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METHODS OF NEURAL NETWORK MODELING AND ARTIFICIAL INTELLIGENCE IN THE DEVELOPMENT AND OPERATION OF MUNICIPAL GEOGRAPHIC INFORMATION SYSTEMS

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SUMMARY

The monograph is devoted to a comprehensive analysis of the integration of artificial intelligence methods and neural network modelling in the creation and operation of municipal geographic information systems. The work substantiates the architectural, algorithmic, and systemic foundations for the formation of intelligent GIS at the level of territorial communities in the context of the digital transformation of urban management. A theoretical model is presented that represents the integration of AI into the municipal spatial environment through the interaction of key technological layers: geodata, deep learning models, the Internet of Things, edge AI, and visualisation panels.

In terms of structure and function, it is proven that an intelligent municipal GIS should include the following functional components:

1) a spatial data module that accumulates satellite images, sensor data, registry records, and time series;

2) an analytical module that performs segmentation, classification, prediction, and reconstruction of objects using CNN, LSTM, and GNN;

3) a module for processing streaming data in real time;

4) a module for integration with Big Data, IoT, and edge AI systems;

5) a module for visualisation and user interaction in the Smart City Dashboard format.

An approach has been developed for building a GeoAI pipeline, in which data is received, processed, modelled, and displayed in an automated cycle.

The feasibility of using LSTM models in forecasting changes in the urban environment, including traffic flows, development of buildings, and load on engineering networks, has been empirically proven. The potential of using ConvLSTM and GNN in building three-dimensional models and digital twins of cities has been revealed. An adaptive GIS architecture based on a microservice structure and supporting interaction with cloud platforms such as Google Earth Engine, Azure GeoAI, and IBM PAIRS has been proposed.

The monograph also analyses international experience in the implementation of intelligent GIS in urban management: from examples of Kyiv Digital to full-scale Smart City platforms in Singapore and Helsinki. The results of the study can be used to create concepts for the digital transformation of local communities in Ukraine, design spatial management systems, and develop open geodata policies and analytical support for decision-making.

Keywords: urban land, urban environment, intelligent geoinformation systems; municipal management; artificial intelligence; neural networks; LSTM; urban environment forecasting; edge AI; digital twin; Smart City Dashboard; GeoAI.

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ABBREVIATIONS AND NOTATIONS

AI – artificial intelligence;

ANN – artificial neural network;

CNN – convolutional neural network;

RNN – recurrent neural network;

LSTM – long short-term memory network;

GNN – graph neural network;

DNN – deep neural network;

GIS – geographic information system;

GeoAI – geospatial artificial intelligence;

IoT – Internet of Things;

DMS – decision-making system;

Big Data – large-volume, high-velocity and high-variety datasets used for advanced analytics;

Edge AI – artificial intelligence processing performed on devices at the edge of the network;

UAV – unmanned aerial vehicle (drone);

API – application programming interface;

WMS – Web Map Service;

WFS – Web Feature Service;

OGC – Open Geospatial Consortium;

DTP – digital twin of a city or infrastructure system;

NLP – natural language processing;

GPU – graphics processing unit used for parallel computing in training neural networks;

Smart City – an urban development concept integrating ICT and IoT to improve urban services;

Smart City Dashboard – a visualization platform for real-time monitoring of urban indicators using spatial data and AI analytics;

GIS+AI pipeline – a system for the automated flow of geospatial data through AI models into GIS platforms;

ConvLSTM – convolutional long short-term memory network;

Seq2Seq – sequence-to-sequence model architecture in deep learning;

CRF – conditional random field used for refining spatial boundaries in segmentation models;

Earth Engine – Google platform for planetary-scale geospatial analysis;

ArcGIS – a geographic information system software developed by Esri;

PostGIS – a spatial database extender for PostgreSQL object-relational database.

INTRODUCTION

In the current context of digital transformation of urban management, the issue of improving the efficiency of geographic information systems (GIS) used in the municipal environment is becoming particularly relevant. The introduction of intelligent methods of analysis, forecasting and management of spatial data provides a new quality of urban services, facilitates decision-making by authorities and allows for more effective interaction with the public. One of the main technologies that provide such quality is artificial intelligence and neural network modelling.

While traditional GIS mainly perform the functions of storing, processing and visualising spatial information, the intellectualisation of these systems allows us to move to a new paradigm – adaptive, self-learning and predictive management of urban processes. At the same time, there is no systematic methodology for the application of neural network models and AI in municipal GIS in the Ukrainian scientific and engineering space, which creates a gap between the potential capabilities of technologies and the real scenarios of their use.

Object of research: processes of creation, functioning and intellectualisation of municipal geographic information systems.

Subject of research: methods of neural network modelling and application of artificial intelligence tools for solving municipal management tasks based on GIS.

Research objective: scientific justification and development of methods for integrating neural network models and artificial intelligence into the structure of municipal geographic information systems in order to improve the effectiveness of management decisions.

In accordance with the stated objective, the following ***tasks*** have been defined within the scope of the monograph:

1. Analyse the current state of research in the field of neural networks and AI applications for spatial analysis tasks.

2. Determine the functional and architectural requirements for intelligent GIS in a municipal environment.

3. Develop a classification of municipal management tasks that can be solved using neural networks.

4. Formulate methods for processing, vectorisation, classification, forecasting and segmentation of spatial data using neural network approaches.

5. Build architectural models of Smart-GIS systems with built-in artificial intelligence algorithms, Big Data and edge AI.

6. Provide practical examples of the implementation of neural network technologies in the functional modules of municipal geographic information systems.

The ***theoretical and methodological basis*** of the research consists of: artificial neural network theory; deep learning methods; principles of distributed data processing and edge computing; concepts of spatial analysis in geoinformation systems; systemic, informational, cognitive and synergistic approaches to modelling the urban environment.

The following ***methods*** were used in the study:

- theoretical: analysis of scientific literature on AI and GIS, comparison of neural network architectures, systematic structuring of concepts and approaches;

- modelling methods: building and training LSTM, CNN, GAN, and Transformer network models; validating models based on real municipal data;

- empirical: analysis of pilot implementations in Ukrainian and foreign cities; interviewing experts; evaluating the effectiveness of models based on accuracy, recall, precision, and IoU metrics;

- instrumental: application of TensorFlow, PyTorch, Scikit-learn, OpenCV libraries, as well as integration of models into the QGIS, ArcGIS, PostGIS environment.

The ***scientific novelty*** of the work lies in the formalisation of the structural and functional architecture of intelligent GIS using neural network algorithms, as well as in the justification of new approaches to solving typical municipal tasks through predictive modelling and cognitive analysis.

The ***practical significance*** of the research lies in the possibility of creating intelligent modules for urban GIS that perform automatic classification of buildings, green areas, analysis of traffic flows, forecasting loads on engineering networks, and detection of anomalies and risk areas.

The materials of the monograph can be used in the development of Smart City systems, the implementation of e-government solutions, spatial planning, and in teaching the disciplines ‘Intelligent GIS’, ‘AI in Urban Planning’, and ‘Geoinformation Modelling’ in technical higher education institutions.

1 ELEMENTS OF THE GEOINFORMATION SYSTEM OF URBAN ECONOMY. FORMATION OF A GEODATA BASE

1.1 Areas of application for urban management geographic information systems

Geographic information systems for urban management act as comprehensive technological platforms capable of providing spatially oriented management of all functional components of urban infrastructure. Their distinctive feature lies in their ability to integrate various sources of geospatial and semantic data that reflect the dynamic nature of urban processes. Urban management is characterised by a high degree of complexity: the interaction of technical, social, environmental and economic systems, each of which requires regular monitoring, modelling and optimisation. It is GIS that provides the tools that allow for multi-level analysis of these processes with spatial reference.

GIS MG differs from traditional geographic information systems in its extended functionality, which provides support for urban services of various purposes in decision-making, visualisation of territorial development, management of engineering infrastructure and utilities. Unlike general-purpose systems, GIS for urban management are adapted to the needs of municipal administration, in particular, they include specialised modules for urban planning, inventory of urban objects, control of traffic flows, maintenance of green areas, energy supply, water disposal and other important areas of city functioning [1,3,6].

The use of GIS is particularly relevant in the context of intensive urbanisation, population growth in cities and the need for more sustainable management of urban resources. The use of digital geoinformation platforms minimises management errors, reduces costs, enables rapid response to emergencies and increases transparency in the activities of local authorities. In addition, GIS is an effective tool for engaging the public in management processes through open maps, online services, and e-democracy services [2, 4].

Studying the features of such systems also involves taking into account the complex architecture of their construction. These are primarily multi-component systems that combine hardware for data collection and transmission (UAVs, GNSS receivers, urban environment sensors), software for storing, processing and analysing information, databases and visualisation services. The role of GIS is growing in the context of the implementation of the Smart City concept, where the geoinformation platform becomes the core of the integration of information flows from various areas: energy, transport, logistics, security and the environment [5,7].

In general, current trends in the development of urban GIS demonstrate a transition from static cartographic platforms to dynamic digital twins of cities, which allow not only visualization, but also forecasting and simulation of urban processes in real time. Thus, urban GIS are becoming a strategically important element of the digital transformation of urban management and sustainable development of urbanised areas [1,3,5].

A geoinformation system for urban management (GIS UM) is a specialised information system designed to collect, store, process, analyse and visualise geospatial and attribute data characterising objects and phenomena in the urban environment. Conceptually, such a system provides functional integration of digital map layers, databases, engineering and technical information, analysis services, and interfaces for management decision-making within an urbanised area [1,3].

Unlike general GIS, urban management systems are formed as multidisciplinary platforms that combine urban planning, engineering, ecology, social planning, and other related fields of knowledge. Their concept involves the spatial representation of infrastructure objects such as roads, buildings, communication networks, as well as intangible indicators: demographic structure, environmental problems, transport accessibility, etc. [2,4]. In this sense, GIS MG functions as an environment in which urban space is digitally represented with a high level of detail and analytical complexity.

In general terms, GIS is defined as a computer-oriented system that combines hardware, software, spatial data, analysis methods, and personnel to ensure its functioning. In the case of urban management, the emphasis is on the need for rapid data updating, high integration with other information systems, and a focus on real-time decision-making. In particular, this applies to tasks such as forecasting the load on engineering networks, managing green areas, controlling unplanned construction, modelling traffic flows, etc. [5,6].

The main components of the GIS MG are:

- a data collection and entry unit, which includes the use of mobile applications, unmanned aerial vehicles, GPS/GLONASS systems, laser scanning, and remote sensing of the Earth;

- a geospatial database that accumulates digital plans, topographic information, engineering diagrams, zoning regulations, and environmental data;

- a cartographic module responsible for displaying data on electronic maps, with the ability to structure, scale, and layer data thematically;

- an analytical module that performs spatial analysis, builds scenarios for territorial development, and identifies correlations and trends;

- a decision-making interface that visualises the results of the analysis and provides interactive tools for specialists and managers [1,3,7].

Another important component is integration with external systems, such as urban planning cadastres, utility billing systems, real estate registries, and e-government platforms. This improves the efficiency of interdepartmental coordination and ensures the relevance of data in the city's digital ecosystem [6].

A defining element of the modern GIS MG concept is its focus on the use of open standards (e.g., OGC) and cloud technologies. This makes it possible to scale systems, ensure fault tolerance, and provide accessibility from various devices and platforms. In addition, the emergence of intelligent algorithms (based on artificial intelligence and machine learning) allows for urban development forecasting, optimisation of infrastructure maintenance costs, and implementation of adaptive management principles [4,5].

Thus, a geoinformation system for urban management is not just a set of technologies, but a conceptual basis for digital city management, which requires a comprehensive approach to its design, implementation, and support. Its successful functioning is possible provided that there is high-quality source data, competent personnel, legal and organizational support mechanisms, and constant infrastructure updates [1,2,6].

1.2 Fundamentals of spatial data in urban management

Geodata plays an important role in modern urban management, as it allows for the description, analysis and visualisation of various spatial phenomena and objects that form the urban environment. In scientific research and practical urban planning activities, spatial data is the foundation for strategic and tactical decision-making [6]. It covers information about roads, buildings, green areas, engineering infrastructure, demographic indicators, environmental parameters, etc.

In general, the concept of ‘geodata type’ refers to the format and structure of spatial information storage, methods of its collection and ways of representation in geographic information systems. Depending on the nature of the spatial representation, geodata can be divided into several basic categories: vector, raster, three-dimensional (3D), time-spatial, and metadata. In addition, depending on the application in specific urban management tasks, network data, remote sensing data (satellite and aerial photographs), etc. are also distinguished.

1. Vector geodata [4]. The vector format is one of the most popular in GIS systems, especially when it comes to describing objects with clear spatial boundaries. In the vector approach, all elements of the model are described using geometric primitives: points, lines (arcs) or polygons (polygons). Each primitive has spatial coordinates that indicate its location on the map.

Point objects usually model real objects that occupy a small area compared to the display scale or do not have dimensions that are important for analytical description. In urban management, point objects can represent, for example, lampposts, road signs, fire hydrants, post boxes or tree plantings.

