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REVIEW ARTICLE

DIGITAL TECHNOLOGIES IN SEMIOTIC MODELING OF ALMATY'S PUBLIC SPACES

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Abstract. *Urban digitalization requires not only geometric and functional modeling, but also a systematic interpretation of the symbolic and perceptual meanings embedded in public space. This review article examines how digital technologies can support the semiotic modeling of Almaty's public spaces and proposes an integrated analytical framework for research and design. The study combines a review of national and international publications with a case-based analysis of key public spaces in Almaty using GIS and BIM materials, field observations, photo documentation, and comparative semiotic coding of architectural and digital elements. A symbolic-semantic consistency coefficient k is introduced as a comparative indicator for assessing the alignment between the spatial image, local cultural codes, and digital interventions; the coefficient is used for relative comparison of cases rather than as an absolute metric. The results identify typical gaps in current practice, including fragmented data, weak coordination between design stages, and insufficient interpretation of local identity, and demonstrate how GIS/BIM models, digital twins, and immersive visualization tools can be integrated into a unified semiotic analysis workflow. The proposed approach can improve design decisions, preserve place identity, and support the sustainable development and management of public spaces in Almaty.*

Keywords: *semiotic modeling; public spaces; Almaty; digital technologies; BIM; GIS analysis; digital twins; AR/VR visualization; symbolic-semantic coding*

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ШОЛУ МАҚАЛАСЫ

АЛМАТЫ ҚОҒАМДЫҚ КЕҢІСТІКТЕРІНІҢ СЕМИОТИКАЛЫҚ МОДЕЛЬДЕУІНДЕГІ ЦИФРЛЫҚ ТЕХНОЛОГИЯЛАР

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Аңдатпа. *Қалалық ортаны цифрландыру қоғамдық кеңістіктерді тек геометриялық және функционалдық тұрғыдан модельдеуді ғана емес, сонымен бірге олардың символдық және қабылдаулық мағыналарын жүйелі талдауды талап етеді. Бұл шолу мақаласында Алматының қоғамдық кеңістіктерін семиотикалық модельдеуде цифрлық технологияларды қолдану мүмкіндіктері қарастырылып, зерттеу мен жобалауға арналған интеграцияланған талдамалық тәсіл ұсынылады. Зерттеу отандық және шетелдік ғылыми жарияланымдарды шолуды, сондай-ақ Алматының негізгі қоғамдық кеңістіктерін GIS және BIM материалдары, далалық бақылаулар, фотофиксация және сәулеттік әрі цифрлық элементтерді салыстырмалы семиотикалық кодтау негізінде кейстік талдауды қамтиды. Кеңістіктік бейне, жергілікті мәдени кодтар және цифрлық интервенциялар арасындағы сәйкестікті бағалау үшін символдық-мағыналық келісімділіктің k коэффициенті салыстырмалы көрсеткіш ретінде енгізілді; бұл коэффициент абсолюттік өлшем емес, кейстерді өзара салыстыру үшін қолданылады. Нәтижелер қазіргі тәжірибедегі негізгі шектеулерді (деректердің фрагменттелуі, жобалау кезеңдерінің әлсіз үйлесуі және жергілікті бірегейлікті жеткіліксіз интерпретациялау) айқындап, GIS/BIM модельдерін, цифрлық егіздерді және иммерсивті визуализация құралдарын бірыңғай семиотикалық талдау үдерісіне біріктіру мүмкіндігін көрсетеді. Ұсынылған тәсіл жобалық шешімдердің сапасын арттыруға, орынның бірегейлігін сақтауға және Алматының қоғамдық кеңістіктерін тұрақты дамыту мен басқаруға қолданылуы мүмкін.*

Түйін сөздер: *семиотикалық модельдеу; қоғамдық кеңістіктер; Алматы; цифрлық технологиялар; BIM; GIS-талдау; цифрлық егіздер; AR/VR визуализациясы; символдық-мағыналық кодтау*

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ОБЗОРНАЯ СТАТЬЯ

ЦИФРОВЫЕ ТЕХНОЛОГИИ В СЕМИОТИЧЕСКОМ МОДЕЛИРОВАНИИ ОБЩЕСТВЕННЫХ ПРОСТРАНСТВ АЛМАТЫ

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Аннотация. *Цифровизация городской среды требует не только геометрического и функционального моделирования общественных пространств, но и системного анализа их символических и перцептивных значений. В настоящей обзорной статье рассматриваются возможности применения цифровых технологий в семиотическом моделировании общественных пространств Алматы и предлагается интегрированный аналитический подход для исследований и проектирования. Исследование сочетает обзор отечественных и зарубежных публикаций с кейс-анализом ключевых общественных пространств Алматы на основе GIS- и BIM-материалов, полевых наблюдений, фотофиксации и сравнительного семиотического кодирования архитектурных и цифровых элементов. Для оценки согласованности пространственного образа, локальных культурных кодов и цифровых интервенций введен коэффициент символико-семантической согласованности k как сравнительный индикатор; коэффициент используется для относительного сопоставления кейсов и не рассматривается как абсолютная метрика. Результаты выявили основные ограничения текущей практики (фрагментарность данных, слабая координация между стадиями проектирования и недостаточная интерпретация локальной идентичности) и показали возможность интеграции GIS/BIM-моделей, цифровых двойников и средств иммерсивной визуализации в единый контур семиотического анализа. Предложенный подход может использоваться для повышения качества проектных решений, сохранения идентичности места и поддержки устойчивого развития и управления общественными пространствами Алматы.*

Ключевые слова: *семиотическое моделирование; общественные пространства; Алматы; цифровые технологии; BIM; GIS-анализ; цифровые двойники; AR/VR-визуализация; символико-семантическое кодирование*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

