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DEVELOPMENT OF THE REAL ESTATE DATA PROCESSING MODEL BASED ON MODERN GEOAI APPROACHES

The object of the research is geographic information systems (GIS) used in the real estate market. Currently, a significant problem in analyzing market information is the absence of a geographic component when evaluating property costs. This deficiency leads to a simplified understanding of market processes, reduces assessment accuracy, and complicates forecasting methods. During the research, system analysis and geostatistics methods were used to transform data from a discrete to a continuous form. Adding a spatial component to property information and updating data online allows for identifying pattern chains and creating forecast scenarios in the shortest possible time. A generalized scheme for processing large data sets was developed in combination with the GeoAI algorithm flowchart. This allows for developing a full-fledged model of a geographic information system with an adaptive artificial intelligence function, enabling users to rapidly process information for making investment decisions. The article analyzes modern GIS with artificial intelligence functions used to solve various global real estate problems. The proposed a scheme for processing large data sets with GeoAI, reflecting the general structure of interaction between GIS, input/output data arrays, and a neural network used for analyzing and predicting spatial processes. Practical calculations have shown that by using GeoAI, the time for processing large data sets is reduced by more than 10 times.

Keywords: geographic information system, artificial intelligence, real estate, developer, stakeholder, machine learning.

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1. Introduction

Real estate market research using geographic information systems (GIS) is of great importance for market professionals. Appraisers, stakeholders, developers, and realtors are currently extremely interested in adding a spatial component to information about a real estate object and in constantly updating data, that is, in accessing it 24 hours a day [1]. Such requirements can only be achieved using specialized software and the capabilities implemented in the “digital city” concept. Results that will satisfy stakeholders can be obtained by combining artificial intelligence and geographic information systems.

According to the analytical company Mordor Intelligence, the geospatial analytics market is showing significant growth. In the US, the average annual growth rate of this market is expected to be 24.14% over the next five years. Geospatial artificial intelligence (GeoAI) combines artificial intelligence methods with geographic information systems (GIS) to analyze spatial data. In the real estate sector, GeoAI is actively used to evaluate objects, predict market trends, and optimize property management. GeoAI in real estate is used to estimate the value of objects. GIS technologies allow users to visualize and model real estate data, considering various factors that affect pricing.

Because GeoAI involves the use of traditional artificial intelligence methods to obtain spatial data by extracting, classifying, and discovering information from structured and unstructured data, the use of GeoAI enables solving complex problems by analyzing spatial data, identifying patterns, and making spatial and temporal predictions. The use of GeoAI allows for significantly increasing the speed

of processing complex data sets and obtaining valid results. According to the use of the digital city concept, it becomes possible to solve the most complex tasks in the real estate market.

Despite the availability of research, the issue of integrating GeoAI into real estate market analysis remains insufficiently covered. That is why serious attention is paid to the study of the patterns of formation of both the primary and secondary markets [2]. Many researchers are engaged in the study of similar problems [3]. Since 2022, i. e., during hostilities, global changes have occurred in the sales segments of both primary and secondary real estate. There are many factors affecting the value, but real estate has proven to be quite resistant to fluctuations in geopolitical risks [4]. That is, the real estate market quickly adapts, changes, and certainly suffers under the influence of external adverse factors [5].

In some countries, there are computer systems that allow the creation of accurate price maps of land plots based on data on land prices for housing construction in cities [6]. For the development of GIS projects on real estate, it is possible to use ready-made cartographic data from various open web sources. For example, it is possible to add base maps such as Open Street Map, Google Maps, National Geographic maps, and others. The development of conceptual foundations for creating web services for visualizing the results of cadastral assessment and real estate market data is promising and in demand by state authorities and local governments [7].

Italian scientists conducted a study of the dependence of real estate prices in industrial cities on the ecological situation and the environment. The city of Taranto, a coastal city in southern Italy, was chosen as the object of the study.

Taranto has developed steel and iron foundries, oil refineries, a chemical industry, shipyards for the construction of warships, and food enterprises. Due to the emissions of pollutants into the atmosphere by factories in this area, Taranto is the most polluted city in Italy and Western Europe. This example demonstrates how spatial factors (ecology) critically affect pricing, which confirms the necessity of using GIS for accurate assessment. Using the example of the Taranto agglomeration, models of the impact of environmental quality on real estate prices were developed [8].