Linear objects describe phenomena that extend in space along specific routes or communications. Road networks, pipelines, power lines, railway tracks, and bicycle paths are all examples of linear objects that form the basis of urban infrastructure. Linear objects can be represented as sets of segments connecting points (nodes) of the network. For such geodata, information about the length of the object, throughput (for transport networks), material (for pipelines), type of pavement (for roads), etc. is important. In the analysis of transport infrastructure, linear objects allow you to study and model traffic, plan new public transport routes, and assess the impact of road closures on the mobility of residents [4,6].

Polygonal objects are used in situations where it is necessary to display areas with clear boundaries and measurable area. For example, buildings, land plots, neighbourhoods, parks, artificial reservoirs, administrative districts or any other spatial units that have their own boundaries. Polygons are formed by connecting a sequence of points into a closed line. In urban management tasks, polygonal geodata is most important for spatial planning, zoning, cadastral registration, monitoring the state of development, planning green areas, etc. [6].

Vector geodata is characterised by high accuracy and suitability for topological analysis [6]. Thanks to topological relationships (e.g., 'adjacency,' 'belonging,' 'intersection'), it is possible to quickly identify neighbouring buildings, find optimal routes between points (nodes), and perform buffering — creating zones of influence for a specific object. A big advantage of vector data is the ability to relatively easily change the scale and projection while maintaining the clarity of lines and boundaries.

2. Raster geodata [4]. Unlike the vector model, the raster model describes space as a set (matrix) of pixels (cells), each of which has a specific value of some characteristic (color, reflection, etc.). Most often, this type of geodata is used for images — satellite images, aerial photographs, scanned maps. However, raster data is also used to display continuous fields such as elevation, temperature, humidity, etc.

Satellite images and aerial photographs. Thanks to the development of space technology and unmanned aerial vehicles, cities have access to a huge number of high-resolution images. For example, satellite data allows for the analysis of building dynamics, the state of green areas, and the level of urbanization. For urban management, this opens up opportunities to quickly assess the consequences of natural disasters (floods, fires), plan capital works, and identify illegal construction. Aerial photographs taken from UAVs provide more detailed views of individual areas or construction sites, allowing micro-level problems to be identified (e.g., roof damage, condition of facades) [6].

Digital terrain models [6]. A digital terrain model is an example of raster data where each pixel represents the height of the surface above a specific geodetic datum. In urban management, DMRs are used to analyse engineering networks (e.g., drainage schemes), plan construction work on complex terrain, and assess flood risks. Based on DMRs, it is possible to create derivative products — maps of slope steepness, slope orientation, analyse catchment basins, etc.

Thematic rasters [6]. In addition to images themselves, there are ‘thematic’ rasters, where each cell has not a colour shade, but a categorical or quantitative value (e.g., land cover type, population density, noise level). Such data can be the result of classification of satellite images or remote sensing data, as well as various geostatistical interpolation methods.

In general, raster data is ideal for analyzing continuous phenomena and visualizing surfaces, while vector data is better for displaying objects with clear boundaries. Hybrid approaches are often used in urban management, where raster and vector data are integrated within a single GIS to achieve maximum information content.

3. Three-dimensional (3D) geodata [7]. Modern GIS tools increasingly offer three-dimensional visualization of urban landscapes. Given the complexity of the urban environment, 3D models are particularly useful for a number of tasks:

- modelling architectural and construction projects;
- analysing insolation (the amount of solar radiation on facades or plots);
- determining noise impact zones;
- checking visibility (for example, when placing advertising structures or security cameras);

- assessing the impact of new high-rise buildings on the city skyline, etc.

Three-dimensional geodata can be obtained from various sources. Popular methods include laser scanning (LiDAR), which provides high accuracy of terrain and building outlines. Photogrammetry using drones, which take a series of overlapping images, also allows you to create 3D models. In addition, there are ready-made databases of 3D buildings in CityGML, KML, and other formats. All of this data contains the geometry of objects and possible additional semantic attributes, such as facade material, number of floors, and building purpose [6].

Three-dimensional models allow you to virtually ‘walk’ through the streets and assess how the proposed development project will fit into the existing environment. To calculate insolation or shading, software packages use spatial geometry algorithms to analyse at what times of day the sun's rays reach different areas or how shadows from tall buildings spread. This is particularly relevant in dense developments, where the issue of living comfort is directly related to natural lighting. Such analyses are also useful when choosing locations for solar panels or green roofs [5].

In addition to the ‘above-ground’ part, cities have an extensive system of tunnels, collectors, and engineering networks. Some modern GIS allow you to create 3D models of underground infrastructure, which helps to coordinate repair work more efficiently and avoid damage to communications during construction.

4. Temporal (temporal-spatial) geodata [8]. In an urban environment, everything is constantly changing: new buildings appear, the transport network changes, the population of a particular area grows or decreases, etc. Therefore, a static snapshot of a city at a given moment in time may not be sufficiently informative. Spatio-temporal data allows us to analyse the dynamics of urban processes over time.

Examples of temporal changes:

- Expansion of development: how the city limits have gradually changed, where new areas have appeared, what was the original use of the land.

- Transport flows: at what times traffic jams occur, which routes are congested during peak periods.

- Demographic processes: changes in population size, age structure, migration flows between districts.

- Environmental conditions: monitoring of air pollution, noise levels, and the number of green spaces over several years.

To implement time slices in GIS, each object stores spatial and temporal information: creation date, update date, period of validity. This makes it possible to ‘play back’ changes over a certain period of time, identify trends and predict future scenarios for the city's development. In particular, tools for animating temporal and spatial data allow you to visually see the evolution of a neighbourhood's development or changes in the landscape [8].

Network geodata. In the context of urban management, it is often necessary to work with ‘networks’ — transport, engineering, and information networks. Network data contains nodes and edges (lines) that describe the complex infrastructure through which people, transport, water, electricity, etc. flow [8].

Analysis of transport networks (roads, bus routes, railways) makes it possible to determine the optimal routes, calculate travel time, and identify congestion points and intersections with high accident rates. In cities with smart planning, public transport data is updated in real time, allowing bus and tram movements to be tracked and congestion to be responded to quickly.

Thanks to network geodata, it is possible to coordinate the laying and repair of gas pipelines, water mains, heating mains, and electrical cables, minimising costs and inconvenience to the population. If the layout of underground utilities is known, in an emergency situation it is possible to quickly determine which areas will be affected and how to shut off the damaged section to minimise losses.

6. Remote sensing data [10]. Modern methods of remote sensing of the Earth (RSE) provide a wealth of material for urban management. The use of satellite images or aerial photographs provides operational information on the state of buildings, green spaces and water bodies. In addition to visual analysis, spectral analysis is used in research to identify specific features (types of vegetation, thermal anomalies, pollution).

Images can contain data in different ranges of the electromagnetic spectrum (visible, infrared, ultraviolet, etc.). Processing such images makes it possible to distinguish between different types of surfaces: asphalt, concrete, soil, grass, trees. In urban planning, this is important for land inventory, green space planning, and detection of illegal construction [10].

Radar satellites (e.g., Sentinel-1) can operate regardless of cloud cover and time of day, allowing data to be obtained on soil movement, building subsidence, and the presence of floods and flooding. For megacities with tall buildings, radar interferometry is an effective method for monitoring the stability of structures [10].

7. Metadata [8]. Metadata is ‘data about data’ that describes the source, author, creation time, collection methods, accuracy, projection, and other key attributes of the geodata itself. In urban management, metadata ensures transparency, reproducibility, and compatibility of data between different departments and institutions. For example, if the transport department has layers with roads and routes, and the cadastral department has information about land plots, then in order to merge them seamlessly, it is necessary to know the coordinate system and storage format. Metadata helps to quickly assess the suitability of a dataset for a specific task and prevent errors associated with incorrect sources.

There are international and national standards for metadata formatting, such as ISO 19115. Within the European Union, the INSPIRE Directive requires structured approaches to the formation of metadata for spatial information. This increases interoperability and facilitates data exchange between government agencies [9].

The accuracy, relevance and completeness of geodata is particularly relevant for urban management. If a road network database contains outdated information or missing streets, this can lead to routing errors and unnecessary road repair costs. Therefore, data collection and updating requires clearly defined regulations, the use of reliable sources, and the application of proven verification methods [9].

The variety of geodata types — vector, raster, 3D, spatiotemporal, network, remote sensing data, as well as metadata — create a universal basis for comprehensive analysis and management of urban areas. The successful functioning of a modern city largely depends on the ability to implement and maintain an up-to-date, accurate, and high-quality spatial data base. Combining different types of geodata within integrated GIS solutions helps to optimise infrastructure, ensure environmental stability, improve service delivery to the population and promote balanced planning for future development [9].

Spatial objects are a basic concept in the geoinformation environment, particularly in the context of urban management. They cover all entities that can be displayed on a city plan or geographical map and have a specific geographical location [11]. Spatial objects reflect real elements of urban infrastructure: buildings, roads, bridges, parks, engineering networks, as well as natural components (rivers, reservoirs, relief) and administrative boundaries. Their clear definition, classification and analysis form the basis for decision-making in urban planning, transport flow organisation, land resource management, environmental monitoring, etc. [4].

In the most general sense, a spatial object is any entity that can be identified and located in geographical space using coordinates. Geographic information systems allow you to store and process not only the geometry (shape and location) of an object, but also descriptive attributes – textual or numerical information about it. In an urban context, attributes may include data on the owner of the building, year of construction, number of floors, functional purpose, construction materials, availability of communications, etc. [6].

Thus, a spatial object in urban management plays a dual role [11]:

1. Geometric representation. Where exactly it is located, what it looks like in terms of shape, size, and orientation.

2. Semantic content. What function the object performs, what class it belongs to, what characteristics it has (e.g., number of residents in a building, level of amenities, etc.).

Given the vector data model, spatial objects are mostly considered in the form of points, lines, and polygons. However, in modern GIS practice, there are also more complex types (e.g., 3D objects and multi-component objects).

1. Point features. These are the simplest in terms of geometry. A point indicates a specific location in space using two or three coordinates (X, Y, sometimes Z). On a city scale, point features can represent small but numerically significant infrastructure elements: lampposts, rubbish bins, public transport stops, road signs.

2. Line features. Lines represent objects that are elongated in one or more directions and have a length but a negligible (or formally zero) width compared to the display scale. These include roads, pipelines, power lines, bike paths, rivers (in cartographic simplification), and railway tracks.

3. Polygon features. Polygons are used when referring to areas with clearly defined boundaries and measurable areas. These can be parks, neighbourhoods, reservoirs, football fields, industrial zones, administrative districts, and buildings.

4. Multi-part Features. They consist of several separate geometric components but are semantically combined into a single entity.

5. 3D Objects. With the spread of 3D modelling in GIS, it is now possible to store and display not only a two-dimensional projection of an object, but also its height, depth, or more detailed geometry. Three-dimensional spatial objects make it possible to recreate a building with all its architectural elements, without being limited to a projection ‘from above’.

Topology in geographic information systems defines the rules of spatial adjacency and interaction between objects [9]. Topology is extremely important in an urban environment because:

- Adjacency allows you to identify which polygonal objects (e.g., districts) are adjacent to each other.

- Intersection helps to determine which infrastructure layers are in a common area (e.g., roads and communication networks).

- Disjointness indicates that two objects do not have common points (e.g., when separate buildings do not overlap).

- Containment is important for objects that are completely contained within others (e.g., a lake inside a park).

Thanks to topology, you can create 'smart' queries: find all buildings adjacent to a main street, identify intersections of utility networks, determine the list of houses within a certain area, etc.

In addition to purely geometric parameters, each object has a set of attributes that describe its essence and functions. In urban management, these attributes can be extremely diverse [4]:

- Identification: unique code or name of the object (e.g., street name, cadastral number of the plot, building code).

- Address: address, postcode, street reference, house number.

- Operational: date of last inspection, repair status, presence of technical malfunctions.

- Legal: form of ownership, permits and licences, registration data.

- Historical: when the object was built, whether it has the status of an architectural monument, whether renovations have been carried out.

- Socio-economic: type of use (residential, commercial, industrial), number of residents, household composition, etc.

Such semantic content allows for in-depth analytical research. For example, urban planning can take into account the age of buildings, their population density, access to public spaces, and noise pollution levels. Attributes can also be variable over time, which allows tracking the dynamics of changes — for example, recording an increase in the number of residents, re-profiling of industrial zones, replacement of engineering networks [6].

Thus, spatial objects are the basic unit in decision-making processes. Knowledge of their geometric, topological, and attributive characteristics is crucial for many areas of urban management: from land management to transport development, from environmental monitoring to ensuring comfortable living conditions for residents. It is thanks to appropriately structured and well-maintained sets of spatial objects that a city can develop in a balanced and effective manner, responding to contemporary challenges and providing a database for smart technological solutions.

Coordinate systems play an extremely important role in urban management, as they enable the unambiguous determination of the location of objects on the Earth's surface and ensure the consistency of spatial data within various GIS projects. If there is no single agreement on coordinates, data from different sources may not match and lead to significant errors in the design, construction, and operation of engineering networks, transport systems, and other elements of urban infrastructure [9]. Thus, coordinate systems are the ‘language’ of geodesy, cartography, and geoinformatics, which is used by all specialists dealing with spatial information. In urban management, geographic and projection (flat) coordinate systems are most often used, and many cities may also have local systems designed to solve problems at the local level. Understanding the principles of constructing and applying coordinate systems is necessary not only for surveyors, but also for architects, builders, urban planners, and ecologists who plan and carry out work related to spatial objects and processes [11].