During the preparation of this manuscript, the authors used artificial intelligence tools (ChatGPT) solely for editorial assistance, such as improving phrasing and checking grammar, spelling, and punctuation. All ideas, interpretations, and conclusions are the responsibility of the authors, who take full accountability for the content of the article.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу жеке қаржыландыру көздерін пайдалана отырып жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

Мақаланы дайындау барысында авторлар жасанды интеллект құралдарын (ChatGPT) тек редакциялық көмек мақсатында пайдаланды: тұжырымдарды жетілдіру, грамматикалық, орфографиялық және тыныс белгілеріндегі қателерді тексеру үшін. Барлық идеялар, интерпретациялар мен қорытындылар авторларға тиесілі, және олар мақаланың мазмұнына толық жауапты.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось с использованием частных источников финансирования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

При подготовке рукописи авторы использовали инструменты искусственного интеллекта (ChatGPT) исключительно для редакторской поддержки: корректировки формулировок, проверки грамматических, орфографических и пунктуационных ошибок. Все идеи, интерпретации и выводы принадлежат авторам, которые несут полную ответственность за содержание статьи.

1 INTRODUCTION

In recent decades, the digital transformation of architectural design has become a defining factor in the development of the urban environment. Information technologies not only alter the methods of visualizing and coordinating design processes, but also shape a new mode of thinking in which architecture is regarded as a dynamic system of meanings and data. Modern cities are increasingly perceived as complex codes, in which physical forms, visual images, and digital interfaces together constitute a unified semiotic structure **(Castells M., 2010)**

Since the mid-twentieth century, the scientific foundation of architectural semiotics has been established - ranging from the ideas of Kevin Lynch and Umberto Eco regarding the "language of the city" to the works of Robert Venturi and Charles Jencks, who viewed the building as a carrier of multilayered meanings **(Lynch K., 1960; Eco U., 1980; Jencks C., 1977; Venturi R., 1972).** In the postmodern period, this field evolved toward the understanding of architecture as a system of cultural and visual codes **(I. Ostapenko, K. Bekturganova, D. Dyussenova, R. Chekaeva, A. Yessenbayev, 2025)**, and in the digital age, toward the conception of architecture as an interface that facilitates communication between the individual and the city **(Schumacher P., 2020).**

Today, the concept of digital architecture extends beyond visual modeling. BIM (Building Information Modeling) and GIS (Geographic Information Systems) technologies enable not only the reproduction of the morphology of objects, but also the integration of layers of semantic and social data **(Muktiono, A. 2024)**. The development of AR/VR technologies is generating a new "superstructure" over the urban environment, where digital information becomes an integral component of the perception and identity of place **(Azuma, R., 2019).**

In the Kazakhstani context, architectural digitization is accompanied by a search for cultural identity and a re-examination of the legacy of both Soviet and national morphologies **(G. Abdrassilova, E. Danibekova, G. Adilbay, A. Tuyakayeva 2025; G. Abdrassilova, E. Danibekova, A. Tuyakayeva, A. Syzdykova., 2024)**. The works of I.I. Ostapenko and E.A. Lapshina emphasize the importance of semiotic analysis for understanding the architecture of Kazakhstan as a multilayered cultural and informational system codes **(I. Ostapenko, K. Bekturganova, D. Dyussenova, R. Chekaeva, A. Yessenbayev, 2025)**. The studies of A. R. Tengizbayeva and D. B. Mukhamedzhanova reveal the potential of digital modeling for managing the urban environment of Almaty while the works of K. Murzabayeva demonstrate that digitalization should be integrated with cultural continuity and contextual perception **(A.E. Kozhakhmetov, A.Z. Abilov, A.S. Seidakhmetova, 2023; J. Imankulov, 2024)**.

Recent studies show that digital modeling can not only reflect but also generate new architectural meanings.

The methodological contribution of this research is the proposal of an exploratory coefficient of symbolic coherence (k) for the comparative assessment of the relationship between cultural-semiotic and digital components of architectural space within BIM/GIS-based representations **(A. Elsheikh, Hadeal H. Alzamili, Sora K. Al-zayadi, Ali S. Alboo-hassan, 2020; J. Schiewe, A. Krek, I. Peters, H. Sternberg and K. Traub, 2008).** The coefficient is used in this article as an operational indicator for case comparison rather than as a universal substitute for full sociological or perceptual measurement. This approach forms the basis of the present study devoted to the digital-semiotic modeling of public spaces in Almaty.

The objective of this work is to develop and test a methodology for the digital-semiotic analysis of public spaces, enabling a comparative quantitative assessment of the degree of coherence between cultural codes and digital elements within the urban environment **(Nurbatsin, A., Kireyeva, A., Gamidullaeva, L., & Abdykadyr T., 2024).** In domestic architectural scholarship, this article positions itself as a methodological attempt to integrate semiotic and digital analysis into a unified system of indicators for the case of Almaty.

The practical significance of this work is that the results obtained may be used in the development of digital reconstruction projects and interactive public spaces in Almaty, as well as in edu-

cational courses on BIM design and the semiotics of architecture **(U. Fitrawan, K. Iwan, W. Haryo, 2024).**

Thus, digitalization in architecture constitutes not only a technological process but also a cultural transformation, altering the modalities of perceiving and transmitting meanings. Understanding this process necessitates the integration of semiotic methods, digital analysis, and spatial modeling, which collectively determine the structure of the subsequent research **(Norberg-Schulz C., 1980).**

Contemporary architecture is experiencing profound transformations driven by the integration of digital technologies into the processes of design, analysis, and interpretation of the urban environment. Whereas in the mid-twentieth century the focus of architectural theory was placed on composition and form, today attention is shifting towards information, interaction, and meaning. In this context, architecture is understood not only as the material embodiment of ideas, but also as a mediator between physical and digital space (**Schumacher P., 2020).**

The theoretical framework of digital semiotics was established by the works of K. Lynch and K. Norberg-Schulz, who were the first to interpret the city as the "language of space" **(Norberg-Schulz C., 1980; Lynch K., 1960)**. They demonstrated that the perception of the architectural environment is founded on visual and semantic reference points that shape the cognitive map of the city. U. Eco and Ch. Jencks expanded this concept by introducing the notion of architecture as a sign system, wherein each element - from the facade to the planning structure - carries semantic significance and is capable of transmitting a cultural code **(Eco U., 1980; Jencks C., 1977)**.