A qualitative assessment of the market value of real estate objects can be obtained if there is an integration of economic and construction information with spatial analysis, since GIS can reflect more accurate and objective information about the characteristics of a particular site. The use of GIS will help the appraiser to easily justify how exactly it assessed the value of real estate objects and what factors directly and indirectly affect their value. And if this information is combined and integrated with economic, financial, and analytical data, it will be possible to automate some elements of the property valuation process. This, in turn, will lead to a shortening of the valuation process and ensure a more accurate assessment of market value [9].

Current research explores promising directions for developing geographic information systems combined with artificial intelligence (GeoAI). One key study combines LiDAR, SAR, and optical images using deep learning techniques, such as fully convolutional networks. This approach ensures the accurate classification of urban objects, including buildings, roads, and vegetation. A review of self-supervised learning (SSL) methods of artificial intelligence for processing geospatial data: points, polylines, polygons, i. e., scarce labeled data, has been performed [10].

There are studies on the application of GeoAI in urban planning: the use of ML for forecasts, analysis of urban planning scenarios, visualization, and spatial planning [11]. Some works consider how to use meta-heuristics, spatiotemporal data to solve infrastructure problems, for example, integrating AI into GIS (applying GeoAI models) to predict accidents in water supply networks [12]. GeoAI is increasingly used in the field of quantitative human geography – in studies of city dynamics, social indicators, and demographics [13].

In the cited scientific sources, the real estate market is analyzed based on separate groups of factors: economic, spatial, or technological. However, most studies lack a comprehensive approach to considering the interaction of these factors within a single analytical model. In particular, the integration of artificial intelligence methods with geographic information systems for spatially oriented market analysis remains insufficiently explored. Furthermore, the use of consumer behavioral data combined with the geospatial characteristics of real estate objects requires further development. To address these limitations, this article proposes a new approach. It suggests a synergistic combination of GeoAI and GIS tools to improve the accuracy of market analysis and forecasting processes.

The object of the research is geographic information systems (GIS) used in the real estate market.

The aim of the research is to develop the geospatial data model based on GeoAI approaches to reduce the time for processing large datasets. The tasks of the research are:

1. To determine the features of the application of GIS and geospatial artificial intelligence in global real estate markets and in Ukraine.
2. To analyze the shortcomings of using modern GIS.
3. To develop of a scheme for the application of GeoAI in the real estate market.

2. Materials and Methods

The research employs methods of system analysis, geostatistics, and spatial analysis within GIS, as well as AI and neural network methods

to identify spatial patterns and forecast real estate market processes. Comparative analysis was used to evaluate modern intelligent GIS.

The choice of methods is driven by the spatial nature of the real estate market, characterized by territorial heterogeneity and spatial dependencies. Geostatistical and spatial analysis methods ensure that the geographic component is accounted for during data processing, while AI methods effectively analyze large, heterogeneous datasets and identify non-linear patterns. System analysis ensures the integration of GIS and GeoAI into a unified model.

The combination of artificial intelligence with geographic information system technology will make it possible to implement many complex projects. Artificial intelligence has found its application in almost all sectors of industry. GeoAI, or geospatial artificial intelligence, is a combination of geographic information systems and new technologies, such as machine learning, deep learning, and artificial intelligence. The amount of spatial data is increasing daily with the advent of remote sensing satellites (both optical and radar), unmanned aerial vehicles, aircraft, and LiDAR data [14]. The application of artificial intelligence algorithms to these spatial data arrays to simplify processing makes it possible to detect hidden patterns.

Some GIS, such as ArcGIS by Esri, already integrate the capabilities of artificial intelligence (AI) with geospatial data [15]. Most GIS, regardless of the developer, are formed on a modular basis. Base modules contain the main functions, and extension modules allow adapting the system to specific needs. Analysis of these GIS for capabilities, functionality, availability, ease of use, and support allows understanding which of these products best meets the needs in solving modern problems in the real estate market (Table 1).