Historically, the first coordinate systems were geographical, based on latitude and longitude. They are the most natural for describing objects at the global level, as they reflect real angular distances on a reference ellipsoid or spherical model of the Earth. Each point is defined by a combination of latitude (angle from the equator) and longitude (angle from the zero meridian, usually Greenwich). These angles are often expressed in degrees, minutes and seconds or in decimal format. In practice, geographic coordinates are useful for displaying objects on global or regional maps, as well as for reconciling data from GPS/GNSS receivers, satellite imagery, or other remote sensing methods. However, for most urban planning tasks, where planes and straight-line distances are important, geographic coordinates are inconvenient due to the curvature of the Earth's surface and the complexity of performing calculations on a spheroid or ellipsoid. Therefore, the geographic coordinate system or the results of satellite measurements are usually converted into some kind of projection [4,6].

The concept of ‘cartographic projection’ implies a mathematical method of mapping (projecting) the Earth's surface with its curvature onto a plane, while preserving or approximating certain metrics: areas, shapes, distances or directions [6]. No projection can perfectly avoid distortions, so the choice of a specific projection always involves a compromise between different properties. In urban planning, projections that minimise distortion within relatively small areas of a city or region are most often used so that the metric characteristics (lengths, angles) differ as little as possible from the 'real' ones on the Earth's surface. For example, universal transverse cylindrical projections, such as UTM (Universal Transverse Mercator), have become widespread in a number of European countries and around the world, where the entire surface of the Earth is divided into zones, each with its own local coordinate system. At the same time, for some countries, including Ukraine, there are state coordinate systems based on the Gauss-Krüger projection or newer developments, such as USK-2000 (Ukrainian Coordinate System 2000), which take into account the necessary geodetic references and parameters [4].

Urban management requires coordination of coordinates during land surveying, cadastral procedures, urban planning, geoinformation research, and engineering surveys. If different departments or contractors use different coordinate systems and projections, confusion arises: vector data layers may differ by metres or even tens of metres. For construction and cadastral purposes, such a shift is unacceptable, as it can lead to incorrect determination of land boundaries, inaccurate design of roads and engineering networks, incorrect calculations of earthworks, etc. Therefore, city authorities or relevant state bodies usually establish mandatory or recommended coordinate systems for project work. In Ukraine, for example, the SK-42 system (and its derivatives) was previously in use, then SK-63 was applied, and more recently, USK-2000 has been introduced. USK-2000 is based on a nationwide geodetic system linked to international standards (WGS-84), which enables accurate alignment of data with global sources (e.g. GPS). However, the coordinates in this system differ from geographical latitudes and longitudes: each point has 'flat' coordinates (X, Y) in metres from a specific reference line based on a transverse cylindrical projection [6,9].

As for geographic coordinate systems, they are based on latitudes and longitudes, as already mentioned. These angles can be considered on different models of the Earth, but in fact, the de facto standard for global applications (e.g., GPS, Galileo) is WGS-84. If a city has its own geodetic network that is aligned with another datum, systematic displacement may occur when GPS coordinates are used directly without transformation. This issue is very relevant for anyone involved in collecting geodata ‘in the field’: for example, utility workers who use field GPS receivers to record the location of manholes, poles, storm drains, etc. If they do not know or do not take into account the difference between WGS-84 and UCS-2000, these points may subsequently ‘drift’ by several metres when combined with cadastral data [9].

Therefore, the correct selection and coordination of coordinate systems is a prerequisite for the effective functioning of GIS in urban management. Most urban tasks require flat coordinates for ease of measurement and calculation, but these coordinates must be linked to a single state system, which in turn is based on a defined reference ellipsoid and datum.

1.3 Geodata in urban management

The formation of an effective geoinformation system for urban management involves the integration of various data sources that reflect the structural, functional and spatial characteristics of urban infrastructure. Current trends in urbanisation, digitalisation and dynamic changes in the urban environment, as well as the completeness, accuracy and relevance of sources, are becoming important for ensuring continuous monitoring, planning and management of infrastructure facilities [1,2].

One of the main features of data sources in the field of urban management is their heterogeneity, both in terms of format and method of acquisition. In particular, data can have both raster and vector structures, be primary or secondary processed, arrive in real time or be updated periodically. Such heterogeneity necessitates the standardisation of data collection processes, the unification of metadata, and the development of an effective integration system on the GIS platform [3].

The information support of the urban management system includes numerous thematic layers, the sources of which are state cadastral and registration systems, topographic surveys, urban planning documentation, project materials, as well as modern means of remote sensing of the Earth. Data from engineering services — water supply, heat and power, electricity networks, gas utilities — which have databases on the technical condition and location of underground and above-ground communications, play a significant role. These sources form the basis for creating the infrastructure framework of the GIS, which allows the functional structure of the urban environment to be displayed in space and time [2,4].

An essential component of the information content is the results of geodetic and topographic surveys, which provide accurate geospatial positioning of infrastructure objects. Such data are obtained using tacheometric surveys, GNSS technologies, laser scanning, mobile mapping and photogrammetric methods. Their combination with archival materials allows updating digital models of urban areas, taking into account physical wear and tear, reconstruction and new construction [5,6].

Remote data sources based on high-resolution satellite imagery, as well as aerial photography and UAV imaging products, play a special role in modern conditions. They make it possible to detect changes in the urban environment with high frequency and minimal costs. In addition, remote sensing can be used to obtain data on green areas, building density, road surface distribution, flooding areas or thermal anomalies, which is extremely important for strategic planning [3,7].

It is also important to note that urban infrastructure is increasingly moving towards a digital twin model, where data is sourced from modern tools and equipment that record the parameters of objects in real time: temperature, pressure, resource consumption, traffic intensity, etc. The collection of such data is automated, which significantly increases its efficiency, but at the same time requires the implementation of effective mechanisms for validation and management of information flows [4,8].

Thus, urban infrastructure data sources form a multi-level information system that covers static and dynamic parameters of urban space. Their integration into a single digital environment based on GIS is a task for improving the effectiveness of management decisions, ensuring sustainable urban development and improving the level of service for citizens [1,6,8].

The process of creating and collecting information for the purposes of geoinformation support of urban management is an important stage in the formation of an effective system for managing the city's spatial resources. The accuracy of analytical conclusions, the validity of management decisions and the effectiveness of urban development planning depend on the quality, completeness and relevance of the data. In this context, information collection is not limited to recording the physical characteristics of objects, but also includes attributive, legal, technical, and social parameters that ensure a multifaceted description of urban infrastructure [1,2].

The creation of urban infrastructure geodata bases usually begins with the design of an information model, which involves defining the types of objects (buildings, roads, networks), their spatial structure (points, lines, polygons), coordinate systems, metadata, and logical relationships between elements. This process is carried out in compliance with international and national standards, such as ISO 19100 or DSTU-N B V.2.1-18:2016, which regulate the construction of geoinformation databases [3,4].

With regard to direct data collection, modern practice involves the use of a wide range of methods and technologies. First and foremost, these are geodetic instruments: electronic total stations, GNSS receivers, digital levellers, and laser scanners. They are used for high-precision positioning of infrastructure objects, creation of topographic plans, and construction of 3D models of buildings and engineering networks. Total station surveys are used to form a reference network, and GNSS methods allow you to quickly fix the coordinates of objects even in dense buildings, provided that RTK technologies or post-processing are used [5].

Remote sensing methods play a significant role in data creation. Satellite imagery, aerial photography, and unmanned aerial vehicles provide effective monitoring of buildings, green areas, road infrastructure, and changes in land use. Thanks to their high update frequency and spatial diversity, modern satellite platforms (Sentinel-2, WorldView, PlanetScope) are becoming an indispensable source of operational geodata [6,7].

In addition to primary collection, the process of digitising archival information plays an important role. Much of the technical documentation on engineering networks, transport schemes, and historical buildings is stored in the form of paper materials that need to be scanned, georeferenced, and vectorised. Digitisation allows such data to be integrated into GIS and compared with the current state of objects. Cartometry, a method of reading coordinates and semantics from ready-made digital plans and diagrams, is also actively used [2,8].

The latest approaches are focusing more on automated ways to collect info. Mobile apps and web services let both municipal workers and regular folks report changes in the urban environment, like damaged roads, illegal construction, or lack of amenities. Such tools are actively integrated into the Smart City system and ensure rapid enrichment of GIS data in real time [4,9].

One of the problems in collecting information is ensuring its accuracy, completeness and relevance. These parameters are determined by the quality of the equipment, as well as the collection methodology, staff preparedness, the availability of reference databases and the regularity of data updates. Thus, modern systems contain information about the objects themselves, as well as a history of changes, which is stored in the form of journals, logs and versions [3].

Thus, the creation and collection of information for urban infrastructure GIS is a complex multi-stage process that combines traditional geodetic methods, remote technologies, digitisation of archives and the latest mobile solutions. Effective management of this process provides a high-quality spatial basis for supporting the functioning of all links in the urban economy — from engineering to the social sphere [1,5,9].

1.4 Integration of different types of data into urban GIS

The integration of different types of data into the urban GIS is a decisive step towards creating a comprehensive ‘digital twin’ of the city, covering all aspects of urban space – from infrastructure and transport systems to environmental monitoring and socio-economic processes. This allows management departments and specialists from various fields to operate a single information base in which data on roads, buildings, engineering networks, demographics, natural resources, and historical monuments are available in a harmonised form [6]. However, the very idea of ‘integration’ is quite complex from a technical and methodological point of view, as it involves taking into account a multitude of formats, structures, projections, scales and data sources. In urban management, it is often necessary to deal with different formats of geodata (vector, raster, 3D models), thematic layers (transport, ecology, cadastre, urban zoning) and the procedure for converting one format into another. Below is a summary of the key aspects that should be mastered when building a unified urban GIS, focusing on the study of formats, information layers, and data conversion methods [8].

In terms of geodata formats, it is worth mentioning that the vector format (Shapefile, GeoJSON, GML, KML, etc.) is still the most common for storing objects with clear geometric boundaries. Shapefile, familiar to GIS specialists, consists of several files (.shp, .shx, .dbf, .prj), where .shp stores geometry, .dbf stores attribute information, and .prj stores projection. GeoJSON, on the other hand, stores all information (both geometry and attributes) in a single JSON file. In some cases, KML is widely used in urban environments, as it is well suited for displaying data in Google Earth, or GML (Geography Markup Language) when it is necessary to follow OGC (Open Geospatial Consortium) standards and store complex structures or object hierarchies.

At the same time, the GeoPackage format (based on SQLite) is gradually replacing Shapefile in more advanced GIS projects, as it allows you to store multiple layers and their styles in a single database. For complex 3D models required in urban planning, CityGML is increasingly being used – a format that allows not only to store three-dimensional geometry, but also to link semantic information to it at the level of individual elements of the facade, roof, floors [9].

Raster formats (GeoTIFF, JPEG 2000, IMG, and others) are mostly used for satellite images, aerial photography, and digital terrain models. GeoTIFF is distinguished by the fact that it contains georeferencing directly in its header, so GIS software immediately determines the coordinates and projection of the image. JPEG 2000 allows for significant data compression, but possible quality losses must be taken into account. For storing complex scenes (complex 3D terrain or building models), LAS/LAZ formats (for LiDAR data), BIM formats (IFC), or the aforementioned CityGML can be used. Integrating with this data is quite difficult, as it differs in structure and logic of storing spatial and attribute elements [9].

When organising layers of information in an urban GIS, the concept of 'layering' plays an important role, which involves dividing the common spatial data base into logically or thematically separate sets of objects [9]. For example, one layer may contain the road network, another may contain buildings, a third may contain green spaces, a fourth may contain administrative boundaries of districts, and a fifth may contain hydrography.

This approach allows you to independently control the display of different types of geographic information: turn layers on and off, filter by attributes, and apply different styles. When it comes to large scales (1:1000, 1:2000), there is a need to create more detailed layers, for example, buildings are divided into separate types (residential, industrial, public, historical). In the transport layer, in addition to the actual street lines, there may be separate layers for traffic lights, signs, stops, parking areas, and bicycle lanes. Network communications (water pipes, heating mains, electrical and communication cables) are often organised in their own layer for easier analysis and design [11].

An important aspect is that urban GIS layers can be stored in various formats and even in different database management systems [8]. In one project, a Shapefile may be used for buildings, in another — a GeoPackage for roads, in a third — PostGIS (a PostgreSQL extension) for cadastral information, and in a fourth — a raster database for aerial photographs. However, in the end, all of this must be harmonized into a single cartographic "scene" or a unified web portal where the user can freely switch between layers. This functionality is achieved through OGC standards: WMS (Web Map Service) for raster map renderings, WFS (Web Feature Service) for vector data, and WCS (Web Coverage Service) for raster coverages [4]. The use of these services facilitates integration between various geoportals and departmental systems, eliminating the need to duplicate all data — it is enough to connect to the appropriate web service.