The transition to the digital age has made possible the quantitative analysis of architectural meanings. B. Kolarevic and K. Kensek consider BIM and GIS not only as tools for automation, but also as platforms for storing and interpreting data related to context, perception, and identity **(Kolarevic B.,2013; Kensek, K., Noble D., 2015)**. These technologies enable the integration of geometry and semantics into a unified model, which is particularly important in the study of public spaces **(A.V. Mukhacheva, M.N. Ugryumova, I.S. Morozova, & M.Yu. Mukhachyev, 2021).**

Recent research demonstrates that the development of AR/VR environments and machine-vision algorithms establishes a new level of architectural analysis in which spatial data become interactive and adaptive **(Azuma R., 2019; B.E. Sönmez., D.E. Önder, 2019)**. As a result, architecture ceases to be static and comes to be perceived as a living structure responsive to user behavior **(A. İbiş., N. Cakici Alp, 2023)**.

In Kazakhstan and the countries of Central Asia, architectural digitization is undergoing a phase of cultural adaptation. The studies of Ostapenko examine the architecture of Kazakhstan as a multilayered semiotic system in which traditional ornaments and symbols are integrated into modern digital forms **(I. Ostapenko, K. Bekturganova, D. Dyussenova, R. Chekaeva, A. Yessenbayev, 2025)**. Lapshina and Sainova regard the process of digital modeling as the foundation for a comprehensive analysis of the urban environment **(Y.V. Bushmakina, P.A. Balyberdina, M.K. Dmitrieva, M.V. Gogoleva, 2017)**, while Tengizbayeva identifies the interconnection between digital tools and spatial management strategies in Almaty **(Zh.Nurbekova, B. Nurbekov, 2023).**

Studies by K. Murzabayeva underscore the necessity of preserving cultural codes in the process of digitalization. The author observes that technological modernization without semiotic analysis leads to a "rupture of meanings," resulting in the loss of local identity and the visual continuity of the urban environment **(A.E. Kozhakhmetov, A.Z. Abilov, A.S. Seidakhmetova, 2023).**

Meanwhile, there is increasing interest in global practice in hybrid methodologies that combine digital modeling, perception analysis, and semiotic interpretation **(Benis, K., Reinhart, C., & Ferrão, P., 2018; Kalantari, F., Tahir, O. M., Joni, R. A., & Fatemi, E., 2019)**. These approaches demonstrate that architectural digitization can be not only a tool for rationalization, but also a means of preserving cultural meanings **(A.Melnychuk., O. Gnatiuk, 2019).**

A review of the literature shows that, in domestic architectural scholarship, there is still no unified methodology that integrates digital and semiotic methods of analysis. Existing research focuses either on engineering or on cultural aspects, while their integration remains an unresolved challenge **(Nurbatsin, A., Kireyeva, A., Gamidullaeva, L., & Abdykadyr T., 2024; A. Nur-**

batsin, 2025). This study seeks to address this gap and to develop an approach that enables the evaluation of the interrelationship between the cultural and digital layers of the architectural environment, using the public spaces of Almaty as an example.

2 MATERIALS AND METHODS

The methodological framework of this research is grounded in an interdisciplinary synthesis of architectural analysis, semiotics, and digital modeling. This approach allows the urban environment to be viewed not only as an aggregate of physical objects, but also as a multilayered cultural and informational system, wherein digital technologies become instruments for recording, analyzing, and transmitting meanings.

The structure of the interaction among the cultural, symbolic, and digital levels of analysis is presented in **Figure 1.**

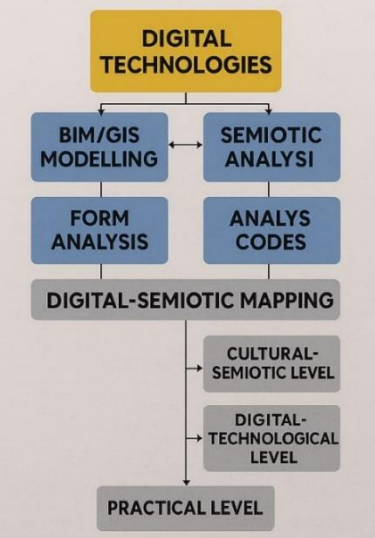

Figure 1 – Methodological scheme of digital-semiotic analysis of the urban environment (authors' material)

This study adopts an analytical and interpretive approach aimed at identifying patterns in the integration of digital technologies into the semiotic modeling of public spaces in Almaty. The empirical basis of the article includes open-access 3D models, cartographic and GIS materials, published visual documentation, and the results of digital mapping and comparative visual observation. The study is therefore case-based and exploratory: it demonstrates a reproducible analytical procedure using openly available materials rather than a full municipal digital twin dataset **(Y.V. Bushmakina, P.A. Balyberdina, M.K. Dmitrieva and M.V. Gogoleva, 2017)**.