Table 1

Analysis of software products

Criterion	ArcGIS	QGIS
Cost	High (license fees)	Free
Functionality	A wide range of possibilities	Various plugins
Ease of use	Difficult for beginners	Intuitive
Data format support	All possible, closed source program	All possible, open source
Spatial data analysis	Powerful tools	Sufficient opportunities
Flexibility	High/Limited (depends on license)	High (plugins)
Support	Big	Medium
Documentation	Extensive and detailed	Good, but can be limited
Cross-platform compatibility	Windows, Mac	Windows, Mac, Linux
Integration with other systems	High	Medium
Visualization capabilities	Advanced features	Sufficient
Educational materials	Many resources	Basic and separate materials on plugins

The application of GeoAI can be demonstrated using the example of Honolulu, Hawaii. When a law was passed requiring short-term rental property owners to pay housing taxes, it was found that there were only 800 legal vacation rental properties paying taxes and approximately 8,000 illegal ones [16]. To monitor all owners renting out real estate, the capabilities of 3D GIS were used. In Honolulu, information maps and databases are available through the City and County Land Information System (HoLIS). In this case, GIS helped to quantify and visualize rental landholdings and track taxes paid (Fig. 1).

Another example of using GIS models is the city of Vilnius (Lithuania), which uses drones and AI functions to manage the city and decide how to modify its structure in the future. In Vilnius, photos taken by drones and mapping systems form the basis of municipal functions. Subsequently, artificial intelligence models scan the photo material to mark the condition of streets, sidewalks, and other public spaces. Traffic data applied to the map allows planners to analyze and change the city's infrastructure. Digital models are becoming an increasingly common tool for city authorities to understand and manage city assets. The digital twin of the city in Vilnius functions as a three-dimensional aid to city planners, creating adaptive models that show the likely consequences of proposed changes (Fig. 2). Thus, the created digital twin of the city, as a planning tool, provides a way to strengthen and optimize decision-making by city services.

An illustrative example is the use of a snow removal model. High speed of removal (within hours) was achieved through a combination of artificial intelligence, location technology, and aerial photography. A few minutes after the end of the blizzard, a drone was deployed, taking images of the streets. An AI model trained to recognize snow-covered streets conducted a quick analysis. The result was displayed on the city map, which was part of the digital model. According to this, a digital map was built after the blizzard, on which the streets were marked with different colors depending on the measurements of the model created by the AI. For example, if the street is red, it means it has not been cleaned; if it is yellow, it means it needs to be inspected by a person; and if the color is green, the street is completely cleared.

According to the possibility of publishing geospatial data on the Internet, one can easily develop one's own web application for data visualization or any analytical results using the appropriate modules of the QGIS geoinformation system (Fig. 3) [18].

The dataset obtained from the presented application includes characteristics related to the cost of a square meter of secondary real estate over certain periods. That is, researchers could track changes that occurred in a certain segment of real estate in the market of one-, two-, and three-room apartments. Combining maps with infographics provides a deeper understanding and explores common assumptions. The input dataset can be enriched with any spatial information. The Python API allows integrating data on demographics, citizen solvency, and the ecological state of the environment. This can be expanded by adding socio-economic data such as age, income, education level, and many other parameters.

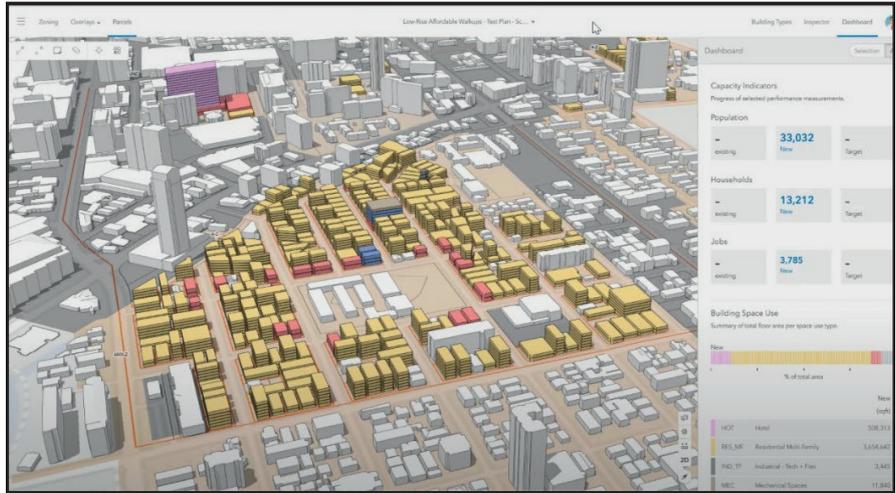


Fig. 1. Digital model of the city of Honolulu. Detecting payment for rental properties (adapted from website “Esri” [16])

