sample of several small urban districts in North Kazakhstan Region. Such testing would enable assessment of the stability of the benchmark-based approach, identification of consistently available indicators, and refinement of the descriptive indicators for broader regional application.

Conclusion

Despite formally satisfactory unemployment rates, Bulaevo Urban District demonstrates low sustainability according to most standardized indicators, with an integrated index of 0.19. Of the nine verified indicators, only two meet the benchmark. Systemic deficits spread across all three blocks with standardized indicators. The most acute problems are observed in preschool education, employment, and the agricultural burden on land.

The scientific significance of the study lies in the finding that district-level passport documentation, previously not considered a basis for indicator assessment, was sufficient to build a reproducible system of 18 indicators. The proposed instrument closes the methodological gap between regional studies of the sustainability of Kazakhstan's cities and real planning practices at the district level.

The practical value of the results is that the developed system of indicators enables a transition from general observations to measurable indicators with regulatory substantiation. The findings point to four priorities for possible improvements in district-level planning: expanding the network of preschool institutions, creating a cultural facility in Medvezhka, diversifying employment, and reducing pressure on agricultural land through pasture-use monitoring and clarification of land-use structure. Each priority has a target value or a measurable planning reference derived from the current norms of the Republic of Kazakhstan, UN documents, or passport-based resource-use indicators, thereby providing a methodological justification for its inclusion in district development programs.

Conflict of Interest

The authors declare no conflicts of interest.

Funding

This research did not receive any financial support.

References

[1]. OECD, Reinforcing Rural Resilience. OECD Rural Studies. OECD Publishing, Paris, 2025. Doi: https://doi.org/10.1787/7cd485e3-en

[2]. A. Krasnikov, O. Korotun, Simulation Model for Predicting Ecological Condition of Urban Areas at Traffic Intersections. E3S Web of Conferences, 515, 2024, 03011. Doi: https://doi.org/10.1051/e3sconf/202451503011

[3]. N.A.S. Hasnash, B.A.H. Bedewy, Z.A. Nasar, A Sustainable Digital Framework: Analysis of Sustainable Environmental Design Indicators for the Sultan Complex in the City of Najaf. International Journal of Sustainable Development and Planning, 21 (2), 2026, 739-755. Doi: https://doi.org/10.18280/ijsdp.210224

[4]. G. Nyussupova, L. Kenespayeva, D. Tazhiyeva, M. Kadylbekov, Sustainable Urban Development Assessment: Large Cities in Kazakhstan. Urbani izziv, 33 (1), 2022, 70-81. Doi: https://doi.org/10.5379/urbani-izziv-en-2022-33-01-01

[5]. A. Krasnikov, I. Nikishina, N. Rebus, K. Grabovyy, Transport Planning of a Metropolis Street Using Simulation Modeling. E3S Web of Conferences, 403, 2023, 07002. Doi: https://doi.org/10.1051/e3sconf/202340307002

[6]. N.D. Samushkin, Pravo i ekonomika v kontekste tekhnologicheskikh revolyutsiy. Probely v rossiyskom zakonodatel'stve, 17 (5), 2024, 26-30 (in Russian). Doi: https://doi.org/10.33693/2072-3164-2024-17-5-026-030

[7]. N. Appasova, A. Kornilova, K. Tesler, M. Tashtamirov, L. Anikina, Planning, Architectural, and Construction Solutions to Create a Comfortable Environment for Small Cities Near Megacities. Construction Materials and Products, 8 (4), 2025, 10-10. Doi: https://doi.org/10.58224/2618-7183-2025-8-4-10

[8]. T.V. Portnova, Futurism Concept in the Design and Architectural Solutions of the 20th and Early 21st Centuries. Civil Engineering and Architecture, 11 (3), 2023, 1125-1136. Doi: https://doi.org/10.13189/cea.2023.110302

[9]. N.A. Abuov, G.S. Iliasova, S.K. Ualieva, Malyye Goroda Severo-Kazakhstanskoy Oblasti: Istoriya i Analiz Tekushchey Situatsii. Asian Journal “Steppe Panorama”, 12 (3), 2025, 679-695 (in Russian). Doi: https://doi.org/10.51943/2710-3994_

[10]. I. Abdullayev, A. Rozhok, O. Levichev, M. Litwinowa, A. Trubcheninova, S. Levicheva, Digital Transformation in Agricultural Cluster Management: Interrelated Factors and Model Applicability. Journal of Global Innovations in Agricultural Sciences, 13 (4), 2025, 1301-1308. Doi: https://doi.org/10.22194/JGIAS/25.1840

[11]. M. Logachev, D. Goncharov, Simulation Model of Crop Yields. BIO Web of Conferences, 93, 2024, 02015. Doi: https://doi.org/10.1051/bioconf/20249302015

[12]. V. Bobkov, I. Shichkin, Chapter 18: Labour and Forced Migration into Post-Soviet Russia, in: Handbook on Migration and Development. Edward Elgar Publishing, Cheltenham, 2024, 281-298. Doi: https://doi.org/10.4337/9781789907131.00027

[13]. D. Liu, F. Li, M. Qiu, Y. Zhang, X. Zhao, J. He, An Integrated Framework for Measuring Sustainable Rural Development Towards the SDGs. Land Use Policy, 147, 2024, 107339. Doi: https://doi.org/10.1016/j.landusepol.2024.107339

[14]. L.A. Balgarina, S.A. Jumabayev, Y.K. Shokamanov, Sustainable Development of Regions: Assessment Methodology and Analysis (Approbation for Kazakhstan). Economic Studies Journal, 34 (2), 2025, 179-198.

[15]. O. Korotun, D. Goncharov, Simulation Modeling in Environmental Aspect of Sustainable Development in Retail Sector. BIO Web of Conferences, 130, 2024, 08014. Doi: https://doi.org/10.1051/bioconf/202413008014

[16]. N.K. Nurlanova, F.G. Alzhanova, Z.T. Satpayeva, Sustainable Development of Cities: Rating Assessment Methodology and Risk Analysis (Using Kazakhstan as an Example). Economy of Regions, 19 (2), 2023. 343-354. Doi: https://doi.org/10.17059/ekon.reg.2023-2-4

[17]. M.T. Yermekov, O.V. Rozhkova, S.G. Sandibekova, Ye.T. Tolysbayev, A.V. Vetyugov, O.A. Turbin, E.V. Belenko, Storage of the Industrial Waste of the Mining and Smelting Industry of Kazakhstan, Landfills Arrangement, Efficiency and Operational Features. News of the National Academy of Sciences of the Republic of Kazakhstan Series of Geology and Technical Sciences, 6 (444), 2020, 83-89. Doi: https://doi.org/10.32014/2020.2518-170X.134

[18]. I.A. Rozhdestvenskaya, P.V. Stroev, Raznoobraziye usloviy i strategiy razvitiya monogorodov. Problemy ekonomiki i yuridicheskoy praktiki, 20 (5), 2024, 187-194 (in Russian). Doi: https://doi.org/10.33693/2541-8025-2024-20-5-187-194
[19]. A. Krasnikov, V. Simonov, S. Boykov, Features of Development of a Digital Twin of the Transport System of an Urban Area Using Simulation Modeling Methods. E3S Web of Conferences, 535, 2024, 04004. Doi: https://doi.org/10.1051/e3sconf/202453504004
[20]. Yu. Altunina, O. Korotun, I. Polevshchikov, Simulation Model of a Queuing System in the Service of State Registration, Cadastre and Cartography. E3S Web of Conferences, 535, 2024, 05003. Doi: https://doi.org/10.1051/e3sconf/202453505003
[21]. M. Safiullin, L. Elshin, A. Mingulov, Impact of Transformation of Foreign Economic Supply Chains on the Sustainability of Regional Economic Development. International Journal of Sustainable Development and Planning, 20 (9), 2025, 3895-3905. Doi: https://doi.org/10.18280/ijsdp.200920
[22]. V.S. Eliseev, Sootnosheniye sel'skokhozyaystvennogo i pravovogo regulirovaniya v sel'skokhozyaystvennom sadovodstve. Lobbirovaniye v zakonodatel'stve, 3 (4), 2024, 22-28 (in Russian). Doi: https://doi.org/10.33693/2782-7372-2024-3-4-22-28
[23]. V. Grankina, D. Vasilyev, Digital Transformation Modeling for Agricultural Land Irrigation. BIO Web of Conferences, 141, 2024, 02005. Doi: https://doi.org/10.1051/bioconf/202414102005
[24]. I. Abdullayev, L. Battalova, G. Kostyleva, R. Enikeev, A. Khaliapin, A. Shelygov, Estratégias Para Um Planejamento Tributário Eficaz NA Gestão de Negócios. Relações Internacionais no Mundo, 3, 49, 2025, 351-363.
[25]. A.T. Aliev, K.V. Baldin, Otsenka sostoyaniya ustoychivosti razvitiya promyshlennogo proizvodstva s tsel'yu narashchivaniya ekonomicheskogo potentsiala strany. Problemy ekonomiki i yuridicheskoy praktiki, 20 (3), 2024, 174-178 (in Russian). Doi: https://doi.org/10.33693/2541-8025-2024-20-3-174-178
[26]. E. Kuandykova, D. Bekezhanov, I. Nessipbaeva, A. Rzabay, K. Jumabayeva, A. Zhuldybayeva, Regulation of Mechanisms for Management of Environmental Issues of Rational Use of Natural Resources and Pastures. International Journal of Sustainable Development and Planning, 19 (11), 2024, 4509-4517. Doi: https://doi.org/10.18280/ijsdp.191138
[27]. Z. Nokusheva, B. Nasiyev, E. Kantarbayeva, N. Zhanatalapov, A. Bekkaliyev, A. Khairush, A. Okshebayev, Bio-Organic Fertilizer Application for Forage Quality Improvement and Rangeland Restoration in Northern Kazakhstan's Steppe Ecosystems. International Journal of Design and Nature and Ecodynamics, 20 (10), 2025, 2363-2373. Doi: https://doi.org/10.18280/ijdne.201014
[28]. V. Grankina, I. Krasnikova, Y. Smirnova, I. Kulibaba, V. Barinov, Digital Transformation of the Educational Process in Schools of Kazakhstan: The Concept of Intelligent Assistant in School Physics Curriculum. Frontiers in Education, 11, 2026, 1766616. Doi: https://doi.org/10.3389/feduc.2026.1766616
[29]. I. Krasnikova, I. Dyakonova, O. Evdoshenko, Simulation Modeling as a Means of Integrating Infrastructure for Individual Mobility in Urban Environments. E3S Web of Conferences, 535, 2024, 04003. Doi: https://doi.org/10.1051/e3sconf/202453504003
[30]. D. Ramazanova, A. Togaibayeva, A. Suguraliyeva, B. Zhubatyrova, G. Biissova, A. Bukhaeva, Evaluation of Pre-Service Teachers' Views on Their Ability to Use Instructional Technologies. World Journal on Educational Technology: Current Issues, 13 (3), 2021, 428-436. Doi: https://doi.org/10.18844/wjet.v13i3.5951
[31]. G. Saparov, Y. Dutbayev, A. Amanzholkyzy, K.R. Islam, K. Tireuov, N. Hakimov, E. Zudilova, R. Shichiyakh, O. Shoykin, B. Ganiyev, I. Otcheskiy, M. Trushin, A. Kozlov, Assessing Heavy Metal Contamination for Soil Reclamation: Implications for Sustainable Urban Development. International Journal of Design and Nature and Ecodynamics, 19 (6), 2024, 2197-2204. Doi: https://doi.org/10.18280/ijdne.190636
[32]. M. Logachev, Ya. Beresneva, Simulation Modeling of Forest Plantation Condition. BIO Web of Conferences, 93, 2024, 01017. Doi: https://doi.org/10.1051/bioconf/20249301017
[33]. A. Saibulatova, D. Dyussenova, A. Yessenbayev, A. Toishiyeva, Semiotics of Architecture of Low-Rise Residential Buildings in an International Context. Project Baikal, 23 (87), 2026, 139-145. Doi: https://doi.org/10.51461/issn.2309-3072/87.2753

Nailya Appassova, Doctor of Philosophy (PhD) in Architecture *(Republic of Kazakhstan, Astana) – Kazakh Agrotechnical Research University named after S. Seifullin, appassova@mymail.academy*

USE OF FIBER-REINFORCED PLASTICS IN BRIDGE CONSTRUCTION IN RUSSIA

Aleksey Nerovnykh[1]*, Artem Ivanov[1], Kirill Kobelev[1], Viktor Shilimov[1]

[1]*Siberian Transport University, Novosibirsk, RF*

Abstract: *Research on composite materials for use in bridge structures began at the Siberian Bridge Research Institute (SBRI) of STU in 2007. Over time, numerous laboratory, field, and theoretical studies have been conducted on various types of composite materials, fiberglass structures, and carbon fiber-reinforced concrete elements. In 2014, with the participation of SBRI specialists, the first road bridge in Russia with supporting structures made of fiberglass was designed and built. The research results presented in the article formed the basis for many regulatory documents on the design of composite superstructures and external reinforcement systems for strengthening spans and supports with insufficient load-bearing capacity.*

Keywords: *polymer composite material, reinforcement, bridge, span, test, composite structures, fiberglass, carbon fiber plastic.*

Aleksey Nerovnykh*
E-mail: aleksey@nerovnykh.ru

Received: 01.06.2026
Revised: 26.06.2026
Accepted: 15.07.2026

Introduction

Over the last 20 years, sales of polymer composite materials (FRP) and products made from them have more than tripled, from $41.5 million to $130 million. In particular, in the construction industry, the use of FRP is steadily increasing, owing to the high strength of composite materials, their low specific self-weight, resistance to aggressive influences, and other advantages over steel and concrete. These advantages allow not only to increase the service life and maintenance periods of bridge structures, but also to reduce the cost of transportation and installation of materials and products, and maintenance of structures in general.

The main directions of using FRP in bridge construction are the manufacture of bearing and auxiliary structures from them, as well as the reinforcement of spans and supports with external reinforcement systems.

The experience of designing and examining bridges with FRP-made or FRP-reinforced elements consistently shows that the potential of composite materials in such structures is not yet fully realized. Existing calculation methods, constructions, and approaches to the technical condition of composite auxiliary structures require improvement to enhance the efficiency of using composite materials, while the scope of application for these structures remains inadequately addressed.

Materials and Methods

The use of FRP as bearing elements in bridge spans. The first road bridge in Russia featuring a composite span (Fig. 1) was commissioned in 2014 in the Novosibirsk region. The span structure, with a total length of 18 meters, consists of six multi-braced fiberglass trusses and a reinforced concrete deck. This design was first implemented in global bridge engineering practice [1]. The adopted layout of the span structure facilitates the passage of vehicles on a 4.5-meter roadway and pedestrians on sidewalks, each 0.75 meters wide.

All node connections of the fiberglass elements, including the tie attachments, are made with 12-mm-diameter rigid bolts. To eliminate the influence of bending moments on the operation of the braces, their connections to each other are designed as hinged. The roadway slab is made of monolithic reinforced concrete after the trusses have been installed in their design position. Consequently, the calculations have taken into account stages of the operation of the span structure in accordance with the technology of sequential slab concreting. The connection of the roadway slab to the trusses was made using stops that prevent the displacement of the slab relative to the trusses and its detachment from the upper chords of the trusses.

Fig. 1. *General view of a bridge with a composite span*

The analysis of the span structure was conducted utilizing the Midas Civil software package, taking into account the staged construction process. Fiberglass was considered as an anisotropic material, with its properties specified along three orthogonal axes.

Before the bridge was put into operation, static and dynamic tests on the span structure were conducted [2]. Two four-axle trucks with a gross weight of 51 and 55 tons were used as a test load (Fig. 2). To determine the response parameters of the span structure to the dynamic impact of a moving load, loaded trucks were driven across the bridge at speeds of 20...30 km/h.

Fig. 2. *Static test of the composite span*

During the tests, local deformations were measured using mechanical strain gauges and TDM electronic strain gauges from the Tensor-MS system. The deflections of the span structure were recorded using an optical level with the rails.

During subsequent bridge operations, SBRI specialists conduct annual inspections and instrumental measurements in accordance with a specially developed monitoring program [3]. The main parameters recorded during these works are the stress-strain state of the span and its dynamic characteristics.

The use of FRP for strengthening of bearing structures. Research on composites as elements of external reinforcement systems for reinforced concrete bridge structures was initiated at the SBRI in 2009 and was among the first in Russia [4-6]. The main part of the laboratory tests was performed on reinforced concrete beam specimens measuring 1650x160x220 mm and column specimens measuring 800x200x200 mm [7]. Scaled models of beam spans, each 4 meters long, were also tested. In addition to laboratory tests, strengthening and subsequent static tests were carried out on spans of two road and one railway bridges located in the Novosibirsk region.

Static laboratory tests of reinforced concrete elements were carried out on a WPM-300 press (Fig. 3). In total, more than 50 sample series were tested, differing in the design of the external reinforcement system and the type of FRP composite used. An additional factor for column specimens, the influence of which on the effectiveness of the reinforcement was investigated, was the value of the eccentricity of the load application to the structure – centrally and eccentrically compressed specimens were considered.

Beam specimen *Column specimen*

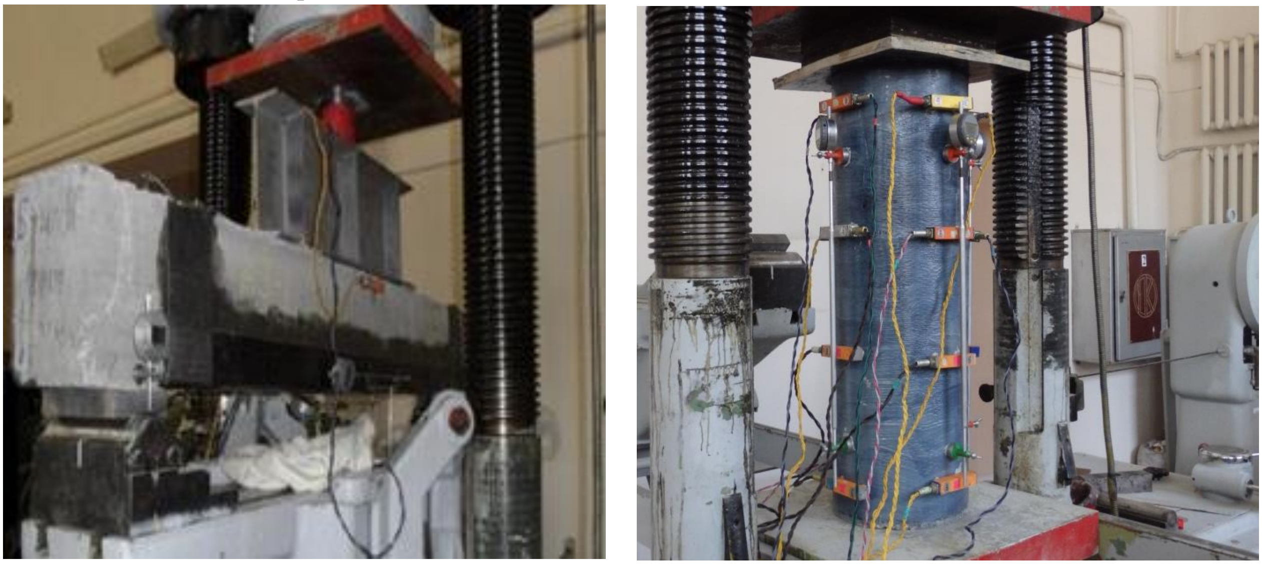


Fig. 3. *Reinforced concrete specimens during static testing*

Laboratory tests on beam-span models were performed on a power stand. The samples were T-beams with a length of 4 meters, a height of 30 cm, and a web and flange thickness of 7 cm.

To assess the degree of involvement of the external reinforcement system in the joint work with the beams of operating bridges (Fig. 4), static tests were carried out before the installation of FRP, after the completion of the epoxy binder polymerization process, and one year after the structure was operated in normal mode.

Fig. 4. *Bridge beams strengthened in the support section against shear force*

Triaxial and four-axle trucks, each with a total weight of 35 to 55 tons, were used as test loads. To assess the spatial behavior of the span structures, various loading schemes were implemented during the tests, differing in the location of the load across the bridge (Fig. 5). During the tests, the overall deformations of the span structures were recorded, as well as the local deformations of the elements of the external reinforcement system and the concrete of the beams at the closest possible points.

In all tests conducted, strain, displacement, and force sensors of the "Tensor MS" system, as well as mechanical strain gauges, were used as measuring instruments.

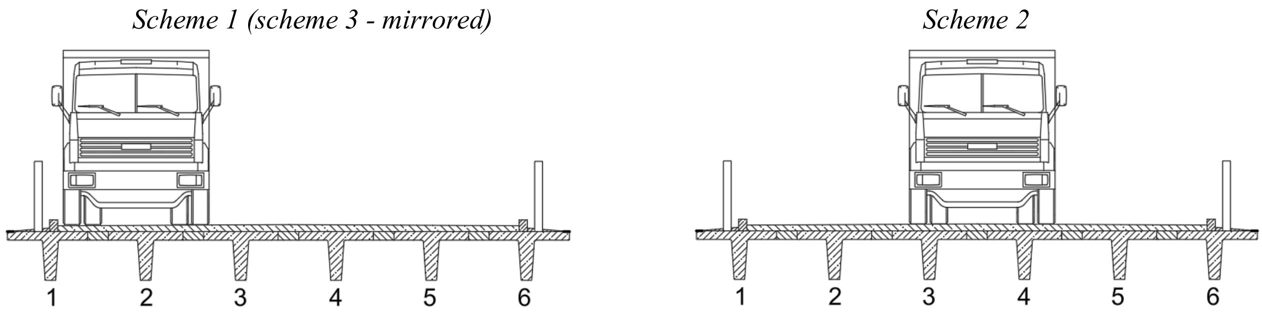


Fig. 5. *Test load arrangement schemes during testing*

The use of FRP in auxiliary structures. Laboratory static tests were performed to determine the holding capacity of the composite railing and to assess its suitability for use on bridges. The tests were carried out on railing sections made of fiberglass elements with a rectangular cross-section. The tests evaluated the bearing capacity and deformability of the railings under vertical and horizontal loads, with magnitudes corresponding to the requirements of current regulatory documents. The sections were fixed to a concrete base using metal studs in accordance with the manufacturer's recommendations. The load was applied using a hydraulic jack and transferred to the structure via a special traverse (Fig. 6). During the tests, both the applied load and the deformation of the railing elements were recorded.

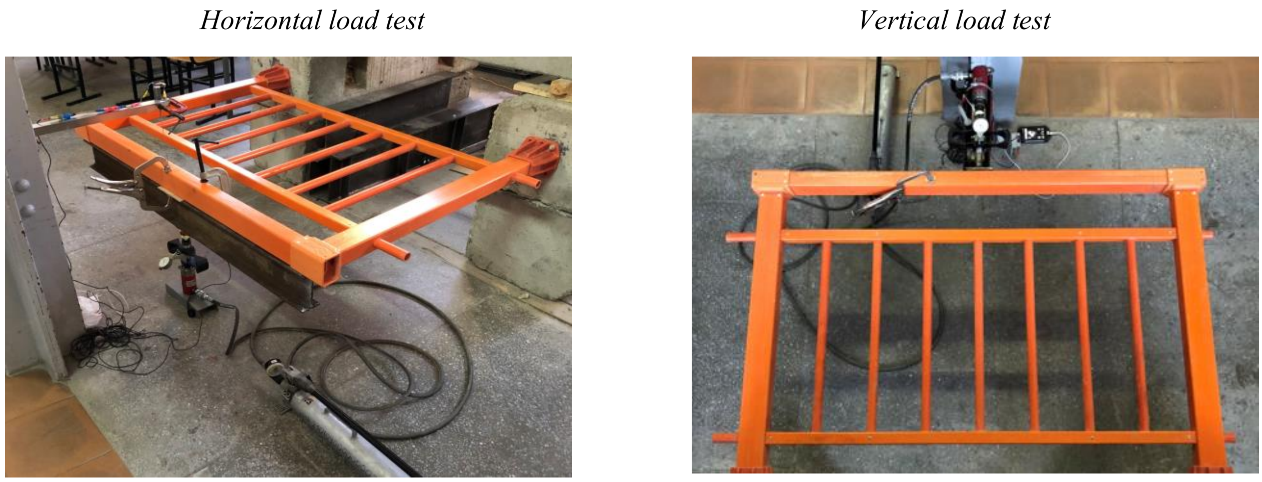


Fig. 6. *Sample of the railing during static tests*

Results and Discussion

The use of FRP as bearing elements in bridge spans. The test results for the composite span showed that the construction coefficients (ratio of actual to calculated values of controlled parameters) for all trusses and gauges across all controlled sections ranged from 0.75 to 0.98. These values indicate good design performance and consistency of actual and estimated data.

The analysis of vibrograms of span oscillations showed that the structure at different points along its length vibrates in phase, with the same frequencies and intensity – no changes in the stiffness of the span along its length before and after the tests were detected. There are no significant changes in the frequency of the own oscillations after testing.

The results of monitoring the bridge's technical condition, based on the values of general vertical deformations in the span's farms, show that the initial arching of the farms, 15 cm at the end of all installation works, has decreased to an average of 8.2 cm. During the first year of operation, overall construction rose slightly, likely due to improved connections, but it returned to its previous level over time. This effect is due to changes in material properties, especially in concrete, where the rheological effects are noticeable in the first 2 years after laying. The deformation is now stable. Dynamic design parameters (natural frequencies and logarithmic decrement) are also stable for 10 years.

The use of FRP for strengthening of bearing structures. Tests of the rectangular cross-section beam samples showed that the bearing capacity of the reinforced elements was 40-190% higher for bending moment and 20-70% higher for shear force.

Column samples, reinforced with FRP, had a bearing capacity of 10-50% higher than unreinforced samples. The efficiency of the reinforcement depended largely on the location where the compressive force was applied – the farther from the gravity center of the cross-section it was applied, the smaller the increase in the sample's load capacity.

Tests on exploited road bridges showed that the elements of external reinforcement systems were well integrated into the joint work with beams under transport loads. The overall and local deformation of the beams did not exceed the calculated values. The structural coefficient values ranged from 0.8 to 0.9, indicating that the design assumptions were consistent with the actual design performance. The use of composite materials increased the bearing capacity of the spans for both bending moment and shear force, ensuring that active design loads A14 and H14 could pass through the bridges without restrictions.

The use of FRP in auxiliary structures. According to the test results for the railing sections, the loads causing sample destruction were significantly higher (by 50-150%) than the normative loads. The deformation of the railing under normative loads did not exceed 4 mm vertically and 34 mm horizontally. There are no defects caused by normative loads in the samples. The destruction of samples usually resulted from the rupture of anchor studs that secured them to the concrete base.

Summary

The use of FRP as bearing elements in bridge spans. Static and dynamic tests of the composite span showed, in general, satisfactory compliance of design assumptions taken into account and the actual operation of the installed structure. The technical condition of the span has remained stable throughout all 10 years of its operation. According to the results of the last inspection of the structure, no power or mechanical damage to bearing structures was found. There are no signs of degradation of the fiberglass and reinforced concrete elements of the span; the coating condition is good. There are no defects that reduce the structure's bearing capacity – the actual bearing capacity matches the design loads.

The results of tests and monitoring of the technical condition of a span show that such construction can be applied on pedestrian and road bridges. Large bearing capacity and stability in real operating conditions indicate the feasibility of its use in bridge construction and reconstruction.

The use of FRP for strengthening bearing structures. Research on FRP components of external reinforcement systems, as well as on reinforced concrete elements strengthened by these systems, has shown that this technology is efficient and cost-effective. Its use extends the service life of bridges by at least 25 years.

During the research, many normative documents were developed, which enabled the accelerated and expanded introduction of such external reinforcement systems in Russia's bridge construction industry.

Currently, research is being carried out in the SBRI to use FRP as an external reinforcement system for curved and stretched steel elements in spans.

The use of FRP in auxiliary structures. Tests of the fiberglass railings have shown that they fully meet the requirements of current normative documents for stiffness and bearing capacity. The operation of such railings, as well as the drainage channels made of FRP, demonstrates their sufficient durability.

It should be noted that the use of electric lighting poles, viewing and operating devices, and other auxiliary constructions made of FRP is possible on bridges. However, this requires additional research to confirm their reliability.

Conflict of Interest

The authors declare no conflicts of interest.

Funding

This research did not receive any financial support.