The principal objects of study were three representative urban spaces: Panfilov Street, Abay Square, and the Esentai Riverwalk embankment. Their selection was based on differences in morphology, functional specificity, and degree of digital saturation, which enabled a comparison between traditional and innovative modes of perceiving the urban environment **(A.E. Kozhakhmetov, A.Z. Abilov, A.S. Seidakhmetova, 2023)**.

The following methods were applied in the analysis:

– Semiotic analysis, aimed at identifying cultural codes and symbolic elements embedded within architectural forms **(Mustafa Aziz Amen, Hourakhsh Ahmad, 2021);**

– BIM/GIS modeling, which ensures spatial visualization of semiotic structures and documentation of digital elements in the urban environment **(Asser Elsheikh, Hadeal H. Alzamili, Sora K. Al-zayadi, Ali S. Alboo-hassan, 2020)**;

– Comparative-typological analysis, allowing for the identification of differences in the nature of digital-semiotic integration between entities **(U. Fitrawan, K. Iwan, W. Haryo, 2024).**

Special emphasis is placed on the comparative quantitative assessment of the coherence between cultural and digital components of the environment, represented by the coefficient of symbol-

ic coherence (k). In the present study, k is used as a screening indicator for comparing cases and for making the semiotic coding procedure explicit **(Formula 1)**.

$$k=C/D \quad (1)$$

where C is the number of identified digital elements that demonstrate an explicit and traceable connection to local cultural-semantic codes (for example, ornament, memorial narrative, historically meaningful route logic, or context-sensitive visual scenario),

and D is the total number of digital elements identified within the analyzed object and included in the coding sheet. Accordingly, the coefficient is bounded by $0 <= k <= 1$.

Values of $k > 0.8$ indicate a harmonious interaction between the cultural and digital layers,

$0.5 \leq k \leq 0.8$ indicates partial integration,

and $k < 0.5$ indicates a discontinuity between the technological and semantic layers of the urban environment.

The coefficient was calculated using a structured expert coding procedure. A group of three specialists in architectural semiotics and digital modeling independently coded each identified digital element in the three cases using a binary scale (1 = culturally integrated element, 0 = non-integrated or purely technical element). The coding sheet included the element type, the location within the space, the digital function, and the observed semiotic reference. Divergences in coding were discussed and reconciled, and the final case value was fixed by the median (consensus-oriented) estimate **(J. Imankulov, 2024).**

This procedure increases transparency and reproducibility of the comparison, while still preserving the interpretive nature of semiotic analysis. For this reason, the resulting k values should be read as comparative analytical indicators, not as absolute measures of urban meaning.

In addition to analytical and visual methods, AI-based tools for the reconstruction of three-dimensional models from photographs were employed. The application of neural network systems (Meshroom, Luma AI, Reality Capture) enabled the reconstruction of volumetric forms of the urban environment without the need for costly laser scanning **(G. Bektemyssova, A. Bykov, A. Moldagulova,G. Shaikemelev,S. Nuralykyzy, D. Umutkulov, 2025).**

These technologies offer high levels of detail (up to 2 cm/pixel) and facilitate the integration of 3D models into the BIM environment **(J. Schiewe, A. Krek, I. Peters, H. Sternberg and K.Traub, 2008).**

The primary advantages are rapid processing and flexibility; among the disadvantages are sensitivity to lighting conditions, the necessity for manual refinement of textures, and significant load on graphics processors **(Francis R. A., & Lorimer J., 2011).**

Nevertheless, their potential is particularly significant for the study of historical and hard-to-access objects, where traditional modeling methods are problematic **(J. Imankulov, 2024)**.

The criteria for evaluating the symbolic coherence of architectural objects are presented in **Table 1**. The same criteria were used as a coding framework for the case descriptions and for the summary interpretation in **Tables 3-5**.

Table 1
Criteria for evaluating the symbolic coherence of digital objects

Criterion	Indicator	Interpretation
Correlation between cultural and digital elements (k)	0.00-1.00 (share of culturally coherent digital elements)	Indicates the level of semiotic integration
Presence of symbolic archetypes in the digital model	0 = absent, 1 = present (binary coding)	Indicates the presence of cultural codes in the digital environment
Degree of visual legibility of the space	High / Medium / Low	Describes the perceived identity of the environment
Interactivity of digital elements	Yes / Partial / No	Evaluates the level and semiotic relevance of user interaction
Contextual adaptation of technologies	High / Medium / Low	Determines alignment with the local context

3 RESULTS AND DISCUSSION

The digitalization of architectural design in Kazakhstan is gradually expanding beyond visualization and is becoming a tool for the semantic analysis of the urban environment. In the context of Almaty, this is reflected in the shift from traditional 3D modeling to the integration of data on perception, movement flows, lighting, and users' social activity. Such a comprehensive model facilitates not only the design but also the interpretation of the city as a living system of meanings and interactions **(Figure 2).**

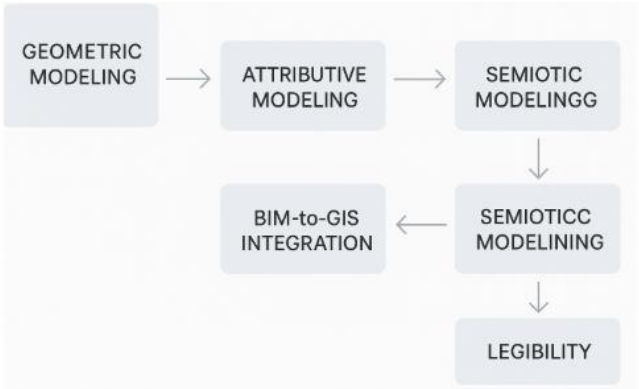

Figure 2 - Stages of the digital transformation of architectural modeling (from geometry to semantics) (authors' material)

Contemporary approaches to modeling urban morphology are based on the integration of BIM (Building Information Modeling) and GIS (Geographic Information Systems). These technologies enable the combination of spatial geometry with metadata regarding building use, pedestrian routes, navigational elements, and visual landmarks. As a result, a "digital shell of the city" is formed, in which each element serves as a bearer of not only geometric but also semantic information **(Asser Elsheikh, Hadeal H. Alzamili, Sora K. Al-zayadi, Ali S. Alboo-hassan, 2020).**

In Almaty, this transformation has been advanced within the framework of the Smart Almaty program, which is aimed at establishing digital twins of key public zones. The central emphasis is placed on the creation of digital models that reflect not only physical parameters but also the semiotic structure - for example, sites associated with historical memory, traditional routes, or local symbols.