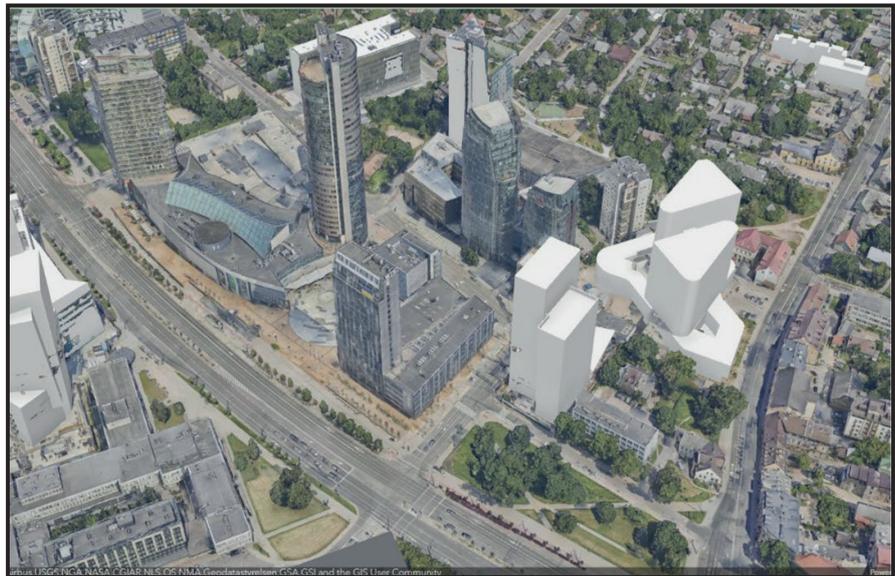


Fig. 2. Digital twin of Vilnius (adapted from website “Mayors of Europe” [17])

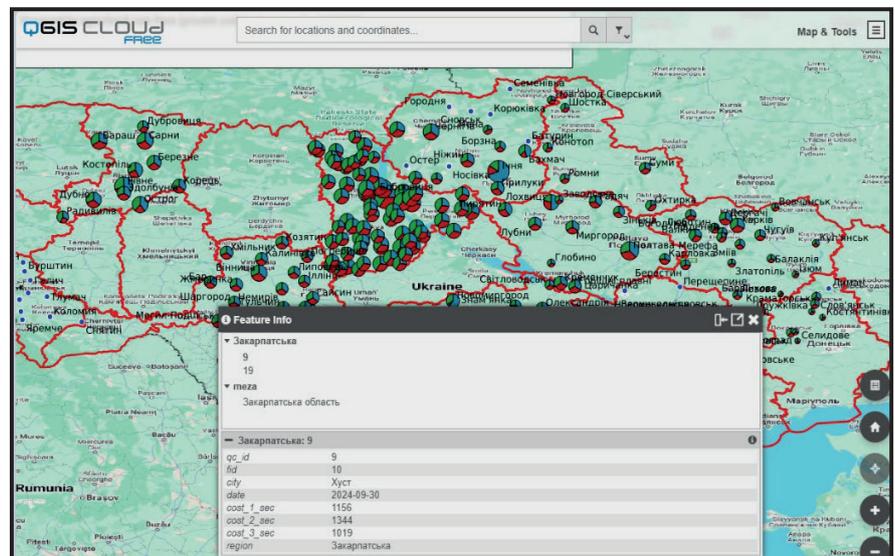


Fig. 3. View of the published informational digital map with data on the cost of m² of real estate in the secondary housing stock

An example of using GIS in Ukraine to process large amounts of real estate data is the portal “Lun Statistics” [19]. On this portal, there is a possibility of creating user filters to systematize information about real estate according to one's needs. As a result, digital maps are created that allow to obtain up-to-date information about the state of the real estate market. It shows an example of the resulting digital map of the secondary real estate market in Kyiv (Fig. 4).



Fig. 4. An example of using the “Lun Statistics” geoportall (borrowed from website “LUN” [19])

Regarding the use of GIS in Ukraine for real estate research, the following developments can be analyzed. Another example of using GIS for real estate market research is the Geoportall “UVECON” [20]. It performs the following functions:

1. Real estate market analysis.
2. Preparation of ready-made analytical reports and results of real estate market research.
3. Automation of real estate valuation.
4. Preparation and functioning of a geospatial database.
5. Geocoding of the sample and distribution of data by segments, types, and classes of real estate, grouping of objects by area and geography.