References

[1]. A.N. Ivanov, Proyektirovaniye gibridnogo proletnogo stroyeniya avtodorozhnogo mosta. Stekloplastik v proletnom stroyenii avtodorozhnogo mosta: Collection of articles. LAMBERT Academic Publishing, Saarbrücken, Deutschland, 2014 (in Russian).

[2]. A.N. Ivanov, Ispytaniye avtodorozhnogo mosta s proletnym stroyeniyem iz polimernogo kompozitsionnogo materiala. Stekloplastik v proletnom stroyenii avtodorozhnogo mosta: Collection of articles. LAMBERT Academic Publishing, Saarbrücken, Deutschland, 2014, 44-53 (in Russian).

[3]. A.N. Ivanov, P.Y. Kuzmenkov, Monitoring the technical condition of the road bridge across the Pashenka River. Bulletin of the Siberian State Transport University, 2, 2016, 20-27 (in Russian).

[4]. S.A. Bokarev, A.N. Yashnov, D.N. Smerdov, A.A. Nerovnykh, V.A. Slepec, L.Y. Soloviev, Usileniye zhelezobetonnykh elementov mostovykh konstruktsiy polimernymi kompozitsionnymi materialami. Siberian State Transport University, Novosibirsk, 2019 (in Russian).

[5]. S.A. Bokarev, D.N. Smerdov, A.A. Nerovnykh, Otsenka vynoslivosti izgibayemykh zhelezobetonnykh konstruktsiy, usilennykh kompozitnymi materialami. Mezhdunarodnyy sbornik nauchnykh trudov "Dal'niy Vostok. Avtomobil'nyye dorogi i bezopasnost' dvizheniya", Khabarovsk State Technical University, 10, 2010, 287–294 (in Russian).

[6]. S.A. Bokarev, A.N. Kostenko, D.N. Smerdov, A.A. Nerovnykh, Experimental Studies of Reinforced with Polymer Composites Ferroconcrete Specimens at Low and High Temperatures. Internet journal Naukovedenie, 3, 2013, 168 (in Russian).

[7]. K.V. Kobelev, Laboratornyye eksperimental'nyye issledovaniya zhelezobetonnykh obraztsov, usilennykh polimernymi kompozitsionnymi materialami. XIV International Conference of students, graduate students and young scientists "Prospects of fundamental sciences development" (vol. 6. Construction and Architecture). Tomsk Polytechnic University, Tomsk, Russia, April 25-28, 2017, 89-91 (in Russian).

Aleksey Nerovnykh, Doctor of Philosophy (PhD) in Engineering *(Russia, Novosibirsk) – Siberian Transport University, Associate Professor at the Department of Bridges, Head of the Department of Innovative Methods for Bridge Repair and Reinforcement in Siberian Bridge Research Institute, aleksey@nerovnykh.ru*

Artem Ivanov, Doctor of Philosophy (PhD) in Engineering *(Russia, Novosibirsk) – Siberian Transport University, Associate Professor at the Department of Bridges, Head of the Department of Composite Materials and Structures in Siberian Bridge Research Institute, a.n.ivanov1@mail.ru*

Kirill Kobelev *(Russia, Novosibirsk) – Siberian Transport University, Process Engineer at the Department of Composite Materials and Structures in Siberian Bridge Research Institute, jamkka@mail.ru*

Viktor Shilimov *(Russia, Novosibirsk) – Siberian Transport University, Engineer at the Department of Innovative Methods for Bridge Repair and Reinforcement in Siberian Bridge Research Institute, shilimoviktor@gmail.com.*

PASSIVE VENTILATION SYSTEMS IN HISTORIC TOGH

Manushak Titanyan[1], **Anna Karamyan**[1], **Emma Harutyunyan**[1]

[1] *National University of Architecture and Construction of Armenia, Yerevan, RA*

Abstract: *This study investigates the natural ventilation systems integrated into the historical architectural structures of Togh village in the historical province of Dizak in Artsakh. The village is situated on the eastern slope of Mount Togh and has been inhabited since ancient times. At its center stands the eighteenth-century Melik Yegan Palace. The study aims to identify the design principles of the natural ventilation systems, analyze their spatial and structural characteristics, and evaluate their functional significance. The relevance of the research is driven by the need to study and preserve traditional engineering solutions in historical architecture, while its scientific novelty lies in the comprehensive analysis of the ventilation systems preserved in Togh's historical buildings. The research employs architectural analysis, field observations, and comparative methods. The results demonstrate that passive ventilation operated not only in residential spaces but also in basements, including rooms without direct external openings. The study identifies the structural characteristics and spatial organization of these systems and highlights their role in regulating the indoor microclimate. The findings have practical significance for the conservation and restoration of historical buildings and may also contribute to the development of contemporary sustainable architectural design.*

Keywords: *Togh, Melik Yegan, historical structure, microclimatic conditions, passive ventilation, green buildings.*

Anna Karamyan *
E-mail: a.karamyan@nuaca.am

Received: 03.06.2026
Revised: 28.06.2026
Accepted: 23.07.2026

Introduction

Vernacular architecture represents the accumulated knowledge of generations that adapted the built environment to local climatic, geographical, and socio-cultural conditions. The use of locally available materials, passive environmental strategies, and construction techniques refined over centuries suggests that traditional buildings incorporated passive environmental strategies that may have contributed to effective environmental control. As noted by previous studies, vernacular dwellings provide valuable evidence of environmentally responsive design and demonstrate how human needs were satisfied through simple but highly efficient architectural solutions [1].

Togh village is located in the historical province of Dizak in Artsakh, on the eastern slope of Mount Toghasar (Fig. 1). The settlement has been continuously inhabited since ancient times. It is first documented as a monastic village in a 1246 inscription from Gtchavank [2]. Melik Yegan (Avan), the founder of the Togh Melik dynasty, was officially recognized as a melik by Shah Tahmasp II of Persia. Togh subsequently became the administrative center of the Dizak Melikdom. Melik Yegan later received the title of *Beklarbeg* of Artsakh from Nader Shah, as confirmed by an inscription on the Melik Palace [3]. Historical information on the settlement's structure, economy, and patterns of occupation is further documented by Arakel Vardapet [4]. The architectural heritage of the settlement includes ecclesiastical buildings, khachkars, defensive complexes, bridges, and funerary monuments [5].

Heritage represents an important component of a nation's cultural identity and plays a significant role in its historical and political continuity. The historic center of Togh began to develop in the eighteenth century. It continued to evolve until the early twentieth century (Fig. 2). The settlement developed as a unified urban organism, characterized by planning features typical of steep-slope settlements, including a road network, small public squares, and a natural spring. Buildings were constructed using locally quarried, roughly hewn tuff sandstone, ensuring a consistent material palette, scale, and construction technique throughout the village.

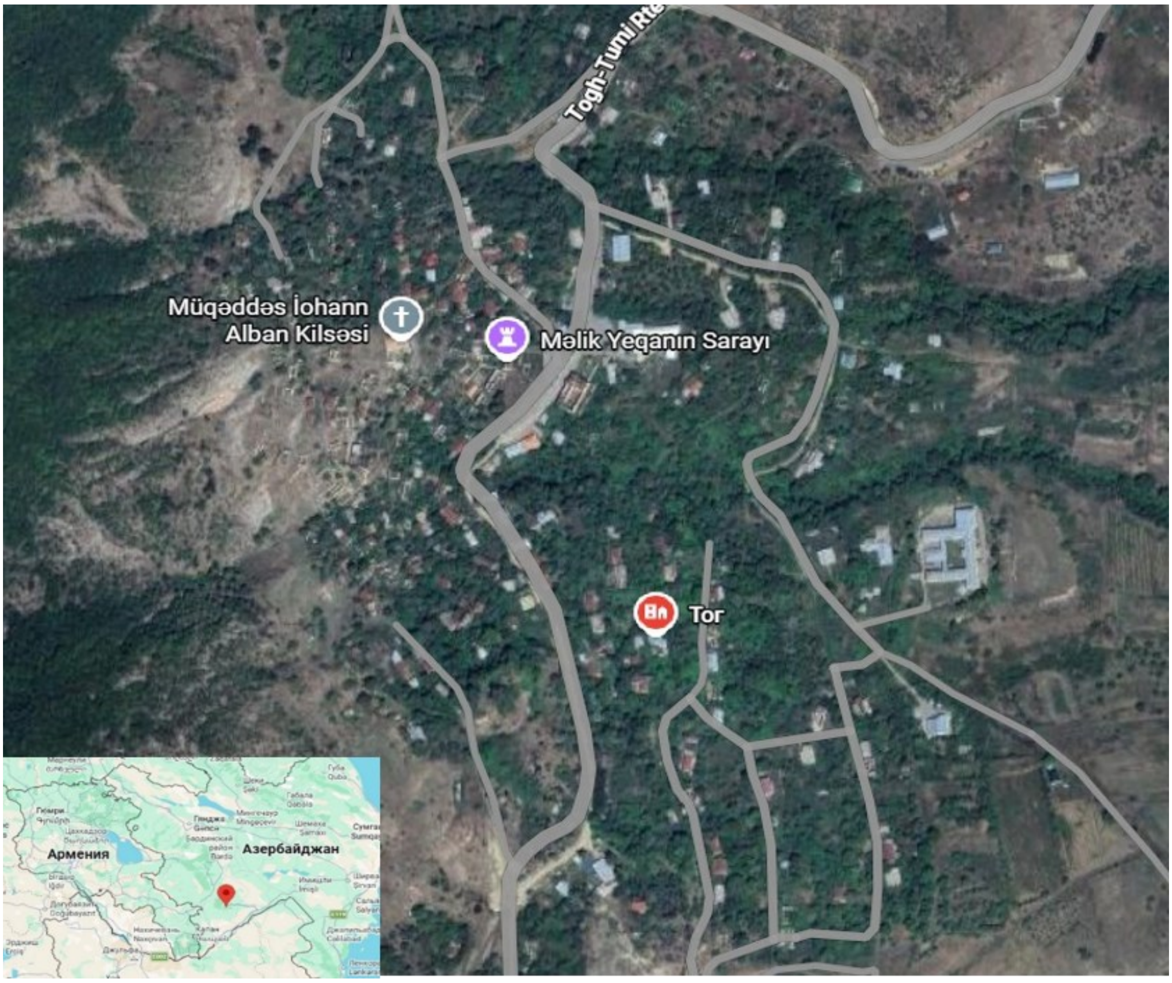


Fig. 1. *Satellite image (Google Earth) of the geographical location of Togh village*

Fig. 2. *The general view of Togh village*[1]

[1] https://www.flickr.com/photos/danielyans/14970234110/in/photostream/

At the center of the settlement stands the Melik Palace complex, while multi-story residential buildings were subsequently constructed in the surrounding areas. This historically developed architectural environment reflects the social organization, domestic life, and security requirements of the eighteenth and nineteenth centuries. Despite chronological differences, the buildings exhibit a shared tradition of advanced construction techniques, demonstrating continuity in local architectural practice and the high level of engineering knowledge of their builders.

The Melik Yegan Palace is a significant example of late medieval Armenian architecture. Its historical background, architectural characteristics, and spatial composition have been examined by M. Sargsyan [6] and A. Ghulyan [7]. In 2010, a restoration project for the monument was prepared by "VEM" LLC, and the restoration works were completed in 2016[2].

This study aims to investigate the integrated passive ventilation systems incorporated into the historical buildings of Togh and to evaluate their architectural configuration, engineering principles, and functional performance. The study addresses the following research questions:

- What architectural and structural characteristics define the passive ventilation systems preserved in the historical buildings of Togh?
- How do these ventilation systems operate with respect to airflow organization and regulation of the indoor microclimate?
- What is the engineering and functional significance of these passive ventilation systems for the conservation of historical buildings and contemporary architectural practice?

This article examines the integrated passive ventilation systems incorporated into the historical buildings of Togh, particularly in spaces with limited or no window openings. Field investigations and architectural surveys indicate that these systems played a crucial role in maintaining favorable indoor microclimatic conditions in buildings of various functions. The specially designed openings served not only as sources of natural light but primarily as passive ventilation and cooling elements. Their geometric configuration and interconnected air passages reflect a sophisticated understanding of environmental behavior by traditional builders. The architectural evidence suggests that empirical knowledge of local climatic conditions was effectively incorporated into the design of these systems. The arrangement of ventilation openings and airflow channels suggests careful consideration of prevailing wind directions, solar exposure, and thermal gradients. The identified systems regulated airflow via pressure differentials and buoyancy-driven mechanisms, ensuring continuous air exchange and helping control indoor temperature and humidity. These engineering solutions illustrate a high degree of environmental adaptation achieved through accumulated construction experience. Overall, Armenian builders successfully integrated passive ventilation principles into masonry structures, creating thermally efficient systems that are consistent with the fundamental concepts of passive environmental design.

Preserved examples of these passive ventilation systems have been documented in the basement and first-floor levels of the Melik Yegan Palace reception hall, as well as in the basement of later multi-story residential buildings. These features represent a relatively underexplored category of passive environmental control systems within Armenian architectural heritage and provide valuable evidence of the engineering knowledge embedded in traditional construction practices.

Scientific Novelty

The scientific novelty of this research lies in the first systematic architectural and engineering investigation of integrated passive ventilation systems preserved in the historic buildings of Togh. The principal original contributions of the study are as follows:

---

[2] Authors: M. Sargsyan, R. Kharazyan

- the identification and documentation of previously undocumented passive ventilation elements integrated into the masonry structures of the Melik Yegan Palace and adjacent historic residential buildings,
- the architectural and functional interpretation of these systems based on field investigations, measured drawings, and comparative analysis,
- the preliminary engineering assessment of their ventilation performance through airflow calculations based on measured geometric characteristics,
- the demonstration that these ventilation systems represent an indigenous environmental strategy adapted to the climatic conditions, topography, and construction traditions of historic Armenian architecture, differing from the better-known Middle Eastern wind towers,
- the establishment of a scientific basis for the conservation of these engineering features and for their consideration as a source of knowledge for contemporary architectural design.

Beyond its engineering significance, the study preserves architectural documentation of historic structures that are currently inaccessible for further field investigation, thereby contributing to the long-term documentation and safeguarding of Armenian architectural heritage.

Materials and Methods

This research is based on a combination of field investigation, architectural analysis, environmental assessment, and comparative study methods to identify and evaluate natural ventilation systems in the historical structures of Togh village (Table 1).

Table 1. Research Framework: Stages, Methods, and Expected Outputs

N	Research Stage	Method	Expected Output
1.	Literature review	Review of traditional ventilation and vernacular architecture	Research gap framework and knowledge gap
2.	Selection of case studies	Selection of representative historical buildings based on preservation, authenticity, accessibility, and presence of ventilation elements	Representative sample of investigated buildings
3.	Field survey and documentation	On-site investigation, measurements organization and building organization	Architectural documentation and measured drawings
4.	Architectural and spatial analysis	Analysis of ventilation channels, spatial organization and building orientation	Identification of passive ventilation systems
5.	Environmental assessment	Analysis of climatic conditions, geology and natural resources	Environmental context and engineering parameters
6.	Comparative analysis	Comparison with Persian Badgirs and Egyptian Wind Towers	Functional and Typological assessment
7.	Interpretation and Conservation Implications	Evaluation of ventilation performance and heritage significance	Conclusions and conservation recommendations

Literature Review

Recent international research often reflects a gradual shift from descriptive studies of national architecture to interdisciplinary research that integrates heritage conservation, building physics, and environmental engineering. Studies by E. Lucchi and F. Ascione highlight the importance of building performance modeling for understanding the environmental behavior of historic buildings, while acknowledging the methodological limitations associated with heritage structures [8, 9]. They argue that successful conservation requires a balance among historical authenticity, environmental performance, and energy efficiency. These studies provide advanced analytical frameworks for assessing historic buildings, focusing primarily on European stone heritage that has undergone renovation. In contrast, passive ventilation systems embedded in traditional Armenian stone architecture have largely gone undocumented in the international literature. Therefore, the current study addresses this research gap by providing architectural documentation and a preliminary engineering interpretation of a previously unexplored passive ventilation strategy preserved in Togh's historic buildings.

Since antiquity, natural ventilation techniques have been employed to improve indoor air quality and thermal comfort in built environments. Among these, wind towers (*wind catchers* or *badgirs*) are among the most effective passive environmental control systems. Designed to capture cooler outdoor air and channel it into interior spaces while exhausting warmer air through vertical shafts or openings, these systems have been documented in the architectural traditions of Egypt, Persia, and other regions of the Middle East [10]. Their effectiveness has been widely recognized in the scientific literature, where they continue to serve as important references for contemporary passive cooling strategies.

A substantial body of research has been devoted to the engineering analysis of historical buildings and passive environmental control technologies [11]. In addition to ventilation, studies have highlighted the importance of moisture management in preserving historic masonry structures, identifying rising damp caused by capillary water transport as one of the principal mechanisms of material deterioration [12]. These investigations demonstrate that environmental performance is an essential aspect of both the conservation and functional assessment of architectural heritage.

Research conducted in regions with climatic conditions comparable to those of Armenia has further demonstrated the effectiveness of traditional passive design strategies. Alwetaishi *et al.* investigated thermal comfort in historic buildings in Saudi Arabia and showed that thermal mass and appropriate building orientation significantly improve indoor thermal conditions without mechanical systems [13]. Similarly, Nassim *et al.* analyzed traditional wind towers (*badgirs*) as an effective passive cooling technology that operates through pressure differences and thermal buoyancy. Their study confirmed the ability of these systems to provide continuous natural ventilation and improve indoor environmental conditions in hot climates [14] (Fig. 3).

Fig. 3. *The historical town of Yazd in Persia and the wind towers. Photo by M. Titanyan*

The accumulated research suggests that traditional passive environmental systems incorporate engineering principles that remain highly relevant to contemporary sustainable and energy-efficient architecture. The environmental logic embedded in these historical solutions provides valuable guidance for reducing energy consumption and improving indoor environmental performance in modern buildings [14].

Despite the growing body of research on passive environmental systems in historical architecture, comparable studies of Armenian architectural heritage remain limited. Previous investigations have primarily focused on the historical and architectural significance of monuments, while the integrated passive ventilation systems preserved in traditional Armenian masonry buildings have received little scientific attention. Consequently, their architectural configuration, engineering principles, and environmental performance remain insufficiently documented and evaluated. The present study addresses this research gap by providing a systematic architectural and engineering analysis of the passive ventilation systems preserved in the historical buildings of Togh village.

Selection of case studies

The study focuses on the historical buildings of Togh village, with particular emphasis on the palace of Melik Yegan and adjacent multi-story residential structures dating from the eighteenth and nineteenth centuries. The investigated buildings were selected according to the following criteria:

- preservation of their historical authenticity,
- presence of identifiable passive ventilation elements,
- accessibility for field documentation and architectural measurements at the time of the survey,
- representativeness of the traditional residential architecture of Togh.

The selected buildings are the surviving historic structures accessible during the field investigations. Consequently, the present study is based on the complete set of field documentation collected during the accessible period, which constitutes the primary empirical dataset for the research.

Field Survey and Documentation

Fieldwork was conducted through on-site surveys, visual inspections, photographic documentation, and measurements of preserved architectural elements, including ventilation openings, wall thicknesses, and spatial configurations. The documentation focused on identifying the location, geometry, and connectivity of air channels within the masonry structures.

Architectural and Spatial Analysis

The documented data were analyzed to determine the spatial organization and structural integration of ventilation systems. Particular attention was given to the relationship between ventilation openings and building orientation, floor levels, wall construction, and the functional organization of interior spaces. The analysis also examined the operation of the ventilation systems in rooms lacking direct external openings.

Environmental and Functional Assessment

The study evaluates the performance of the identified systems based on passive ventilation principles, including airflow driven by pressure differentials and thermal gradients. The analysis considers local climatic conditions, solar exposure, and prevailing wind directions to interpret the effectiveness of these systems in regulating indoor microclimate (temperature and humidity).

Comparative Analysis

A comparative analysis was conducted using published studies on traditional passive ventilation systems from regions with climatic conditions comparable to those in Armenia. The calculated ventilation performance of the investigated systems was also compared with contemporary normative ventilation requirements for buildings of similar function.

For the environmental assessment, the climatic conditions of Togh were analyzed based on long-term meteorological data. As the study focuses on the functional principles of passive ventilation rather than precise historical climate reconstruction, contemporary climatic data are considered an appropriate basis for evaluating the environmental performance of the identified ventilation systems. Long-term averaged data from the Varanda (Fizuli) and Hadrut meteorological stations, located near Togh, were used to calculate key values of outdoor air temperature for both summer and winter conditions (Table 2). These data form the basis for evaluating the environmental performance of the observed ventilation systems. The analysis indicates that the climate of Togh is mild and temperate, with characteristics closely resembling a dry subtropical climate, which is particularly relevant for the application of passive ventilation strategies.

Table 2. Outdoor air design values of Togh. By A. Karamyan

Name of the settlement	Altitude, m	Atmospheric pressure, Pa	The season	Air temperature,° C	Relative air humidity, %	Wind speed, km/h	Wind Frequency Direction
TOGH	800	888.8	Summer	26.8	57	2.3	S
			Winter	-14	64	2.6	SW

Limitations of the Study

Several limitations should be considered when interpreting the findings of this study. First, the investigation is based on a limited number of well-preserved historical buildings in Togh that retained identifiable passive ventilation elements and were accessible for detailed architectural documentation during the field survey. Following the loss of physical access to the study area after 2023, no additional field investigations, repeated measurements, or verification of the documented structures have been possible.

Second, the engineering assessment is based on measured architectural parameters and theoretical assumptions regarding airflow characteristics. Since direct measurements of historical airflow velocities under their original operating conditions are not possible, typical air velocity ranges for natural ventilation systems were adopted as reference values. Consequently, the presented calculations should be regarded as a preliminary engineering assessment based on theoretical assumptions rather than experimentally verified performance values**.** Computational Fluid Dynamics (CFD) simulations, smoke visualization tests, tracer-gas experiments, and long-term in-situ environmental monitoring were beyond the scope of the present research.

Despite these limitations, the integration of field measurements, architectural documentation, comparative analysis, and engineering interpretation provides a reliable basis for identifying the passive ventilation principles incorporated into the historic buildings of Togh. The findings establish a foundation for future interdisciplinary investigations employing advanced environmental simulation and monitoring techniques.

Results and Discussion

The Melik Yegan Palace reception hall occupies a central position within the architectural complex (Fig. 4). According to the inscription engraved on the entire facade of the second-floor entrance, the palace was constructed in 1737 by Melik Yegan, the founder of the Dizak estate and a prominent political figure in eighteenth-century Armenia [4]. The building is a slightly irregular rectangular, two-story structure oriented along the north–south axis. Its spatial organization and structural configuration provided favorable conditions for integrating airflow systems, making it an appropriate case study for investigating traditional environmental control strategies.

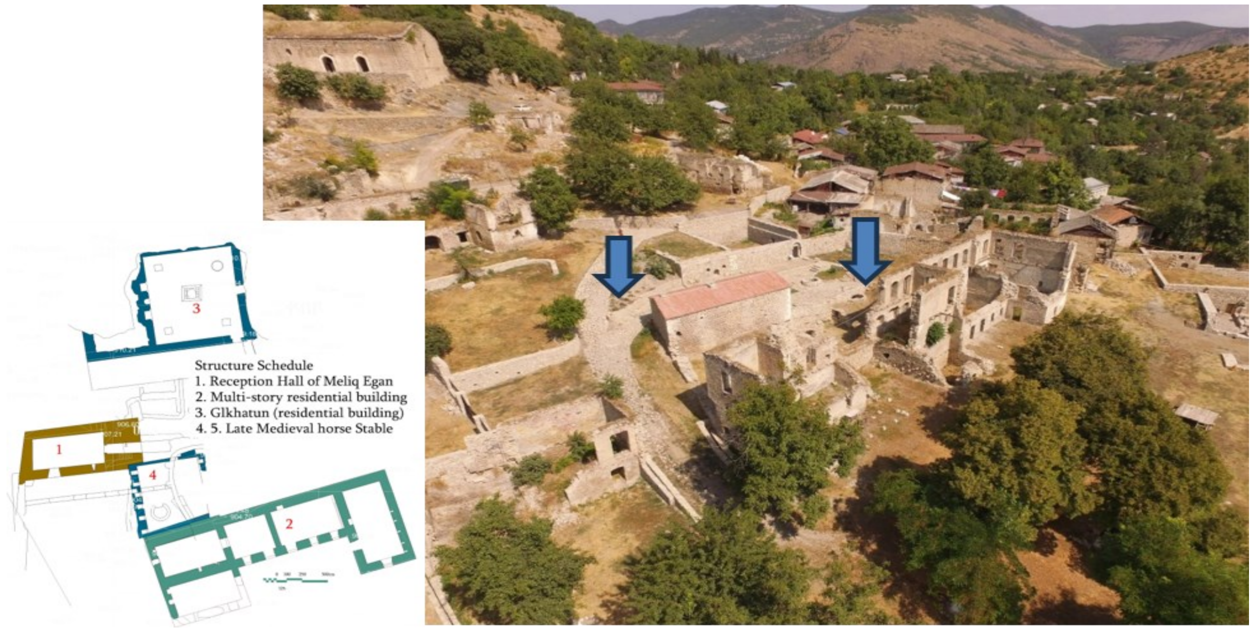


Fig. 4. *Melik Yegan's Palace view from above. The tiled structure in the center is the restored reception hall building. On the right is the multi-story residential house built in the XVIII-XIX centuries. Photo by A.Mkrtchyan*[3]

The basement level consists of a vaulted hall devoid of natural lighting (Fig. 5)[4]. The only external opening is the entrance door, which opens outward. Based on this feature, M. Sargsyan suggested that the basement may have functioned as a prison cell [6]. However, the architectural evidence documented during the present investigation suggests an alternative interpretation. The integrated ventilation mechanism and the absence of internal locking provisions indicate that the space was more likely used as a storage or utility area rather than a detention facility. Buildings intended for economic purposes, rather than for habitation, generally did not require internal locking mechanisms, whereas controlled ventilation was essential to preserve stored goods and maintain a stable indoor microclimate.

Within the mass of the southeastern wall, which has a thickness of 103 cm, two openings (41×66 cm and 67 cm deep) are embedded (Fig. 6a)[5].

These connect to a horizontal ventilation duct with a cross-section of 22×22 cm (Fig. 6b, c). The vents are positioned approximately 0.70 m above the basement floor level. The horizontal duct extends through the wall and opens onto the exterior façade at a height of 2.76 m above the basement floor, forming a rectangular outlet measuring 36×40 cm (Fig. 7). The remaining walls are solid, emphasizing the intentional, localized design of the ventilation system.

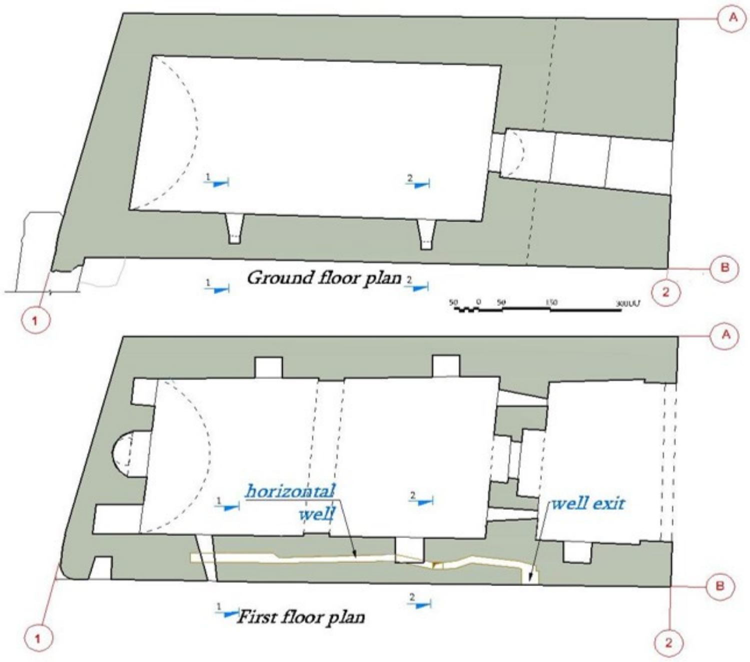


Fig. 5. *Melik Yegan's reception hall, basement, and first-floor plans by M. Sargsyan, R. Kharazyan*

[3] https://monumentwatch.org/wp-content/uploads/2023/12/001-2-1-1-2048x1536.jpg
[4] Measurements and photos made by the authors
[5] The photos were taken during the measurement phase before restoration

Fig. 6. *The nipple opening* (a) *and the horizontal wells* (b, c*) are embedded within the mass of the southeastern wall. Photo by M. Titanyan*

The first floor functioned as the reception area. It consists of a vaulted hall connected to a vaulted corridor on the northeastern side. Beneath this corridor, a narrow, sloping vaulted passage provides access to the basement (Fig. 8a). The entrance to the reception hall is architecturally emphasized. The façade contains two small windows (17×35 cm and 18×25 cm) with deeply splayed internal reveals (Fig. 8b), while a third opening (20×16 cm) is located on the southeastern façade. The limited dimensions of these openings indicate that they were not designed primarily to provide daylight. Instead, natural illumination was supplemented by a skylight incorporated into the vault (Fig. 9). The configuration of the openings suggests that their primary function was to promote natural air circulation while minimizing direct solar gain, thereby helping regulate the indoor microclimate.