Particular attention is given to BIM-to-GIS technologies, which allow for the integration of architectural data with urban infrastructure and sociocultural scenarios. This integration forms the basis for analyzing the semantic relationships between physical space and user behavior.

A key indicator of the effectiveness of digitalization is the capacity of the architectural environment to preserve semiotic legibility - that is, the possibility of interpreting space as part of the cultural context. Therefore, digital modeling should encompass parameters of perception, symbolism, and identity, rather than be limited solely to geometry. The criteria for assessing the success of digital transformation are summarized in **Table 2**, which reflects the shift from formal modeling to semantically rich digital structures oriented toward user perception and spatial interaction.

Table 2
Criteria for successful digital transformation of architectural modeling.

Criterion	Traditional modeling	Digital-Semiotic Modeling
Type of Digitalization	3D Visualization of Objects	Integration of BIM and GIS
Level of Data Integration	Limited to geometric data	Complete interconnection of spatial and semantic data
Consideration of semiotic parameters	Absent	Cultural and symbolic codes incorporated
Environmental interactivity	Minimal (static models)	High (AR/VR-interactivity, digital panels)
Contextual adaptation	Low, context not considered	Adaptation to local identity and perception
User orientation	Focus on form	Focus on user experience and meaning

To evaluate the level of integration of semiotic codes within the digital model, a semiotic mapping procedure was applied. Each case was decomposed into observable spatial and digital el-

ements, after which the elements were coded by semiotic type (identity, interaction, perceptual, contextual, and evolution codes) and linked to a digital attribute. Figure 3 presents the logic of these relationships, while **Table 3** systematizes the parameters and examples used in the analysis.

Semiotic mapping was supported by GIS-based analytical tools, which enabled the identification of clusters of symbolic density and the detection of areas where cultural codes are weakened or disrupted. In the present article, the GIS layer is summarized analytically (through diagrams and tables) because the journal format does not include raw GIS screenshots or full BIM model outputs; however, the coding logic and case-by-case interpretation are made explicit in the text and **Tables 3-4**.

The use of digital modeling platforms also made it possible to analyze the interaction between symbolic layers and dynamic elements of the urban environment - for example, lighting scenarios, pedestrian flows, and interactive installations. According to recent research on the semiotic legibility of public spaces, such dynamic components significantly influence the cognitive and emotional perception of the city **(A.Alisharipov., K. Kussainov, D. Yesmagambetov & Z. Arynova, 2024).**

Finally, the integration of semiotic analysis into the BIM/GIS workflow allows the formation of a unified interpretive model of space, where cultural identity, visual perception, and digital interfaces are combined into a coherent system. This methodological approach responds to the challenges identified in Kazakhstan's architectural scholarship, which emphasizes the need to preserve symbolic continuity in the context of technological modernization **(G. Abdrassilova, E. Danibekova, A. Tuyakayeva, A. Syzdykova, 2024; J. Schiewe, A. Krek, I. Peters, H. Sternberg and K.Traub, 2008).**

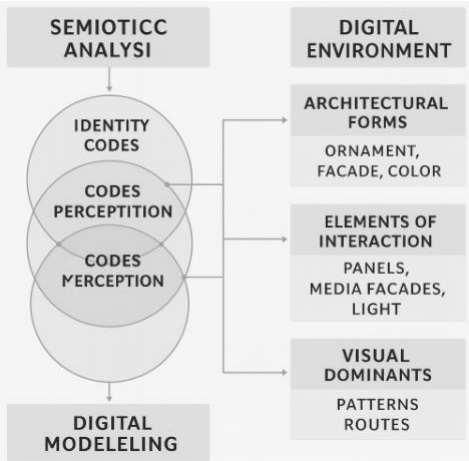

Figure 3 – Diagram of the integration of semiotic analysis into the digital modeling of public spaces (authors' material)

Table 3
Classification of semiotic codes and their digital equivalents.

Type of semiotic code	Description of architectural expression	Digital equivalent / recording tool	Example of application in Almaty
Identity codes	Visual and morphological elements reflecting local culture, traditions, and history	3D-models of facades with ornament parametrization; BIM-libraries of cultural motifs	Ornamental structures on the facades of Panfilov Street
Codes of interaction	Elements enabling user interaction with the space (light, sound, movement)	AR/VR-interfaces, interactive media facades, presence sensors	Media facades and sensor panels on the Esentai Riverwalk
Perceptual codes	Spatial scenarios shaping emotional perception and movement trajectories	GIS-flow maps, visual heatmaps of attention, eye-tracking-models	Pedestrian flow analysis on Abay Square
Contextual codes	Socio-functional links between objects and users	Digital models of connections (CIM - City Information Modeling), neural network algorithms for contextual analysis	Correlation of user activity within the framework of the 'Smart Almaty' program
Codes of evolution	Transformation of symbols and their adaptation to contemporary digital conditions	Chronological 3D-layers, database of changes in the visual environment	Comparison of historical layers from 2010 to 2025 according to open-data GIS

The case analysis of public spaces in Almaty enabled the identification of different patterns of interaction between the cultural and digital layers of the urban environment. Three sites were se-

lected for the study - Panfilov Street, Abay Square, and the Esentai Riverwalk embankment. For each case, the analysis recorded (1) dominant cultural codes, (2) the type of digital intervention, and (3) the degree of linkage between them, which was then summarized by the k indicator **(Table 4)**.