For example, an appraiser, using GIS functions, can obtain information on prices in the real estate market upon request in accordance with a comparable object and, in fact, complete material for drawing up a report on the assessment of the market value of real estate. Such a multifunctional system can be used by bankers, investors, appraisers, forensic experts, realtors, scientists, and many other specialists who study the real estate market in their daily activities. As an example, it is possible to cite the geoportall “Uvecon”, where heat maps with the cost of a square meter of housing, whether for rent or for buying real estate, allow selecting a region or district of the city with a suitable apartment cost (Fig. 5) [20].

In such a geoinformation system, depending on the value, the color of zones varies from light brown with affordable housing to dark brown

with the most expensive offers. The search for apartments by conditions is supplemented by the ability to explore the infrastructure in detail – one can assess the area and density of development, see the nearest shops, schools, and the number of parking spaces near the house.

3. Results and Discussion

3.1. Features of applying modern GIS in the real estate market

GIS is one of the most convenient tools for processing data on real estate objects; it allows viewing the location on a map depending on the selected market segment, as well as selecting and analyzing other necessary data if needed. Today, the technological functionality of GIS systems is used only partially, and when using only a part of the information, it is uninformative or completely ineffective. This is especially important for experts and professionals in the valuation industry, where the main priority is the availability of complete and high-quality information.

Geoportalls are a powerful tool for managing property complexes. One of the most expensive elements of a geoportall is the formation and updating of cartographic content. Modern GIS allows solving a wide range of tasks related to working with spatial data, including tasks related to the development of the structure, content, and layout of electronic maps for functioning in a single, specialized geoinformation system, for example, in the real estate market.

The first step towards creating a GIS project using geospatial artificial intelligence in the real estate market is to create a database. The database contains spatial and descriptive geographic information.

Geospatial data for the proposed model includes functional purpose of real estate, transport infrastructure elements, urban infrastructure locations, attribute characteristics of the studied objects, and real estate value indicators. Open geospatial data and information from online sources, subject to constant updates, were utilized in the research.

Each object on a digital map presented in a vector GIS can be described by a large amount of attribute data. The technology for collecting and analyzing information used in real estate GIS is a “raster” method of presenting information, in which the entire territory under study is covered by a regular network of equivalent cells, in each of which the average value of some indicator is determined, in particular market value (other indicators may include the number of offers, exposure terms, etc.). Assuming that the closer objects are located geographically, differing only in location, the smaller the difference in their market indicators, it is possible, based on the results of processing a set of market data collected over a certain territory by statistical methods, to calculate characteristics that determine average indicators and their errors, i. e., the degree of reliability of the assessment result provided that a sample of comparable objects is selected within the territory.

The disadvantage of this technology, as well as all others related to the collection of market information about real estate objects, is the limitation of the number of objects included in the calculation. The smaller the territorial coverage and the greater the gradation by pricing factors, the smaller the number of objects included in the sample.



Fig. 5. An example of using the Uvecon geoportall to search for housing in Ukraine where color changes from light (cheaper) to dark (more expensive) within: a – the country; b – the city; c – the part of the city [20]

3.2. Analysis of the shortcomings of existing GIS solutions

The main disadvantages of the GIS solutions listed above are:

- lack of a complete generalized primary database based on which the analysis was conducted (closed data);
- limited time (short-term retrospective);
- limited tools for using an interactive map in terms of services;
- lack of data for synchronization of information between databases.

Given the availability of such capabilities, the user will have the opportunity not only to independently visualize data but also to conduct their own research according to selected parameters. This will allow for the fastest possible analysis of both large data sets and small volumes of information from local sources. And the use of machine learning algorithms to predict demand and identify influencing factors makes it possible to analyze geodata and research demand changes with reference to the specific location of the real estate object.

3.3. Development of a scheme for the application of GeoAI in the real estate market

To automate calculations, speed up the time for information processing, and ultimately obtain a more reliable result, it is proposed the scheme developed by the authors for processing large arrays of information with GeoAI (Fig. 6).

This scheme demonstrates the stages of interaction of spatial data with the artificial intelligence model to form forecasts of real estate market development. The authors presented a scheme for processing large arrays of information in a GIS with an integrated neural network for analyzing and predicting large arrays of spatial data.

At the initial stage, an input data array is formed, which contains spatial (geographic) and attribute information. These data are sent to the GIS module, which performs their spatial processing, visualization in the form of a geographic map, and construction of a zoning map, which allows determining the boundaries and characteristics of the studied territories. All primary spatial and attribute data (topographic information, coordinates of objects, etc.) enter the formed GIS, where structured data arrays are formed.