Adjacent to the reception hall stands a multi-story residential building that was documented and surveyed by VEM LLC during the preparation of restoration and adaptive-reuse projects. The structure is predominantly three stories high, with a four-story section on its southeastern side, and exhibits clear evidence of several reconstruction phases.

Fig. 7. *The first-floor window (left) and the exit of the horizontal well (right) in the southeastern facade. Photo by M. Titanyan*

Despite these later modifications, the building preserves its original basement spaces with integrated passive ventilation elements, making it an important subject of the present architectural and engineering investigation[6].

[6] Author: M.Titanyan

a.

b.

Fig. 8. *The northeast facade of the reception area* (a): *The basement level is accessed through a narrow vaulted corridor. Photo by G.Budaghyan*[7]*. The small opening of the window* (b) *expands at a steep angle as it progresses inward. Photo B by M.Titanyan*

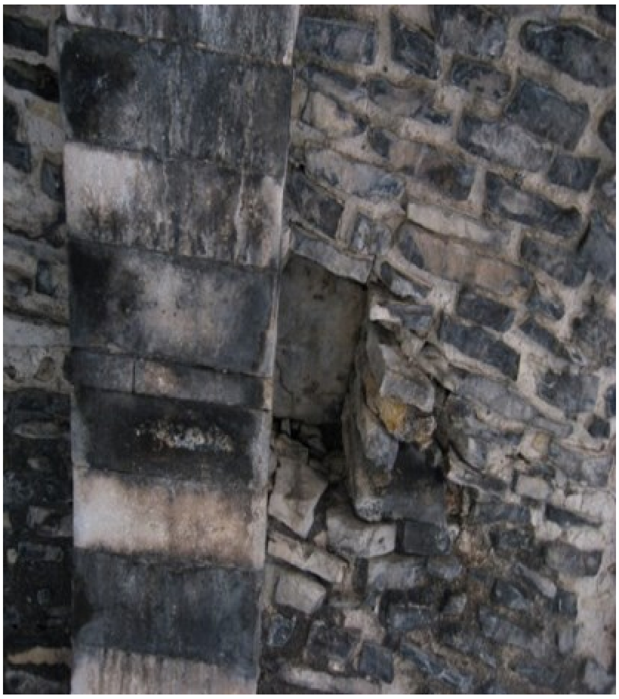


Fig. 9. *The view of the skylight from the roof and from the hall. Photo by M. Sargsyan*

Of particular interest is the southwestern room at the semi-basement level (Fig. 10). This space features a vaulted ceiling and exceptionally thick masonry walls measuring 137 cm, approximately 35 cm thicker than those of adjacent rooms. Two niches (31×54 cm and 31×36 cm, each 50 cm deep) are integrated into the southeastern wall. These niches are connected to a horizontal ventilation duct embedded within the same wall structure. The duct terminates through a 12×12 cm opening leading into an adjacent room.

[7] https://monumentwatch.org/wp-content/uploads/2023/12/002-2-1-1.jpg

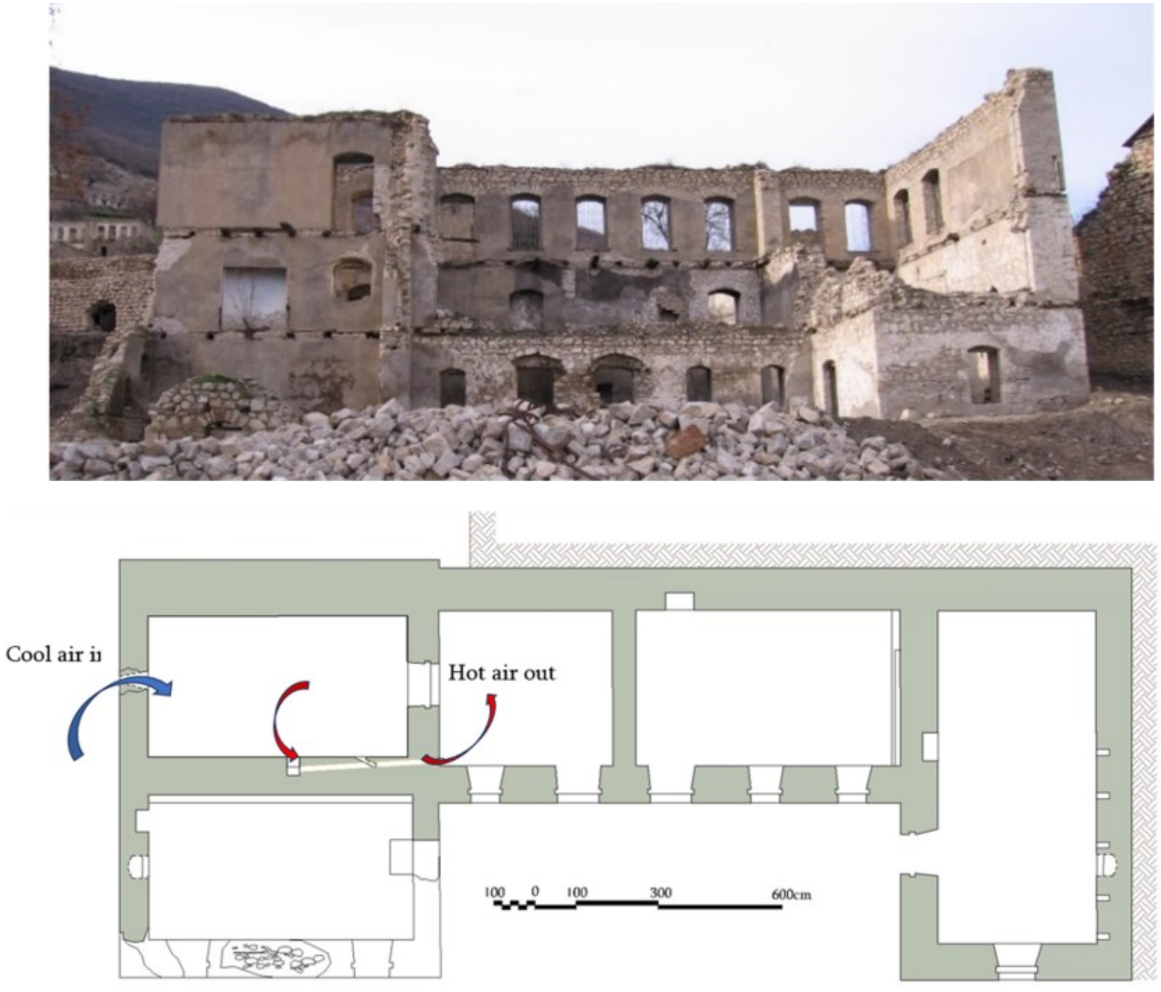


Fig. 10. *Multi-story residential building, facade, first-floor plan. Photo and plan by M.Titanyan*

The configuration of these elements suggests that the ventilation channel was originally designed as part of a passive air circulation system. Although subsequent reconstruction phases appear to have enclosed the duct's external connection and sealed it with oak (Fig. 11), the preserved architectural elements may be interpreted as evidence of an earlier integrated passive ventilation system. Based on the available architectural evidence, it is likely that the room belonged to the eighteenth–nineteenth-century construction phase; however, this interpretation cannot be verified through direct archaeological investigation. The preserved elements provide evidence of an earlier integrated ventilation solution. This indicates that the room likely belongs to the eighteenth–nineteenth-century construction phase and was later incorporated into a modified structural system. Notably, it represents the only preserved stone-vaulted space within a building that was otherwise reconstructed with wooden intermediate floors.

A partially preserved window opening is visible on the transverse façade of the room, with original dressed stone elements preserved on one side. The opening appears to have been relatively small and positioned at a higher external level, which may explain its limited visibility in the present condition. Given its location and connection to the internal ventilation duct system, this opening likely served as a wind-catching element, facilitating the introduction of external air into the interior space (Fig. 12).

Examination of the historical structures of the Togh Melik Palace indicates that rooms with limited window openings employed a similar environmental control strategy. The spatial arrangement of openings and internal air channels suggests that cooler external air entered the rooms through small façade openings and downward-oriented vents, while warmer air was directed through internal vaulted niches, collected within horizontal ducts, and discharged through higher-level outlets. On the upper floor, a roof opening appears to have functioned as an exhaust element, supporting vertical air circulation within the building (Fig. 13).

Fig. 11. *The niches of the vaulted room in the semi-basement, the exit of the horizontal vault extending from the room. Photo by M. Titanyan*

Fig. 12. *General view of the "wind-catching" window in the half-floor vaulted room, including the preserved shingle stones. Photo by M. Titanyan*

This configuration indicates a deliberate application of passive ventilation principles based on thermal buoyancy and pressure differentials. The presence of an organized ventilation system suggests that the basement space may have been used for storage, particularly to maintain conditions suitable for preserving food products, as continuous air exchange would have helped maintain thermal stability and humidity control.

Since direct measurements of historical airflow velocities are not possible, typical air velocity ranges for natural ventilation systems (0.5–1.5 m/s) were adopted as reference values for the preliminary assessment of airflow through the identified openings and horizontal ducts. Based on these assumptions, a simplified engineering calculation was performed to estimate the ventilation performance and develop a schematic representation of air movement within the basement space (Fig. 13).

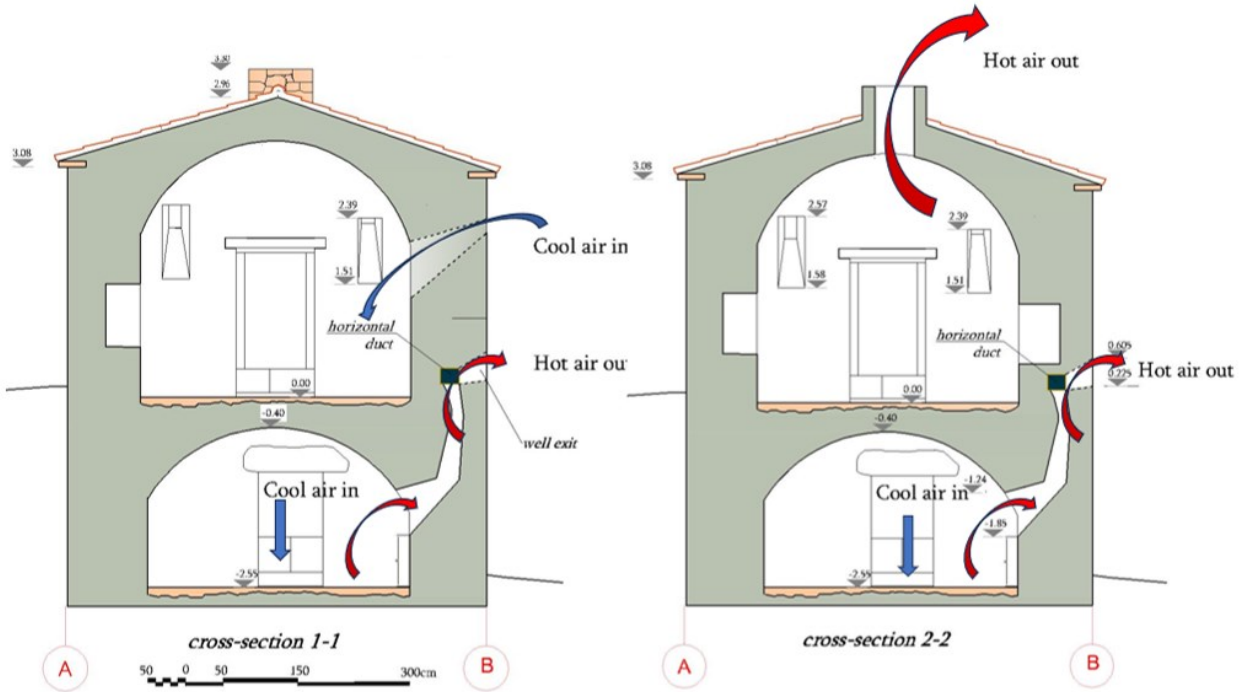


Fig. 13. *Cross-section of Melik Yegan reception hall, schematic diagram of air movement. By M.Titanyan*

Initial data for calculation

The assessment of the ventilation efficiency in the basement area is based on measurements and the geometric characteristics of the preserved ventilation elements.

According to the measurements, the total volume of the basement is approximately 63.5 m³. The ventilation system consists of inlet openings, horizontal pipes embedded in the stone walls, and an outlet opening located at a higher level on the facade.

The main geometric parameters are: the dimensions of the fresh air inlet opening are 0.41×0.66 m ($S \approx 0.27$ m²), and the cross-section of the horizontal pipe is 0.22×0.22 m ($S \approx 0.048$ m²). The dimensions of the exhaust air outlet opening are approximately 0.36×0.40 m ($S \approx 0.144$ m²).

Since the system operates under natural conditions, i.e., without mechanical pressure, the dimensions of the ventilation shaft were selected based on values typical for natural ventilation systems. Lower velocities were assumed for the inlet openings, in the range of 0.2–0.3 m/s, while higher values of up to 1.0–1.5 m/s were taken into account for the ducts and outlet sections, reflecting the acceleration of the air flow due to pressure differences.

Calculation Approach and Results

To estimate the airflow rate, a standard relationship between airflow, velocity, and opening area was applied:

$$L = v \cdot 3600 \cdot S. \qquad (1)$$

This equation allows the determination of airflow rate (m³/h) based on the cross-sectional area of the opening (S) and the average air velocity (v)[8].

By substituting the measured geometric parameters and applying aerodynamic assumptions, the airflow rates and velocities for different sections of the system were determined. The results are illustrated in the corresponding schematic diagram (Fig. 14).

[8] HHSHN IV-12.02.01-04, Jerrutsum, odapekhum yev odi lavorakum. Yerevan, 2004 (in Armenian). Available at: https://www.arlis.am/hy/acts/19533. Accessed on August 08, 2026.

First, the airflow through the inlet opening was estimated. Taking an average velocity of 0.23 m/s and an opening area of 0.27 m², the airflow rate is approximately: L ≈ 225 m³/h.

Given the presence of two similar inlet openings, the total inflow can be estimated at 440–450 m³/h. For the horizontal duct, where airflow is more confined, a higher velocity of about 1.3 m/s was assumed. With a cross-sectional area of 0.048 m², the corresponding airflow rate is approximately: L ≈ 225 m³/h. At the outlet section, where warm air is discharged, the velocity was assumed to be around 1.0–1.1 m/s. This results in an exhaust airflow rate close to: L ≈550 m³/h.

Taking into account all sections of the system, the overall airflow rate can be reasonably approximated as: L ≈ 550 m³/h.

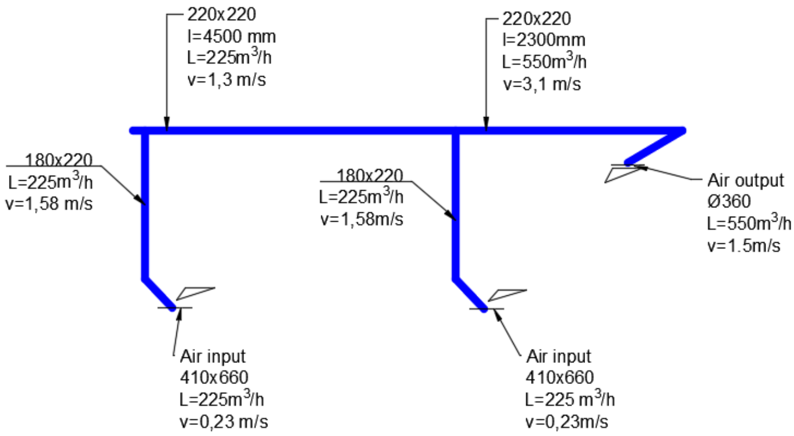


Fig. 14. *Diagram of the exhaust ventilation system. By A.Karamyan*

To evaluate the efficiency of the ventilation system, the air exchange rate (n) was calculated as follows: (air exchange rate reflects how many times per hour a given volume of space is ventilated):

$$n = \frac{L}{V} \ , \tag{2}$$

where L is the total air flow in (m^3/h), V is the volume of the space (m^3).

Substituting the obtained values:

$$n \approx 550 / 63.5 \approx 8.6 \text{ h}^{-1}.$$

This means that the air in the basement is renewed approximately 8–9 times per hour.

Comparison with Persian Badgirs and Egyptian Wind Towers

Wind towers are among the most studied airflow systems in traditional Middle Eastern architecture. These structures capture prevailing winds at roof level and direct fresh air through vertical shafts into interior spaces. Air circulation is driven by a combination of wind pressure, buoyancy, and thermal mass, enabling passive cooling without mechanical equipment[9]. Archaeological evidence suggests that wind-absorbing systems were used in ancient Egyptian architecture, in which raised openings directed cooler air into interior spaces, while warmer air was expelled through higher openings[10]. Similar principles were later developed throughout the Middle East.

In contrast, the natural ventilation systems mentioned in Togh do not rely on tall wind-absorbing towers. Instead, ventilation appears to have been achieved through integrated horizontal stone ducts, combined with strategically placed inlet and outlet openings. The airflow path is embedded in the thick stone walls, where pressure differences and thermal buoyancy create continuous natural ventilation. These observations may indicate an alternative engineering solution adapted to the mountainous terrain and architectural features of Armenian stone construction.

While Persian wind towers require significant vertical structures above the roofline, Togh’s system is fully integrated into the building envelope. These observations suggest that this configuration may reduce visual impact, improve structural protection, and allow the ventilation system to operate even in buildings with compact layouts and partially underground spaces.

---

[9] HHSHN IV-12.02.01-04, Jerrutsum, odapekhum yev odi lavorakum. Yerevan, 2004 (in Armenian). Available at: https://www.arlis.am/hy/acts/19533. Accessed on August 08, 2026.

[10] Ibid.

The ventilation method used in Togh is more akin to modern environmental control strategies, which aim to minimize building energy consumption while maintaining acceptable indoor environmental quality.

The ventilation systems described in Togh exhibit several characteristics that are consistent with modern passive ventilation principles. The arrangement of inlets at low levels and outlet openings at high elevations promotes buoyancy-based airflow. Thick stone walls provide thermal mass that moderates indoor temperature fluctuations, while embedded ducts create controlled air paths comparable to modern environmental engineering solutions.

Although the builders had no formal knowledge of air-movement mechanics, the architectural solutions considered demonstrate an empirical understanding of airflow behavior. Their design effectively exploited the interaction of thermal gradients, wind pressure, and building geometry to ensure continuous natural air exchange.

Comparing the Togh ventilation example with modern ventilation standards, we obtain a calculated ventilation rate of approximately 8.6 air changes per hour, indicating that such an airflow system could maintain a constant air renewal in the given area. The calculated air exchange rate coincides with the range recommended in modern ventilation practice for food storage, basements, and certain service areas[11]. It is especially noteworthy that such efficiency was achieved exclusively by natural means. The airflow is due to pressure and temperature differences caused by the wind, without any mechanical assistance.

Overall, comparative analysis indicates that Togh environmental engineering solutions reflect adaptation to local climatic conditions, mountainous topography, and building traditions. The engineering performance evaluated in this study indicates that these systems can provide effective natural ventilation comparable to modern passive ventilation objectives. Table 3 shows the structural and functional comparison of the studied ventilation systems.

Table 3. Comparison table of natural ventilation systems used in the past

Feature	Persian Badgir	Egyptian Wind Tower	Historic Togh System
Driving mechanism	Wind + stack effect	Wind + buoyancy	Buoyancy + wind pressure
Air channel	Vertical shaft	Vertical shaft	Horizontal masonry duct
Integration	Roof tower	Roof tower	Embedded in thick stone walls
Thermal mass	Moderate	Moderate	Very high
Main function	Cooling	Cooling	Ventilation, cooling, humidity control
Suitable climate	Hot-arid	Hot-arid	Mountainous temperate/subtropical
Mechanical energy	None	None	None

These past structures should be considered not only as examples of vernacular architecture but also as complex environmental engineering systems developed through centuries of accumulated experimental knowledge [15, 16].

Conclusion

This study investigated the natural ventilation systems integrated into the historical architectural structures of Togh village, with particular focus on the Melik Yegan Palace complex. The aim was to identify the design principles, spatial organization, and functional performance of these systems within the framework of passive environmental control.

The results suggest that traditional buildings in Togh incorporated effective environmental control strategies adapted to local climatic conditions, mountainous terrain, and the characteristics of stone masonry construction. The investigated ventilation systems were not limited to residential spaces but were also applied

[11] HHSHN IV-12.02.01-04, Jerrutsum, odapekhum yev odi lavorakum. Yerevan, 2004 (in Armenian). Available at: https://www.arlis.am/hy/acts/19533. Accessed on August 08, 2026.

in basement and semi-basement areas, including spaces with limited or no direct openings. The analysis revealed that these systems were based on the coordinated use of air inlets, horizontal wall-integrated ducts, and elevated outlets, enabling continuous air movement through thermal buoyancy and pressure differences.

The study suggests several important characteristics of the ventilation systems.

1. Stone-vaulted basement and semi-basement spaces were widely incorporated into eighteenth- and nineteenth-century structures, while rooms intended for storage and auxiliary functions achieved improved environmental stability through passive air exchange.
2. Rooms intended for economic purposes, despite lacking natural lighting, maintained stable internal conditions through effective ventilation.
3. The configuration appears to reflect the deliberate application of passive ventilation principles. Although direct evidence of the original design intentions is unavailable, the observed spatial arrangement is consistent with airflow mechanisms driven by thermal buoyancy and pressure differences.
4. The calculated air exchange rate of the investigated basement space suggests that a considerable ventilation capacity was achieved without mechanical assistance.
5. Roof openings in vaulted structures enhanced vertical airflow and improved indoor environmental regulation.
6. The volumetric and spatial configuration of the Melik Palace reception hall reflects a design that ensured both environmental control and functional resilience, including enhanced security and reduced fire risk.

The scientific novelty of this research lies in the systematic identification and functional interpretation of integrated passive ventilation systems within Armenian architectural heritage. Supported by field measurements, architectural documentation, and airflow calculations, the study goes beyond descriptive analysis to reveal the engineering principles underlying these historical solutions. Unlike widely studied wind towers of the Middle East, the Togh examples demonstrate a distinct approach in which ventilation mechanisms were incorporated directly into massive stone walls and adapted to local architectural and climatic conditions. The documentation and analysis of environmental engineering solutions, such as those identified in Togh, contribute to a more comprehensive understanding of heritage structures and support the development of informed conservation and adaptive reuse strategies. The findings contribute to the development of engineering thought within Armenian architectural heritage and open new directions for future research.

The identified passive ventilation systems demonstrate the continued relevance of vernacular environmental strategies for contemporary architectural practice [17]. Their adaptation to local climatic conditions provides valuable insights for heritage conservation, passive environmental design, and the development of energy-efficient and climate-responsive architecture.

Conflict of Interest

The authors declare no conflicts of interest.

Funding

This research did not receive any financial support.

References

[1]. M. Philokyprou, A. Michael, Environmental Sustainability in the Conservation of Vernacular Architecture. The Case of Rural and Urban Traditional Settlements in Cyprus. International Journal of Architectural Heritage, 15 (11) 2021, 1741-1763.
Doi: https://doi.org/10.1080/15583058.2020.1719235

[2]. S. Barkhudaryan, Divan hay vimagrutyan (5, Artsakh). National Academy of Sciences of Armenia, Institute of Archaeology and Ethnography, Yerevan, 1982.
Available at: https://surl.li/fvybiu. Accessed on August 08, 2026.

[3]. Arrakel Vardapet, Dizaki melikutyuny (1, Nyuter hay melikutyan masin). Yelektrasharzh tparan sb. Ejmiatsin, Vagharshapat, 1913.

[4]. H. Papazyan, Melik Yegani mutki vimagir ardzanagrutyuny (LHG, 5). Academy of Sciences of Armenian SSR, 1985. Available at: https://surl.li/dlenve. Accessed on August 08, 2026.
[5]. Sh. Mkrtshyan, Lerrnayin Gharabaghi patma-chartarapetakan hushardzannery. Hayastan, Yerevan, 1988 (in Armenian).
[6]. M. Sargsyan, Melikakan bnakeli hamakarruyts Togh avanum. Patmabanasirakan handes, 3, 1987, 132-140 (in Armenian). Available at: https://surl.li/cxrytf. Accessed on August 08, 2026.
[7]. A. Ghulyan, Artsakhi yev Syuniki melikakan aparanknery. National Academy of Sciences of the Republic of Armenia. Gitutyun, Yerevan, 2001 (in Armenian). Available at: https://surl.li/nvimrt. Accessed on August 08, 2026.
[8]. E. Lucchi, Energy Efficiency of Historic Buildings. Buildings, 12 (2), 2022. Doi: https://doi.org/10.3390/buildings12020200
[9]. F. Ascione, R.F. De Masi, M. Mastellone, S. Ruggiero, F. Tariello, G.P. Vanoli, Energy Performance of Buildings: Improvements, Limits and Future Perspectives during the Last Twenty Years of Energy and Sustainability Policies. 6th International Conference on Smart and Sustainable Technologies, 2021. Doi: https://doi.org/10.23919/SpliTech52315.2021.9566444
[10]. M.A. Nessim, A. Elshabshiri, V. Bassily, N. Soliman, K. Tarabieh, S. Sherif Gourban, The Rise and Evolution of Wind Tower Designs in Egypt and the Middle East. Sustainability, 15 (14), 2023, 10881. Doi: https://doi.org/10.3390/su151410881
[11]. H. Bakhtiari, J. Akander, M. Cehlin, Evaluation of Thermal Comfort in a Historic Building Refurbished to an Office Building with Modernized HVAC Systems. Advances in Building Energy Research, 14 (2), 2020, 218-237. Doi: https://doi.org/10.1080/17512549.2019.1604428
[12]. A.S. Guimarães, M.J. Teixeira, Project Design Abacus for Wall Base Ventilation Drying Systems to Control Dampness. Drying Technology, 34 (11), 2016, 1380-1396. Doi: https://doi.org/10.1080/07373937.2015.1117488
[13]. M. Alwetaishi, A. Balabel, A. Abdelhafiz, U. Issa, I. Sharaky, A.Shamseldin, M. Al-Surf, M. Al-Harthi, M. Gadi, User Thermal Comfort in Historic Buildings: Evaluation of the Potential of Thermal Mass, Orientation, Evaporative Cooling and Ventilation. Sustainability, 12 (22), 2020. Doi: https://doi.org/10.3390/su12229672
[14]. S. Clarke, Balancing Environmental and Cultural Impact against the Strategic Need for Wind Power. International Journal of Heritage Studies, 15 (2-3), 2009, 175-191. Doi: https://doi.org/10.1080/13527250902890688
[15]. T. Winter, Climate Change and Our Heritage of Low Carbon Comfort. International Journal of Heritage Studies, 22 (5), 2016, 382-394. Doi: https://doi.org/10.1080/13527258.2016.1157092
[16]. P. Puma, E. Harutyunyan, Knowledge Strategies Applied to Cultural Heritage Buildings: The Architectural Survey for the Restoration and the Enhancement of Katoghike Tsiranavor Church of Avan in Yerevan, Armenia. Proceedings of the 11th International Conference on Contemporary Problems of Architecture and Construction, Yerevan, RA, Oct. 14-16, 2019, 133-141. Available at: https://surl.li/krwmni. Accessed on August 08, 2026.
[17]. H.R. Masoumi, N. Nejati, A.A. Ahadi, Learning from the Heritage Architecture: Developing Natural Ventilation in Compact Urban Form in Hot-Humid Climate: Case Study of Bushehr, Iran. International Journal of Architecture Heritage, 11 (3), 2017, 415-432. Doi: https://doi.org/10.1080/15583058.2016.1238971

***Manushak Titanian, Architect, Associate Professor** (RA, Yerevan) - National University of Architecture and Construction of Armenia, Researcher, Lecturer at the Chair of Theory, History and Heritage of Architecture, manushaktitanyan@nuaca.am*

***Anna Karamyan, Doctor of Philosophy (PhD) in Engineering, Associate Professor** (RA, Yerevan) - National University of Architecture and Construction of Armenia, Head of the Chair of Heat and Gas Supply and Ventilation, a.karamyan@nuaca.am*

***Emma Harutyunyan, Doctor of Philosophy (PhD) in Architecture, Professor** (RA, Yerevan) - National University of Architecture and Construction of Armenia, Head of the Chair of Theory and History of Architecture and Heritage, eharutyunyan@nuaca.am*

ADAPTATION PROJECT OF THE "ROMAN HALL" IN THE CITY LIBRARY OF BELGRADE

Ivana Filipovic Yorke[1]*, Nevenka Novakovic[1]

[1]*Cultural Heritage Preservation Institute of Belgrade, Serbia*

Abstract: *The adaptation project of the "Roman hall" within the City Library of Belgrade, a cultural monument, began in 2015. The project was initiated to enhance this unique space, primarily used for lectures and book promotions. The building housing the City Library of Belgrade was originally constructed as a hotel in 1869. The City Library moved into the building after World War II. During the 1985 excavation works for the basement, parts of a Roman castrum dating from the last decades of the 2nd century were discovered. The new project focused exclusively on the "Roman hall" in the Library's basement, where the Roman rampart and gate are located. Before executing the project, extensive research was conducted. This included analyzing all available documentation related to the building and the Roman rampart, including historical records, old plans, archaeological reports, previous construction works, and the Library's operational systems. An archaeological investigation was carried out "in situ", and the rampart was carefully treated and conserved. In addition to the conservation process, the entire space was completely transformed, incorporating new interior design, electrical systems, and climate control. Implementing much-needed safety measures was also a crucial component of the project. This paper aims to demonstrate how valuable cultural heritage can be integrated into contemporary interior design, serving the public interest and the institutions that hold it. In this manner, parts of cultural heritage become more available to the public while careful design raises awareness of their importance.*

Keywords: *Cultural Monument, Roman Rampart, Adaptation, Interior Design, Conservation, Reuse, Safety*.