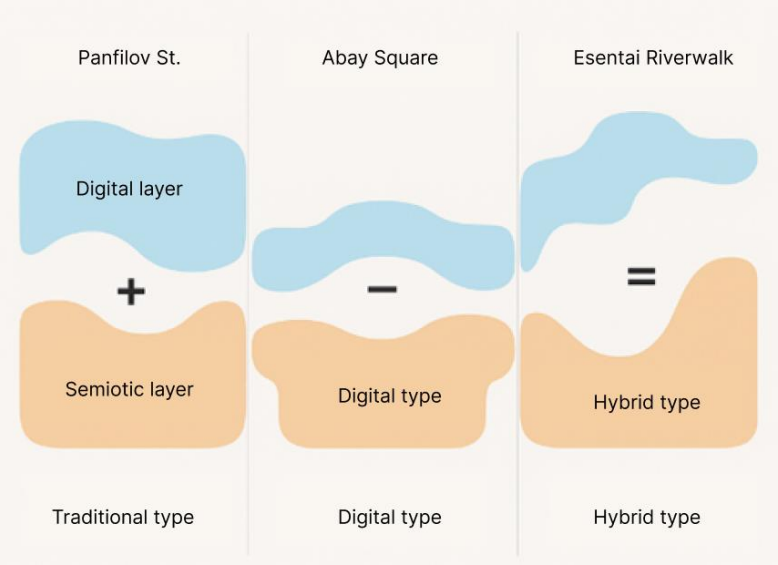

Figure 4 – Diagram of the distribution of semiotic and digital layers within the public spaces of Almaty (authors' material)

The reconstruction of Panfilov Street (2017) demonstrated a comparatively strong integration of historical identity and digital solutions. In semiotic terms, the key cultural codes are the preserved linear pedestrian route, ornamental facade motifs, and the recognizable historical atmosphere of the street. The digital layer (adaptive lighting, media navigation, and service interfaces) is interpreted as supportive because it reinforces wayfinding and evening legibility without suppressing the historic visual hierarchy. This corresponds to the findings on the semiotic layering of architectural forms in Kazakhstan **(I. Ostapenko, K. Bekturganova, D. Dyussenova, R. Chekaeva, A. Yessenbayev, 2025)** and to the importance of cultural continuity in modern reconstructions (**G. Abdrassilova, E. Danibekova, A. Tuyakayeva, A. Syzdykova, 2024).**

The analytical GIS layer and flow heatmaps indicate that the areas of greatest activity coincide with sites containing culturally significant objects and orientation markers. In the coding procedure, this case produced high values of symbolic coherence (k = 0.84-0.93), which is consistent with spatial behavior models in public spaces described in recent urban morphology studies **(A.E. Kozhakhmetov, A.Z. Abilov, A.S. Seidakhmetova, 2023).**

Abay Square illustrates a different scenario. The square preserves a strong monumental and memorial code (the Abay monument, ceremonial open space, fountain composition), yet the observed digital interventions are more weakly connected to this symbolic structure. Analysis of the BIM/GIS description and the AR/media layer indicates that screens and lighting operate primarily as technical additions and are not consistently linked to the square's memorial narrative, which produces a 'code rupture' effect. This pattern aligns with findings on digital-cultural mismatches in Central Asian architecture (J. Imankulov, 2024).

In the coding procedure, Abay Square yielded k values in the range of 0.58-0.67, indicating partial correspondence between cultural and digital layers and a predominance of the technical layer over the semiotic one. This pattern is comparable to the conditions described in studies on digital identity fragmentation in post-Soviet cities **(A. Melnychuk, O. Gnatiuk, 2019).**

Esentai Riverwalk represents the most technologically advanced case and demonstrates how a new (rather than inherited) urban semiotics can be formed through digital interaction. Here, the semiotic codes are generated by scenarios of movement, visual attention, leisure behavior, and interface-based engagement. Digital panels, projection lighting, and AR elements do not reproduce historical symbolism, but they create a recognizable identity of place based on interactivity and temporal visual scripts. This corresponds to current discussions on AR-based interpretation of cultural

landscapes (**A. Ibis, N. Cakici Alp, 2023)** and the shift toward dynamic forms of digital interaction in urban environments **(Kalantari, F., Tahir, O. M., Joni, R. A., & Fatemi, E., 2019)**. Flow modeling **(Table 4)** demonstrated a correlation between zones of visual interest and areas of increased user activity, with a comparatively high k coefficient (0.80-0.88).

Table 4
Comparative Indicators of the k Coefficient for Three Cases of Public Spaces in Almaty.

Object of study	Type of spatial organization	Nature of digital integration	Semiotic saturation	Mean value of coefficient k	Interpretation of the integration level
Panfilov Street	Historic public space with a linear structure and preserved morphology	Intelligent lighting, media installations, sensor-based navigation	High (historical motifs, route memory, and facade ornament codes are preserved)	0.84-0.93	Harmonious integration of cultural and digital layers
Abay Square	Open memorial and cultural space	Digital screens, dynamically controlled fountains, media elements lacking contextual linkage	Moderate (memorial symbolism preserved, weak linkage with the media layer)	0.58-0.67	Partial integration, predominance of the technical dimension over the semantic
Esentai Riverwalk	Contemporary recreational space with a linear-functional structure	AR-installations, interactive panels, projection lighting	High (a new digital identity is formed through interactive scenarios)	0.80-0.88	Emerging digital-cultural equilibrium

Comparison of the three cases made it possible to identify a general pattern: the higher the level of adaptation of digital solutions to local culture, the more stable the formation of the semiotic structure of the environment. This confirms the thesis that architectural digitization is not the destruction of tradition, but a tool for its reinterpretation and prolongation in the digital context.