The issue of data conversion is considered extremely relevant, as a city may receive information from historical drawings, scans, paper plans, archival documents, as well as from modern sources (GPS measurements, high-resolution satellite imagery, laser scanning, etc.). First, georeferencing must be performed — a process in which known control points with precise coordinates are tied to an image or plan. As a result, the scanned document acquires real coordinates and can be used as a raster layer. Second, there is the issue of digitization — converting the outlines of objects (roads, buildings, parcel boundaries) into vector form. A common model is having a historical master plan from which building polygons, road lines, etc., are manually or semi-automatically drawn, and then saved in Shapefile or GeoPackage format [11].

The next level of transformation is related to coordinates and projections. For example, older data may be in SK-42, while newer data is in USK-2000 or WGS-84. Integration requires the use of reprojection tools (for example, the ogr2ogr command in GDAL or the functionality of ArcGIS and QGIS), with mandatory specification of the source and target projection (EPSG codes) and transformation parameters [11]. If this is not done correctly, the layers may be offset by several meters or even tens of meters, which is unacceptable for technical work. When a high level of accuracy is required (centimeter or decimeter), additional calibration on benchmarks, determination of shifts, rotations, and scale coefficients may be necessary. Such procedures require geodetic expertise.

Another important task is the harmonization of classifiers and semantics [9]. Data from different departments may use different names for the same type of object: in the transport department, "roads" may be classified as "expressways," "local streets," or "public roads," while in the cadastral register these same objects may have completely different terminology. Therefore, at the integration stage, unified directories of object types and their attributes must be established so that, for example, "residential building" in one database corresponds to "residential building" in another, and is not merged with "public building" or "industrial facility." Such harmonization is often referred to as "semantic transformation." If it is not carried out, the building layer may be loaded into the GIS, but different categories will not be distinguished, making analysis more difficult [11].

Given the wide range of tasks in urban management, transformation concerns not only the spatial component but also the attribute component: data on the year a building was constructed, its technical condition, or the number of residents may be stored as text files, basic Excel spreadsheets, or in external registries. The integration task involves importing this data into a GIS with linkage to an existing building polygon — using a unique identifier, address, cadastral number, or coordinates. Software platforms such as QGIS, ArcGIS, or PostGIS offer tools for joining tables by key fields (join, relate). When table formats are inconsistent, it may be necessary to additionally use Python scripts or other methods to clean and reformat attributes before joining [9].

Special attention should be paid to modern web-integration and distributed data storage technologies, where the "don't duplicate, connect" principle comes to the forefront. For large raster datasets (e.g., aerial photography) occupying tens of gigabytes, it is advisable to deploy a dedicated server (GeoServer, MapServer) that provides access via WMS or WMTS. In this way, all other subsystems of the urban GIS (cadastral, transportation, environmental, architectural) can request these raster backdrops for visualization. This approach simplifies updating and administration: it is sufficient to update the database on a single server, and all others immediately receive up-to-date layers without the need to duplicate them.

The same applies to vector data: through WFS, a road layer can be made available to various departments in real time. However, if the design department uses this data and makes changes (e.g., adding a new road section), integration must be two-way: either the person working in the GIS has editing rights via a transactional WFS (WFS-T), or there is another mechanism that allows centralized saving of changes. This is how the concept of a "single window" for access to spatial information is implemented.

1.5 Creation and Management of Geospatial Databases for Urban Management

One of the most important features of a geospatial database for urban management is the need to integrate large volumes of heterogeneous information. This includes data from administrative-territorial divisions, address registers, real estate cadastre, transportation networks, utility infrastructure, and statistical reports. According to standard practice, each type of data is stored in specialized layers; however, all of them must be harmonized in terms of coordinate systems, formats, and attribute fields. This enables the execution of complex spatial queries — for example, determining all objects located within a certain distance from main gas pipelines or identifying areas where air pollution levels exceed established standards (fig. 1.1).

The figure schematically shows how different streams of information (address register, cadastral records, statistics, utility networks) "flow" into the core of the city's unified geodatabase. Each source is stored in its own layer, yet the end user can perform consolidated analysis of all layers simultaneously.

A city has a complex hierarchy of territories, including administrative boundaries (e.g., districts, neighborhoods), functional zones (residential, industrial, recreational), public facilities, and infrastructure (roads, parks, power lines). Therefore, when designing a geospatial database, it is important to provide a logical model that will [12]:

1. Ensure hierarchy nesting (for example, buildings belong to blocks, blocks belong to districts, and districts belong to the city).
2. Preserve thematic differentiation (each object must have the appropriate classification, as residential development has different characteristics than industrial zones).
3. Support the necessary spatial relationships (adjacency, intersections, containment, "snapping" of boundaries).

This approach makes it possible to execute queries such as: "Find all buildings within the historic city center that have the status of architectural heritage" or "Identify industrial enterprises within walking distance of residential blocks.” The ability to answer such questions significantly increases the efficiency of territorial management and assessment of the urban environment [7].

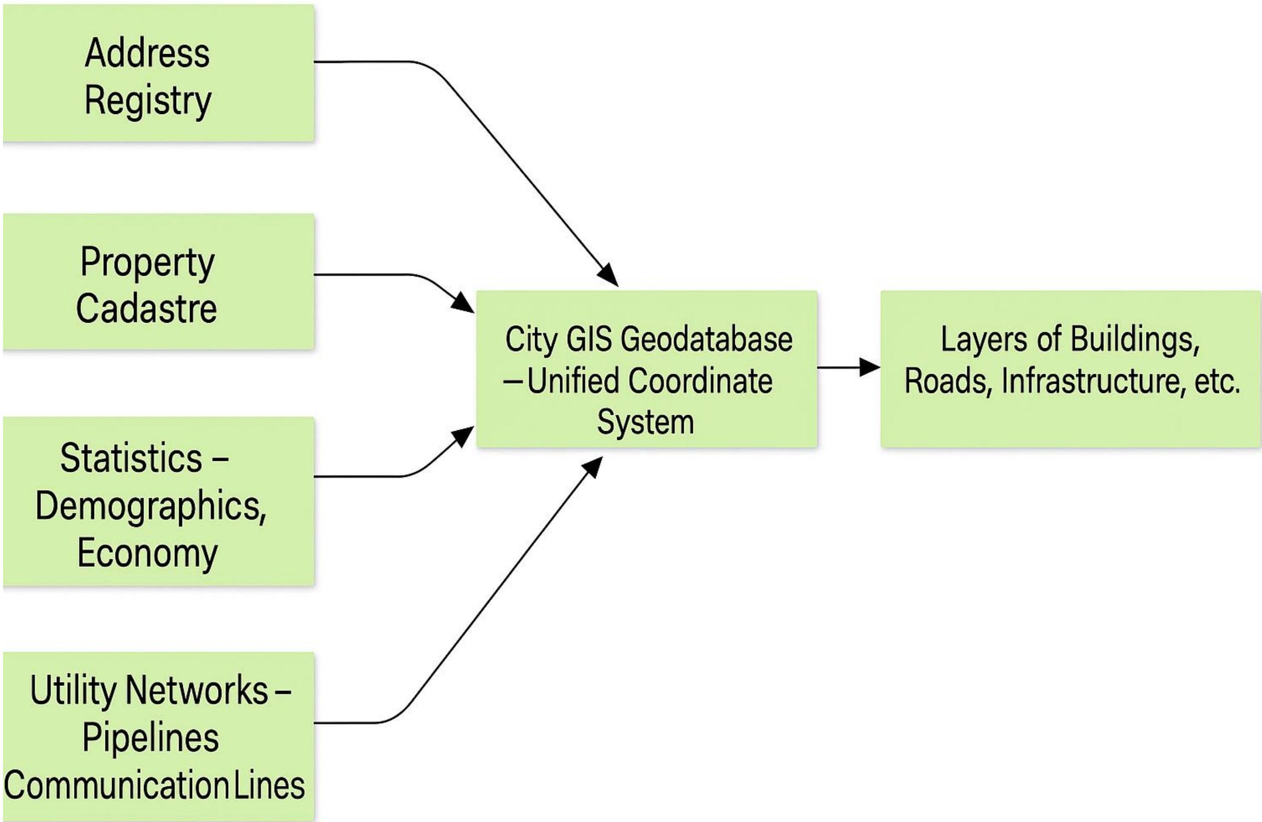

Fig 1.1. A Schematic Representation of Heterogeneous Data Sources Integrated into a Unified Urban Management Geodatabase

Since urban management involves working with precision data (such as the exact location of buildings and utility network nodes), there is a need to use a unified or mutually compatible coordinate system. Several standards exist; however, at the municipal level, national or regional systems (for example, USK-2000 or other locally harmonized systems) are often applied, as they help minimize errors during field measurements or cadastral works [9].

It is important to ensure data format standardization, particularly when exchanging information with other agencies. For this purpose, formats such as GeoJSON, GML, and GeoPackage, which comply with Open Geospatial Consortium

(OGC) requirements, are actively implemented. This approach facilitates data integration and enables multiple reuse across various subsystems of urban management [11].

In the urban environment, it is often necessary to perform complex topological checks: block boundaries must not overlap, and utility networks must be represented in such a way as to clearly identify their intersection points and junctions. Therefore, during geodatabase design, it is crucial to define topological rules:

- No gaps or overlaps: boundaries of adjacent parcels must coincide along their shared border.
- Nodes and edges: the system must "know" exactly where linear objects connect (for example, two streets or multiple sewer collectors).
- Correct spatial orientation: if an object is an internal polygon (e.g., a lake within a park), it must be intact and embedded within the larger polygon of the park.

Violations of topological consistency lead to errors during spatial calculations or map rendering: for example, automated procedures may fail to recognize adjacent parcels as neighbors if a microscopic "gap" remains between them due to incorrect boundary drawing.

An urban management geodatabase must be designed from the outset with consideration for large volumes of information and future expansion. Urban areas are constantly changing: new construction is carried out, utility networks are upgraded, and demographic conditions evolve. Therefore, it is important to provide for:

1. An optimal indexing structure: spatial indexes that facilitate the search and filtering of objects by coordinates.
2. Backup mechanisms: large volumes of spatial data require reliable tools for storage and rapid recovery in case of failure.
3. Support for cloud or distributed systems: at the scale of a large city, database clusters are often used, allowing simultaneous processing of requests from numerous users.

The success of an urban management GIS largely depends on how effectively the geodatabase can "communicate" with other departmental systems — such as accounting, administrative, and e-government systems. This enables the automation of various processes (fig. 1.2):

- Permit issuance: when information on construction, property owners, and planning restrictions is received directly from the GIS.
- Electronic queues and registers: which use data on object locations and zoning.
- Emergency response systems: for example, displaying on the map the nearest fire hydrants and the address of an emergency incident.

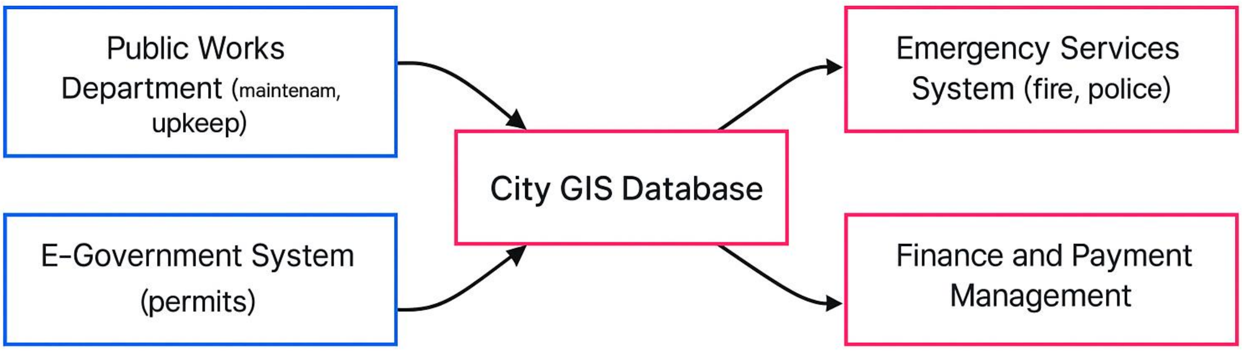

Fig 1.2. Diagram of GIS Geodatabase Interaction with Related Urban Management Services

The figure illustrates how the GIS database serves as a central "hub" to which various municipal services are connected. Each of these services has its own spatial data needs and, at the same time, can enrich the database with up-to-date information about changes.

Thus, the key features of designing an urban management geodatabase lie in the need to integrate heterogeneous information sources, build a hierarchical structure of urban objects, ensure topological consistency and scalability, and maintain security and version control. A properly designed geodatabase becomes a powerful tool that enables the prompt acquisition of a comprehensive picture of the urban environment and supports informed decision-making in the fields of planning, management, and monitoring. These features form the foundation for project processes and the structuring of geoinformation.

Establishing a clear system for data storage and management within an urban management GIS involves a series of actions aimed at logically organizing, classifying, and linking different types of data. This concerns not only properly organized layers (vector or raster), but also how these layers “coexist” in a unified environment, ensuring multifunctional interaction. This section provides an overview of approaches to structuring data that help maintain relevance, searchability, and flexibility of analysis in an urban management GIS [14].