Ivana Filipovic Yorke*
E-mail: vanaica69@gmail.com

Received: 04.06.2026
Revised: 02.07.2026
Accepted: 30.07.2026

Introduction

The building housing the City Library of Belgrade, located at 56 Knez Mihailova Street, represents a sophisticated intersection of Belgrade's multilayered history. Originally constructed in 1869 as the "Serbian Crown" hotel, it was the city's most representative and modern accommodation of its time. Designed in the spirit of academicism with romanticist elements, the building's architecture uniquely preserved the layout of traditional Turkish lodgings, with its structure organized around a central courtyard. Situated at the terminus of a primary urban artery during the city's post-Ottoman liberation, the building stands as a testament to 19th-century urban transformation[1] (Fig. 1a,b). The site carries multiple layers of legal protection, reflecting its immense cultural value. It is designated as the "Serbian Crown" cultural asset (Decision on Proclamation, "Official Gazette of the City of Belgrade" No. 19/81). It sits within the protected "Ancient Singidunum" archaeological site (Decision of the Institute No. 176/8 of 30.6.1964) and the "Knez Mihailova Street Area", a zone of exceptional importance (Decision on Designation, "Official Gazette of the Republic of Serbia" No. 14/79). While the decision to relocate the City Library to this site was made in 1975, the transformation was not concluded until 1986 [1]. During the extensive reconstruction and adaptation works (1983–1986), significant archaeological remains were unearthed beneath the former atrium. Excavations revealed a rampart and tower dating from the late 2nd to the early 3rd century, identified as a vital segment of the original Roman

[1] Cultural Heritage Preservation Institute of Belgrade, Documentation: 1985 Adaptation Project (in Serbian).

castrum. This discovery redefined the project, leading to the creation of the “Roman Hall”, a subterranean space where ancient fortifications are integrated into the Library’s functional interior.

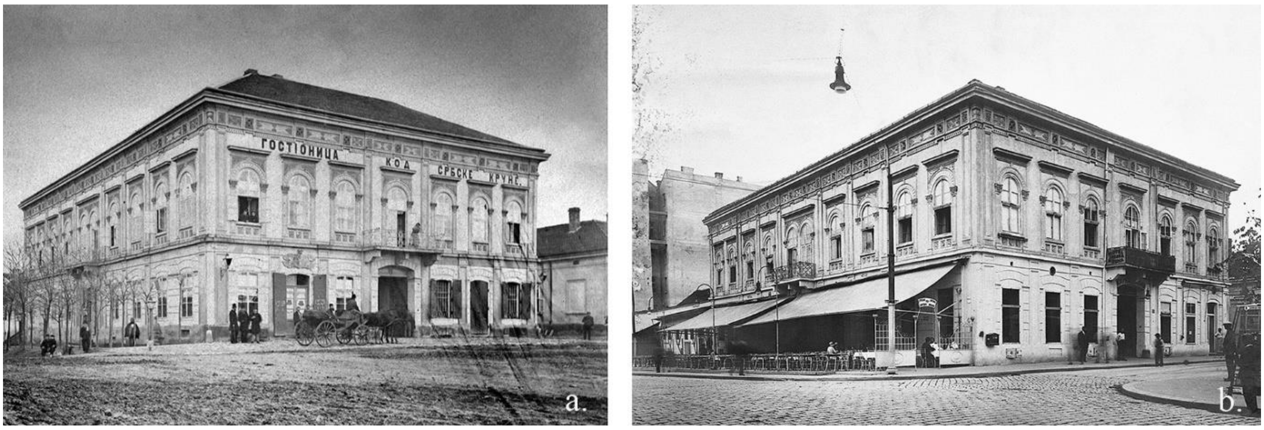


Fig. 1. a. *Hotel “Serbian Crown” in 1895*; b. *Hotel “Serbian Crown” in 1927*

The Aim of the Adaptation

The primary objective of this paper is to examine how significant cultural heritage can be seamlessly integrated into contemporary interior design to serve public interests. The adaptation of the “Roman Hall” reflects a broader global paradigm in which creative reuse spans diverse typologies and epochs. International precedents, ranging from the conversion of 17th-century barns in the Netherlands to industrial locomotive factories in Germany, demonstrate that repurposing existing structures is a vital driver of urban renewal and environmental sustainability [2].

By transitioning from a hospitality-focused past to a library-centric present, the project highlights how "architectural recycling" preserves a monument's soul. The adaptation of the “Roman Hall”, previously used as a modest space for book promotions, now seeks a more refined design approach. This study provides new insights into how underground heritage can be activated for contemporary use, balancing archaeological preservation with the functional requirements of a modern cultural institution.

Materials and Methods

This paper employs a multi-disciplinary case study approach to analyze the adaptation of a protected cultural monument from its original hospitality function to a modern public library. To evaluate the project’s success, the research is structured into five sequential stages: historical and archival research: documentation of the "Serbian Crown" hotel and the broader history of the site, architectural analysis: an examination of the 19th century academic/romanticist structure and its Turkish-style atrium layout, analysis of prior interventions: a review of the 1983–1986 reconstruction and initial adaptation, definition of Project objectives: identifying the goals for contemporary interior design within a heritage context and technical finalization: documentation of the specific conservation and design works required for the “Roman Hall”.

The Roman Period and the Ancient Singidunum - Historical Context and Strategic Significance

Belgrade’s urban fabric comprises numerous cultural layers, with the antiquity layer (1st–6th centuries AD) among the most significant. Singidunum was established at a critical geographical crossroads where the river and land routes of Southeastern Europe intersected. By the 1st century AD, it had become a prominent border stronghold of the Roman Empire, serving as a primary military link in the Danubian Limes (Fig. 2a). Historical sources, including the 6th-century writings of Hierocles, identify Singidunum as one of the five key cities in the province of Moesia Superior, alongside Viminacium, Tricornium, Gratiana, and Horreum Margi [3]. Following the destruction of the earlier Celtic settlement, the Romans established a permanent presence around the 1st century AD. Under Septimius Severus, the settlement was granted *municipium* status and eventually rose to the rank of a Roman Colony after 293 AD [4].

The camp of the Legion IV Flavia Felix was transferred from Viminacium to Singidunum circa 91 AD. This legionary camp became a vital fortification that, according to Procopius, was later rebuilt by Justinian in the 6th century [5,6]. Today, the remains of this castrum, with approximate dimensions of 568 × 430 meters [7], lie beneath modern Belgrade. Today, what was once a great military fort of Flavia's Legion lies beneath modern structures, and its shape and form can be understood, aside from literature, only through archaeological excavations and sporadic discoveries that have appeared over the years in different parts of Belgrade [8,9] (Fig. 2b).

Investigative Archaeology and Key Findings

Systematic archaeological research in Belgrade began in the late 19th century [10]. Significant breakthroughs occurred during the German occupation in 1942, when Wilhelm Unverzagt conducted excavations on the northern rampart of the Belgrade Fortress [11,12]. In later decades, the *Porta Praetoria* (the northwestern gate) was discovered (Fig. 2a) [13]. The route of the castrum reveals that the gate discovered within the City Library building sits directly opposite the *Porta Praetoria*, aligned on a central axis [14]. The remains discovered during the 1985 Library excavation belong to the Southeast Rampart [15], specifically a portion of the *Porta Decumana* (the southeastern gate). This massive structure, measuring 28 meters in length and 9 meters in width, was situated on the route of the ancient *Via Cardo*—today the site of Belgrade's main pedestrian street, Knez Mihailova.

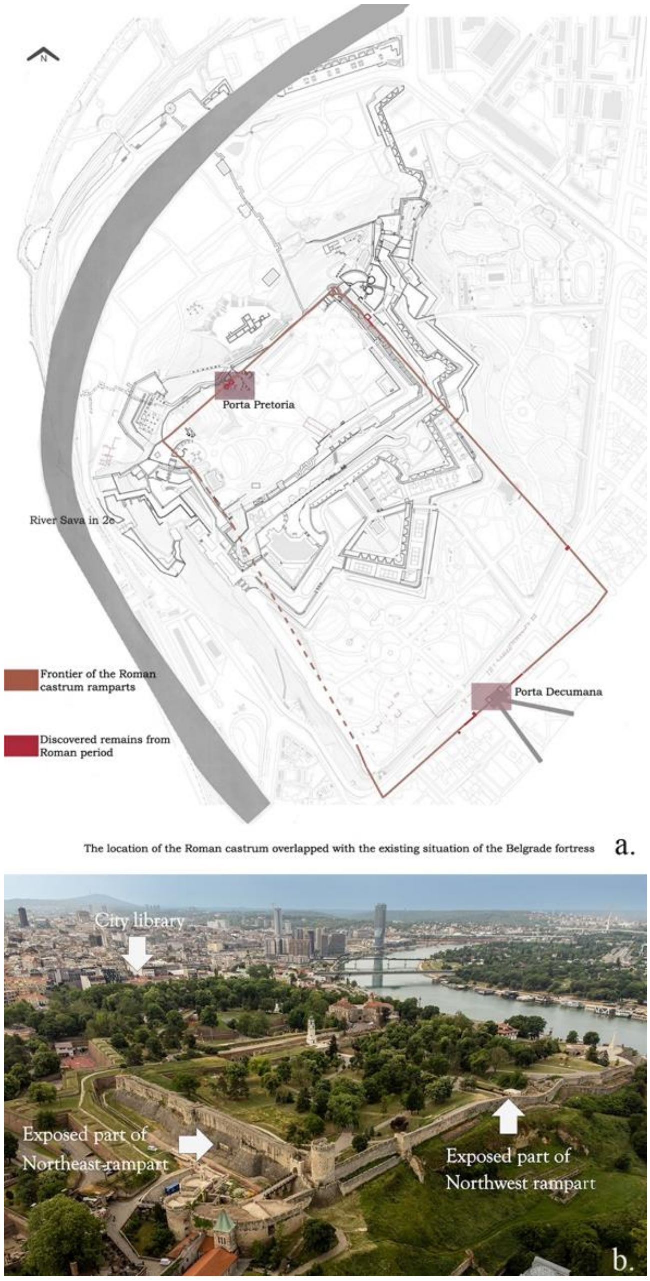


Fig. 2. a. *Plan of Belgrade fortress with incorporated plan of Roman castrum and discovered archaeological remains*; b. *Parts of the Roman ramparts exposed at the Belgrade fortress, with the position of the City Library*

The gate's passage originally consisted of three archways: a central portal for carts and two flanking portals for pedestrians. Based on the foundation depth, the structure is estimated to have stood over 20 meters tall, making it one of the most imposing buildings in ancient Singidunum. Additional findings in the Library include: A lead pipe, which was part of a sophisticated aqueduct system that supplied the fortress with water, medieval well attributed to the Turkish period, which was discovered near the Roman tower (recorded in 1985 but not currently exposed) and *Via Decumana*: one of the main streets of the fortress, identified in 2009 under modern tram tracks, which led from this southeastern gate toward the *praetorium* (commandant's building) [16].

While many parts of the castrum have been re-covered after documentation, the remains within the City Library are among the few preserved *in situ* and accessible to the public, forming the heart of what is now known as the "Roman Hall" (Fig. 3a,b).

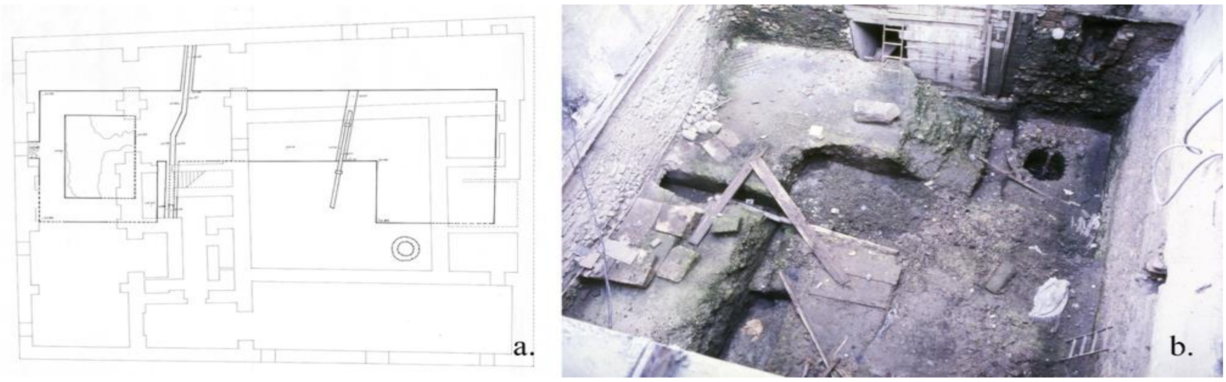


Fig. 3. a. *Plan of the remains of the Roman southeast rampart discovered in the City Library in 1985*[2]; b. *Photo of discovered findings in 1985*

The 2015 Adaptation Project: Methodology and Implementation - Project Background and Initial State

In 1985, during the initial conversion of the "Serbian Crown" hotel into the City Library, the discovery of significant Roman remains led to a pivotal design shift. The space originally intended for book storage was redesigned as the “Roman Hall”, a multipurpose venue for cultural events. However, between 1985 and 2014, the interior remained largely unchanged (Fig. 4a-d).

By 2014, the Library management initiated a modern adaptation project. Initial investigative works revealed that the Roman ramparts and tower were in a state of advanced degradation. Mortar was crumbling, and the absence of physical barriers allowed visitors to walk directly over the ancient masonry. The hall was cluttered with unsuitable furniture, outdated lighting, and poor ventilation, while the "lapidarium" collection on the walls, though valuable, visually burdened the space and distracted from the *in-situ* remains (Fig. 4c,d).

Fig. 4. a. *Plan of “Roman hall” before the works in 2015*[3]; b.[4];
c, d. *Photo of “Roman hall” in the basement of the City Library before 2015*

[2] Zavod za zaštitu spomenika kulture grada Beograda, Tehnička dokumentacija: 1985 Arheološki nalazi u Biblioteci grada Beograda (in Serbian).

[3] Zavod za zaštitu spomenika kulture grada Beograda, Tehnička dokumentacija: 2015 Projekat adaptacije Rimske dvorane u Biblioteci grada Beograda (in Serbian).

[4] Belgrade City Library (BGB), “Roman Hall” with Archaeological Site, official website (in Serbian). Available at: https://bgb.rs/sr/rimska-dvorana/ (accessed on August 3, 2026).

To establish a sound conservation strategy, the project began with a thorough analysis of the existing environment. This included: documentation review, analyzing 1985 archaeological reports and photographs to compare the current state with the original discovery; material analysis, assessing the degree of endangerment and risks to the Roman stone and mortar; stakeholder interviews, consulting with the Library Director and technical staff to understand operational requirements; and technical recording, creating a high-precision survey of the hall, including the ramparts and tower. The complexity of the site, an underground archaeological zone within a cultural monument, required an integrated design team. The Cultural Heritage Preservation Institute of Belgrade led the project, coordinating with external specialists to develop mechanical and electrical systems. Designers were granted creative freedom by the investor, with the only specific requirement being a collaborative choice of the primary color palette.

Architectural and Conservation Intervention

The primary goal was to elevate the Roman remains from a "background element" to the hall's focal point. This was achieved through a four-segment strategy: conservation, interior redesign, and the modernization of mechanical and electrical installations. Professional conservators and archaeologists performed a deep cleaning of the masonry (Fig. 5). Damage from years of physical contact was repaired with materials compatible with the original Roman construction. To prevent future degradation, the rampart was physically separated from the public area. To create a neutral backdrop that highlights the ancient stone, the design used industrial, minimalist materials: a three-level, stepped wooden structure was installed for seating. This "tribune" style maximizes space and integrates modern technology, featuring built-in power and USB sockets for visitors. A suspended ceiling and rear wall were constructed from drawn steel mesh. This choice provides a contemporary aesthetic while allowing for the discrete integration of HVAC and lighting systems.

Fig. 5. *Cleaning of the rampart in 2015*

The outdated lighting was replaced with a dual-layered system. Overhead lights are hidden above the steel mesh, while a steel U-profile was installed along the base of the rampart to house LED strips. These graze the stone surface, emphasizing its texture and historical weight (Fig. 6a-d).

The floor was replaced with a modern cast floor (cement screed base), providing a seamless, durable surface. To demarcate the "sacred" archaeological zone, a bed of pebbles was placed in the steel U-profile, serving as both a visual and physical barrier without the need for intrusive fences.

Fig. 6. *Roman hall.* a, b. *before the works*; c, d. *after the works*

Results and Discussion

The 2016 renovation successfully integrated four critical sectors: archaeological conservation, interior design, and the modernization of mechanical and electrical systems. By December 2016, the project, led by the Cultural Heritage Preservation Institute of Belgrade, had achieved a delicate balance between preserving the Roman fortifications and optimizing the hall's cultural utility.

The primary achievement of the project was the affirmation of the Roman rampart and tower. By reducing seating density and physically distancing the furniture from the masonry, the design created a clear distinction between the ancient ruins and the modern venue. This "coexistence of eras" is facilitated by physical protection: the introduction of a pebble-filled U-profile serves as a non-intrusive barrier, preventing physical contact while allowing for close visual inspection and technological modernization - the hall now functions as a high-tech cultural hub, equipped with integrated sound systems, projectors, and discreet electrical connectivity (USB and power sockets) within the tiered seating (Fig. 7a-d).

Fig. 7. *a,b,c,d. Reuse of the "Roman hall" after the works*

Adaptive Reuse (AR) as a Theoretical Framework

The transformation of the Belgrade City Library serves as a sophisticated example of Adaptive Reuse. The project navigates several layers of AR: the building as built heritage, a historic monument, and an architectural landmark.

The essence of AR is the transition to a new purpose that differs from the original design intent. In this case, the discovery of the Roman castrum in 1985 forced an "unplanned" but vital shift in the building's evolution. While the 1980s intervention followed the standards of its time, preserving the facade and adapting the interior, the 2016 project represents a more nuanced, modern approach to AR. It acknowledges that the discovery of the subterranean layer fundamentally redefined the basement's utility, shifting it from a storage site to a public monument [17-19].

The "Roman Hall" stands as a rare success story in the Belgrade context. Historically, many significant findings in the city, including Roman baths, hospitals, and even the *Porta Praetoria*—were documented and re-covered with soil (*reburied*) [20] rather than presented to the public (Fig. 8a). In other instances, "reconstructions" were built above ground level, losing the authentic *in-situ* connection (Fig 8b), or presentation was reinterpreted with the artefacts brought from other archaeological sites dated from the same period as in Shopping center Rajiceva – next to the City Library [21] (Fig 8c).

Fig. 8. a. *Excavated Roman baths in 1972;* b. *"Reconstruction" of Roman baths above the original ones;* c. *Reinterpretation of artefacts*

In contrast, the "Roman Hall" project aligns with best practices observed across Europe, where archaeological discoveries made during infrastructure works are integrated into the living city. By keeping the *Porta Decumana* visible and accessible, the project avoids the destructive "above-ground reconstruction" models and instead provides an authentic encounter with Belgrade's ancient origins.

Conclusion

The adaptation of the “Roman Hall” demonstrates that even within the structures of a high-value cultural monument, innovative interior design can revitalize stagnant heritage sites. This project serves as a definitive case study proving that the preservation of ancient structures does not require the exclusion of modern technology. On the contrary, the two can enhance one another, creating a space that functions simultaneously as a high-performance library and a living museum.

Achieving a successful synthesis between these disparate historical periods requires a design philosophy that prioritizes the ancient fabric above all else. In the case of the “Roman Hall”, the immeasurable value of the archaeological site dictates that the modern intervention remains subservient. Because the inherent "beauty of the space" is already articulated by the Roman masonry, contemporary design elements, such as the steel mesh and timber seating, were simplified and reduced to their functional essence to avoid competing with the past.

The discovery and subsequent revitalization of these ruins serve as a powerful narrative of Belgrade’s development. These structures, buried for centuries and rediscovered at the confluence of the Sava and Danube, testify to the city's enduring strategic and cultural wealth.

The process of designing and executing this project was both intellectually demanding and technically challenging. It required a delicate balance between the rigid requirements of conservation and the fluid needs of a modern library. Ultimately, it has been a distinct honor to contribute to the new identity of the “Roman Hall”, ensuring that the Roman rampart and tower are no longer mere relics of the basement but central, celebrated figures in Belgrade's living cultural landscape.

Conflict of Interest

The authors declare no conflicts of interest.

Funding

This research did not receive any financial support.

References

[1]. J. Petrović, Belgrade City Library. National Library of Serbia, Belgrade, 2002 (in Serbian).
[2]. P. Hauke, K. Latimer, R. Niess, New Libraries in Old Buildings: Creative Reuse. IFLA Publications, 2021.
[3]. C. Băjenaru, Minor Fortifications in the Balkan-Danubian Area. Editura Mega, 2010.
[4]. B.B. Gavela, Protohistorical and Ancient Singidunum, in: Z. Simić-Milovanović (ed.), Yearbook of the Belgrade City Museum, II. Belgrade City Museum, 1955, 5-22 (in Serbian).
[5]. D. Garašanin, Archaeological Monuments in Belgrade and its Surroundings, in: Z. Simić-Milovanović (ed.), Yearbook of the Belgrade City Museum, I. Belgrade City Museum, 1954. 59-60 (in Serbian).
[6]. F. Barišić, Vizantinski izvori za istoriju naroda Jugoslavije, I. Naučna knjiga, 1955 (in Serbian).
[7]. M. Bajalović Hadži-Pešić, Unutrašnje utvrđenje beogradskog grada, Godišnjak grada Beograda. Muzej grada Beograda, XXXVIII (38), 1991, 35-54 (in Serbian).
[8]. V. Ivanišević, S. Nikolić-Đorđević, New Traces of Ancient Fortifications in Singidunum – Knez Mihailova 30 street. Singidunum, 1, 1997, 65–150 (in Serbian).
[9]. N. Novaković, I. Filipović Yorke, N. Mićović, Reconstruction, Restoration and Presentation of the XVI Century Fountain at the Belgrade Fortress. Multidisciplinary Reviews, 7, 2024. Doi: https://doi.org/10.31893/multirev.2024ss015
[10]. S. Pop-Lazić, The Necropolises of Roman Singidunum. Singidunum, 3, 2002 (in Serbian).
[11]. C. Kott, Kunstschutz im Zeichen des totalen Krieges. Praehistorische Zeitschrift, 81, 2006, 262 (in German).
[12]. W. Unverzagt, New Excavations in Belgrade Fortress. Praehistorische Zeitschrift, XXXVI, 1958, 271-274 (in German).
[13]. D. Bojović, Rezultati arheoloških iskopavanja na ubiciranju rimskog vojnog logora u Singidunumu, Starinar, XXVI. Arheološki institut, 1975 (in Serbian).

[14]. D. Bojović, Singidunum, Beograd-Rimski kastrum, Jugoistočni bedem kastruma. Arheološko društvo Jugoslavije, Arheološki pregled, 15, 1973, 44-46 (in Serbian).
[15]. D. Bojović, Singidunum-Pariska ulica, Jugoistočni bedem kastruma. Arheološko društvo Jugoslavije, Arheološki pregled, 20, 1978, 56 (in Serbian).
[16]. S. Nikoli, N. Gavrilovic, S. Redžić, I. Bogdanović, S. Pop-Lazic, V. Vujadinović, L. Jevtović, I. Dankovic, S. Vuković, M. Marjanović, The Roman Limes and Cities on the Territory of Serbia. Serbian Academy of Sciences and Arts, 33, 2018.
[17]. L. Wong, Adaptive Reuse of Heritage Buildings, **Birkhauser,** 2016.
[18]. P.A. Bullen, P.E. Love, Adaptive reuse of heritage buildings. Structural Survey, 29 (5) 2011, 411-421. Doi: https://doi.org/10.1108/02630801111182439
[19] M. Kuipers, W. de Jonge, Designing from Heritage: Strategies for Conservation and Conversion. TU Delft, 2025. Doi: https://doi.org/10.59490/mg.133
[20]. Lj. Bjelajac, Z. Simić, Rezultati zaštitnih arheoloških istraživanja na prostoru ulice Kneza Mihaila. Yearbook of the Belgrade City Museum, XXXVIII, 1991 (in Serbian).
[21]. B. Plemić, Roman remains in Rajićeva shopping centre: A new tourist attraction in Belgrade or a case study in devastation of cultural heritage? Turističko poslovanje, 21, 2018, 5-12. Doi: https://doi.org/10.5937/TurPos1821005P

Ivana Filipović Yorke, Architectural Engineer, Senior Associate, Architect *(Serbia, Belgrade) - Cultural Heritage Preservation Institute of Belgrade, vanaica69@gmail.com*
Nevenka Novakovic, ***Doctor of Geosciences, Architectural Engineer***, ***Senior Associate, Architect*** *(Serbia, Belgrade) - Cultural Heritage Preservation Institute of Belgrade, Vice-president of ICOMOS Scientific Committee of Stone, nevenkan@gmail.com*

THE INTEGRATION OF ARTIFICIAL INTELLIGENCE IN ARCHITECTURAL SURVEYING AND CULTURAL HERITAGE: DEVELOPMENTS, METHODOLOGIES, AND PERSPECTIVES OF THE DIGITAL TWIN

Ivan Paduano

Sapienza University of Rome, Italy

Abstract: *The digital evolution in construction engineering, architecture, and heritage conservation has accelerated at an unprecedented pace, thanks to the integration of Artificial Intelligence (AI), advanced acquisition systems, and the Digital Twin paradigm. This paper comprehensively analyzes the latest innovations in architectural surveying, semantic segmentation of point clouds, and Heritage Building Information Modeling (HBIM) [1,2]. The analysis unfolds through the classification of Machine Learning and Deep Learning algorithms for the automatic recognition of architectural elements, exploring the effectiveness of neural architectures such as PointNet++ and DGCNN, and their ability to generalize on heterogeneous datasets. The transition from descriptive to predictive and prescriptive models is also examined, with an in-depth focus on case studies of global relevance, including the In-Heritage platform applied to the Palazzi dei Rolli in Genoa for IoT microclimate monitoring, and the Aïoli platform used for the post-disaster reconstruction and virtual anastylosis of Notre-Dame de Paris. Through a critical evaluation of the ethical implications, the interpretability of algorithms (overcoming the "black-box" paradigm), and the integration of immersive reality (VR/AR) for spatial use, the research synthesizes the state of the art. It outlines prospects for a holistic, transparent, and technologically advanced approach to protecting built heritage [3].*

Keywords: *perspective, image analysis, building engineering, photographic survey, artificial intelligence, HBIM, digital twin, machine learning, semantic segmentation, virtual reality.*

Ivan Paduano
E-mail: ivan.paduano@uniroma1.it

Received: 05.06.2026
Revised: 01.07.2026
Accepted: 02.08.2026

Introduction

The construction engineering, architecture, and monumental conservation sector has historically been resistant to the widespread adoption of automated digital technologies, favoring traditional analytical approaches and established investigative methodologies. However, over the past decade, unprecedented technological convergence has bridged this gap. The drastic reduction in the cost of sensing hardware, combined with the exponential increase in computational power, has allowed Artificial Intelligence (AI) to permeate the operational practices of structural diagnostics and architectural surveying. This transition has transformed spatial data from a mere inert geometric representation to a dynamic, semantically rich, and searchable information ecosystem in real time.