The development of digital-semiotic systems in the architecture of Almaty demonstrates that the effectiveness of digital transformation is determined not only by the level of technological advancement, but also by the degree of semantic coherence among the elements of the urban environment. Unlike purely engineering approaches, in this context digital technologies serve as mediators between cultural memory and contemporary spatial usage scenarios. This affirms the key thesis of the research: architecture of the twenty-first century is not merely a form, but an interface of meanings, accessible for reading and interpretation by the user (**Figure 5**).

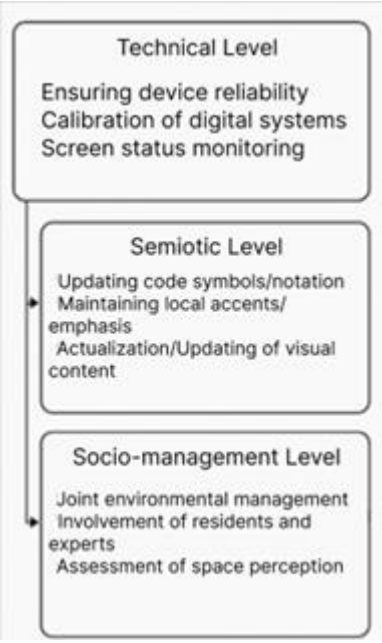

Figure 5 - Model of the three-level integration of digital and semiotic systems within the urban environment (authors' material)

One of the most productive directions has been the integration of interactive media elements - projection screens, touch panels, and AR markers - into the context of historically established spaces. Their function extends beyond visual aesthetics: media interfaces facilitate a 'dialogue' between the user and the space, while data from sensory systems constitute a new material for architectural analysis. This trend fully corresponds to global findings on AR-based enhancement of cultural environments **(A. İbiş., N. Cakici Alp, 2023)**.

The case of Esentai Riverwalk demonstrates that the use of adaptive screens responsive to movement flows enables the formation of 'living' semiotic structures, in which digital and cultural components mutually reinforce one another. Similar effects of digital interfaces on perception and spatial behavior were identified in GPS-based and sensor-driven urban studies **(B. E. Sönmez., D. E. Önder, 2019).**

The existence of management and maintenance mechanisms is essential to the sustainability of such systems.

Within the framework of the study, a three-level model is proposed, comprising:

Technical level - ensuring the reliability and calibration of digital devices, as well as monitoring the condition of screens, sensors, and lighting systems.

Semiotic level - maintaining the relevance of visual codes, updating content, and preserving local symbolism and visual accents.

Socio-managerial level - engaging residents and professional curators in collaborative management and assessment of spatial perception.

The application of this model not only enhances the operational reliability of systems, but also reinforces the symbolic resilience of the environment, fostering a sense of involvement and identity among users - an approach consistent with recent research on digital twins and participatory management models in urban design **(A.V. Mukhacheva, M.N. Ugryumova, I.S. Morozova, & M.Yu. Mukhachyev, 2021)**. In this article, 'participatory design/management' is understood as the structured inclusion of residents and local stakeholders in the evaluation and periodic adjustment of digital content; the present study introduces this principle conceptually and does not report a separate sociological survey.

Summary data on the impact of digital-semiotic integration on key parameters of the urban environment are presented in **Table 5**. The indicators in this table are comparative analytical summaries derived from the case review and literature synthesis; they should not be interpreted as direct

instrumental measurements for all public spaces in Almaty.

Table 5
Influence of digital-semiotic integration on the parameters of the architectural environment in Almaty.

Indicator	Prior to digital integration	Following digital-semiotic integration	Key effect
Visual legibility of space	Fragmentary, limited to physical landmarks	Augmented by ARnavigation and dynamic lighting patterns	Enhancing user identification and orientation
Cultural identity	Maintained in specific architectural elements	Strengthened through digital projections and interactive narratives	Development of the 'new semiotics' of the city
User engagement	Passive perception of the environment	Active interaction via media interfaces and applications	Growth of social activity and participation
Informational transparency of the environment	Static visual communication	Dynamic content updating, user feedback	Enhancement of the adaptability and relevance of the visual environment
Energy efficiency	Unregulated lighting and media devices	Sensor-based regulation of brightness and operating time	Potential reduction of energy consumption (analytical estimate: 15-25%)
Symbolic coherence (k)	0.40-0.60	0.75-0.88	Increase in the coherence between the cultural and technological layers

The durability and effectiveness of digital-semiotic systems are directly dependent on the quality of management, the regularity of maintenance, and content updating. The digital environment is not static - its visual and semantic elements are susceptible to wear, obsolescence, and the loss of symbolic expressivity. Therefore, managing digital-semiotic structures requires a combination of engineering and humanities competencies **(Figure 6).**

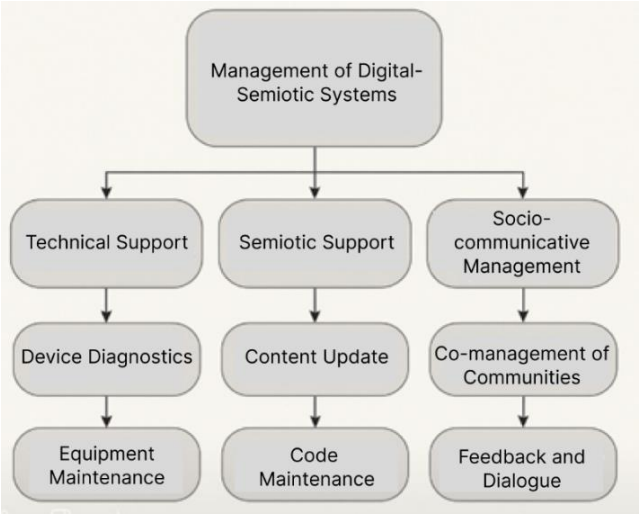

Figure 6 - Model for the management and support of digital-semiotic systems (authors' material)

The first level is technical support.