One of the important elements of geodata structuring is the division of information into thematic blocks (or “themes”), each reflecting a particular aspect of the urban environment [13]:

1. Administrative and territorial boundaries: districts, blocks, neighborhoods.
2. Engineering infrastructure: water supply, sewerage, power grids, heating networks.
3. Transport and road networks: highways, streets, intersections, public transport routes.
4. Real estate objects: buildings, structures, land parcels.
5. Natural and recreational areas: parks, water bodies, green spaces.
6. Socio-economic information: demographics, distribution of commercial zones, educational and medical institutions.

Each of these thematic groups can contain several layers (for example, “Residential buildings,” “Public buildings,” “Industrial buildings”). Such a structure simplifies access to the required set of objects and speeds up query execution, as it eliminates the need to search through the entire database, allowing users to immediately focus on the relevant layer [6].

In urban management, there are dozens, if not hundreds, of object categories — ranging from types of roads and utility lines to the functional designation of land parcels. To avoid confusion, GIS uses classifiers (lists of allowable values) and reference tables (with information on object codes and names). For example, for buildings [6]:

- Code “Ж” – residential,
- Code “П” – industrial,
- Code “Ад” – administrative.

The presence of such reference tables ensures consistency between different modules and allows search automation: instead of typing “residential building” each time, a filter such as “code = Ж” can be used. This is especially important for large projects where many employees work simultaneously and data may come from different sources.

For each layer (for example, “Buildings”), a minimum set of attributes should be defined, without which an object has no meaningful value in the context of urban management. Such a set typically includes:

- Unique identifier (ID): so that each building or parcel has its own code, regardless of name or ownership changes.
- Object type (according to the reference table).
- Address or link to the address register.
- Area/dimensions (for polygons).
- Additional characteristics: number of floors, wall material, year of construction, availability of utility connections, etc.

It is important to clearly define which of these attributes will be mandatory (records cannot be entered into the system without them) and which will be optional. This helps maintain a balance between the sufficiency of information and the speed of data entry.

Often, within a single theme, there may be several levels of detail. For example, “Roads” can be divided into “Highways,” “Residential access roads,” and “Bicycle lanes.” The same applies to “Buildings” layers: multi-apartment residential buildings can form a separate layer, while individual housing development can be in another. Such hierarchy:

- Facilitates access: there is no need to switch on irrelevant layers.

- Promotes systemization: different departments can work with a single macro-layer “Buildings,” but filter it to show only the needed subtypes.

At the same time, it is important to keep the structure balanced: excessive fragmentation (dozens of layers under one heading) can complicate maintenance and hinder data retrieval [14].

In the urban environment, situations often arise where one object is related to several others. For example, a road may cross multiple districts, and a building may have multiple functions (residential with commercial premises on the ground floor). To address such cases, the following are sometimes used:

- Entity–relationship models with intermediate tables (for example, an “Object_Purpose” table where each record specifies the object ID and the purpose code).
- Nested polygons (for example, an enclosed area containing other objects within it).

It is especially convenient to create and maintain these relationships using relational or object-relational DBMSs (PostGIS, Oracle Spatial) that have built-in tools for storing spatial data while accounting for such relationships.

To improve database navigation and ensure data consistency, it is advisable to agree on naming conventions for layers, tables, and fields. For instance, each layer can have a prefix indicating its thematic group (e.g., RD_ for roads, BL_ for buildings), and fields should have clear, unambiguous names without abbreviations that could be misinterpreted. In addition, it is important to maintain metadata — describing the data source, date of collection, accuracy level, and author of changes. This helps quickly determine whether certain layers are outdated and identify the person responsible for updates.

The last, but extremely important, aspect is dynamic structure maintenance. The urban environment is constantly changing — new categories of objects appear (such as electric vehicle charging stations or new bicycle highways) and existing ones change (demolition of old buildings, reconstruction of utility networks). Therefore [11]:

1. Regular review intervals: auditing layers and attributes to check whether previously created fields are still relevant and to detect possible duplicates.

2. Ability to add new subtypes: for example, if there was no separate layer for EV charging stations before, it may be necessary to create one without disrupting the rest of the structure.

3. Merging and cleaning mechanisms: when data is obtained from multiple sources, discrepancies in coordinates or identifiers may occur, so the system needs automated and semi-automated validation tools.

Thus, structuring information for an urban management GIS is a process that goes far beyond simply "arranging data into layers." It is essential to ensure logical and thematic organization, plan relationships between tables and layers, establish clear naming rules, and maintain metadata. Only with a well-thought-out approach to structuring information can an up-to-date and consistent database be maintained — one that serves municipal services, city authorities, and the public in making informed decisions about urban development.

1.6 Metadata and Their Role in Geospatial Data Management

Creating metadata sets for urban management geographic information systems is a complex, multi-stage process that requires a systematic approach and strict adherence to established standards. The effectiveness of future use, search, exchange, integration, and updating of geospatial data depends on the quality of implementation at each stage [11].

Stage 1. Needs analysis and defining metadata requirements. The first and most important stage is determining the specific metadata requirements based on a thorough analysis of user needs and the specifics of urban management tasks. This stage includes the following activities [14]:

- Identifying the main stakeholders (government agencies, utility services, architects, engineers, urban planners, the public).

- Gathering requirements regarding the types of information to be described by metadata: technical parameters (formats, coordinate systems, accuracy), organizational access conditions (access levels, copyrights), requirements for data currency and update frequency.
- Establishing regulatory requirements and standards (for example, ISO 19115, INSPIRE, national standards of Ukraine) according to which metadata will be created [14].

Thus, the analysis stage provides the foundation for the entire metadata creation process, ensuring an understanding of which parameters are required and which standards should be applied.

Stage 2. Development of a conceptual metadata model [14]. At this stage, a generalized scheme for the metadata set is created, containing the main categories and attributes. The conceptual model helps to organize information in a convenient and understandable format, taking into account all essential aspects:

- Structuring metadata by categories (descriptive, technical, administrative, quality-related, origin information).
- Defining a set of attributes for each category (e.g., layer name, scale, accuracy, source, usage conditions).
- Aligning the model with international standards to ensure compatibility and integration of metadata.

The conceptual model serves as the basis for further implementation and guarantees unified approaches to metadata creation by all participants in the process (fig. 1.3).

Stage 3. Collection of primary information and dataset description. Once the conceptual model is in place, the process of collecting metadata information begins. This stage involves:

- Collecting and verifying primary data on existing datasets (layers) in the GIS.
- Interviewing responsible persons and data developers regarding the specifics of creating each layer (methods, accuracy, origin).

- Filling in metadata forms according to the chosen model for each dataset.

At this stage, it is essential to ensure the accuracy and completeness of the information, as this determines the quality of future use of geospatial datasets.

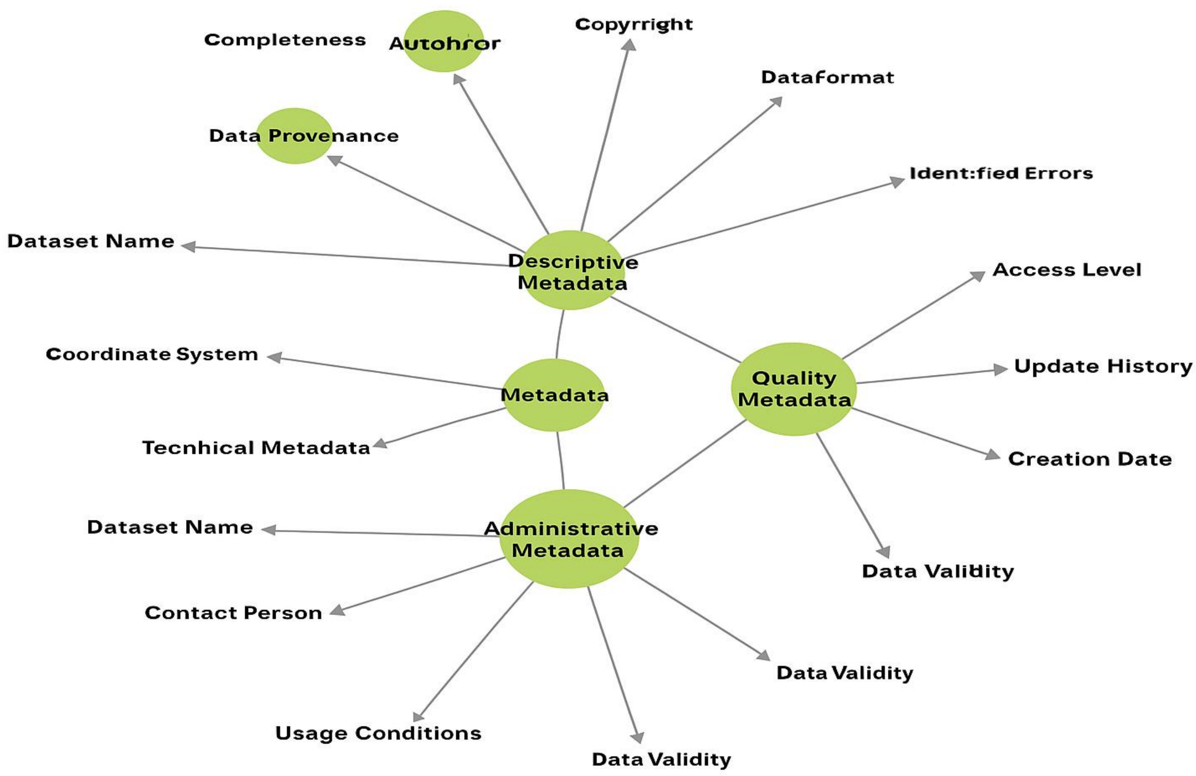

Fig 1.3. Conceptual Model of an Urban Management GIS Metadata Set

Stage 4. Standardization and formalization of metadata. After collecting primary data, metadata must undergo standardization and formalization:

- Converting the collected information into standard formats (XML, JSON, ISO 19139).
- Using specialized software products (e.g., GeoNetwork, ArcCatalog) that allow structured storage of metadata.
- Checking metadata compliance with current standards and correcting any inconsistencies.

Formalization ensures the ability to integrate metadata into global catalogs and national spatial data infrastructures.

Stage 5. Integration of metadata into catalogs and geoportals. Once formalized, metadata is integrated into specialized metadata catalogs, enabling convenient search and access to data:

- Creating a unified catalog of municipal geospatial data accessible to city users and services.
- Publishing metadata on geoportals, making it available to a broad range of users (the public, utility services, municipal administration).
- Providing interactive search mechanisms (by keywords, by geographic area, by dataset types).

Stage 6. Verification, testing, and quality control of metadata. This stage involves assessing the quality and completeness of the created metadata:

- Checking that all required fields are fully populated.
- Testing search queries to ensure the ability to retrieve information using metadata.
- Conducting periodic metadata audits to ensure relevance and accuracy.

Regular quality control builds a high level of trust in geospatial datasets.

Stage 7. Organization of regular updating and maintenance of metadata. The final stage involves creating mechanisms for regular updates:

- Establishing clear rules for updating metadata when geospatial data changes.
- Assigning responsible persons to maintain up-to-date information.
- Implementing automatic reminder and notification systems about the need for data updates.

Thus, the creation of urban management metadata sets is a cyclical and systematic process that ensures the effectiveness of geospatial data management, maintaining the relevance, quality, and accessibility of spatial datasets essential for the efficient functioning of the urban environment.

The management and storage of metadata in an urban management GIS is a complex process involving a range of activities, methods, and organizational procedures aimed at ensuring the effective use, accessibility, security, and relevance of information about geospatial datasets. In conditions of constant changes in the urban environment, the growing volume of data, and the intensive exchange of information between different services and organizations, high-quality metadata management becomes a decisive factor for the successful operation of the entire municipal GIS [14].

The main tasks of metadata management include [14]:

- Maintaining data integrity and consistency. Ensuring unified standards for dataset descriptions, controlling the correctness, accuracy, and completeness of metadata entries to avoid contradictions and duplication.
- Timely updates and relevance maintenance. Regularly updating metadata in response to changes in the geospatial data itself (for example, changes in map scales, updated cadastral boundaries, reconstruction of utility networks, etc.).
- Ensuring accessibility and transparency of information. Creating and maintaining metadata search systems, publishing metadata on geoportals and catalogs accessible to different user categories (authorities, utility services, the public).
- Organizing information security and access. Establishing clear rules for access to metadata, monitoring compliance with authorship rights and usage regulations to protect data from unauthorized use or confidentiality breaches.

For metadata storage, various specialized technical solutions are used that meet modern requirements for scalability, accessibility, and performance. The most common approaches include [12]:

- Relational Database Management Systems (RDBMS). For example, PostgreSQL with the PostGIS extension, Oracle Spatial, and MS SQL Server Spatial. These allow efficient storage and management of large volumes of metadata with indexing and advanced querying capabilities.
- Document databases and storage systems. Solutions such as MongoDB or ElasticSearch are well-suited for storing metadata in JSON or XML formats, offering fast keyword search and supporting system scalability.

- Metadata catalogs (e.g., GeoNetwork, ArcGIS Server). These specialized software products not only store metadata but also provide powerful search, access management, and integration capabilities with other GIS systems.