Recent scientific literature has systematized this revolution by identifying seven fundamental operational macro-categories in which AI-based image analysis [4] is redefining contemporary construction engineering: advanced photomodeling, intelligent thermographic mapping, automatic object recognition, infrastructure inspections assisted by Remotely Piloted Aircraft (UAV), synergistic implementation in BIM (Building Information Modeling)[1] [5] and FEM (Finite Element Method), the continuous monitoring of structural health (Structural Health Monitoring) and, finally, the early identification of cracks and material damage. Each of

[1] S. Menconero, Final report on research activity, Sapienza University of Rome, 2023.

these areas is no longer a silo, but an interconnected node within a holistic workflow that culminates in the creation of high-fidelity Digital Twins.

The deepest implication of this paradigm shift lies in the transition from the quantitative to the qualitative and predictive dimensions. The primary objective is no longer just the extraction of high-precision spatial coordinates, but the semantic interpretation of these coordinates. The current scientific challenge focuses on training neural networks to distinguish a load-bearing structural element from a decorative partition, correlate surface thermal variations with the shear strength of a wall facing, and predict structural collapse by analyzing imperceptible geometric deviations. This article aims to explore these developments in depth, analyzing the algorithmic architectures, data processing flows, and the ethical-epistemological implications of adopting AI in the delicate discipline of cultural heritage protection.

Data Acquisition Methodologies and Advanced Integrated Survey Techniques

The foundation of any advanced digital model, whether an HBIM database or a predictive digital twin, lies in the granularity, accuracy, and spectral richness of the data captured in the field. Architectural surveying technologies have evolved from direct, manual methods to hybrid reality-capture systems that blend digital photogrammetry, terrestrial laser scanning (TLS), and high-resolution infrared thermography.

LiDAR Sensors, UAVs, and Rapid Mapping in Complex Environments

The introduction of UAVs (Unmanned Aerial Vehicles) has significantly addressed the challenge of surveying roofs, inaccessible facades, and large-scale architectural complexes. Remote flight, coupled with ultra-high-definition optical sensors and miniaturized LiDAR systems, enables the automatic generation of precision orthophotos and dense point clouds, drastically reducing risks to human operators and acquisition times. Modern drones operate according to pre-programmed flight plans based on topological optimization algorithms, ensuring photographic overlays that are ideal for Structure-from-Motion (SfM) and Multi-View Stereo (MVS) algorithms.

However, surveying engineering faces unique challenges in confined, hypogeal, or underground spaces, where the Global Navigation Satellite System (GNSS) signal is absent, and UAV maneuverability is impaired. In these scenarios, research is moving towards the use of solid-state LiDAR sensors integrated into mobile devices (smartphones and tablets). Recent experiments on rock architecture and hermit complexes that are difficult to access, such as the Grotta dell'Angelo in Montesano sulla Marcellana, Italy, have shown that these low-cost sensors offer extremely promising, fast survey procedures. Although these devices have a higher noise floor than traditional massive TLS scanners, their portability enables them to extract valuable spatial information and document speleological features previously impossible to detect with conventional techniques, thereby accelerating preliminary investigations and democratizing access to 3D digitization.

Multisensory Integration and Intelligent Thermographic Analysis

Infrared thermography (IRT) has been a fundamental non-destructive, non-invasive technique in historical diagnostics for decades. However, the inherent low spatial resolution of traditional thermal sensors has historically limited their applicability for precision metric mapping. Recent methodological developments have overcome this limitation by allowing the algorithmic fusion (data fusion) of two-dimensional thermographic data with three-dimensional geometric data (point clouds and meshes).

This multisensory integration enables going beyond mere qualitative visualization of surface degradation. By applying advanced neural networks for instance segmentation (such as Mask R-CNN) directly on thermal imaging sets, it is now possible to automatically isolate specific façade elements, such as fixtures, wall portions, and structural thermal bridges. Even more relevant is the ability of these intelligent systems to directly calculate thermal transmittance (U) values from recorded temperature gradients, thereby transforming visual data into a quantitative thermo-physical estimate of the building's energy behavior. In addition, projecting the thermal mapping onto the photogrammetric models reveals invisible pathologies in the visible spectrum, such as subcortical rising-damp lenses, discontinuities in wall texture, and hidden plaster detachments, thereby directing subsequent endoscopic investigation campaigns and restoration sites with extreme precision.

Artificial Intelligence for Image Analysis and 3D Semantic Segmentation

The semantic enrichment of three-dimensional data is the most complex and promising frontier in geomatics and architectural surveying. The ultimate goal is no longer geometric recording ("where" a certain point in space is located), but rather its ontological interpretation ("what" that point represents: an arch, an entablature, a cross vault, or biological degradation).

Point Cloud Classification: The Evolution to Automation

Until the last five years, the procedures for annotating and classifying point clouds were predominantly manual. Experienced operators isolated and grouped the points using modeling software in an extremely subjective process that was prone to human error and computationally unsustainable for urban- or monument-scale datasets. The introduction of Machine Learning (ML) algorithms and Deep Learning (DL) architectures has automated the identification of architectural elements, the quantification of material conservation states, and the abstraction of structural elements preparatory to subsequent FEM simulations.

The intelligent classification of the raw data fulfills several key functions. Firstly, it allows us to distinguish and map different historical construction techniques, deepening the architectural and stratigraphic exegesis of the building. Secondly, it isolates evidence of previous restorations and quantifies the materials' state of conservation, an unavoidable step for scheduled maintenance strategies. Finally, it clearly separates the structural elements (pillars, wall partitions) from the purely decorative ones (stuccoes, moldings), facilitating the engineering of the BIM model and optimizing calculation performance.

Traditional Machine Learning vs. Deep Neural Networks

The algorithmic landscape is mainly divided between classic Machine Learning approaches, which rely on the preventive extraction of features (feature engineering), and Deep Learning models, which can learn directly from raw data [6].

In the Machine Learning domain, algorithms such as Random Forests (RF), Support Vector Machines (SVMs), and K-Nearest Neighbors (kNN) have demonstrated remarkable effectiveness and efficiency. The success of these approaches depends on the quality of the *features* calculated a priori for each point or cluster of points. A consolidated workflow involves extracting geometric covariance metrics from the local tensor (such as flatness, linearity, sphericity, anisotropy, and scattering) and integrating colorimetric attributes derived from photogrammetry (RGB, HSL, and HSV color spaces). Scientific evidence suggests a strong statistical correlation between the geometric features of covariance and the morphologies of classical architectural elements: flatness predominates in wall facings, whereas linearity or cylindricity is clearly evident in columns and ribs. This discretization enables precise identification of degradation patterns (such as biological patinas or saline blooms) and classification of stone materials.

On the other side of the spectrum, deep learning has introduced neural networks specifically designed to process the inherently sparse, unstructured, and grid-free nature of point clouds. Pioneering architectures such as PointNet and its evolution, PointNet++, address the lack of point ordering by using symmetric functions (typically *max pooling*) to aggregate information, achieving remarkable results in segmenting simple objects. More advanced models, such as the Dynamic Graph Convolutional Neural Network (DGCNN), seek to overcome PointNet's limitations in understanding the local spatial context. DGCNN employs "EdgeConv" modules to dynamically construct k-nearest-neighbor graphs around each point, thereby recalculating the gaps in the feature space layer by layer. This mechanism allows the network to capture geometric edges and sharp transitions between adjacent architectural surfaces with extreme sensitivity.

The scientific literature offers rigorous comparisons between these methodologies. Surprisingly, the application of DL models not specifically optimized for point clouds (such as 1D and 2D CNN networks or recurrent Bi-LSTM networks forcibly adapted to point sequences) has often shown severe limitations in the recognition of complex historical geometries, being surpassed in terms of Overall Accuracy by traditional ML algorithms such as Random Forest. To overcome this problem, researchers have developed hybrid architectures. One of them is DGCNN-Mod+3Dfeat, an innovative framework that combines the robustness of locally pre-computed geometric-radiometric features with the hierarchical abstraction capabilities of DGCNN dynamic graphs, thereby maximizing predictive performance on complex datasets, such as those in cultural heritage (Table 1).

Table 1. Comparison of AI Architectures for Heritage Point Clouds

Methodology / Architecture	Operating Principle	Advantages of Cultural Heritage	Limitations
Random Forest (ML)	Construction of multiple decision trees based on pre-extracted features (geometric covariance, radiometry, and LiDAR return intensity)	Excellent variable interpretability, effective texture management, and low computational cost during training	Strong reliance on manual feature engineering; less capacity for complex hierarchical abstraction
PointNet / PointNet++ (DL)	Application of a multi-layer perceptron (MLP) on individual points and aggregation through symmetric functions (Max Pooling)	End-to-end learning directly from spatial coordinates; PointNet++ adds hierarchical analysis at multiple scales	Difficulty in capturing intricate topological structures at very high resolution without a prohibitive computational burden
DGCNN (DL)	EdgeConv modules for dynamically updating the local graph for each neural layer in feature space	Superior understanding of local spatial relationships and a clear definition of the edges of historical architectural elements	Demand for massive computing resources; need for huge and semantically perfect training datasets

The Generalization Problem and the ArCH Benchmark

One of the most difficult operational challenges in applying AI to historical heritage is the generalization problem [7]. Models frequently exhibit extremely limited transferability across different geographic regions, architectural styles, and acquisition conditions. A neural network meticulously trained to segment the moldings of a Greek Doric temple will inevitably fail to classify the pinnacles and buttresses of a Flemish Gothic cathedral, forcing operators to grueling, manual fine-tuning sessions.

Cutting-edge research has addressed this barrier by demonstrating that a Machine Learning model (specifically Random Forest), when trained on a transversal, essential set of architectural macro-classes (walls, roofs, openings, columns) and based on a selected core of invariant geometric features, possesses an unsuspected ability to generalize. This methodological approach enabled exporting a pre-trained model's weights to a 3D scenario that is entirely invisible to the network (an "unseen scenario"), yielding consistent classification regardless of the original acquisition technique (photogrammetry or LiDAR) or the geometric resolution of the data.

The historical absence of large-scale labeled datasets has hindered the training of high-performance DL networks for years. This gap has been partially addressed by the creation of public benchmarks, such as the *ArCH* (Architectural Cultural Heritage) dataset.

These datasets provide, for the first time, a standardized and rigorous validation ground comprising countless complex historical scenes, manually annotated by domain experts, enabling the scientific community to objectively measure and compare the performance of emerging algorithms.

Architectural Style Recognition and Visual Analysis via CNN

While three-dimensional segmentation analyzes volumetric spatiality, two-dimensional analysis of urban facades has benefited greatly from Convolutional Neural Networks (CNNs). The identification of the architectural style is not merely a purely historical-artistic exercise; it is a tool for objectively tracing the evolution of urban morphology, decoding the flows of cultural influence, and understanding the dynamics of social stratification within the building fabric.

Morphological Classification and Activation Maps (CAM)

The leap forward in large-scale visual classification is due to the exploitation of datasets extracted from massive digital archives. Foundational studies have used corpora comprising hundreds of thousands of panoramic images from Google Street View (for example, analyzing 150,000 elevations of the city of Paris over two centuries) to train CNN architectures that automatically discover and categorize visual patterns.

Advanced statistical models, such as Multinomial Latent Logistic Regression (MLLR) applied to features extracted from convolutional networks, and classifiers supported by Gabor filters, have been successfully employed to map the distinctive stylistic elements of specific construction periods. However, the greatest scientific value lies in interpreting the neural network's cognitive mechanisms. Using Explainable AI techniques such as Class Activation Mapping (CAM), researchers have generated heatmaps that "illuminate" the specific regions of the input image that the CNN focuses its mathematical attention on to formulate its probabilistic prediction.

The results of the CAM analyses offer surprising insights and are in perfect consonance with the theory of architectural composition. Neural networks, without any explicit programming (hard-coding), learn to systematically ignore spurious elements of the urban environment (pedestrians, cars, advertising signs) and almost entirely neglect the ground floors of buildings, which have historically been the most subject to invasive renovations and functional alterations for commercial purposes. On the contrary, algorithmic attention is heavily focused on the upper levels, the intersections between the base and the main floor, and predominantly on the shape, splay, and decoration of the fixtures and openings. This empirical discovery confirms the axiom that the window and its rhythm on the façade score constitute the primary genetic marker for tracing the evolution of the architectural style and the dating of the building (Table 2).

Table 2. Algorithmic Models for Architectural Style Recognition and Visual Analysis

Algorithmic Model	Type of Input	Objective and Main Output	Key Findings
Deep Convolutional Neural Network (DCNN)	Street View images (e.g., Paris)	Classification of the construction period and architectural style	Autonomous identification of diagnostic elements (windows, cornices); F1-score above 0.85 for historic buildings
Class Activation Mapping (CAM)	Final convolutional layers of DCNN networks	Visual localization (heatmap) of "areas of interest" for classification	Network validation: The algorithm ignores modern cars and shop windows, focusing on the decorative details of the noble floors
LR-CNN / Gabor Filters	Low-resolution or warped images	Object recognition under conditions of strong visual noise or degradation	Ability to distinguish complex styles (e.g., Baroque, Neoclassical) even in the absence of high-quality textures

Generative Design and Typological Flexibility

AI is not limited to the passive classification of the existing; it also extends to active architectural design. Generative and deep learning algorithms can process stylistic data to provide direct inspiration to designers during the concept phase, automating the exploration of layout alternatives (layout generation) and highlighting unexpected relationships between spatial constraints and programmatic instances.

A fascinating area of application concerns the design of dynamic and flexible facades, inspired by the principles of fractal geometry and algorithmic composition. Recent research shows that using specific fractal patterns (such as the golden triangle "1-2-√5") to generate textures and planar decompositions of cladding panels optimizes bioclimatic performance. These algorithmic-generative approaches support the creation of reactive architectural skins, capable of autonomously regulating the flow of solar radiation, preventing glare and limiting unwanted thermal loads, maintaining optimal visual comfort inside the building in response to changing external environmental conditions.

Heritage Building Information Modeling (HBIM) and Ontological Development

The semantically enriched metric data described so far constitute the necessary substrate for Heritage Building Information Modeling (HBIM). HBIM transforms the inert survey into a relational, parametric, and three-dimensional database, becoming the central pillar for the sustainable Life Cycle Management of the historic building and for the design of restoration interventions.

The Scan-to-BIM Paradigm and the Architectural Type

The conversion of raw survey data (point clouds) into a structured parametric model is referred to as *the Scan-to-BIM* methodology. In older workflows, point clouds were triangulated and converted into textured meshes; However, the inherent limitation of a mesh-only approach (mesh manipulation) lies in its ontological rigidity. A mesh lacks parametric intelligence: it does not know whether it is a wall, a window, or a floor, and it cannot be interrogated, quantified, or modified in accordance with the complex relational logic typical of BIM.

The epistemologically correct approach involves developing libraries of 3D objects (parametric families) from scratch, specifically designed to handle the anomalies, irregularities, and uniqueness of historical elements, rather than relying on standardized industrial libraries designed for orthogonal contemporary architecture. In this context, the HBIM is not merely a simple geometric container but rather a "process of knowledge" in continuous evolution and a means for developing and analyzing the *architectural type*.

Contemporary methodological guidelines impose strict parameters for the structural integration of geometric data with non-spatial information, such as historiographical data, archival sources, wall stratigraphy, petrographic analyses, and degradation reports. HBIM models thus serve as centralized virtual simulacra that support multidisciplinary teams. They enable precise quantification of estimative metric calculations for different design alternatives, advanced energy simulations, and the planning of maintenance interventions aimed at preserving material authenticity. New frontiers include the use of cloud-based artificial intelligence (such as Aurivus) that integrates directly as a plug-in into authoring BIM software, dramatically accelerating the recognition and translation of LiDAR scans into CAD/BIM models.

Levels of Detail (LoD) and Information Responsibility

A theoretical and extremely practical topic in HBIM modeling is the definition of the Level of Detail (LoD) or Level of Geometry (LoG). Conceptually derived from CityGML urban models, the concept of LoD organizes the description of the historical object according to a hierarchy of representation scales, governing the transition from the general volume to the meticulous detail (Table 3).

The classification developed by regulatory bodies such as Historic England outlines a path of increasing complexity: from LoD 1, which offers a basic conceptual representation of the volume, we progress towards LoD 3, a generic model that implements the classification of constituent materials, up to LoD 6, which represents the definitive "As-Built" model, incorporating all physical alterations, out-of-plumb and differential failures[2].

[2] BIM for Heritage. Historic England, 2017.

The selection of the optimal level of detail need not depend passively on the maximum resolution guaranteed by the available laser sensors. On the contrary, it is constrained by the client's desired output, legal liability considerations, and national public procurement guidelines. The unjustified increase in LoD involves immense computational burdens and slows down the fluidity of information management. In addition, interoperability among different authorial BIM platforms remains a heated topic of academic discussion, underscoring the urgency of adopting open formats (such as IFC) to ensure the longevity and long-term accessibility of heritage memories.

Table 3. Levels of Detail (LoD) for HBIM

Scala LoD (Historic England)	Definition and Degree of Accuracy	HBIM Purpose and Application
LoD 1 / LoD 2	Basic volumetric model; simplified conceptual representation without architectural details	Urban feasibility studies, mass analysis, and solar simulations on a neighborhood scale
LoD 3	Generic representation of the object with theoretical specification of structural components and materials	Preliminary thermal analysis, summary computation, preliminary design
LoD 4 / LoD 5	Detailed model with accurate physical dimensions, visible structural connections, and defined assemblies	Executive planning of the restoration, preliminary FEM calculation, and clash detection
LoD 6	"As-Built" model of very high metric rigor; It includes construction anomalies, chronic deformations, and high-resolution photorealistic textures	Real-time structural monitoring (Digital Twin), immersive virtual reality, and philological documentation of degradation

The Digital Twin Paradigm: IoT Ecosystems and Case Studies on a Global Scale

If the HBIM model represents the static database, or the faithful "As-Built" snapshot of a building at a given moment in time, the *Digital Twin* constitutes its dynamic, bidirectional, and interconnected evolution. A Digital Twin merges semantic three-dimensional geometry with a stream of continuous data from Internet of Things (IoT) sensor networks, transforming the building from a passive subject of investigation to an organism monitored in real time. This shift transforms models from purely descriptive to predictive, and ultimately to prescriptive.

In-Heritage and Microclimatic Monitoring: The Palazzi dei Rolli in Genoa

A paradigmatic case study of the application of the Digital Twin for environmental and urban protection is the "IN-HERITAGE" platform, operationally implemented in a pilot phase starting from December 2022 in the heart of the UNESCO site of the Palazzi dei Rolli in Genoa (directly involving the precious facades of Palazzo Tursi, Palazzo Reale, and Palazzo Spinola di Pellicceria) (Fig. 1).

The platform is engineered as an advanced decision support system to assess the resilience of architectural heritage to degradation factors exacerbated by climate change. The basic infrastructure consists of a rigorous geometric mapping obtained through TLS and photomodeling with drones, on which a photothermal diagnostic layer is superimposed. The real technological leap is the symbiotic integration with external IoT sensor networks and satellite big data. In-Heritage exploits the services provided by the global *Aura* sensors, which can monitor and transmit in real time the concentrations of severe pollutants that act as triggers for the chemical-physical erosion of the stone (such as NO_2, PM_{10}, $PM_{2.5}$, SO_2, H_2S) and measure humidity, pressure, and environmental noise.

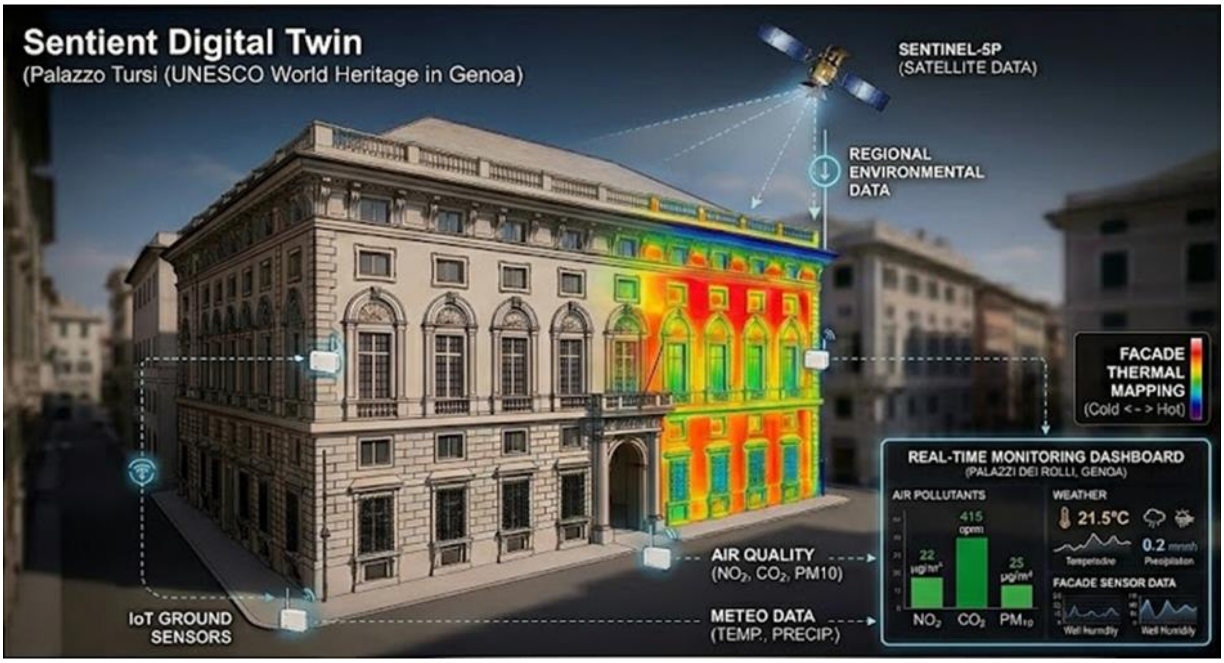


Fig. 1. *Conceptual representation of a "Sentient Digital Twin" applied to historical heritage (Palazzo Tursi, Genoa). The model integrates 3D geometry (HBIM), thermographic mapping of facades, and the flow of real-time environmental data acquired by ground-based IoT sensors and satellite surveys (Sentinel-5P)*

At the same time, the system collects data from the *Smart Rainfall System* (SRS). This disruptive, highly innovative technology estimates the intensity of atmospheric precipitation by analyzing, in real time, the attenuation of electromagnetic waves in satellite television signals received from a distributed network of pre-existing commercial dishes. The intersection of these variables transforms the perception of risk: the Digital Twin does not record damage a posteriori but calculates the probability of degradation by correlating acid rain or pollution peaks with the weakening of the stone binder.

In addition, the DT adds value to strategic urban planning and the tourism economy. By analyzing the data, the city administration was able to correlate peaks in microclimatic stress within the buildings (increases in CO2 and vibrations) with overcrowding caused by the simultaneous disembarkation of thousands of tourists from cruise ships in the Port of Genoa. This prescriptive approach enables real-time modulation of entrances and reorganizes infrastructure maintenance in harmony with tourist dynamics, thereby extending the monument's overall useful life.

Post-Disaster Reconstruction and Virtual Anastylosis: The Cathedral of Notre-Dame de Paris [8]

In emergency contexts of post-disaster reconstruction, the Digital Twin abandons its mere maintenance function to assume the dual role of a custodian of stratified memory and an experimental computing environment for structural restoration. The catastrophic fire that devastated the Cathedral of Notre-Dame de Paris in 2019 triggered an international scientific convergence, leading to the development of an n-dimensional digital ecosystem managed by specific working groups for digital data (Fig. 2).

The technological fulcrum of this undertaking is the *Aïoli* platform, a cloud-based tool developed specifically to allow multidisciplinary teams (chemists, structural engineers, art historians) to apply collaborative semantic annotations in both 2D and 3D formats. For Notre-Dame, the Digital Twin is not intended as a simple and fascinating computer-graphics replica, but rather as the intersection of all human knowledge inherent in the structure [9]. The system aggregates medieval construction sketches, dendrochronological surveys of burnt trusses, historical preservation reports, and the massive LiDAR scanning campaigns serendipitously acquired before and logically after the collapse into a single logical space. The infrastructure models the semantics of topological and mereological spatial relationships (the relationships between parts and wholes), ensuring irrefutable tracking of the origin and reliability of each piece of information, in compliance with the CIDOC CRM ontological protocols.

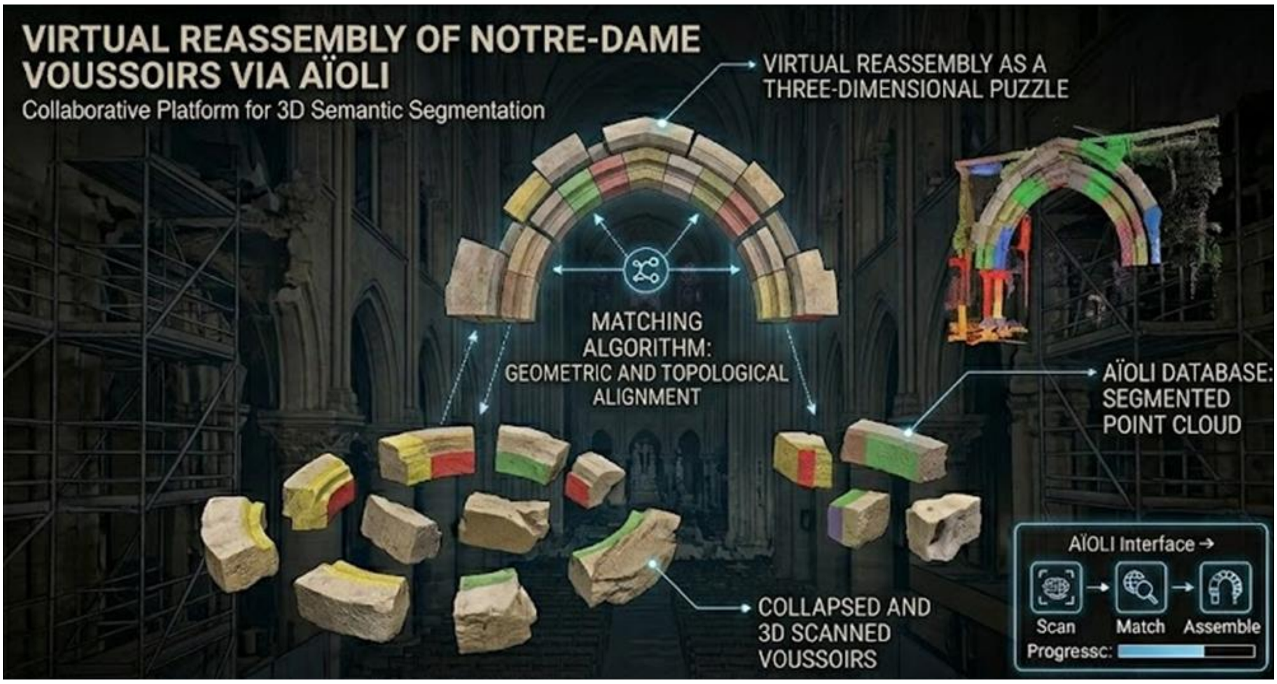


Fig. 2. *Virtual reassembly of the collapsed ashlars (voussoirs) of Notre-Dame de Paris using the collaborative platform Aïoli. The illustration shows the coupling algorithm based on the geometric and topological alignment of the 3D scans, managing the fragments as a complex three-dimensional puzzle*

One of the most daring engineering and theoretical applications within this Digital Twin is the virtual anastylosis of the nave's collapsed stone arches. Following the collapse, thousands of ashlars (voussoirs) were recovered from the rubble, cataloged, and individually scanned at very high resolution. The problem of their exact original repositioning has been addressed by artificial intelligence as a mathematical optimization problem and as an extremely complex three-dimensional puzzle. Combining operational research theories and reverse-engineering algorithms, the AI analyzed fracture planes, mortar residues, joint inclination, and shear impressions to couple the virtual segments, exploring an incalculable number of permutations that the human mind could not calculate. This simulation enabled the formulation and validation of physically and statistically accurate reconstruction hypotheses in the virtual environment before undertaking the physical handling and anastylosis of the heavy stone blocks, thereby acting as an essential bridge between the lost historical structure and the contemporary construction site.