This level includes the diagnostics and maintenance of digital devices such as sensors, media panels, lighting systems, AR interfaces, and server nodes. At this stage, it is important to ensure the uninterrupted functioning of hardware components, data synchronization, and protection against failures.

In Almaty, solutions based on the urban system 'Smart Almaty,' which enable real-time monitoring of energy consumption and the condition of lighting elements, are already being implemented in practice. Looking forward, the implementation of predictive maintenance models utilizing machine learning to forecast technical failures is feasible.

The second level involves semiotic maintenance.

Its objective is to sustain the relevance of visual codes and semantic associations. Periodic content updates are a prerequisite for maintaining cultural relevance. As demonstrated by the analysis of Esentai Riverwalk, architectural media screens function effectively when visualization scenarios are updated quarterly in accordance with national holidays and local cultural events. At the same time, the continuity of visual patterns and the principle of environmental 'legibility' must be preserved so as not to undermine the established symbolic system.

The third level is socio-communicative governance.

It is founded on the involvement of residents and local communities in the processes of co-management of the urban environment. In practical terms, this includes public feedback channels, periodic review of media scenarios, and co-curation of culturally significant content. Such procedures operationalize the participatory principle discussed above and help connect digital interfaces with the local symbolic context.

Effective operation necessitates the introduction of a responsibility matrix, which delineates the spheres of activity for municipal services, contracting organizations, content curators, and civic participants. Such a model not only enhances service quality but also reduces costs through resource allocation and engagement of local initiatives.

The implementation of these principles ensures the sustainable development of digital-semiotic architecture, whereby the urban environment preserves its semantic richness, adapts to technological change, and remains open to cultural interpretation.

The key operational parameters of the systems and the frequency of their maintenance are provided in **Table 6.**

Table 6

Frequency of maintenance and functions of stakeholders within the operational cycle of digital-semiotic systems.

Level of Management	Key Operations	Frequency	Responsible Entities	Expected Outcome
Technical Support	Diagnostics of sensors, media panels, and lighting; Calibration and software updates	Monthly / in the event of malfunctions	Municipal services, IT contractors	Stable equipment operation, absence of downtime
Infrastructure Maintenance	Network node inspection, backup, and energy consumption monitoring	Quarterly	Contractor organizations, Smart Almaty service	Predictive management and cost optimization
Semiotic support	Updating of content, visual scenarios, and cultural narratives	Quarterly / event-dependent	Content curators, Department of Culture	Preservation of semantic relevance and environmental identity
Socio-communicative management	Collection of user feedback, organization of surveys, and public consultations	Continuous / event-based	Municipality, district curators, active residents	Enhancement of participation and trust in digital infrastructure
Comprehensive system audit	Analysis of effectiveness, revision of the responsibility matrix, and updating of service standards	Annually	Joint commission comprising architects, engineers, and public representatives	Long-term sustainability and adaptability of the system

The present study has three limitations. First, the empirical material is based on open-access models, published visual documentation, and analytical reconstruction rather than full municipal

BIM/GIS datasets. Second, the k coefficient is an exploratory comparative indicator and does not replace detailed sociological, behavioral, or eye-tracking measurements. Third, the article uses synthesized diagrams and tables instead of full raw GIS or AR screenshots due to the format constraints of the journal. These limitations do not invalidate the proposed methodology, but they define the scope of interpretation and indicate the next stage of research.

4 CONCLUSIONS

1. Digital transformation as an emerging semiotic framework

The results of the case comparison show that the digital transformation of architectural design in Almaty should be interpreted not only as technological modernization, but also as a change in the way urban meanings are produced and read. BIM, GIS, AR/VR technologies, and interactive navigation systems increase the analytical and communicative capacity of public spaces when they are linked to the cultural logic of a specific site.

2. Integration of semiotic analysis into digital modeling

The article demonstrates a transparent procedure for integrating semiotic analysis into digital modeling through coding of cultural and digital elements and through the exploratory coefficient of symbolic coherence k. For the studied cases, k varies from 0.58 to 0.93. Higher values (Panfilov Street and, in a different way, Esentai Riverwalk) indicate stronger linkage between digital solutions and the semantic structure of place, while lower values (Abay Square) reveal the need for more context-sensitive digital scenarios.

3. Practical significance of the methodological model

The practical significance of the study lies in the proposed methodological model (Figure 6), which encompasses three levels of management for digital-semiotic systems:

- technical level,
- semiotic level,
- socio-communicative level.

This structure supports the resilience and adaptability of the urban environment amid ongoing technological transformations. It can be used by architects, urban planners, and municipal operators as a framework for aligning technical maintenance with the preservation of symbolic identity.

4. Digital architecture as cultural communication and future research

The study supports the interpretation of digital architecture in Almaty as a form of cultural communication in which data, visual representations, and social practices are interrelated. At the same time, the conclusions remain limited by the case-based and open-data nature of the research. The proposed approach should therefore be further developed through expanded empirical datasets, raw GIS/BIM evidence, and direct user participation studies. Priority directions for future work include:

- measuring the semantic density of the urban environment with field-validated indicators,
- developing visual analytics tools for BIM/GIS-based semiotic mapping,
- constructing interactive systems that support public participation in shaping urban semiotics.

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