To improve the efficiency of metadata management processes, specialized tools are used [9]:

- Tools that automatically track changes in data and generate corresponding metadata updates (for example, automatically updating the "last modified" date or dataset parameters after new data is added).
- Web services and software modules that allow users to independently view, add, and edit metadata information, significantly simplifying the process of keeping it up to date.
- Systems that regularly check the quality and relevance of metadata, notifying responsible personnel when updates or corrections are required.

Access control for metadata in urban management is an essential component of information security. The following access levels are typically distinguished [11]:

- Public metadata sets that can be used by a wide audience, such as metadata on the city's master plan or public transportation network.
- Metadata for internal municipal use that includes information on utility networks, reconstruction projects, or detailed territorial plans, access to which is restricted.
- Metadata containing sensitive or strategically important information (e.g., the location of critical infrastructure, emergency response plans), where access is regulated with particularly strict controls.

An important aspect of management is ensuring the preservation of metadata. Given the importance of this information, the following methods should be applied [11]:

- Creating daily, weekly, or monthly metadata backups with the ability to quickly restore them.
- Using services such as AWS, Azure, or private cloud solutions to provide convenient access and secure storage with high reliability.

- Keeping historical versions of metadata in specialized archives for further analysis or audit.

In addition to technical aspects, the organizational structure of metadata management plays a key role [9]:

- Assigning specific specialists or departments responsible for maintaining metadata accuracy and quality.
- Clearly defining procedures for metadata creation, updating, quality control, and access.
- Conducting regular training and educational seminars for personnel working with metadata.

Current trends in metadata management in the urban environment include the following promising directions [4]:

- Using intelligent algorithms for the automatic generation, verification, and updating of metadata.
- Increasing interoperability between urban management metadata systems and open data portals to enhance transparency and openness.
- Implementing interactive interfaces that allow real-time work with metadata, integrating it with municipal services and mobile applications.

2 MODELING URBAN MANAGEMENT OBJECTS

2.1 Modeling Spatial Objects in the Urban Environment

Spatial modeling involves creating virtual models of objects that represent their location, geometric shape, attribute characteristics, and relationships with other objects. In an urban management GIS, these can include buildings, roads, sidewalks, utility networks, green spaces, public facilities, and more [14].

The objectives of modeling spatial objects in urban management include [9]:

- Visualizing the current situation in the city.
- Supporting decision-making in territorial planning and management.
- Ensuring efficient use of urban infrastructure.
- Optimizing the design of new facilities.
- Analyzing relationships between objects and phenomena in the urban space.
- Forecasting changes occurring in the urban environment.

In geoinformation modeling of the urban environment, different levels of object model detail are used depending on the tasks and scale of analysis (fig. 2.1).

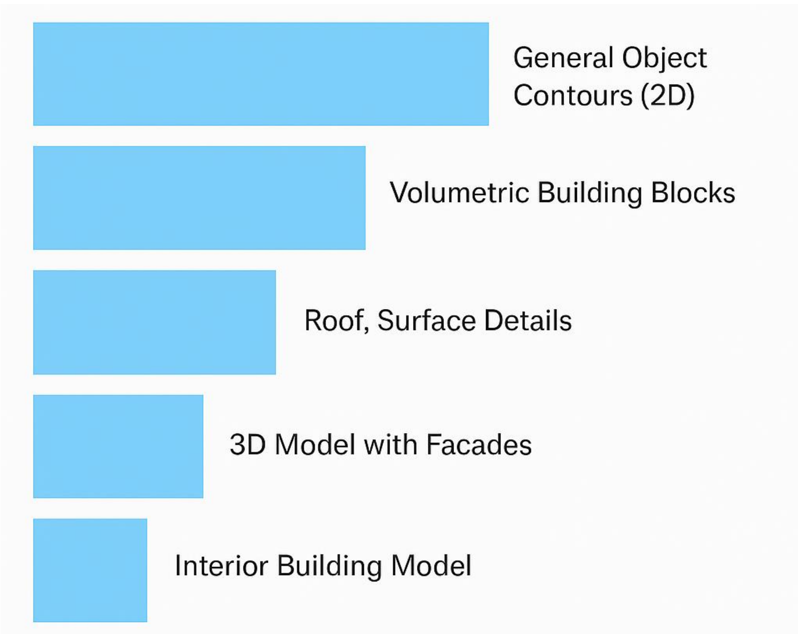

Fig 2.1. Levels of Detail of Spatial Object Models

Modeling urban management objects must take into account a number of specific features [7]:

- High building density: modeling complexity is driven by the close placement of objects and the need for precise geometric definition of boundaries and relationships.
- Variety of object types: buildings, roads, green areas, networks, etc., differ in nature, geometry, and attribute structure, requiring flexible models.
- Dynamic changes: the urban environment is constantly evolving — construction, reconstruction, and network expansion require regular model updates.
- Need for interconnected analysis: for example, a road reconstruction project cannot be developed without considering the location of underground utilities, heritage protection zones, and building restrictions.

In GIS, two main paradigms of spatial object representation are used — vector and raster (fig. 2.2). For modeling urban management objects, the vector model is most often applied, as it allows for precise description of an object's shape, coordinates, area, perimeter, and associated attributes.

Characteristic	Vector model	Raster model
Geometry	Points, lines, polygons	Pixels (grid)
Representation type	Objects with coordinates	Matrix of values
Accuracy	High	Medium/low
Application	Cadastre, planning, infrastructure	Imagery, orthophotos, elevation
Analysis	Topologic, attribu-te, network	Classification, change detecction

Fig 2.2. Comparison of Vector and Raster Modeling

To ensure logical spatial analysis between urban environment objects, it is crucial to account for topological relationships — that is, spatial interconnections between objects [11]:

- Adjacency: two polygons (e.g., neighboring parcels) share a common boundary.
- Intersection: objects overlap (e.g., a utility network route crosses a building footprint).
- Containment: one object is fully located within another (e.g., a park within a neighborhood).

Real estate modeling in urban management GIS is an essential area of spatial analysis. In the urban environment, real estate is not only buildings as physical structures but also a combination of legal, technical, functional, and socio-economic characteristics that describe its value, functionality, and impact on the surrounding environment. The goal of real estate modeling is to create a spatial–attribute model that enables the analysis of its condition, development, market activity, and relationships with other urban infrastructure objects [14].

A digital real estate model in GIS combines two main components [7] (fig. 2.3):

- Spatial — the geometry of the object (footprint, location, area, height, number of floors), represented as a polygon or a 3D model.
- Attribute — information about the building: address, functional purpose, year of construction, technical condition, owner, cadastral number, and legal status.

To build a complete real estate model, it is necessary to use various sources of geospatial and legal information [11]:

- State Land Cadastre (SLC): provides the geometry of land parcels under the objects.
- State Register of Property Rights to Real Estate: includes data on owners, forms of ownership, and encumbrances.
- Technical inventory from the Bureau of Technical Inventory (BTI): contains information on structural elements, areas, number of floors, and year of construction.

- Orthophotos and 3D models: used to verify geometry and building height/number of floors.

Architectural passports: can serve as a source of information on functional purpose and construction permits.

```
Object: Building No.1208
├─ Geometry:
|  ├─ Type: polygon
|  ├─ Coordinates: [(x1,y1),
|  ├─ Height: 21.4 m
|  ├─ Stories 6
├─ Atributes:
|  ├─ Address 15 Centralna St.
|  ├─ Functiion: residential
|  ├─ Year: satisfactory
|  ├─ Cadastral number: 631013600:01:123:4567
|  ├─ Owner:  KP "Zhytloservice"
```

Fig 2.3. Structure of a Real Estate Object Model in GIS

An important area is the modeling of legal boundaries of objects — outlines of cadastral parcels, boundaries of multi-apartment buildings, zones of easements, encumbrances, and similar legal limits. These boundaries are overlaid on building models and make it possible to [11]:

- Analyze the legal status of an object.
- Identify the responsible party for the object's maintenance.
- Check for violations of construction boundaries.
- Generate analytical reports for territorial communities.

For each real estate object, it is advisable to store the following attribute fields [15]:

- ID (unique identifier);
- Address;
- Cadastral number;

- Functional purpose;
- Year of construction;
- Number of floors;
- Wall material;
- Building condition;
- Date of last reconstruction;
- Ownership type;
- Information source (fig. 2.4).

ID	Address	Type	Floors	Condition	Owner
1023	123 Shevchen St.	residen	5	good	community
2045	45 Lomosonov St.	admin	3	fair	regional council
3020	67 Myru Ave.	commer-cial	2	good	private
3020	67 Myru Ave.		2	good	

Fig 2.4. Example of an Attribute Table for Real Estate Models

Modeling roads and urban infrastructure is one of the most important areas of geographic information systems (GIS) application in urban management. Its essence lies in creating digital models that accurately represent the spatial location, geometric characteristics, and functional connections between objects in the urban environment. Such models form the basis for analysis, forecasting, and decision-making regarding the reconstruction, development, or maintenance of infrastructure facilities [1,2].

In a GIS environment, the modeling process begins with building a basic spatial structure. For a road network, this primarily involves a topological model that accounts for intersection nodes, traffic directions, roadway width, pavement type, intersection control, speed limits, and traffic lanes. Such models enable spatial navigation, optimization of traffic flows, simulation of load on road infrastructure, and planning of repair works [3,4].

Road modeling also requires processing elevation data obtained from digital elevation models (DEMs) and digital surface models (DSMs), which allows consideration of slopes, curvature radii, elevation differences, and problematic areas in zones with increased erosion or flood risk. Modern LiDAR scanning and UAV photogrammetry technologies make it possible to create highly accurate road surface models with centimeter-level precision, significantly improving design efficiency and operational assessment [5,6].

Modeling urban infrastructure as a whole uses the multi-layer architecture principle. Each layer in the GIS structure represents a separate infrastructure system: power supply, water supply, sewerage, gas supply, telecommunications, lighting, etc. The spatial relationships and technical interactions between these layers make it possible not only to visualize the current state of systems but also to identify potential conflicts — for example, at the intersection of underground utilities or during the development of new residential neighborhoods [1,7].

The integration of 3D modeling has become a new stage in the development of urban management GIS. Three-dimensional models provide a more realistic representation of buildings, structures, streets, and engineering networks, allowing the simulation of shading, wind loads, acoustics, as well as the assessment of the visual impact of construction on the urban environment. The development of such models uses LiDAR scanning data, photogrammetric reconstructions, BIM components, and mobile mapping data [5,8].

The predictive functions of modeling involve using infrastructure development scenarios. For example, when modeling the street and road network, it is possible to simulate various transport load scenarios during peak hours, emergency situations, the impact of new developments on transport accessibility, or travel time delays. Such simulations are implemented using spatial logistics modules in environments such as

ArcGIS Network Analyst, TransCAD, CityEngine, and QGIS with road modeling plugins [3,9].

Special attention should be given to the digital twin concept, which involves creating an interactive city model with a complete set of up-to-date infrastructure data, the ability to monitor changes in real time, and integration with other information systems (environmental monitoring, utility services, transport operators, etc.). These approaches make it possible to analyze the current state of infrastructure and effectively manage the lifecycle of its facilities — from design to decommissioning [4,8].

Thus, modeling real estate, roads, and urban infrastructure in a GIS environment is a complex, multi-level process that ensures spatially grounded planning, efficient resource management, risk minimization, and improvement of the urban environment's quality. The reliability of such models depends on the completeness of input data, the accuracy of georeferencing, the frequency of updates, and the degree of integration with other information platforms [1,2,9].

2.2 Digital Elevation and Surface Models for Urban Planning

Digital Elevation Models (DEMs) and Digital Surface Models (DSMs) are fundamental geospatial components widely used in the design, planning, and management of the urban environment. Their application in urban management GIS ensures accurate representation of the earth's surface configuration and allows consideration of its morphological characteristics when analyzing engineering infrastructure, hydrological conditions, transport modeling, and environmental assessment of territories [1,2].

A digital elevation model represents the elevation characteristics of the terrain in the form of a regular or irregular set of points with spatial coordinates that indicate absolute or relative height. A digital surface model, in turn, includes both the terrain itself and the objects located on it — buildings, trees, technical structures — thus enabling the modeling of the surface in its real form [3].

Methods for creating DEMs and DSMs can be classified as traditional, semi-automated, and automated, depending on the data sources, accuracy level, volume of input information, and intended purpose of the model. One of the classical methods is topographic interpolation using contour lines, implemented through vectorization of paper maps or processing of scanned images. With GIS tools (such as ArcGIS or QGIS), contour data is converted into a point grid from which raster elevation models are generated [4,5].

Another common method is point elevation interpolation, which constructs a continuous elevation model based on a sample set of control points obtained by field surveys or remote sensing. The most widely used interpolation algorithms include Inverse Distance Weighting (IDW), Kriging, Natural Neighbor, and the Triangulated Irregular Network (TIN) method, which provides high accuracy in complex terrain by using an adaptive triangle structure [6].

In modern practice, laser scanning methods are gaining priority, allowing the creation of highly detailed DEMs with spatial resolution down to a few centimeters. Aerial laser scanning is applied for large-scale coverage of urban areas, while terrestrial laser scanning is used for detailed surveys of individual objects and technical systems. The result of laser scanning is a point cloud, which, after filtering and classification, is transformed into a DEM (terrain only) or a DSM (including above-ground infrastructure) [7].