Accessibility, Ethics (XAI), and Immersive Reality in the Context of Artificial Intelligence

The progressive delegation of diagnostic, analytical, and design responsibilities to high-complexity algorithms raises unavoidable epistemological and ethical questions, especially in humanistic and empirical disciplines such as architectural restoration.

Algorithmic Transparency and Overcoming the "Black-Box"

The pervasive inclusion of Artificial Intelligence in protection decision-making processes raises a potential conflict between the appeal of technological innovation and the imperative of philological reliability. Renowned researchers and experts engaged in heritage restoration frequently exhibit justified skepticism towards emerging software tools, driven by deontological fear of irreversibly altering the historical authenticity of the work due to fallacious machine-based predictions.

The central point of this academic and legal debate lies in the constitutive opacity of deep neural networks, a phenomenon known as the "black-box" problem. In complex Deep Learning models, the layers of hidden nodes and myriad nonlinear matrix operations prevent a human operator from retrospectively reconstructing the logical causal chain that prompted AI to provide a given result. If a neural network recommends the removal of a plaster based on a thermal pattern, but is unable to "explain" the physical principle behind its statistical deduction, the professional is faced with an unacceptable leap of faith in forensic engineering.

This limitation is compounded by the concept of "infrastructural embeddedness" explored in technological jurisprudence [10]: when AI systems become inextricable parts of the administrative and evaluation infrastructure, the lack of transparency creates significant liability gaps. Algorithmic decisions often rely on mere statistical correlations, depriving analysis of the fundamental causal explanation (intuitive causality) required in materials science. In the absence of transparency, there is a very high risk of training models that introject systemic biases, thereby perpetuating classification errors that disfavor vernacular architectural styles or minority typological anomalies that are poorly represented in the original training datasets.

To mitigate these risks, software engineering is transitioning to ethically responsible models based on Explainable AI (XAI) or "white-box" systems. The research aims to generalize explanatory visual frameworks that render the weighting variables driving neural network decision-making entirely intelligible. At the same time, it becomes imperative to structure sectoral ethical guidelines, specifically drawn up for the domain of cultural heritage, so that the choices made through AI are documented and slavishly comply with the Charter of London (transparency on the use of 3D models) and the Principles of the Seville Charter, ensuring that predictive reconstructions are always distinguishable from the surviving material original.

Virtual Reality, Space Anamorphosis, and Scientific Dissemination

The immense number of parametric digital assets and HBIM models produced in these investigations has a natural and highly effective application in museology, public communication, and interactive tourism through Immersive Virtual Reality (iVR) and Augmented Reality (AR) technologies. These tools possess the gift of democratizing the understanding of spatial hierarchies otherwise illegible to the lay public.

One of the most fascinating frontiers where survey, descriptive geometry, and iVR converge is the analytical simulation of ancient optical illusions, trompe-l'œil, and deceptive perspective machines, such as the paradoxical spaces engraved by Giovan Battista Piranesi in the *Prisons*. To fully decode imaginary architectures from non-rigorous perspectives, the researchers integrated the architectural survey with geometric analysis of perspective restitution and eye-tracking technologies, resulting in complex, navigable 3D models.

Specifically engineered virtual environments, such as the *AnGA* (Anamorphic Gallery) platform, immerse the user in modeled rooms, dynamically revealing the anamorphic illusion – a complex technique in which an image appears correct only from a specific, singular vantage point. In this context, iVR addresses and resolves a complex optical dichotomy: the physical use of anamorphosis in nature ideally requires monocular observation to eliminate depth perception, whereas immersive viewers rely on stereoscopic (binocular) vision. By parametrically managing the projection centers, these ecosystems blend the mathematical rigor of Renaissance optics with modern interactivity.

In addition, national initiatives of great magnitude, such as the *e-Archeo* project, have demonstrated the ability to translate vast diagnostic and stratigraphic databases into real, explorable ecosystems designed to enhance archaeological parks in Italy. Through AR and intelligent human-machine interfaces, the non-expert visitor can now physically visualize, in situ, the anastylotic hypotheses generated by scientific computing, observing the original volumes at full scale, superimposed in real time on the archaeological ruins, or cognitively interact with the stratifications of geophysical investigations applied to the ground.

Conclusion

The systematic and multidisciplinary investigation of the state of the art unequivocally confirms that Artificial Intelligence, advanced remote sensing techniques, and Digital Twins are no longer mere technological extensions for three-dimensional graphic representation, but have established themselves as a total cognitive paradigm, capable of refounding the methodologies of civil engineering, archaeology, and architectural restoration.

From solving mobility and scale challenges by coupling UAVs and compact LiDAR sensors for ultra-fast mapping, to integrating deep convolutional neural networks (such as DGCNN and PointNet variants) that automate the semantic segmentation of point clouds with previously unthinkable confidence rates, the industry has moved beyond the stage of manual abstraction. The demonstration that specific Machine Learning algorithms, such as random forests based on spatial geometric covariance, can address the critical problem of generalization, enabling the transversal interpretation of heterogeneous architectures and formal arrangements without costly retraining, represents a crucial juncture for the industrial scalability of historical relief [11] (Fig. 3).

The obligatory passage through the ontological structuring of objects in HBIM databases, whose detailed hierarchies (LoDs) encode both the deformational roughness of the historical monument and the legal responsibility of the professional, serves as a foundation for the dynamic interactions of Digital Twins. As crystallized in the formidable case studies of the Palazzi dei Rolli (interfaced with the atmospheric measurements of the SRS dishes) and the forensic reconstruction of the vaults of Notre-Dame, the Digital Twin elevates the building to a sensor of itself. By correlating microclimate, anthropogenic flows, and structural dynamics, the discipline transitions from an obsolete paradigm of reparative care to an era of predictive and prophylactic protection.

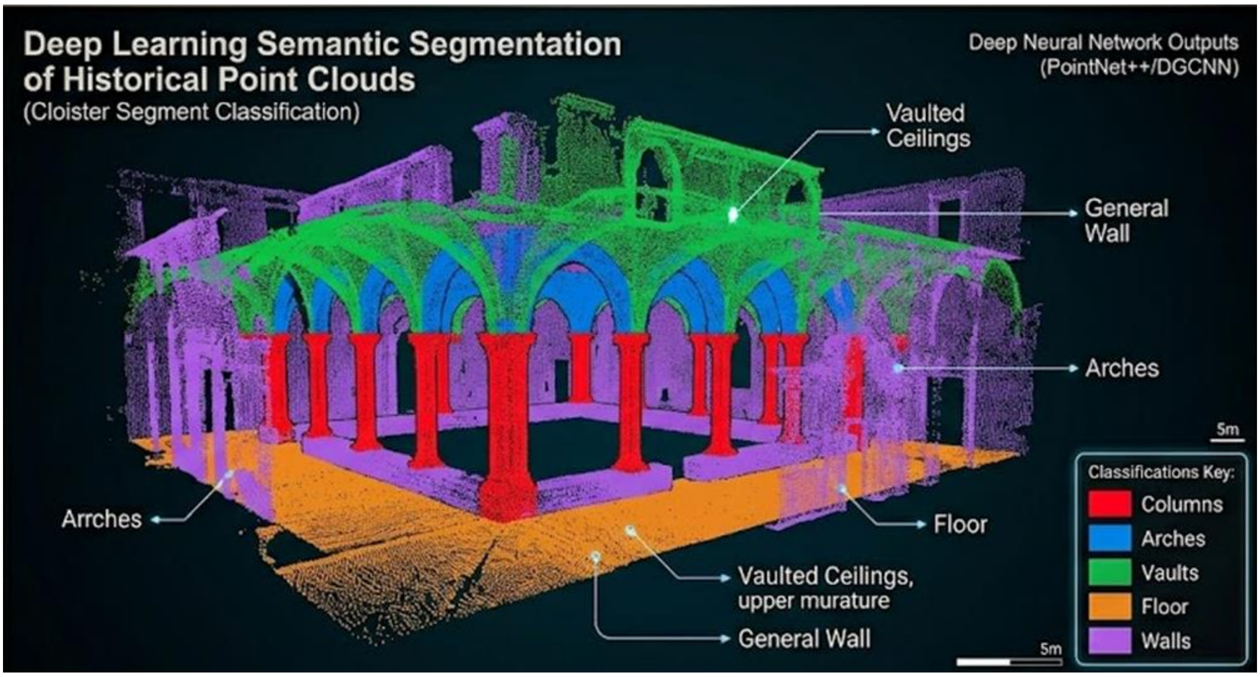


Fig. 3. *Semantic segmentation of a complex point cloud through Deep Learning architectures (e.g., PointNet++, DGCNN). The different architectural elements (columns, arches, vaults, masonry) are automatically classified and isolated to facilitate structural analysis and subsequent parametric modeling*

The research priorities of the next decade will focus on refining Explainable AI (XAI) logics to ensure the transparency and ethics of automated deliberations, and to avoid harmful interventions arising from black-box architectures. Equally decisive will be the bidirectional harmonization between the openBIM languages (IFC) and the complex FEM algebraic solvers to eliminate information degradation. With the widespread, mature adoption of these hybrid tools, heritage disciplines are intended to safeguard not only the material integrity but also the historical and expressive authenticity of the built civilization.

Conflict of Interest

The author declares no conflicts of interest.

Funding

This research did not receive any financial support.

References

[1]. Y. Arayici, J. Counsell, L. Mahdjoubi, G. Nagy, S. Hawas, K. Dweidar, Heritage Building Information Modelling. Routledge, London, 2017

[2]. M. Attenni, M. L. Rossi, HBIM come processo di conoscenza: modellazione e sviluppo del tipo architettonico. Franco Angeli, 2022.

[3]. V. Cera, Il rilievo dell'Architettura tra identificazione tipologica e strutturazione semantica. La Certosa di San Lorenzo a Padula nella rappresentazione digitale per il Cultural Heritage, PhD thesis, University of Naples Federico II, Italy, 2018.

[4]. I. Paduano, A. Mileto, E. Lofrano, A Perspective on AI-Based Image Analysis and Utilization Technologies in Building Engineering: Recent Developments and New Directions. Buildings, 13 (5), 2023, 1198. Doi: https://doi.org/10.3390/buildings13051198

[5]. J.H. Lee, N. Gu, Historical Building Information Model (BIM)+: Sharing, Preserving and Reusing Architectural Design Data, in: J. Kramer-Smyth (ed.), Partners for Preservation. Cambridge University Press, 2019, 123-144. Doi: https://doi.org/10.29085/9781783303496.011

[6]. E.S. Malinverni, R. Pierdicca, M. Paolanti, M. Martini, Ch. Morbidoni, F. Matrone, A. Lingua, Deep Learning for Semantic Segmentation of 3d Point Cloud. The International Archives of the Photogrammetry Remote Sensing and Spatial Information Sciences XLII-2/W15:735-742, 2019.
Doi: https://doi.org/10.5194/isprs-archives-XLII-2-W15-735-2019

[7]. G. Rocha, L. Mateus, V. Ferreira, Historical Heritage Maintenance via Scan-to-BIM Approaches: A Case Study of the Lisbon Agricultural Exhibition Pavilion. ISPRS International Journal of Geo-Information, 13 (2), 2024, 54. Doi: https://doi.org/10.3390/ijgi13020054

[8]. A. Gros, A. Guillem, L. De Luca, É. Baillieul, B. Duvocelle, O. Malavergne, L. Leroux, T. Zimmer, Faceting the Post-Disaster Built Heritage Reconstruction Process within the Digital Twin Framework for Notre-Dame de Paris. Scientific Reports, 13, 2023, 5981.
Doi: https://doi.org/10.1038/s41598-023-32504-9

[9]. M. Öztürkoğlu, Predicting Various Architectural Styles Using Computer Vision Methods. Journal of Architectural Sciences and Applications, 8 (2), 2023, 811-828.
Doi:https://doi.org/10.30785/mbud.1334044

[10]. Y. Bathaee, The Artificial Intelligence Black Box and the Failure of Intent and Causation. Harvard Journal of Law & Technology, 31 (2), 2018.

[11]. S.Teruggi, E. Grilli. M. Russo, F. Fassi, F. Remondino, A Hierarchical Machine Learning Approach for Multi-Level and Multi-Resolution 3D Point Cloud Classification. Remote Sensing, 12 (6), 2020, 2598. Doi: https://doi.org/10.3390/rs12162598

Ivan Paduano, Doctor of Science (Arts, Design and New Technology), Professor *(Italy, Rome) - Sapienza University of Rome, Contract Professor at the Department of Architecture and Design, ivan.paduano@uniroma1.it*

PONTIC REASONING AND ARCHITECTURAL PARTI: A SYSTEMIC REINTERPRETATION OF C-K THEORY

Serge Monnot[1]*, Suzanne Monnot[1]
[1] *National School of Architecture of Lyon, France*

Abstract: *C-K Theory is currently one of the most sophisticated theoretical frameworks for modelling design processes. Based on the interaction between a space of concepts, C, and a space of knowledge, K, it accurately describes the mechanisms of producing and transforming design objects. However, certain concepts used in architectural practice remain difficult to integrate into this model. This is the case with the architectural concept (architectural parti in French), which is frequently presented as a decisive stage of the project, yet its theoretical status remains unclear. This article aims to shed light on this difficulty based on the hypothesis of a general system in Bertalanffy's sense. Previous research, which has highlighted an isomorphism between the wuxing of the Chinese tradition and Platonic solids, is employed as a heuristic tool to identify several structuring properties of this system: duality of transformation regimes, dynamic antagonism, the role of the 5th polarity, and the activating centre… Comparing these properties with the CKT leads to the identification of a central mediating mechanism, which is scarcely explained in its classical formulation. We interpret the architectural scheme as this very mechanism, this bridge that ensures the transition between the exploratory regime of space C and the stabilising regime of K. The study of this bridge leads to the formulation of the hypothesis of a third modality of rationality, complementary to the causal and correlative reason described by Vandermeersch. This rationality, referred to here as 'bridging reason' in reference to M. Serres, denotes the capacity to establish relationships between heterogeneous domains to enable the emergence of new configurations.*
Keywords: *General System, Isomorphism, C-K Theory, Platonic Solids, Five Chinese Elements, Wuxing, Fifth Element, Bridge Metaphor, Architectural Concept, Causal Reasoning, Correlative Reasoning, Bridging Reasoning.*

Serge Monnot*
E-mail: serge.monnot@lyon.archi.fr

Received: 07.06.2026
Revised: 02.07.2026
Accepted: 04.08.2026

Part One: Problem, Method, Objectives

Background

As teachers and architects grappling with *design* issues, we find that a theoretical framework for the concept of *the 'architectural parti*'—a notion that is often difficult to define and subject to varying interpretations in France—will be a significant challenge.

To address this question, we first drew on previous research [1]. Indeed, the recognition of an *isomorphism* in the mathematical sense (belonging to the same equivalence class, i.e. a perfect structural and functional coincidence between two *systems* [2]), between the founding cosmologies of *processual Chinese culture* – the *five Chinese elements* (*wuxing*), 五行 – and that of Greek geometry – the *five Platonic solids* – enabled me to confirm the existence of a *General System* in the sense of L. v. Bertalanffy's *general systems theory* [3]. The intention is not to start from a few empirical definitions of *the architectural concept* – often equated with *a true synthesis of the various principles that will structure the forthcoming project* [4] but rather to reflect on how to utilise knowledge of this General System as a genuine *systemological tool* [5]. The aim will therefore be to consider how to apply this tool to the modelling of the *design* process, first from a general perspective and then within the theoretical framework of architecture.

In the course of this earlier research, we first highlighted the isomorphism between the two cosmologies and concluded that there exists a ‘meta-system’ of which each cosmology is a particular interpretation (i.e., a *system* belonging to the same *equivalence class* of *the General System*). We then sought other possible *interpretations* of this *General System*, derived from contemporary theories, in particular a general theory of design, the C-K Theory [6], originally developed by A. Hatchuel and B. Weil, two engineers from the École des Mines de Paris. This theory draws on earlier work, notably J.P. Guilford's work on human intelligence [7].

In 2023, at the 2nd ICAHCA International Conference in Armenia, we put forward the hypothesis that it is possible to conceive of an isomorphism between this *C-K Theory* (hereafter referred to as CKT) and the *General System* (hereafter referred to as GS) [8]. This isomorphism is achievable through a few graphical transformations; however, we have noted that a particular stage of the design process, which features in architects’ discourse, is not considered an important step in this system by CKT.

Hypotheses

This appears to be a genuine *blind spot* for the CKT (perhaps because Hatchuel and Weil are engineers rather than architects?); other authors have clearly identified this particular moment, this remarkable phase of transformation – the “passage” between what is broadly referred to as *the research process* and *the development process*.

The hypothesis developed in this article is that this “pivotal stage” of *the design process*, which architects have termed *the architectural concept (architectural parti),* corresponds to the *central phase of inversion* identified in the GS. To envisage the CKT functioning similarly to the GS, it will be necessary to reformulate and reinterpret the CKT, incorporating external theoretical contributions that address this transition phase by detailing its various characteristics.

Methodology and references

To reinterpret the CKT based on the principles that underpin the GS, we propose re-examining and elaborating on these principles using the five Chinese elements (the standard French translation of *wuxing* [9]). This method is therefore based on the *wuxing*, particularly their processual and temporal representation (Fig. 1), as this interpretation of the GS is most directly comprehensible in Western culture. To ensure that this *temporal representation* conveys all the dimensions of *the wuxing* – their *overarching principles* – we will draw on the work of the French sinologist and doctor J.A. Lavier, as he is one of the few authors to have established coherent links with Greek thought within this central framework of traditional Chinese medicine [10]. We shall also refer to the work of L. Vandermeersch concerning the antagonism between Chinese and Greek thought and the inherent question of their epistemological validity [11].

Our approach will therefore involve *comparing* the representations of the GS and the CKT to establish *correspondences*. In practical terms, this will involve describing the *main principles* of GS using the Chinese temporal representation and then transposing them to the CKT representation. Where necessary, we will incorporate concepts from other works into the CKT system – notably those of A. Koestler and M. Serres. Our approach can be characterised by what M. Serres describes as a *process of "rapprochement" – to bring into relation* [12] (Koestler’s being similar). He uses this term not only to denote the *connection* (in the sense of F. Jullien [13]) of concepts that share similarities, but also to express the possibility of relying on a *passage* – provided by a framework we have constructed – which allows thought to "*traverse",* to move *from one sphere of discourse* to another (to use the words of P. Ricœur [14]). This genuine possibility for thought to *traverse* and *connect* different spheres is also closely related to the principle of *metaphor*. The *metaphor* connects by virtue of its dual nature and, as a possibility for linking, can also become a generator of *models* within a systemic context [15]. To use Serres’s vocabulary and approach, the aim is therefore to *bring together* concepts – similar in structure, but of distant geographical, disciplinary, or historical origins. In this article, we shall focus primarily on four areas: philosophy, the design sciences (broadly termed the cognitive sciences), systems theory, and the theoretical framework in the discipline of architecture [16].

Objectives

This approach presents a range of challenges. It provides a *translation* of the logic of *the Five Elements (wuxing)* as applied to a context close to our culture and Western ways of thinking, with an educational focus on project-based teaching methods. It will also enable the development of each of the *wuxing* principles *transposed* to CKT – the aim being to explore, in turn, this new paradigm of GS through this new *interpretation.* At the same time, the aim will be to identify and highlight works that have developed logics converging with GS's, even though the authors did not have access to this general framework. *Bringing* these works *together* allows new connections to be established: the initial aim will be to explore a broader range of metaphors from a heuristic perspective, with the ultimate goal of recognising genuine isomorphisms, which would then serve as proof [12].

Ultimately, incorporating the concept of *an 'architectural parti'* will enable the CKT to be refined through the use of other *metaphorical frameworks*, as practised by Koestler [17] and Serres, whose philosophy has developed a new *category of knowledge* that is essential not only for the training of architects but also for higher education as a whole [18].

Part Two: How to recognise a General System in Bertalanffy's sense

Before detailing the main principles that structure the SG (through the lens of its Chinese *processual* interpretation of *the wuxing*), let us briefly recall *the isomorphism* between these two traditional Greek and Chinese systems and, above all, how M. Serres very early on had the intuition to raise the question of a possible *connection* between Plato's solids and something else that might characterise them. These reminders will help clarify two points that are important for the argument that follows: the strategic choice of Chinese thought, as opposed to Greek thought, to recognise the existence of a fifth element, and, equally important for L. v. Bertalanffy, the need to envisage a truly *general systemology*.

Isomorphism between Platonic solids and Chinese elements: a single General System

In our quest as architects to harmonise built forms with the rhythms of *the inhabitants* [19,20], we first demonstrated that the topological *structure* (spatial forms) and the *functioning* (sequence of temporal *processes*) of both Greek and Chinese cosmologies – *5 Platonic solids* and *5 elements* – are perfectly identical (Fig. 1). These two cosmologies can be regarded as two *systems* in the contemporary sense of the term, even though they appear in 'archaic' contexts (5th century BC) [9]. This then enabled us to argue in favour of a true *isomorphism* (in the mathematical sense and as defined within the framework of *general systems theory* by its specialists [21,22]) between these two *systems*, and thus to address the problem posed by R. Rosen [23]. If one finds a *canonical representative* of an *equivalence class* characterised by *high minimality*, then one can "define" the *General System* conceived by Bertalanffy.

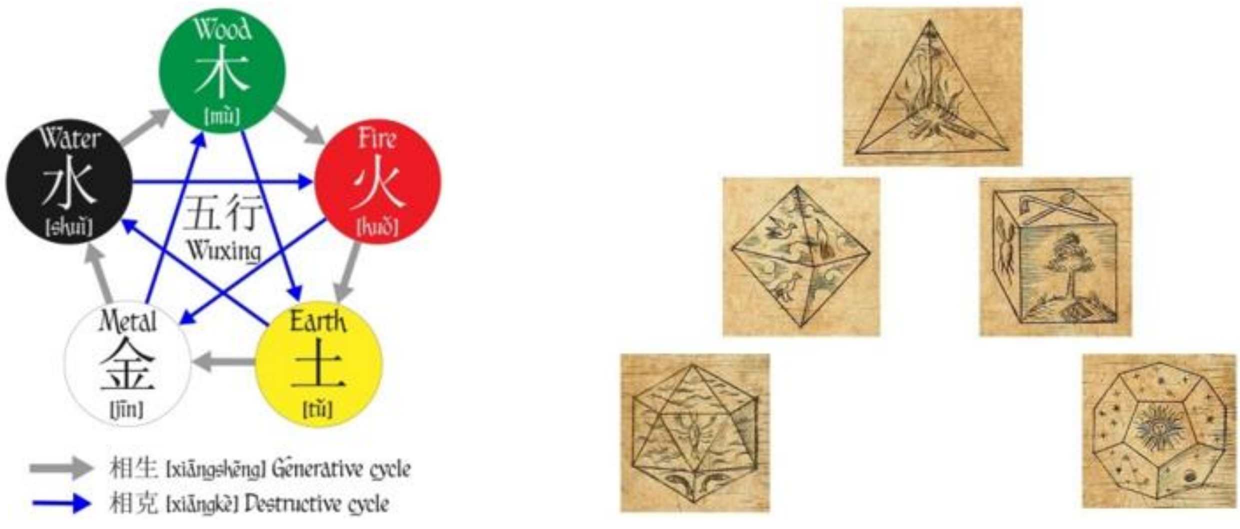


Fig. 1. *Chinese and Greek cosmological systems: the wuxing (translated in French as '5 elements', but more accurately as '5 processes') and the 5 Platonic solids (Illustrations from Wikipedia)*

Isomorphism and the search *for organons*

The demonstration of this *isomorphism* between *Platonic solids* and *Chinese movements* – the starting point of this research [24] – has shown that the Chinese *system* of generalised correspondences (tables associated with the *wuxing* [25]) ultimately aligns well with the concept of the GS developed by practitioners of *general systemology.* Thus, the dual geometric and functional *interpretation* of a single *systemic logic* – which can be described as GS, but also as *a meta-system* or *mother system* – has in turn served to legitimise the coherence of the two cosmologies (Fig. 2). On the Chinese side, the *wuxing* had hitherto been perceived in the West merely as a set of beliefs [26], whose very singularity, the *fifth element*, was regarded by some as nothing more than an anecdotal construct [9]. Through the demonstration developed in the previous articles [19], they become a coherent whole, since they directly *reflect* the fundamental properties of space, in another *language* that might be described as *processual* [27]. On the Greek side, Plato's account (whose two-dimensional geometric explanations seemed incomplete [28]), illuminated by the connection with the *five elements*, ultimately bears witness to genuine knowledge. Indeed, *translating* the *temporal* sequence of *processes* described by the *wuxing* into *spatial* terms makes it possible to understand this part of *the Timaeus,* which had long remained enigmatic.

Simply incorporating Platonic bodies into the *wuxing* framework was not sufficient to claim a true *isomorphism* between the Greek and Chinese systems; whilst the *wuxing* certainly involve networked correspondences, they are also *represented* in China by means of two *models* [29], two *diagrams*. The best-known of these depicts the various *processes* that succeed one another over *time* (Fig. 3a,b).

The other diagram illustrates the relative positions of these *processes* within *the* traditional Chinese spatial framework [10]. To establish a true *isomorphism*, it was therefore necessary to find two equivalent *representations* concerning Platonic cosmology: i.e., ones that utilise the five regular polyhedra, *together, in an oriented space,* whilst *translating*, through the language of geometry, the same relationships and structures expressed by the wuxing… Yet this problem is akin to the search for an *object* that would maximise the geometric properties of regular polyhedra whilst synthesising their relationships – as imagined by various researchers: Kepler in particular [30] or, more recently, J. Conway [31]. Surprisingly, Serres also took up this quest with a keen awareness of the issues surrounding this enigmatic object.

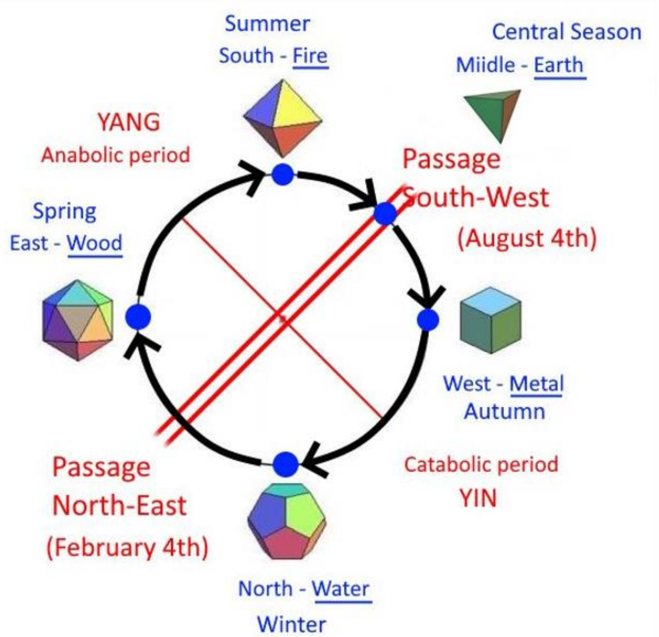


Fig. 2. *Temporal representation of the correspondence between the Chinese movements and Greek polyhedra (personal illustration)*

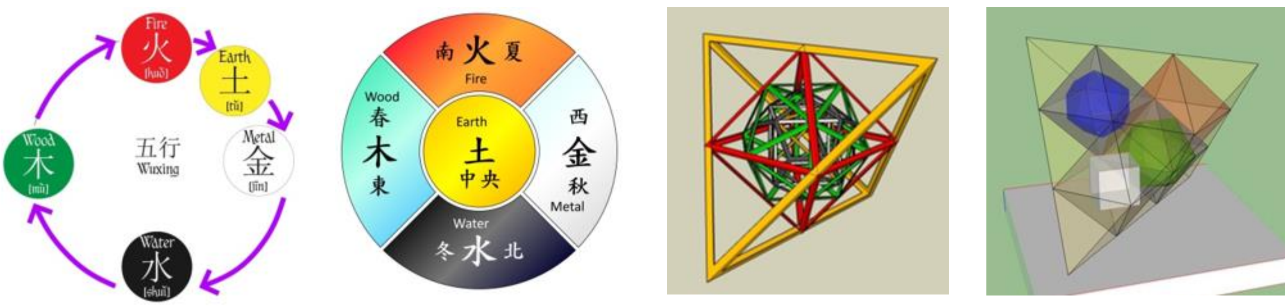
The search for a *geometric organon* in the sense of M. Serres

Indeed, as early as 1969, in the first issue *of Hermès*, *'La* communication', whilst commenting on Foucault's work **The History of Madness in the Classical Age*,* M. Serres made this remark: *If one were to consider it in its purity, that is to say, outside the historical example proposed here […], one could easily arrive at the general organon of the sciences which are still only at the stage of description […], and to which one attempts, through various methods, to apply falsely qualitative structures. Assuming this endeavour were to succeed—which demands the full force of contemporary thought—a new family of true* *sciences would undoubtedly emerge, which might be called morphological sciences. […] the language of this geometry, taken in its nascent state, is capable of providing that set of structures sought, consciously or unconsciously, by many thinkers of our time [32].*

In this book, Serres makes little use of the concept *of the organon* in its original sense (as a formal instrument for the constitution of the sciences). Still, in this quotation, he expands on its definition by pointing out that the primary forms of space are few in number and therefore, in his view, necessarily highly structuring (since, at a deeper level, *causality* is in any case *topological*). He also appears to criticise the fact that certain sciences – biology, linguistics, the humanities… – are still at a stage that is too descriptive and lack a common formal tool – an *organon* – that would enable a transition from empirical description to a true *structural science*. While the choice of the term *'geometric organon'* is particularly apt in this context – we shall adopt it in the remainder of this presentation – Serres nevertheless envisages the need for only a single *organon*, of a *spatial* nature; whereas a few years later, he would write: *"To describe a system, one can sketch its configuration and follow its operation. It is then a question of structures, and of the forces that attach themselves to them and move within them. A topology and an energetics suffice for the description."* [33] - emphasising the need for a dual description. Moreover, he had already emphasised (in the first excerpt) the need "*to apply qualitative structures"* to give meaning to this purely spatial *organon*.