Subsequently, the processed spatial data are transferred to the neural network, which stores information, forms a forecast, learns based on economic, geographic, and retrospective indicators, and creates or modifies a forecasting model with the corresponding array of output data. The result of the neural network's work is an array of output data based on GIS, which is intended for visualization, creating forecast maps, and further analysis of new information using GeoAI.

At the next stage of GIS development, it is necessary to use methods for predicting real estate value, as well as methods for modelling market development. Data transfer occurs between a machine and a person who receives information from the data. In the case of human-machine interaction at the level of artificial intelligence, the object of visualization is no longer data, but the information extracted from it. Until recently, only people could extract information from data. With the emergence of artificial intelligence, machines begin to extract information from data. They play the role of a primary filter for extracting useful information. Without the use of artificial intelligence, machine learning, and augmented reality technologies, a high-quality solution to these tasks is impossible.

The applied significance of the scientific results achieved lies in the proposed improved model for processing geospatial real estate data, developed through an in-depth analysis of existing GeoAI frameworks. This approach enables the seamless integration of spatial, market, and

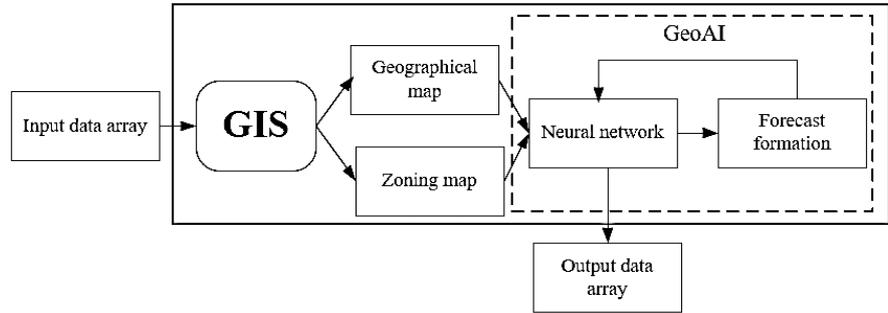


Fig. 6. Scheme of processing large data sets using GeoAI

infrastructure data within a unified GIS environment, facilitating a critical transition from discrete data representation to a continuous spatial form. Such a transformation is essential for effective geostatistical analysis and the implementation of neural network architectures, allowing for the precise analysis and forecasting of spatial-economic processes in the real estate market while accounting for location, value, and other key variables.

The architecture of the proposed real estate GIS involves the integration of GIS, a local database, and GeoAI. This will ensure the automation of real estate valuation and forecasting in the real estate market. The implementation of the GeoAI algorithm in the form of a flowchart for solving this problem is shown in Fig. 7.

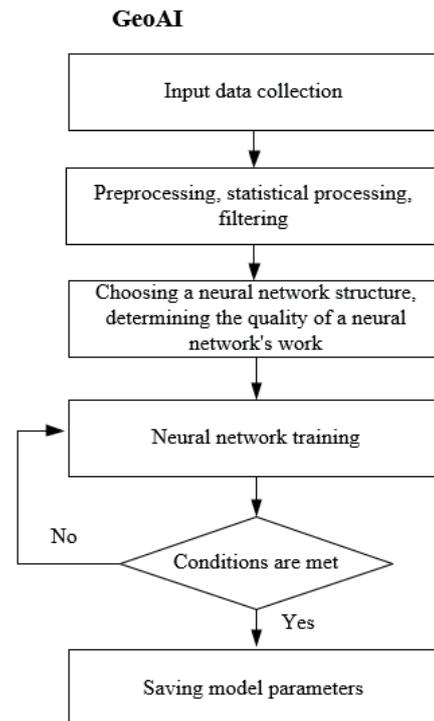


Fig. 7. Flowchart of the GeoAI algorithm

The flowchart of the GeoAI algorithm functioning is designed to solve real estate problems in GIS using GeoAI. The flowchart of this algorithm describes the process of neural network training as the main stage of building and tuning the artificial intelligence model. It is used to model the dependence between input spatial parameters and predicted indicators and to create a model for the real estate market.

The process consists of the following stages:

1. *Collection of input data.* At this stage, input data is accumulated from various sources, including geoinformation systems, databases, and real estate information portals.

2. *Preprocessing, statistical processing, and filtering.* Normalization, removal of anomalies, filling of missing values, and bringing data to a single scale are performed to increase training stability. Also, if necessary, correction of the data obtained is carried out.