An important area is also the use of photogrammetric methods. Digital models are created by processing stereo pairs — aerial or UAV images — which, using computer vision algorithms, automatically calculate elevations based on parallax. This approach is especially effective for generating models in hard-to-reach or densely built-up areas where traditional methods are limited [8].

A separate role is played by the integration of satellite remote sensing data. Products from missions such as SRTM, ASTER GDEM, ALOS, and Copernicus DEM provide baseline DEMs with resolutions from 1 to 30 meters, suitable for regional analysis, zoning, hydrological modeling, or erosion risk assessment. When higher accuracy is required, these models are supplemented or replaced by UAV or LiDAR data [4,9].

The choice of modeling method depends on the intended application. For example, IDW or Kriging may be sufficient for building digital drainage system models or identifying watershed basins. In contrast, BIM design, calculation of earthwork volumes, or solar exposure analysis requires the level of detail that only laser scanning or photogrammetry can provide [5,7].

Thus, the creation of digital elevation and surface models is a multi-level process that combines classical geodetic principles with the latest spatial data processing technologies. The main advantage of the GIS approach lies in its ability to flexibly integrate data from various sources, visualize it, perform analytical processing, and provide interactive use in different areas of urban management — from transport infrastructure to risk management and environmental protection [1,2,6].

Digital elevation models are a fundamental tool in urban planning practice, as they provide accurate and detailed representation of the terrain's height structure — a basic factor for making informed decisions on building placement, transport infrastructure design, utility networks, zoning, and risk management. Relief, as the morphological basis of the urban environment, significantly influences the spatial organization of the city, the formation of building types, drainage systems, transport accessibility, and sanitary conditions [1,2].

In the process of urban territory planning, DEMs are used to calculate key morphometric parameters — slopes, aspects, absolute and relative heights — which affect the choice of architectural and construction solutions, territory zoning, and construction cost optimization. For example, areas with excessive slopes may be deemed unsuitable for dense residential development but can be used for parks, forest parks, or recreational facilities, while flat areas are more suitable for high-rise construction, transport hubs, or industrial facilities [3,4].

Digital elevation models (DEMs) play an important role in hydraulic engineering planning, which includes the analysis of flow directions, local depressions, catchment basins, and flood-prone zones. These tasks are solved using DEM-based hydrological analysis in environments such as ArcGIS, QGIS, GRASS GIS, and others. A DEM makes it possible to identify areas at risk of surface water accumulation, design drainage channel alignments, and plan artificial water removal systems for new residential districts [5,6].

In transport planning, DEMs allow for the modeling of optimal highway routes while considering slopes that affect fuel consumption, traffic safety, and the need for engineering structures (overpasses, bridges, tunnels). When designing bicycle infrastructure or public transportation routes, elevation data helps adapt the network to users' physical capabilities and avoid excessive uphill loads [3,7].

Environmental and urban zoning also requires consideration of terrain. Sloped areas along hillsides often act as sources of erosion processes and wind accumulation, and may be vulnerable to landslides. DEMs help define buffer zones around such hazardous areas. They are also used to simulate noise propagation, calculate solar exposure, and assess wind pressure on buildings — all of which are crucial for designing a comfortable microclimate in residential areas [2,5].

The visualization function of DEMs is particularly valuable for 3D urban environment modeling, virtual tours, and future development mock-ups. The terrain base serves as the foundation for building city digital twins, allowing the integration of architectural models with the real landscape to ensure accurate geospatial alignment [8].

The use of DEMs is becoming increasingly relevant in scenario modeling of territorial development. Terrain analysis makes it possible to forecast changes that may occur under alternative urban development concepts — such as the redevelopment of industrial zones, construction in former quarries, or adaptation of coastal areas. Such models are used to assess environmental impact, calculate earthwork volumes, and justify the economic feasibility of projects [4,6].

The use of digital elevation models (DEMs) in urban planning is also accompanied by certain technical and organizational challenges. One of these is the need for continuous model updates to account for anthropogenic changes: new developments, landscape modifications resulting from engineering interventions, earthworks, and other alterations. Another challenge is the integration of models with varying accuracy and scale, obtained from different sources such as LiDAR scanning, photogrammetry, and satellite products. Addressing these issues requires careful standardization of geodata structures and the use of cloud platforms for their storage and sharing [7,9].

Thus, DEMs serve as both a fundamental element of cartographic support and a strategic tool for geoinformation support in urban planning. Their widespread use enables the transformation of urban analysis processes from purely graphical to a comprehensive digital approach, enhancing calculation accuracy, improving management efficiency, and promoting the sustainable development of urban areas [1,3,9].

2.3 Modeling Transport Networks and Communications

Transport accessibility analysis makes it possible to assess how efficiently people and goods can move across urban areas, taking into account the existing transport infrastructure. This process is important for urban planning, infrastructure development, and improving the quality of life for the population [7]. Through the integration of GIS technologies, it is possible to evaluate the current state of accessibility and model future scenarios for the development of the transport network, enabling the identification of optimal routes, reduction of traffic congestion, and improved access to key social facilities [9].

Transport accessibility is defined as the ability to reach a certain location using transport within a specific time frame or cost. It includes two main aspects: physical and social accessibility [14].

Physical accessibility describes the ability to move between objects using the existing transport infrastructure. It is determined by the distance between objects, the speed of transport movement, and the presence or absence of necessary connections in the transport network.

Social accessibility refers to the accessibility of certain facilities (for example, medical, educational institutions, enterprises) for various social groups (pensioners, people with disabilities, students). It considers distance as well as access options through different modes of transport, concessionary routes, and the availability of public transportation [9].

By taking these factors into account, the level of transport accessibility can be assessed at different scales — from individual residential blocks to the entire city (fig. 2.5).

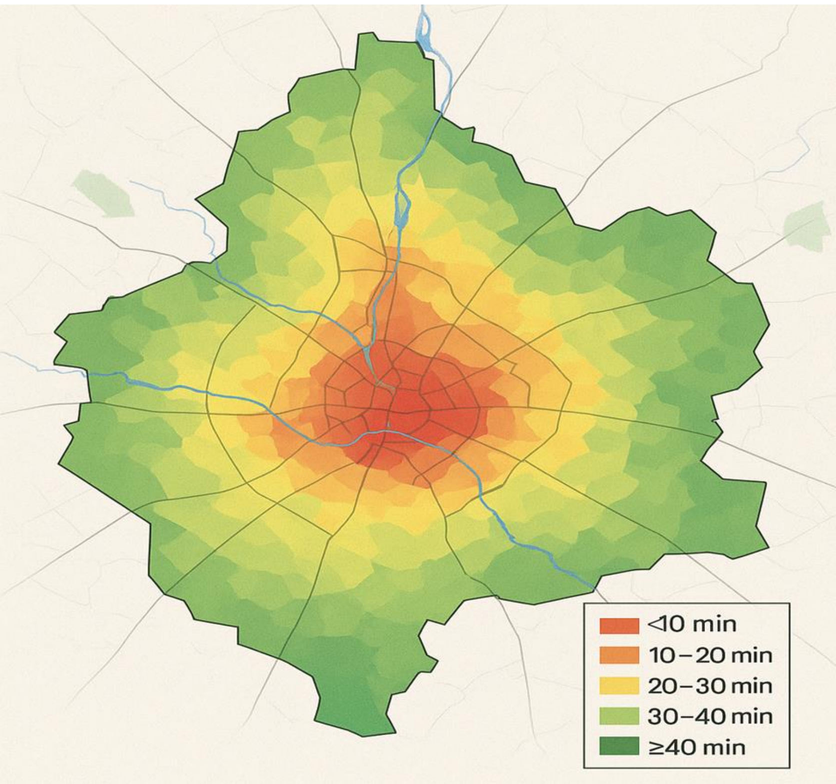

Fig 2.5. Diagram of Transport Accessibility in a Settlement

The diagram presents colored zones representing the level of accessibility to key facilities, taking into account travel time.

For transport accessibility analysis in GIS, several methods are commonly used:

- Buffer analysis method — creates an accessibility zone around specific objects (stops, stations, enterprises) and evaluates the distance from them to other important city points. Buffer zones can be used to build accessibility maps for pedestrians, cyclists, and drivers, helping to identify areas isolated from main routes.

- Network analysis method — used to model transport flows in the network. It calculates the shortest routes while considering road conditions, speed limits, road types, and current restrictions (construction, traffic jams). Network analysis allows estimating travel times between different points in the city and identifying the most efficient routes for public and private transport.
- Accessibility analysis to key social and infrastructure facilities — studies the distance or travel time to hospitals, schools, universities, shops, and other essential infrastructure. This helps identify areas with low accessibility to vital urban facilities.
- Multi-criteria analysis method — considers several factors affecting transport accessibility, such as distance, travel time, cost, service intervals, and the presence of stops. This approach evaluates all possible options for transport network development and selects the most efficient one.
- Key factors affecting urban transport accessibility include:
- Infrastructure: quality of roads, presence of bridges, tunnels, parking facilities, and public transport stops directly determines accessibility.
- Transport modes: choice, quantity, and availability of both public and private transport play a significant role.
- Traffic conditions: density of movement, congestion, accidents, or roadworks can significantly reduce accessibility.
- Environmental factors: restrictions such as bans on heavy vehicles in city centers may influence accessibility.
- Seasonality and weather conditions: winter conditions, heavy rain, or snow can worsen road conditions and lower accessibility levels.

Accessibility evaluation indices used in GIS:

- Transport Accessibility Index — calculated based on travel times to important urban facilities; it provides a composite measure of accessibility across multiple routes and transport modes (fig. 2.6).

- Time Accessibility Index — measures the time required to reach specific destinations and compares it across transport modes and city areas.

ID	Address	Type	Floors	Condition	Owner
1023	123 Shevchen St.	residen	5	good	community
2045	45 Lomosonov St.	admin	3	fair	regional council
3020	67 Myru Ave.	commer-cial	2	good	private
3020	67 Myru Ave.		2	good	

Fig 2.6. Accessibility Index to Key Social Facilities
(for each city district — accessibility to a hospital, school, shopping centers, and metro stations)

Transport accessibility analysis is an important component of effective urban planning. It helps to:

- Identify areas with low accessibility to social and infrastructure facilities, which can lead to social isolation.
- Optimize the placement of new facilities and infrastructure elements.
- Improve traffic management and public transport operations, reducing congestion and enhancing urban mobility.
- Forecast the need for expansion or reconstruction of transport networks based on demographic changes and the development of new residential and commercial zones.

Route optimization involves identifying the most efficient transport paths, reducing travel time, lowering fuel and maintenance costs, and improving service quality. This task requires a comprehensive approach, as route efficiency is influenced by numerous factors: the configuration of the urban transport network, traffic intensity, the availability of alternative routes, road conditions, as well as environmental and economic aspects.

1. Main goals of route optimization:

- Reduce travel time for transport users.
- Improve network throughput, especially during peak hours.
- Lower operational costs for transport companies, including fuel and maintenance expenses.
- Improve accessibility for the population, particularly for people with reduced mobility (pensioners, people with disabilities, children).
- Reduce the load on the city's main transport arteries.
- Minimize environmental impact by lowering CO_2 emissions.

2. Approaches to urban route optimization:

3. Shortest path method — used to find the shortest routes between two points on a map, considering different road options and restrictions. Algorithms such as Dijkstra or A* are used to determine the most efficient route with minimal time or resource consumption.

4. Maximum flow method — uses graph theory techniques to optimize route throughput. This is especially important for freight transport efficiency or urban public transport in conditions of limited resources. Solutions may include changing traffic directions or redistributing vehicle flows.

5. Multi-criteria optimization — considers several criteria simultaneously, such as travel time, fuel cost, pollution level, passenger comfort, etc. This method finds a balance between requirements and optimizes routes for different transport categories.

6. Monitoring and adaptive optimization — integrates real-time traffic data from sensors, GPS devices, and surveillance cameras. Routes can be adjusted dynamically to minimize congestion and improve efficiency.

7. GIS-based modeling — uses spatial analysis tools to consider factors like road condition, building density, travel time, and accessibility for different population

groups. Algorithms for shortest path and most efficient route searches are applied with multiple parameters.

8. Key performance indicators (KPIs) for route optimization:

- Travel time — essential for public transport and freight operations; optimized routes reduce trip duration and congestion.
- Economic costs — reducing fuel, maintenance, and driver labor costs without compromising service quality.
- Environmental impact — selecting efficient, shorter routes lowers CO_2 emissions.
- Network throughput — reducing load on main city arteries improves average speeds and decreases congestion.
- User satisfaction — shorter travel times and improved service increase comfort for passengers.

Urban route optimization is a key tool for improving transport efficiency in cities. It reduces travel times, eases pressure on main transport arteries, enhances accessibility for all population groups, and minimizes environmental impacts. GIS technologies provide accurate, data-driven recommendations for improving transport routes, incorporating real-time information and the specific needs of urban infrastructure.

2.4 Modeling of Utility Networks

A water supply network in an urban environment is a complex system of engineering infrastructure that ensures the continuous delivery of drinking, technical, or firefighting water to consumers. Its functionality depends on a wide range of parameters — from the branching of main pipelines to pressure regimes, hydraulic losses, and malfunctioning sections. GIS-based modeling of the water distribution network enables the creation of digital spatial models that combine geometry, physical and technical characteristics, and load scenarios into a unified structure [11].