The Gascon philosopher, as he likes to describe himself, would never find this *morphological organon*, neither at the time nor even afterwards; but the modes of expression he employs in this part of the work—*geometry in its nascent state*, *the primary qualities of space* [31], a *set of structures…* and later, with direct allusions to *regular polyhedra* in his work on bridges [18]—suggest that he sought this *morphological science* throughout his life.

Finally, we hypothesise that the two remarkable nesting arrangements of regular polyhedra developed as part of the doctoral thesis, as *a geometric interpretation* of Chinese cosmology (Fig. 3) – do indeed constitute *geometric organons*, as M. Serres had envisaged. Similarly, the Chinese cosmological representation, described by the successive processes of wood, fire, earth, metal, and water, is sufficiently qualitative and integrated to be considered, by 'dual parallelism', an *organon,* albeit one that is *processual* and temporal in nature.



a b c d

Fig. 3. *The two Chinese processual (temporal and spatial, with the South on the top) organons and the two Greek geometric organons according to our correspondence hypothesis [1]*

To summarise this first central hypothesis: the cosmology of *the wuxing*, expressed in two variants—spatial and temporal—constitutes two *Chinese processual organons*; in the same way that Greek Platonic cosmology is expressed through two *geometric organons—*also expressed in spatial and temporal versions (described as *centred* and *off-centre)*. Finally, establishing a spatial correspondence between *the geometric integration* of regular polyhedra (with a high degree of *regularity*) and the Chinese *model* of life processes seems to correspond to what M. Serres had more or less consciously sought and intuited.

How might we define the General System?

We have seen that it was *the* Chinese *interpretation* of the GS, when compared and contrasted with the Greek one [19], that enabled us to establish a clear picture of the GS. Precisely because of its generality and adaptability to various contexts, the GS does indeed have a single logical structure and a single identifiable operating principle (which the Chinese have succeeded in summarising). Still, our understanding of this system can only grasp all its facets by engaging with multiple *interpretations*. To support this view, we rely primarily on the work of C. Canullo [34].

One might nevertheless be tempted to imagine that a purely mathematical description of these transformation processes (*graph theory*, *catastrophes*, or *systems of* differential equations…) would provide access to a single definition – an ultimate *truth* of the GS. But here again, it is indeed *the set of correspondences* – always to be completed – that will enable us to explore the various aspects of the GS.

Finally, it may be noted that the intention to identify *a General System* is not insignificant in the contemporary context of *complexity*. This research ambition has been the subject of numerous publications across all disciplines [35] – particularly within the framework of the scientific society dedicated to the development of *general systemology*, SAGS [3]. Establishing this *correspondence* [36] between cosmologies was only possible by adopting an approach that *reverses the perspective,* by employing what J. de Rosnay termed the *macroscope* [37]: in contrast to contemporary practices that tend ever towards greater specialisation [38]!

Thus, the hypothesis of this new systemic *paradigm* [39] opens up a considerable new field of research, within which we wish to explore a new avenue here: comparing the C-K Theory with the structuring principles of the General System.

Part Three: How can C-K Theory be integrated into the General System?

Whilst this work of *establishing connections* has so far helped us to understand the relevance of *the* two *cosmologies* (Greek and Chinese) to *general systemology* and has provided an initial overview of this General System, it has not explored the various *processes* that constitute it – the specific functioning of each of the system's five polarities.

How can the General System be represented to better grasp its principles?

To consider (with the CKT) this new possibility for *interpreting* the GS, let us return to the study of *the* Chinese *interpretation* (since the Greek geometric system is more difficult for a non-specialist to grasp).

With the *wuxing*, the Chinese sought to account for the various *processes* that guide and accompany human life, since Traditional Chinese Medicine is based primarily on the two theories of *yin/yang* and *the five processes* [40]. However, even in China today, there are very different *representations* of *the wuxing*. We shall adopt the remarkably detailed version by J. A. Lavier.

To assess whether a representation is consistent with the principles of the wuxing, one must ensure that it emphasises the most important ones. In Chinese thought, the *wuxing* occupies a central place in the conception of human life, which is itself strongly connected to the practices of traditional medicine. As a doctor and sinologist, Lavier elaborated on these principles in particular detail by contrasting them with possible equivalents in Greek thought [41]. One might even consider that his approach equated *wuxing* with the concept of a *General System*, without his having any *prior* knowledge of Bertalanffy's research.

We will focus on the following five *key principles*.

Point 1. Firstly, thanks to their *analogical* approach, the Chinese associate *space* with the *earth*, *time* with *the sky*, and *humankind* in *the middle, between sky* and *earth*. For the *earth* associated with *space*, they identify four main *directions*: East, South, West and North; and for the *sky* associated with *time*, four *seasons*: Spring, Summer, Autumn and Winter (which correspond analogously to the four phases of the daily cycle: Morning, Midday, Evening and Night). However, the Chinese *seasons* correspond exactly to *the cardinal directions*: they are centred on the solstices and equinoxes and therefore begin earlier than in Greece (Fig. 2). The cycle of the seasons is modelled as a circle with polarities, which constitutes a *temporal system*. These polarities are identified by means of physical phenomena, the *elements* (or *processes*, to use a more accurate translation) that pertain to human daily life: *wood*, *fire*, *metal*, *water*. We shall examine the specificity of the fifth element, *earth,* later on.

Point 2. Second difference from the Greeks: through the direct warming of the sun and the indirect warming of the earth, the Chinese distinguish two major periods: one of warming, which begins on 4 February (corresponding to the North-East) and ends on 4 August (South-West) – thus comprising Spring and Summer; the other of cooling, from 4 August to 4 February – which encompasses Autumn and Winter. The Chinese have characterised this fundamental alternation of life on earth through the two categories *of yang/hot* and *yin/cold*: in the *wuxing*, there is a clear boundary between these two major periods.

Point 3. By choosing to place the South, Summer, and the *Fire* element at the top of the *wuxing* diagram (Fig. 2), the Chinese cleverly draw attention to the notion of *effort* and difficulty associated with any *ascent,* in addition to the fact that the sun is high in the sky, and therefore above us. This allows for a visual representation of the difficult growth and increase in energy required to move from Spring to Summer; whereas the decline in energy from Autumn onwards is depicted by a descent on the right-hand side of the diagram, which is*, in fact*, easier to perceive as a fall, a more rapid one. With reference to TCM, Lavier describes the *yang* ascending period *as anabolic* – i.e. linked to the laborious process of synthesising complex molecules – and the *yin* period as *catabolic*, i.e. the set of breakdown reactions that release energy. The symbols chosen to represent the five Chinese elements corroborate this orientation of the diagram: *wood* and *fire* are two *yang processes* that rise upwards, whilst heated *metal* and *yin water* flow downwards. Lavier, moreover, prefers to represent this temporal cycle not with a circle, but with a sort of distorted ellipse, with a 'bulge' in the South-West [10].

Point 4. In China, there is a fifth season: the *Central Season* between summer and autumn, which the Romans referred to as *the dog days*. What might seem like a minor difference from Greek thought is an essential element in understanding traditional Chinese thought. This consideration of a *central process* allows us to identify a ternary logic at various levels: at the level of the *wǔxíng* as a whole, we identify three periods: *yang-centre-yin*; but also, within each *yang* or *yin* period, we identify three phases of transformation: a time of initiation, then of fullness, and finally of completion.

It should be noted that this ternary structure – characteristic of *Chinese thought* [42] – corresponds analogously to the ternary structure highlighted in the isomorphism, with the polyhedral structural morphology (Fig. 4): geometric progression of polyhedra with 3, 4 or 5 edges for the solid angles, for the *yang* sequence; similarly for the faces in the *yin* sequence.

Let us emphasise this point: the isomorphism *between Platonic solids and the Wuxing* fully validates the choice of traditional Chinese thought to retain a fifth *season* – a central *process*. *The Earth element* serves as a link between the *Yang* and *Yin* periods*,* just as the Tetrahedron serves as *a link* between the two series of polyhedra. Each incorporates within itself the two opposing characteristics: *anabolic/catabolic* for the Chinese temporal system and face-triangle/angle–trihedron for the Greek spatial system. This dual affiliation of the *SG's central polarity* is fundamental to the remainder of this study.

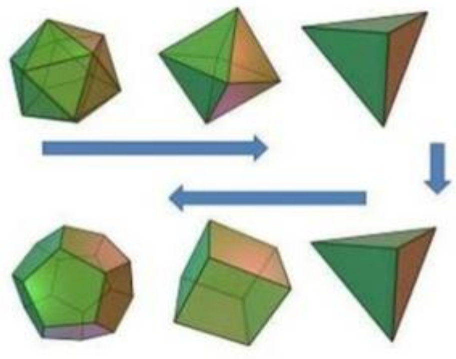


Fig. 4. *Presentation of the 5 Platonic solids following the geometric progression: 3, 4 and 5 edges for the solid angles in the top row and 5, 4 and 3 edges for the faces in the bottom row [43]*

Point 5. Finally, there is one last essential aspect that Lavier places particular emphasis on and that common conceptions fail to capture. The cycle of the wuxing – as *a system* that unfolds in space and time – is driven by a source of energy, which may be regarded as external to the system, yet which flows through it from within. To better understand this paradoxical phenomenon, let us note that in the cycle of the seasons, the *transition* from one season to the next (which corresponds to *the cycle of generation* of the *wuxing* [10]) normally unfolds *of its own accord*: once set in motion by its own momentum, Spring, when it reaches its fullness with time, transforms into Summer, just as Autumn transforms into Winter. However, the *transition* between Summer and Autumn or between Winter and Spring is a "re-energising moment". Much like in *the* ancient Greek *hoop game* – where the movement had to be restarted and maintained with a stick – at these two peak moments, the movement of the wuxing runs out of steam, and above all, changes direction. In the diagram representing the temporal cycle of the *wuxing*, Lavier expresses this external intervention by drawing a slanted line, sometimes double, at 45°. This dividing line in the diagram does not merely indicate that there are two periods, *yang* and *yin;* it also indicates a gap between these two peaks, a *space* traversed by an energy flow [13], which activates these two *passages* of different natures. Lavier calls the phenomenon corresponding to this central line the *'activating centre'.*

How can we understand the concept of *the activating centre*?

How can we understand that this energy of *the activating centre* is external and yet at the same time 'passes through' the wuxing system via the centre? The Chinese believe that we have several sources of energy that nourish our *vital principle* [41]. One of these is considered to come from Heaven and to pass through the being from top to bottom, via what the Chinese call the *central channel* or the *vital vessel* – the *extraordinary meridian Chong Mai*. This central *axis* is represented by the Chinese character wang 王 (king, emperor) [44] or by the pictogram of Mencius, which depicts a man between *Heaven* and *Earth* (an ideogram used by Lavier on the cover of his book *Chinese Medicine, Total Medicine* [10]) (Fig. 5).

In the representation of *the wuxing,* the two specific moments of transformation in the cycle driven by the *activating centre* – the two *passages* through the *activating centre* – are therefore situated on the diagonal separating the *yang* and *yin* periods, in the South-West and North-East (Fig. 2). Of these two specific *passages*, the *South-West Passage* (this notion of *passage* is taken here in reference to the subtitle of Serres' work *Hermès V* [45]) – is certainly the most paradoxical, for it is situated *on* the *Yang/Yin* boundary marked by the presence of a traversing energy flow, whilst simultaneously being the site of the *central* wuxing *process* involving the *earth* element – which corresponds to this 5th *Chinese season (*which does not exist within the framework of the *four elements* of Greek philosophy).

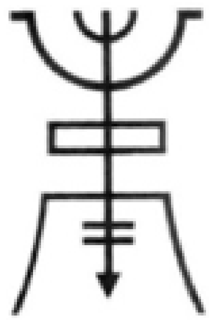


Fig. 5. *An ideogram attributed to Mencius, depicting a central axis specific to the upright human being, situated between Heaven and Earth*

Interpreting the CKT based on the principles of the GS

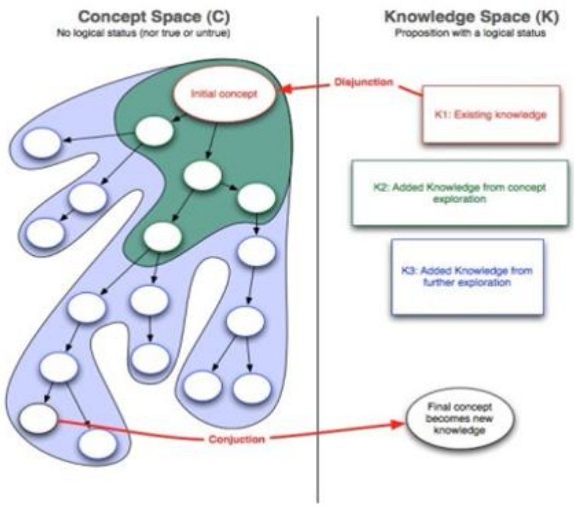


Fig. 6. *Original representation of the C-K Design Theory (Wikipedia)*

It was the similarity of the diagrams representing the *wuxing* and the CKT [8] that first led us to consider their *connection*, to hypothesise a possible *isomorphism* (Fig. 6). Whilst it may be difficult to demonstrate outright a perfect isomorphism between two such disparate systems [2], from a heuristic perspective, there is considerable scope for research in first hypothesising that an isomorphism may exist and then exploring all the consequences that follow from it.

Let us imagine that the CKT, like the *wuxing,* is another *version* of the GS and that it is possible to apply the *principles* of *the wuxing* to the CKT. This process of *transposition* can only be achieved by making a few modifications to Hatchuel and Weill's original diagram to align it with these new assumptions.

This is indeed a new *interpretation* of C-K Theory, just as it is possible to adapt a literary narrative for the cinema. Its value lies in putting the issues and functioning of this theory into perspective – other research teams are, in fact, working along these lines [46,47]. More broadly, this exercise of *"matching"* becomes a veritable testing ground for thought. It allows us to test the GS's functioning in a new context, revealing its as-yet-unexplored facets. It also enables us to envisage new points of reference in design theories for architects, engineers, and all those involved in project processes, as well as in philosophy, systems theory, epistemology…

The central driving force behind this argument – the *passage* – therefore consists in testing this reinterpretation of the CKT, based on the logic of the wuxing system and its *founding principles*. We will examine each initial choice made by the authors of the CKT diagram to verify whether they are consistent with the original intentions. In this way, we will be led to consider new interpretations of these intentions in relation to new challenges. Moving from the original diagram (Fig. 6) to the diagram we'll propose in the next figure is a good way to re-examine the five main principles of the wuxing presented in this third part.

Point 1. In the C-K diagram, the authors most often refer *to space* in the mathematical sense, but in fact, they are describing a *temporal* process. There is, therefore, a clear correspondence between space and time. Another question arises: in the K zone on the right, the CKT diagram is not 'closed off' by arrows, as is the case in any other system. This absence reflects the authors' intuition that there is a real difficulty in understanding how *the generation operator* functions in the *yin* zone of the *wuxing*. Moreover, Lavier has devoted a few pages in one of his works to answering this question [41]. Similarly, the authors identify three colours, and thus three essential polarities, in each C and K period of the cycle (the discussion in Point 4 will shed light on this aspect [8]).

Point 2. As in the *Wuxing*, the CKT diagram is clearly divided into two parts by a boundary. These two parts reflect two logics, two modes of thought organisation – cognitive processes – which are *antagonistic*. On the left of the diagram, the C section – for *Concept* – is conducive to the emergence of ideas or concepts in any order and without concern for their logical status or plausibility. On the right-hand side, the K section – for *Knowledge* – is a space where knowledge can be verified through logical reasoning, ultimately becoming part of the culture's existing body of knowledge, but by reorganising it. Rotating the C-K diagram 45° to the right does not alter the authors' two concepts, but before performing this rotation, let us move on to the following key point.

Point 3. We have seen that the most important thing for understanding the logic of the wuxing is that two major opposing movements express the activities of the human organism in harmony with its environment: first, anabolic, rising to the left, *yang*; then *catabolic*, descending to the right, *yin*. To be able to transpose this *antagonism* [48] to the CKT, we must retain the meaning of the two Greek roots *Ana* and *Kata*. We find these roots in the concepts of *analogue* and *catalogue*. The mode of knowledge expressed by the succession of frames in the K section illustrates quite directly the functioning of a *catalogue* that displays separate objects, perfectly known from the outset, whose presentation is observed from a vantage point. One might also imagine that the search phase in C is of a rather *analogical* nature in the broad sense; these are objects that appear through unpredictable associative mechanisms, without the need to follow any particular logic.

On the other hand, the prefix *'ana'* does indeed mean *'from the bottom up'* in Greek, whereas *'kata'* means *'from the top down*'. Moreover, given the first images that spring to mind when one looks at the left-hand side of the C-K diagram, it can be interpreted as a kind of seaweed or growing plant, as if a process were unfolding. Whereas on the right, the progression is more a matter of verification, of filing things away – once a new solution is found, it is added to the existing body of knowledge.

For both sides, common sense would therefore suggest that the graph should be inverted! This would accurately reflect, on the left, the difficulty of advancing in research by seeking new solutions, and a relative 'ease' on the right – even if reorganising knowledge based on new findings is not as straightforward as this suggests. Finally, if we directly apply the terms *'anabolic'* and *'catabolic'*, we are indeed dealing, on the left, with a process that synthesises new *complex* ideas and, on the right, with a process of destroying the established order of existing knowledge to organise a new order. Because of this renewal, the release of "innovative energies" often destroys the past: here we recognise J. Schumpeter's concept of *creative destruction* [49]. Finally, with this reversal, the direction of rotation of *the temporal system* described by the C-K path is restored: in the same direction as the sun's course across the sky and that of the hands of a clock!

In the 2024 article on the conditions for an isomorphism between GS and CKT, we proposed as a central hypothesis that the periods C and K – which might also correspond to Ricœur's *poetic-speculative* dichotomy – are associated with the two modes of thought identified by L. Vandermeersch as *Greek causal reason* and *Chinese correlative reason*. As he explains, the first is linked to a *temporal* cause-and-effect sequence within a given space; whereas the second is linked to a *spatial* cause-and-effect sequence at a given time (this second type of sequence is commonly referred to as *transmission by resonance*, as with a tuning fork). To avoid changing the name of the C-K diagram, we associate zone C with *Correlative Reason* and zone K with *Kausal Reason* (*causal* in German).

Point 4. Regarding the first three points, the principles organising the *wuxing* lead to simple changes in the orientation of the original diagram by the authors of the CKT, which implies no fundamental transformation. On the other hand, we know that the GS admits a fifth polarity, a *process central* to *the South-West Passage*: is it consistent to apply this principle to the CKT?

In the original C-K diagram, the term *'conjunction operator*' (borrowed from Guilford) is intended to express that there is a *transformation* between the last bubble in space C and the first in space K. But it is in fact the same object; it is simply our attitude – our perspective regarding this object of knowledge – that changes. There is, therefore, in fact, a shift in perspective, a *transition* [50] between what is *perhaps possible* for us, as participants in the research situation, and what becomes *knowledge* to be utilised. Indeed, Hatchuel and Weill likely intuit this, since they still represent it as a bubble within K, whereas rectangular frames characterise space K. We propose that this object be both a bubble and a rectangle and that it be situated on the *boundary*.

Point 5. The Hatchuel *boundary* is a single line, whereas in the GS, there is a double line representing a 'circulation', an 'internal energy flow' that crosses this boundary and feeds into the GS. In the 2024 article, we proposed a new representation without elaborating on this *point* (Fig. 7). What interests us here in this new version is to clarify how this *central process* operates within the framework of the C-K Theory, and more generally in any *research and development* process.

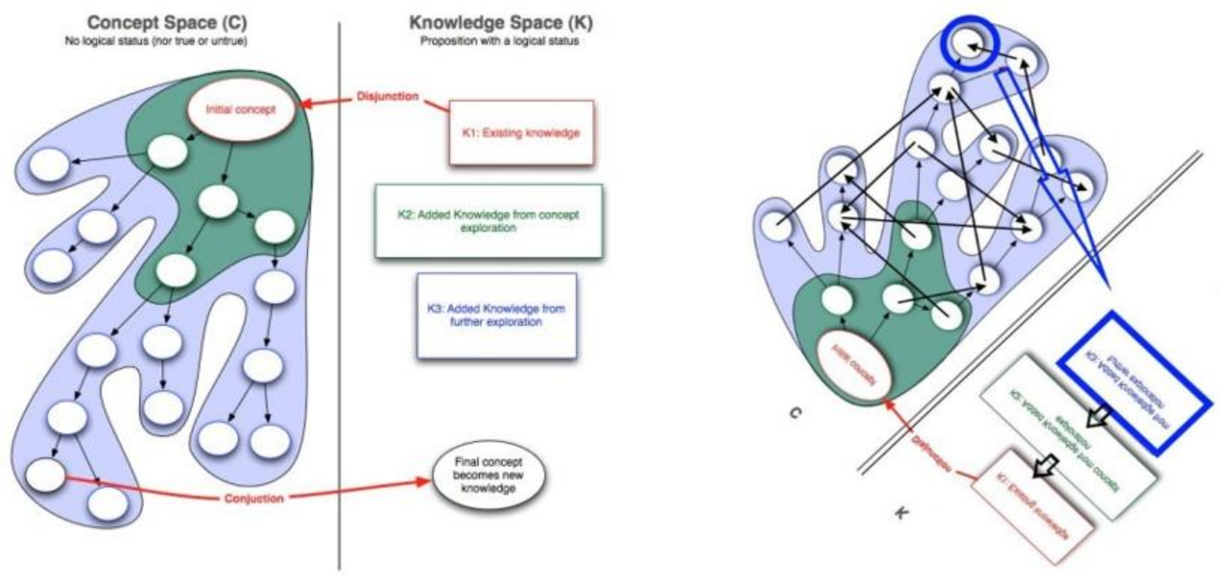


Fig. 7. *The original diagram on the left and the new interpretation of the C-K theory proposed in 2024 on the right [8]. The Concept/Knowledge Passage is not yet represented on the boundary of the activating centre (Personal illustration on the right)*

Between C and K: what *mechanism* enables the *South-West passage*?

In this new representation of the C-K theory, the main divergence from its authors therefore concerns *the conjunction operator*, from C to K – referred to as the *South-West passage* in the *Wuxing* representation. According to our hypothesis, it is thanks to the presence of a specific mechanism for establishing connections and simultaneously centrally reversing the GS's evolutionary dynamics that the passage can occur more easily; unlike the *North-East passage,* where nothing appears to assist *a priori* (this aspect will be the subject of further research). Thus, according to the properties deduced from the *wuxing*, this *South-West passage* is made possible because the central process of the CKT does indeed have a material status – although it lies on the boundary of *the activating centre* – but also because it belongs to both categories C and K at the same time.

To supplement the theoretical foundations of CKT, we propose, in the following section, to draw primarily on two outstanding works of research that have taken into account this distinctive feature *of the South-West Passage*. These are two books: **Archimedes' Cry** [17] by A. Koestler and **The Art of Bridges: Homo Pontifex** [18] by M. Serres. These approaches will then be enriched by J. de Rosnay's reflections on systems theory in **Le macroscope**.

Part Four: How can the *South-West Passage* be represented in a new interpretation of the *CKT*?

To take this investigation further, we must find works that describe a phenomenon akin to the South-West passage and can be integrated into the systemic logic of the CKT: studies that focus on the link between C and K. In order, I shall begin with A. Koestler, who has clearly identified this mechanism of *passage* and its dual affiliation.

A. Koestler's ***'bissociation'***

Koestler is an author who has shown an interest in *innovation* and *creativity*. However, in all creative processes and with a view to systematising a method of creativity, he focused his attention on the processes of transition, of shifting between two (a priori distinct) categories of understanding a statement regarding a phenomenon or a situation… Koestler associated this sudden shift in awareness with Archimedes' cry upon solving the problem of weighing King Hiero's crown, thereby discovering a scientific method. *Eureka* comes from the ancient Greek εὕρηκα (*heúrêka*), meaning 'I have found'.

To underpin and generalise his argument, he brought together three fields in which he hypothesises that there is an *unexpected and sudden shift* between two modes of understanding – and which therefore share a similar structure: the fields of humour, discovery and art:

On the frontispiece, the three panels of a rounded triptych represent three areas of creative activity with blurred boundaries: humour, discovery and art. The reason for this seemingly perverse arrangement – the Sage between the Jester and the Artist – will become clear as the discussion progresses.

Each of the horizontal lines in this triptych represents a pattern of creative activity that appears in the three columns; for example, the comic comparison, the objective analogy, and the poetic image. The first aims to make us laugh; the second to help us understand; the third to fill us with wonder. The logical approach of the creative process is the same in all three cases: it consists of discovering similarities. […] I shall endeavour to show that the types of creative activity are all three-fold: they can serve humour, discovery and art […] [17].

Our interpretation of this study by Koestler is that in all three cases, it involves a *'South-West' passage*: that is to say, a specific, lived experience enables a shift from one *associative context* to another: - whether in *jokes*, where wordplay amuses us when we grasp the *discrepancy (écart* in French*)* between the two registers of meaning; - but also in scientific research, which is broadly described by *serendipity* [51] as well as the notion of *a paradigm* shift in the sense used by T. Kuhn; - or even in artistic metaphor, one might cite Rimbaud's *'Le dormeur du val*'.

Here is how he explains this *passage* and why he calls it *'bissociation*':

It is the clash of these two associative contexts, of these two incompatible codes, that causes the tension to erupt. […] The framework of the two anecdotes is the perception of a situation or an idea L across two reference planes M1 and M2, each with its own internal logic but usually incompatible. One might say that the event L, the point of intersection of the two planes, vibrates on two wavelengths. As long as this unusual situation lasts, L is not simply linked to a single context of association; it is bissociated with two contexts.

If I use this term – 'bissociation' – it is to distinguish between routine reasoning, which operates, so to speak, on a single plane, and the creative act, which always operates […] on more than one plane. In the first case, thought would proceed in a single direction; in the second, it would be a transitional state of unstable equilibrium, divided between two directions, with the imbalance affecting both emotion and thought.

What is particularly interesting in Koestler's research is that he models this *transition* using geometry—the straight line as the intersection of two planes [17]—through a phenomenon, a statement: thus a material object that is the concrete intersection of two families, of two *contexts of association*.