3. *Selection of the neural network structure and assessment of its performance quality.* The architecture of the neural network is formed (number of layers, neurons, type of activation function, etc.). A preliminary assessment of the model's effectiveness on test data is carried out.

4. *Neural network training.* The network is trained on a sample of training data using optimization algorithms. A solution with the parameters of the developed model proposed by the neural network is issued.

5. *Are the obtained model parameters satisfactory (yes or no)?* Control of the model's functioning with the received parameters is performed. If the parameters are not satisfactory, the training process is repeated. After training, the formed model may have the ability to transfer forecast values and parameters to the GIS, where they are displayed in the form of updated maps, analytical layers, or risk zone models. This allows users to receive operational information for making important investments and other decisions.

6. *Saving model parameters.* After obtaining optimal results, the model parameters are saved for further use in forecasting or analytical calculations.

Thus, the GeoAI algorithm flowchart proposed in the article ensures the construction of an adaptive artificial intelligence model capable of generalizing patterns in large arrays of geospatial data and forming reliable forecasts. If necessary, iterative improvement of the model can occur – forecasting results are used again as input data to refine the neural network, creating a feedback loop between the GIS and the artificial intelligence module.

It should be noted that Fig. 6 and Fig. 7 depict interconnected elements of a complex system combining geoinformation technologies and artificial intelligence methods.

The integration of these methods ensures a comprehensive approach to modeling market dynamics in a single analytical environment.

The scheme for processing large data sets with GeoAI (Fig. 6) reflects the general structure of interaction between GIS, input/output data arrays, and the neural network used for analyzing and forecasting spatial processes. The GeoAI algorithm flowchart (Fig. 7) details the stages of functioning of the neural network training module, which is part of the system proposed in the article. Thus, the developed scheme for processing large data sets with GeoAI in combination with the neural network algorithm block will allow developing a full-fledged model of the functioning of a geoinformation system with an adaptive artificial intelligence function in the future. Such a model will ensure automated processing of large arrays of geospatial data, increase forecasting accuracy, and allow developers and stakeholders to make optimal decisions in the real estate market.

Thus, the research conducted in the article on the application of geoinformation systems, with GeoAI, allows drawing conclusions about the importance of using geospatial artificial intelligence. In the case of real estate market research, important factors are the search and processing of large data sets with their parallel visualization.

To form forecasts regarding housing costs without considering the spatial component – the introduction of which immediately increases the number of characteristics for calculation – a linear model of the dependence of housing cost on its class is used

$$Y = aX + b, \quad (1)$$

where Y (dependent variable): average cost of 1 m² of housing (in thousand UAH/m²); X (independent variable): housing class, represented by an ordinal code; a (regression coefficient/slope): the change in value Y when class X changes by one unit; b (intercept): the predicted cost when $X = 0$.

To verify the proposed theoretical principles and assess the applied significance of the developed architecture, econometric modeling

was implemented based on current real estate market indicators. The mathematical procedure for validating the model's adequacy involved the following stages:

1. *Sample formation.* The dependent variable (Y – the cost of 1 m² of housing in thousand UAH) and the independent factor (X – the real estate object class from 1 to 4) were defined.

2. *Construction of the regression equation.* Through statistical data processing, a linear model was obtained

$$Y = 17.73X + 8.85. \quad (2)$$

The coefficient 17.73 indicates the average step of value increase when the property class changes.

3. *Model adequacy assessment.* To verify accuracy, the coefficient of determination was calculated, which is $R^2 = 0.9492$. This means that 94.92% of price changes are explained by the chosen factor (X), which mathematically proves the high predictive capability of the model.

Additionally, a multi-factor model considering structural market variables was constructed. The resulting $R^2 = 0.88$ confirms the robustness of the proposed GeoAI approach even under the influence of complex external factors.

Methodological limitations of such a model:

- only one factor is considered (housing class);
- spatial heterogeneity is ignored (location, transport accessibility, environment);
- non-linear relationships are not accounted for;
- the model is sensitive to outliers and averages the market;
- it requires manual pre-aggregation when scaling large datasets (Big Data).

Compared to the conceptual linear model, which considers only the housing class as a generalized factor, the application of GeoAI ensures a significant reduction in the processing time of large volumes of spatial data due to automation, parallel computing, and the absence of the need for manual pre-aggregation of information. Furthermore, GeoAI allows for considering spatial autocorrelation, non-linear dependencies, and the multifactor nature of pricing in the real estate market, which increases the reliability and stability of the obtained results.

The information processing time when using a linear model can be calculated as follows

$$T_{linear} = O(N \cdot M), \quad (3)$$

where O – asymptotic complexity estimate (meaning that when the number of objects doubles, the time approximately doubles); N – the number of observations (real estate objects); M – the number of analyzed factors (attributes in the table).

The information processing time when using the GeoAI model

$$T_{GeoAI} = O((E \cdot N \cdot M) / P), \quad (4)$$

where E – the number of trainings epochs; P – the number of concurrent calculations.

Comparison of the time spent on calculation/forecast generation

$$\frac{T_{GeoAI}}{T_{linear}} = O\left(\frac{N \cdot M}{\frac{E \cdot N \cdot M}{P}}\right) = \frac{P}{E}. \quad (5)$$

Since in real systems P is always greater than E , assuming $P = 120$ and $E = 10$

$$\frac{T_{GeoAI}}{T_{linear}} = \frac{120}{10} = 12.$$

This demonstrates that the use of GeoAI provides a reduction in processing time by more than 10 times.

To substantiate the advantages of the developed model, a comparative analysis was conducted with traditional appraisal methods (linear regression and standard GIS tools). The comparison results are presented in Table 2.

Table 2

Comparative analysis of real estate market data processing methods

Comparison criterion	Traditional approaches (Linear models/GIS)	Proposed GeoAI model
Data representation	Discrete (point-based)	Continuous (continuous value field)
Factor accounting	Mainly single-factor (class or location only)	Multi-factor (infrastructure, ecology, behavioral data)
Data processing	Manual aggregation and sequential calculations	Automated processing using parallel computing
Processing speed (T)	Complexity $O(N \cdot M)$	Complexity $O(E \cdot N \cdot M/P)$ (>10x acceleration)
Adaptability	Static (requires recalculation upon market changes)	Adaptive (neural network self-learning)

3.4. Research limitations and directions for further development

The practical value of the proposed approach for real estate valuation and forecasting lies in reducing the processing time by more than 10 times.

The integration of a geoinformation application, a local database, and geospatial artificial intelligence will ensure the automation of property valuation. This approach accelerates the processing of large volumes of information and provides a more reliable result. The developed model will ensure automated processing of large arrays of geospatial data, increase forecasting accuracy, and allow developers and stakeholders to quickly make optimal decisions regarding real estate objects.

The limitations of research are due to the high complexity of the research object. The residential and commercial real estate market is formed under the simultaneous influence of economic, spatial, socio-psychological, and technological factors. Using only a single analytical tool often makes it impossible to adequately explain or predict market processes. Therefore, there is a growing need for synergy between artificial intelligence, geographic information systems, and behavioral data.

A prospect for further research is the development of a full-fledged mathematical model based on the proposed architecture for forecasting price trends, considering the spatial heterogeneity of the market. Thus, the developed scheme for processing large data sets in GIS using GeoAI will allow developing a full-fledged model of the functioning of a geoinformation system with an adaptive artificial intelligence function in the future.

4. Conclusions

1. It is determined that the implementation of GeoAI ensures a transition from static methods to dynamic modeling. This allows for considering spatial factors (ecology, infrastructure) as active pricing components, increasing the objectivity of the assessment.

2. The main shortcomings of the studied GIS are identified:

- the lack of a complete generalized primary database on the basis of which the analysis is conducted (closed data);
- limited time (short-term retrospective);
- limited tools for using an interactive map from the point of view of services;

– lack of data for synchronizing information between databases.

Thus, the use of machine learning algorithms for forecasting demand and identifying influencing factors makes it possible to process geodata and study changes in demand with reference to the specific location of the real estate object.

3. The scheme for applying GeoAI in the real estate market to analyzed large geospatial data sets has been developed. This approach will allow using machine learning algorithms to identify influencing factors, forecast demand, and study market changes with reference to the specific location of the real estate object. Practical testing has shown that the use of GeoAI reduces the time for data processing for forecasting by more than 10 times.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

The research was performed without financial support.

Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that no artificial intelligence technologies were used in the creation of this work.

Authors' contributions

Sergiy Kobzan: Conceptualization, Methodology, Writing – original draft; **Olena Pomortseva:** Resources, Data curation, Formal analysis, Validation, Writing – review and editing; **Volodymyr Pankiv:** Data curation, Methodology, Visualization, software.

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