As for *discovery*, i.e. the emergence of a solution from a given problem, the reference to *serendipity*, alongside the difficulty of understanding a play on words, shows just how much finding the connection with another frame of reference, another *family of associations,* relies on a certain prior cultural background and on the ability to *step outside the box*, to *shift perspective*, to *decontextualize (décoïncider* in French [52]). This is illustrated by J. Rouxel's caricature drawing often used to express the concept of serendipity: by depicting a Shadok (a cartoon character, Fig. 8) looking at a field of flowers through his glasses and declaring *"The real difficulty isn't so much finding ideas; it's knowing how to recognise a good idea when you see* one".

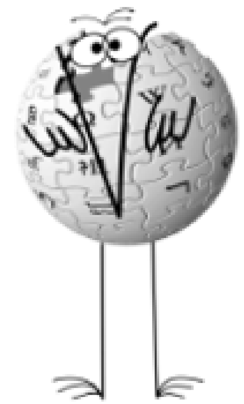


Fig. 8. *The caricature of a Shadok whose body has been replaced by the Wikipedia logo*

Whilst Koestler's model, through both its simplicity and its application to such diverse fields of knowledge, complements the CKT and clarifies the functioning of *the* South-West *passage*, it nevertheless fails to account for the final principle of the GS: the central process of the GS is situated on the boundary of the activating centre whilst at the same time leaving it unobstructed.

The concept of *the bridge* in Michel Serres's philosophical approach

There is only one French-language author – Michel Serres – who 'ticks all the boxes' in offering a coherent, synthetic representation that fosters a better understanding of this *South-West Passage* – and which will truly complement the CKT and thereby provide a better understanding of the GS.

Already in the collection of the five *Hermès* [45], Serres uses the concept of *passage* and introduces the *god of translation*. In **The Educated Third**, he draws on the concepts of *milieu* and interchange… In **Eclaircissements** [12], he emphasises the need to *cross over* and to seek a *theory of relations*. Finally, he elaborates on this metaphor of *the bridge* in his major work, which he regards as a work of synthesis: "*I have never dreamt of anything but bridges, written of nothing but them, thought of nothing but what lies above or below them; I have loved nothing but them. This book on bridges ends up as the book of all my books"* [18].

Serres did not know about *the General System* in the sense in which we develop it (thanks to the isomorphism of *the organons*). Still, he had an intuition of it. His conception of *the bridge* is not only an important contribution to a better understanding of the GS, but, one might even hypothesise, as he developed it, the *bridge*, through its central and strategic position, makes it possible to synthesise and symbolise [53] the entire *process* of the GS. What is truly interesting about this work is that it shows that the *bridge* unites everything whilst enabling a *conversion*, a *translation* between two foreign territories, two geographical-cultural families that, *a priori,* never meet; but that, at the same time, energy flows beneath this bridge and the surrounding activities benefit from this flow. He describes this *bridge* using two main theoretical models (which primarily illustrate the principle of union): first, the *hyphen*, and then the *white domino*:

From which beam, which stone, which concrete should bridges be built so that they may unite different shores? How can a single material—be it wood or iron—touch both right and left, France and Germany, earth and Paradise? The same mystery of simplicity lies in the hyphen […]. As a materialised hyphen, the bridge likewise unites differences. Across the Bosphorus, it short-circuits Europe and Asia. I do not know whether it converts, translates, transmutes or transubstantiates; the fact remains that its material, its substance—be it wood, stone or concrete—adapts to shores that have no connection [18].

For him, it is truly a physical structure that structurally provides two superimposed *passages*, whatever the context – the universal dimension of this function does not escape him. This is why he tries to envisage all manner of *situations of passage*, drawing on numerous metaphors: it is a matter of seeing the world through spectacles that illuminate only the phenomena of *connection, which short-circuits*:

Just as in the line linking two words, as in the deck bringing two banks together, I suspect the universal. […] Without a bridge, then, there is no path; by this I mean a connection from one point, such as this, to another, quite different. Without a bridge, then, there is no method; by this I mean a path from one to the other. (Passages underlined by us).

Serres sees in this *apparatus* — the *bridge* — that which encapsulates the very process of an intelligent and, above all, connecting life, which always proceeds by overcoming the difficulties that arise. It is also an optimistic philosophy: one can always *move* from a familiar family to an unfamiliar one; there is always the possibility of establishing a *passage* between what Koestler calls two *contexts of association*. However, this passage is made via a path that can be difficult, narrow, or even dangerous [*Hermès V*]. And this *bridge* must, of course, be sought out, and often even built, by selecting the most favourable banks, materials, forms, etc.

To understand the bridge, the hyphen and the method, I believe it is best to examine a white domino.[…] The hyphen, the bridge, plays the role of this white double which can, on one side, represent a digit or a number, the 5, for example, and, on the other end, represent a completely different one, for example, a 2. The double blank thus unites the 2 and the 5; it could just as easily link the 6 and the 3, any one to any other. This is the general equivalent; this is the universal token I was seeking. This equivalence permeates the hyphen, soft, and the bridge, hard, whose whiteness suggests a universal method.

Yet the word 'method' denotes a route that passes through, precisely a crossing. Starting from a familiar place, it leads to another, unknown one; it bridges the problem with its solution, knowledge with ignorance, research and invention. Through its crossing, the bridge, conversely, symbolises and realises a method. The same paradox of whiteness, the same universal simplicity, for the one, gentle, as for the other, hard. Both remain homogeneous, on either side, to the right and to the left, whilst they connect two unrelated places, one through signs or equations, and the other through cables, stones or concrete. They function as general equivalents of the relationship (Passages underlined by us)[18].

For Serres, constantly moving from the known to the unknown, from the past to the future, from difficulty to success, is to build bridges – to create passages in the South-West continually. Whether these crossings are material or conceptual, this is the human adventure: "*Building bridges in general becomes an activity so broad that it encompasses, perhaps, the human project, in that our body bridges flesh and word. Homo pontifex*."

Homo pontifex: man (and probably living beings too) is *a bridge-builder*, and whatever the context, this *bridging* always forms part of *the south-western passage* of a system that replicates the same structure as the GS.

Serres sometimes mixes the two types of *passage,* that of the South-West with that of the North-East (to which he often refers in *Hermès V* and in *Le tiers instruit*), but he is aware that these are the two *decisive* *passages* for human activity. It should be noted that even if there is an 'intermediate sequence' between these *passages*, these two moments are instances of renewal and reversal – ascent/descent, anabolic/catabolic – in the *wuxing* diagram as well as in the CKT.

Finally, what flows beneath these bridges is a significant energy for the surrounding activities, if only because it separates territories. It is this breach that establishes differences between regions, both geographical and cultural, and it is these *discrepancies (écarts)—these differentials—that drive* all that lives. From this separation created by the passage of *the activating centre* arises *the gap* that motivates the building of *bridges*: this type of human activity that Serres summarises with the adjective *pontic*. *Pontic* – derived from *bridge*, from *the* Latin *pons* – does not refer solely to the geographical sense – the Black Sea, known as the Pontus Euxinus – but takes on a metaphorical and philosophical meaning here. It denotes that which connects, that which facilitates passage between separate domains, that which enables one to cross obstacles. Throughout Serres's work, the aim is to create connections rather than divisions, to know how and where to link: maritime routes, continents, the sciences and the humanities, specialised and fragmented fields of knowledge…

Thus, the *pontic* is not only an ethics of knowledge; it is also a particular capacity of human intelligence that must be recognised – and even prioritised, particularly in higher education [37]. We hypothesise that this ability to *make connections* (the competence of *reliance* [54]) is just as important to cultivate as our cognitive ability to construct *logical* arguments. Thus, what characterises CKT is also this mode of *crossing through*, which requires a different kind of *reason* – the one that Serres highlighted, and which we shall call *Pontic reason*.

Therefore, to express that, on the global scale of the CKT, there is a third period of central articulation that allows *movement* from C to K, we propose replacing the initial hyphen in C-K with the letter P for 'Pontic' and thus calling it the CPK Theory (CPKT for short), the theory that unifies the three reasons: *Correlative, Pontic and Causal*.

We can therefore conclude that Mr Serres had a keen intuition regarding the *General System* and the importance of *the South-West passage*, which for him symbolised the concrete possibility of always connecting what our Western culture often leads us to separate, with the intention of over-defining. He had understood this central role – and one that is essential for co-knowledge – of *the bridge* as a two-level interchange, which, above, connects two territories and, below, allows the flow of *the* activating centre to remain unimpeded. Always knowing how to recognise where and how to build bridges to cross over: this sums up Mr Serres's true philosophy.

Looking up, I watch through the window the poplar swaying in the light breeze, bridging the celestial light and the mineral salts buried in the subsoil. To think of bridging is to contemplate the world in its detail and to unfold, within the whole, all the functions of the universe. All things form a bridge. Panta Pontes [18].

Part Five: The *architectural concept*, a *bridge*?

The concepts of *bissociation* and *the bridge* thus help to complete the puzzle of Hatchuel and Weill's CKT. There are certainly other pieces still missing, notably the *North-East passage*, but understanding this second passage would require further development. In this fifth and final part, we propose to consider how the transposition and adaptation of these philosophical reflections to the specific field of architecture allow us to explore them in greater depth and ultimately enrich our understanding of this new CPKT.

In architectural design, *adopting a design approach* means finding a *bridge*!

We hypothesise that what architects call '*making an architectural choice*' is precisely the act of discovering this *bridge* described by Mr Serres: a narrow passage that appears suddenly, sometimes difficult or even uncertain, but which triggers a *turning point* when the possibility of a *way out* finally becomes apparent! At that moment, one realises that amongst all the avenues explored – in every direction – there is a general organising principle that appears to be potentially more promising, more fruitful. Whether one refers to concepts of *scale* [16], *schema, operator,* or *target model* [55] to describe the various processes that led to this shift, whatever the vocabulary used, this glimpsed organising principle becomes predominant. One has the intuition that following it will lead to a general structuring of the project.

What is taken into account here, therefore, are not the design processes involved before or after this pivotal moment (in each of the C or K zones), but solely this moment P – as in *Pontic* but also as *in Parti* – where intention and, above all, commitment are reversed. There is indeed, in the *architectural Parti*, the idea from Old French of *'taking a parti'* (not to be confused with *'taking sides'*), that is to say, of making a decision, of committing oneself, amongst solutions that are all relevant, to a particular solution. This notion could be translated by the English word *'strategy'*. However, it is not a strategy decided upon *a priori*; it emerges through study (likely through observation of the situation's potential [56]) and imposes itself as the result of a maturing process. The P in CPKT, therefore, also represents a turning point, like when a curve forms an S: the attitude reverses when the *bridge* appears as *an opening* to *cross*.

Going *upstream* to cross over

To illustrate this shift in attitude, we shall expand on this idea using additional metaphors. Let us place the search for this *bridge* within the broader context of the research process. When outlining the principles that summarise the *wuxing*, we noted that the Chinese represent the *yang* aspect – the left side of the SG – as ascending. In the CPKT, as we have seen, it is also important to symbolically associate the *research* phase with an ascent and the *development* phase with a descent.

Let us imagine the following situation: during the conquest of the American West, whilst exploring unknown territories, a group of pioneers come upon a river. To cross this obstacle, they have two possible solutions: either they cross where they are, as best they can – by swimming or by building a raft (they will then have to climb onto the *deck* from a *pontoon* – the notion of *a bridge* is still present in this method of crossing). Or, it is preferable to go upstream until they find a place where the *crossing* is easier: either a natural *bridge* exists – a tree trunk or a ford… – or it can be easily constructed, as the river is narrower.

The image of this *search* is interesting because it highlights several aspects: firstly, the difficulty of searching for a possible *crossing* upstream, as this involves going upstream and therefore requires extra effort; and, of course, secondly, the relative ease of going downstream; moreover, in a partially known territory, which one has already glimpsed from the other side.

Finally, viewed from this angle, the concept of a bridge can summarise the entire CPK research process. From the outset, *the intention* to explore the unknown leads us to seek a way to cross and finally access this new territory. To summarise this journey, we can also refer to the Chinese bridge, known as *the moon bridge*. Not only does it resolve the following dilemma—it is very much a physical structure (at the centre of the border of *the south-western passage*) and is itself dual in nature, being both an ascent and a descent (Fig. 9)—but furthermore, when one crosses it, during the ascent, the view of the other bank is not immediately revealed. One only truly discovers the other bank during the central swing.

Fig. 9. *Moon Bridge in Yangzhou, Jiangsu Province: the 'synthesis bridge'*

A bridge or a mountain pass

It is difficult to conclude this argument – to shed light on the *Architectural Parti's* research – without noting the similarity between the two metaphors *of bridge* and *pass*. One might look ahead and seek, in the same way, a *pass* to cross from one valley to another: this is also a kind of *bridge* in rugged, hard-to-reach terrain. In this adventure, the *activating centre* is no longer water flowing downwards. Still, the energy of the mountains rising upwards (the *mountain-water* pairing, 山水, shān shuǐ, is, incidentally, essential in China for evoking the *landscape* [57]). One must try to get through – whilst staying as low as possible for many reasons: cold, terrain, oxygen, potential predators… The notion of *a pass* is therefore also the idea of *getting* through difficulties, through a narrow space, whilst trusting that on the other side of the mountain, the path down will also be 'welcoming'. But on the other side, which route leads to the neighbouring valley? Sometimes one will hesitate between different routes: sometimes one will be forced to turn back to try a more favourable path.

These images naturally resonate with the practices of architects and writers. Thus, M. Serres reflects on P. Mérimée's lesson in **Le Tiers–Instruit**:

By drawing networks of forks, Carmen teaches the Third-Educated to perfection, whilst also imparting a philosophy of creation. Whether one follows the course of a river or heads up the valley towards the mountains, one encounters as many confluences as one wishes. And to descend, one must choose: either you go right towards inscriptions and belles-lettres, or you turn left towards the narrative. But, at a certain moment—indeed, at every moment, since forks abound—the adventure remains in the third, in balance, in a common origin […].

The short story describes the <u>crossing of a threshold or a pass</u>: science ascends there, and the tale descends. Clear proof that <u>the spring gushes forth precisely at the crossing of the third bridge</u> […] [38].

To complete this image of *the architectural choice* as a *pass* – a *third place*, a narrow passage where *everything can pass through,* as Serres points out – and to conclude the process of *reliance (re-linking)* begun in this article, we propose to consider a metaphor by J. de Rosnay. To understand *the anatomy of his book*, the general organisation of **The Macroscope**, mirroring the approach he advocates and describes – *his medium* being also *his message* – he explains:

[…] this is the 'logical' approach. This book has the structure of a double cone. At the outset, we examine the structures and mechanisms common to many systems in nature; we observe.

We then move towards the tip of the cone; this is the general method that allows us to connect everything: the systemic approach. We then enter the second cone, focusing on the applications and the various representations, proposals, or suggestions that I submit for your consideration [37].

In this model (Fig. 10), all the information gathered from the first sheet of the cone of revolution *passes* through a point before being 'reversed'. This apex belongs to both sheets, but above all, this zero-dimensional point receives, contains, and enables the conversion and transposition of all information.

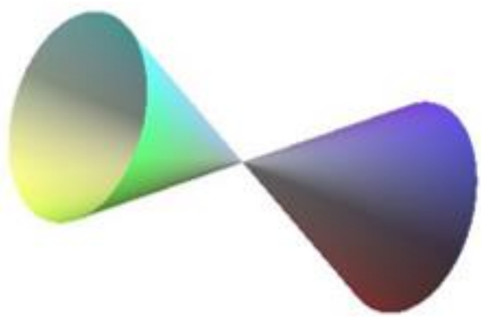


Fig. 10. *Cone of revolution with two sheets and a vertex (Mathcurve)*

It is, of course, difficult to *define* this *centre*: can we speak of a symbolic place, a seed that will germinate and enable a birth, followed by the *project's development*? - The preceding phase being gestation – *research* within this overall process *of research-apex-development*?

In this image (this symbol?), one can also observe that all the information necessary for the project's future is already present in the initial form of the *cone's generating curve*: the research can continue almost of its own accord, with the passage of time. One need only let the cone narrow; then close until it inverts, and *expand* thereafter. Rosnay added an arrow symbolising the direction of time to the cone drawing: can this be considered the *system's activating centre*?

Conclusion: the ***nexialist*** architect, a specialist in pontic reason

If we assume that this metaphor by J. de Rosnay can be applied to architectural design, this *cone's apex* can also encapsulate the idea of *the design concept* – synthetic, yet indefinable: a dimensionless point which, like a seed, paradoxically contains the entire sequence of *temporal development* that precedes and will follow; and which centralises all *spatial relationships*.

However, to designate the point where the most important part of a problem lies, in French we use the metaphorical notion of *a 'node',* for which we find the following meanings in Latin: *Nexus* signifies *sequence*, *intertwining* and/or *link*, *knot*, *embrace*[1].

These properties likely led Alfred Elton van Vogt to write a novel – **The Voyage of the Space Beagle** [58] – in which the main character is familiar with the science of *nexialism*. In the distant future, aboard an exploratory spaceship, a scientist, Elliott Grosvenor, opposes the various heads of specialist departments – academics or engineers – who hold power but are incapable of acting effectively in the face of complex problems. Grosvenor's training could be described as that of *a 'super-generalist*': "*At the Nexialist Institute, we are taught that behind the general principles of every science, there is an inextricable link between that science and all the others*."

Just as Rosnay confuses the *centre* of his *book's system* – the apex of the cone – with the potential summary of all the unfolding processes of *systems theory*, van Vogt evokes this *transdisciplinary science*, this integration of all knowledge, with the metaphor of *the node*, the meeting point of all sciences – *Rosnay's cone* could even become the emblem of nexialism!

But has Serres not developed this transdisciplinary science that A.E. van Vogt heralds throughout his life? Nexialists are specialists in *building bridges* between scientific theories. Through his various works, Serres has developed bridging reasoning not only between the sciences but also with the humanities, including literature...

Ultimately, might we not regard this book - Serres's testament, summed up by these two words, *Homo pontifex* - as the handbook of *nexialism* and, more broadly, of *designers*? All professions involved in *design* in one way or another are led to seek out and build *bridges* to articulate *ecosystems* [59] that are often foreign or even *antagonistic*. For architects, *architecture* can be conceived as a *bridge* between habitation and territory, and architectural design itself as a succession of *bridges* between the search for ideas and their implementation, the testing with models.

In conclusion, we approach the genesis of an architectural *project* with this distinction in mind among the three main stages of *the design process*: *Correlative, Pontic, and Causal (CPK),* with, of course, educational programmes tailored to these three phases in schools. Are architects not in the same position as E. Grosvenor, super-generalists capable of applying a transdisciplinary approach to make decisions that *bridge* and interact with increasingly complex environments? Among these three major 'modes' of *reason*, are architects not, above all, specialists in *pontic reason*: *archi pontifex*?

Conflict of Interest

The authors declare no conflicts of interest.

Funding

This research did not receive any financial support.

References

[1]. S. Monnot, Entre raisonnement et résonance: Proposition d'intelligibilité pour un habiter à la croisée des 5 éléments chinois et des 5 corps platoniciens. PhD thesis, Univ. Lumière Lyon 2, 2023.
[2]. A. Rapoport, The Uses of Mathematical Isomorphism in GST, in: G.J. Klir (ed.), Trends in General Systems Theory. Wiley, New York, 1972, 42-77.
[3]. D. Pouvreau, Une histoire de la "systémologie générale" de Ludwig von Bertalanffy -Généalogie, genèse, actualisation et postérité d'un projet herméneutique. Doctoral thesis. Thesis, École des Hautes Études en Sciences Sociales -Centre Alexandre Koyré, Aubervilliers, 2013.
[4]. P. Boudon, P. Deshayes, F. Pousin, F. Schatz, Enseigner la conception architecturale: Cours d'architecturologie (2e éd.). Ed. de la Villette, 2001.

[1] Dictionnaire Gaffiot latin-français, 1934.

[5]. L. von Bertalanffy, Théorie générale des systèmes. Dunod, Paris, 1973.
[6]. A. Hatchuel, P. Le Masson, B. Weil, Théorie, méthodes et organisations de la conception. Presses des Mines, Paris, 2014.
[7]. D. Sisk, J.P. Guilford, A Pioneer in Modern Creativity Research, in: F. Reisman (ed.), Celebrating Giants and Trailblazers: A-Z of Who’s Who in Creativity Research and Related Fields. KIE Creativity Book Series, 2025.
[8]. S. Monnot, General System and C-K Theory: How Can Design Processes Be Represented? Journal of Architectural and Engineering Research (Special issue), 2025, 52-65. Doi: https://doi.org/10.54338/27382656-2025.si.1-06
[9]. A. Cheng, Histoire de la pensée chinoise. Seuil, Paris, 1997.
[10]. J.A. Lavier, Médicine Chinoise, Médicine totale. Grasset et Fasquelle, Paris, 1973.
[11]. L. Vandermeersch, Les deux raisons de la pensée chinoise: Divination et idéographie. Gallimard, Paris, 2013.
[12]. M. Serres, Éclaircissements, Five Interviews with Bruno Latour. François Bourin, Paris, 1992.
[13]. F. Jullien, L’écart et l’entre, Leçon inaugurale de la Chaire sur l’altérité. Galilée, 2012.
[14]. P. Ricœur, La métaphore vive. Seuil, 1975.
[15]. M. Black, Models and metaphors, Cornel University Press, 1962.
[16]. P. Boudon, P. Deshayes, E. Falk, H. Graille, J.-P. Perrin, F. Schatzet, Architecture et architecturologie. L’idée de l’architecture (Rapport de recherche) 192/83, Ministère de l’urbanisme et du logement - SRA; CEMPA, 1983, hal-01886900.
[17]. A. Koestler, Le cri d'Archimède (Trad. de The Act of Creation). Calmann-Lévy, 1965.
[18]. M. Serres, L'art des ponts, Homo pontifex. Le Pommier, Paris, 2006.
[19]. S. Monnot, La conception architecturale dans l'Ecart entre les solides platoniques et le Wuxing. Proceedings of the 10th International Conference on Contemporary Problems in Architecture and Construction. Beijing, China, September 22-24, 2018.
[20]. S. Monnot, Proposition d'intelligibilité pour habiter le carrefour des cinq éléments chinois et des cinq solides platoniques - entre raisonnement et résonance. Journal of Architectural and Engineering Research, 6, 2024, 56-70. Doi: https://doi.org/10.54338/27382656-2024.6-007
[21]. G.J. Klir, The polyphonic General System Theory, in: G.J. Klir (ed.), Trends in general system theory, 1972. Wiley, New York, 1-18.
[22]. R. Rosen, Old Trends and New Trends in General System Research, International Journal of General Systems, 5 (3173), 1979.
[23]. R. Rosen, Modelling: an algebraic perspective, in: J.D. White (ed.), The general systems paradigm: science of change and change of science. Proceedings of the annual North American meeting (S.G.S.R.), 1977.
[24]. S. Monnot, S. Dermarsoubian Monnot, Un centre de recherches en bio-énergétique, Diplôme d'architecture de l'Ensal, Lyon, France, 1990.
[25]. M. Granet, La pensée chinoise, Albin Michel, Paris, 1999.
[26]. M. Porkert, Theoretical Foundations of Chinese Medicine: Systems of Correspondence. MIT Press, Massachusetts, 1974.
[27]. F. Jullien, La Propension des choses. Pour une histoire de l’efficacité en Chine. Seuil, 1992.
[28]. Platon, Sophiste, Politique, Philèbe, Timée, Critias. Trad. et notes par E. Chambry. Garnier Flammarion, 1969.
[29]. M.S. Morgan, M. Morrison, Models as Mediators. Cambridge University Press, 1999.
[30]. J. Kepler, Mysterium Cosmographicum. Trad. A.P. Segonds, Le secret du monde. Gallimard, 1993.
[31]. D. Sun, S. Schein, Keplerian nest of polyhedral structures in different symmetry groups. Physical Sciences, 2020.
[32]. M. Serres, Hermès I, La communication. Éditions de Minuit, Paris, 1969.
[33]. M. Serres, Hermès IV, La distribution. Éditions de Minuit, 1977.
[34]. C. Canullo, La traduction entre métaphore et vérité. Université de Macerata, Italie, 2013.
[35]. J.P. Juignet, État actuel de la théorie des systèmes. Philosophie, science et société, 2015. Available at: https://shorturl.at/sYArk. Accessed on August 12, 2026.
[36]. T. Ingold, Correspondences. Polity Press, 2020.
[37]. J. de Rosnay, Le macroscope, vers une vision globale. Éditions du Seuil, 1975.
[38]. M. Serres, Le Tiers-instruit. François Bourin, 1991.
[39]. T. Khun, La structure des révolutions scientifiques. Flammarion, 1983.

[40]. C. Feng, La cosmologie de la médecine chinoise: Les cinq cycles et les six souffles - selon les Sept Grands Traités du Suwen du Huangdi Neijing. Thèse de doctorat sous la direction de Marc Kalinowski. Soutenue en 2003 à Paris, EPHE, en partenariat avec École pratique des hautes études (Paris). Section des sciences religieuses. CreateSpace Independent Publishing Platform, 2003.
[41]. J.A. Lavier, Bio-énergétique chinoise. Maloine, Paris, 1976.
[42]. A.Ch. Pengyu. Traducer de First Research Results on Warring States Bamboo Strips Collected by Tsinghua University Released. Tsinghua University. Available at: https://surl.li/fawufk. Accessed on August 04, 2026.
[43]. D. Néroman, La Leçon de Platon. I.- La musique clé du monde. II.- L'homme et le Ciel. Arma Artis, 1989.
[44]. S.J. Wieger, Caractères chinois (8e éd.). Kuangchi Press, 1972.
[45]. M. Serres, Hermès V, Le passage Nord-Ouest. Éditions de Minuit, 1980.
[46]. A. Ullah, R. Mamunur, J. Tamaki, On some unique features of C–K theory of design. CIRP Journal of Manufacturing Science and Technology, 5 (1), 2012, 55-66.
Doi: https://doi.org/10.1016/j.cirpj.2011.09.001
[47]. A.O. Kazakçı, A. Tsoukias, Extending the C-K Design Theory to Provide Theoretical Background for Personal Design Assistants. International Design Conference - Design 2004, Dubrovnik, May 18 - 21, 2004. Available at: https://surl.li/ekiqwf. Accessed on August 04, 2026.
[48]. S. Lupasco, Le principe d'antagonisme et la logique de l'énergie - Prolégomènes à une science de la contradiction. Le Rocher (2e éd.), Monaco, 1987.
[49]. J. Schumpeter, Les cycles des affaires, Business Cycles: A Theoretical, Historical and Statistical Analysis of the Capitalist Process. New York, Toronto, and London: McGraw-Hill Book Company, 1939.
[50]. F. Jullien, Ce point obscur d'où tout a basculé. L'observatoire, 2021.
[51]. S. Catellin, Sérendipité. Du conte au concept. Seuil, Paris, 2014.
[52]. F. Jullien, Dé-coïncidence. D'où viennent l'art et l'existence? Grasset, 2017.
[53]. J. Chevalier, A. Gheerbrant, Dictionnaire des symboles (4 v.). Seghers et Jupiter, 1973.
[54]. M. Bolle De Bal, Reliance, déliance, liance: émergence de trois notions sociologiques. Sociétés, 2 (80), 2003, 99-131. Available at: https://surl.li/ikwmwx. Accessed on August 08, 2026.
[55]. D. Raynaud, Le schème: opérateur de la conception architecturale. Intellectica, 2 (29), 1999, 35-69.
[56]. F. Jullien, Traité de l'efficacité. Grasset, 1997.
[57]. F. Jullien, Vivre de paysage ou L'impensé de la Raison. Gallimard, 2014.
[58]. A.E. Van Vogt, La faune de l'espace (The Voyage of the Space Beagle). J'ai lu, 1952.
[59]. A.J. Willis, The ecosystem: an evolving concept viewed historically. Functional Ecology, 11, 1997, 268-271.

Serge Monnot, Doctor of Philosophy (PhD) in Architecture *(France, Lyon) – UMR CNRS 5600 Laboratory "Environment, City, Society" (Environnement, Ville, Société) – LAURe unit, Associate Researcher at the National School of Architecture of Lyon, serge.monnot@lyon.archi.fr*

Suzanne Monnot, Architect, Holder of a Master's degree in Philosophy, Researcher *(France, Lyon) – UMR CNRS 5600 laboratory "Environment, City, Society" (Environnement, Ville, Société) – LAURe unit, Associate Professor at the National School of Architecture of Lyon (ExCo Master's Study Area), suzanne.monnot@lyon.archi.fr*

ADDRESS : Str.Teryan 105, Yerevan
☏: (+37410) 54 74 12
URL : https://www.jaer.nuaca.am/