The engineering water supply network consists of the following components [15]:

- Water intake facilities — sources of water supply (artesian wells, river intakes, reservoirs).
- Pumping stations — maintain pressure and ensure water delivery.
- Main and distribution pipelines — form the backbone and periphery of the network.
- Regulating fittings — valves, pressure regulators, and check valves.
- Hydrants and metering units — for firefighting and consumption monitoring.
- End consumers — residential, industrial, and public facilities.
- Geoinformation modeling represents the network as a directed graph with:
- Nodes — sources, junctions, and consumers.
- Edges — pipelines, each with attributes such as length, diameter, material, flow velocity, and hydraulic resistance (fig. 2.7).

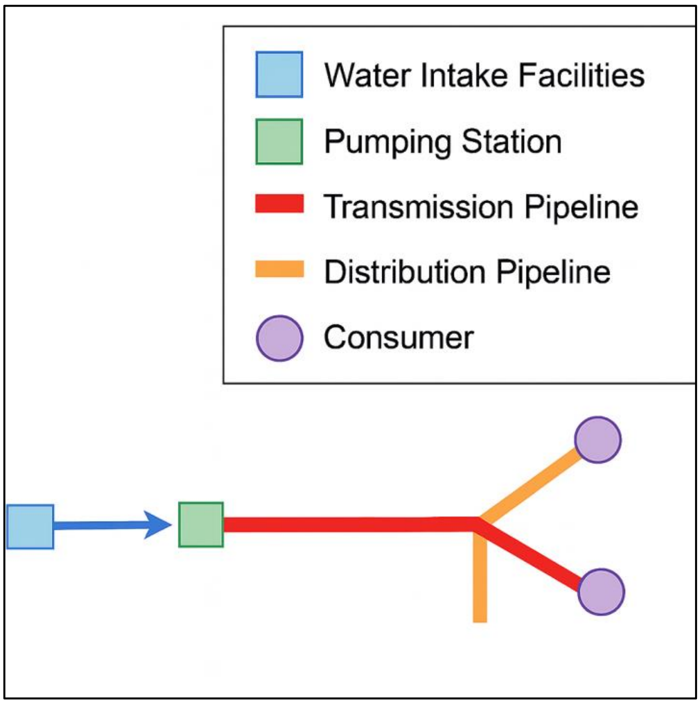

Fig. 2.7. Generalized Scheme of a Water Supply Network in a GIS Environment

The diagram depicts nodes representing pumping stations and consumers, and edges representing pipelines of various diameters with indicated flow direction.

The methodology for building a spatial model of a water supply network involves several steps [15]:

Step 1: Data Systematization — Data sources include:

- Topographic maps at scales 1:500 – 1:2000.
- As-built utility service diagrams.
- Laser scanning of inspection wells.
- GPS measurements of network nodes.
- SCADA system data on pressure and flow rates.
- High-resolution satellite imagery.

Step 2: Formalization and Vectorization — Using QGIS, ArcGIS, or gvSIG tools:

- Creation of a topologically closed network (no "dangling" nodes).
- Georeferencing to a coordinate system (SK-63, WGS84, or local).
- Creation of an attribute table for each element.
- Encoding of pipe classes (steel, polyethylene, cast iron).

Step 3: Hydraulic Modeling — Software used:

- EPANET — calculation of head, velocity, pressure losses, and water quality.
- WaterCAD or WaterGEMS — creation of operational load scenarios.
- Web Visualization — Implemented via:
- GeoServer, MapServer, or ArcGIS Online.
- Base maps (OpenStreetMap, Bing, Leaflet).
- Cartographic styles — depending on diameter, material, or pressure.

Electric power networks, as an integral component of a city's technological infrastructure, have a complex spatial and functional structure that requires precise spatial description, topological organization, analytical validation, and dynamic updates. GIS application in this context enables the creation of a digital model of the city's power system, including network elements, consumption points, power sources, and electricity transmission routes [1,2].

In a GIS environment, power network modeling is implemented by constructing topologically oriented vector models that depict the structure of:

- Power transmission lines.
- Transformer substations.
- Distribution points.
- Switching nodes.
- Consumer connection points.

Each object in the model is described not only geometrically but also semantically, with attributes such as:

- Voltage.
- Load.
- Network type (overhead or cable).
- Year of commissioning.
- Equipment condition [3,4].

A distinctive feature of electric power networks is their branched, hierarchical structure, where each level — high-voltage, medium-voltage, and low-voltage — performs a separate function: transmission, transformation, or distribution. Accordingly, modeling must account for these levels as well as connection logic, enabling the identification of critical nodes, determination of line load levels, location of backup power routes, and detection of potential bottlenecks in the network. GIS platforms such as ArcGIS Utility Network, QGIS with GRASS plugins, or gvSIG Electric Network support the implementation of such complex topologies with simulation capabilities [2,5].

The creation of digital electricity supply models widely uses engineering network cadastre data, along with materials from GPS surveys, total station inspections, and digital photogrammetry. In particular, terrestrial laser scanning and UAV aerial photography provide up-to-date spatial information on the location of overhead transmission lines, their height, pole tilt angles, and potential intersections with other utilities or natural obstacles (trees, buildings) [6].

A digital network model in GIS enables thematic analysis, including the detection of high-load zones, planning of maintenance works, calculation of losses, simulation of outages or failures, and optimization of backup supply schemes. For example, in emergency outage conditions or network overload, the system can automatically generate alternative power supply routes, taking into account technical parameters and spatial constraints [4,7].

A separate modeling direction involves the integration of renewable energy sources (RES) — solar panels, wind turbines, and bioenergy modules. Such objects are also included in the GIS model as active sources, with parameters for generation periodicity, capacity, and connection conditions to the main network. This enables energy balance modeling, assessment of decentralization potential, and analysis of RES impact on voltage levels in different network segments [5,8].

Modeling electricity supply in urban management also involves spatial risk analysis: identifying areas where transmission lines pose potential hazards (e.g., near residential buildings, reservoirs, parks), planning protective zones, and assessing the compliance of line placement with urban planning and electrical engineering regulations. This helps optimize routing for new networks, taking into account environmental and social factors [6,9].

In summary, GIS-based electric network modeling is a comprehensive analytical procedure combining spatial visualization, attribute management, topological analysis, and energy system performance forecasting. This approach not only supports effective management of existing resources but also ensures strategic energy supply planning at the scale of a city, district, or even a single neighborhood [1,3,8].

District heating systems are part of critical infrastructure, whose operation has a direct impact on the comfort, safety, and energy efficiency of the urban environment. Geoinformation technologies make it possible to create digital models of heating networks that reflect not only the physical configuration of pipelines and equipment but also the hydraulic, thermal, and operational parameters of system components [1,2].

In a GIS environment, heating network modeling is based on the construction of a vector-topological model that includes:

- Nodes — heat-generating plants, central heating substations (CHPs), and consumer connection points.
- Linear objects — supply and return pipelines.

Each object is assigned attributes such as: pipeline type, material, diameter, length, installation depth, wear rate, insulation type, and date of last repair. Creating such a model enables spatially oriented analysis, network optimization, equipment condition monitoring, loss forecasting, and emergency situation modeling [3,4].

A specific feature of heating networks is the need for hydraulic and thermal modeling, which requires integration of GIS with engineering calculation platforms such as Bentley OpenFlows, Termis, or specialized modules for ArcGIS. These tools allow simulation of supply temperature, heat losses across the network, pressure at different points, coolant flow direction, circulation time, and load balance during peak and average periods [2,5].

Heating supply modeling in GIS is closely linked to spatial analysis of building density, building typology, and functional zoning. This is because heating loads directly depend on consumer characteristics such as heated area, energy efficiency level, operating schedule, and number of consumers. GIS enables overlaying the infrastructure model onto a cadastral or building map of the city and automatically calculating heating demand for districts or individual buildings [6].

Special attention should be given to heat loss analysis, which arises from network wear, insufficient insulation, hydraulic imbalances, or failures. In the digital GIS model, these losses can be identified based on typical values for different pipelines or calculated using engineering-analytical tools that take into account the actual length, material, and temperature regime. This makes it possible to pinpoint the most critical sections of the network, prioritize repairs, and assess the potential for reconstruction and thermal modernization [4,7].

Current trends also include the modeling of intelligent heating supply systems, where the model is connected to digital sensors, meters, and SCADA systems to enable real-time monitoring. Such digital twins of heating systems are already being implemented in smart city pilot projects, particularly in Scandinavian and Baltic countries, where there is a high level of decentralized heat generation and active use of alternative energy sources [6,8].

GIS models are also used to evaluate options for decentralizing district heating systems. In particular, scenarios are analyzed for transitioning to block-level boiler houses, micro-CHPs, or heat pump systems. Spatial modeling enables comparison of these alternatives based on cost, efficiency, environmental impact, and social effects, while also considering the location of energy sources, backup networks, and built-up zones [2,5].

Thus, modeling heating supply networks in a GIS environment serves not only as a digital inventory function but also as a powerful analytical and planning tool. It supports the implementation of principles of energy efficiency, loss minimization, transparent decision-making, and adaptive management of critical urban infrastructure [1,3,9].

2.5 Geoinformation Monitoring of the Urban Environment

Observation of the urban environment is a fundamental component of managing urbanized territories, as it ensures the detection, analysis, and forecasting of spatial and functional changes occurring within the urban structure. Observation methods are intended to provide a scientifically grounded basis for decision-making in the fields of urban planning, engineering infrastructure, environmental protection, social development, and sustainable planning. In modern practice, geoinformation systems (GIS) serve as an integrating platform that combines diverse data sources and observation methods, creating a unified digital analytical environment [1,2].

The foundation of spatial observation is formed by remote sensing methods, which include satellite imagery, aerial photography, unmanned aerial vehicle (UAV) photogrammetry, laser scanning, hyperspectral, and thermal sensing. These technologies make it possible to perform regular surveys of large areas, ensuring timely updates of information on urban objects and processes. For example, using satellite imagery from Sentinel-2, PlanetScope, WorldView, or Landsat, it is possible to assess building density, the condition of green areas, urbanization changes, thermal anomalies, water bodies, and other parameters with spatial reference [3,4].

An important role in observation is played by instrumental methods based on geodetic and engineering measurements, including GNSS monitoring, total station surveys, close-range photogrammetry, digital mapping, and terrestrial laser scanning. These methods provide high-accuracy data on physical changes in the urban environment — displacement of buildings, structural deformations, ground subsidence, and terrain changes. For example, monitoring landslide-prone areas or infrastructure objects (bridges, overpasses, collectors) is performed using digital inclinometers and 3D scanning, followed by processing in GIS [5,6].

The integration of GIS with sensor systems enables dynamic real-time observation. This applies, in particular, to monitoring air quality, noise pollution, light levels, temperature, humidity, and concentrations of harmful substances. Modern cities are actively implementing smart sensor systems that automatically transmit information to centralized GIS platforms for visualization, analysis, and publication. In this way, so-called "digital shadows" of the city are formed — analytical models that display its condition in real time [2,7].

Observation methods also include social and administrative data sources, such as municipal infrastructure registries, the urban planning cadastre, the land cadastre, utility service records, population census data, statistical yearbooks, and results of sociological surveys. These sources are typically presented in tabular form, but in GIS they are integrated with spatial objects, enabling the creation of thematic layers such as: demographic structure, energy consumption, land use, crime rates, and population mobility [3,8].

The use of mobile data represents a new stage in the development of observation methods. This includes geolocation data from mobile devices, geotags from photo and video content, and information from public portals about the state of road infrastructure, illegal dumpsites, lighting, and safety hazard situations. Such data usually arrives in a semi-structured format, but thanks to big data processing algorithms and GIS visualization tools, it can be quickly transformed into analytical information with spatial interpretation [7,9].

Thus, modern urban environment observation methods are multi-level, comprehensive, and closely linked to the capabilities of GIS platforms. Their effective application involves the use of individual observation tools combined with data integration, format standardization, process automation, and visualization of results to support decision-making at various levels of governance [1,5,9].

Change analysis in the urban space makes it possible to identify the dynamics of territorial development, evaluate the effects of implemented urban planning decisions, detect critical transformation zones, and forecast future changes in the spatial structure. When combined with GIS, this field fully unlocks the potential of spatio-temporal modeling of the urban environment [1,12].

Change analysis in GIS is carried out by comparing thematic and base layers obtained at different points in time. The sources of such data may include satellite monitoring imagery, aerial photography, inventory surveys, topographic mapping, as well as statistical databases and cadastral records. This allows for the assessment of changes in the built environment, functional zoning, land cover, green spaces, transport networks, demographic density, and social infrastructure [13,14].

The main method of spatial change analysis is zonal comparative assessment, where territories are divided into logical units — neighborhoods, blocks, or functional zones — and for each of them changes in certain indicators over time are calculated. These can include variations in the number of buildings, the area of green spaces, traffic intensity, or occupancy rates. Such assessments help to identify trends of densification, degradation, or transformation of the urban landscape [15].

A separate area of focus is spectral change analysis based on Earth observation (EO) remote sensing data. The use of indices such as NDVI (Normalized Difference Vegetation Index), NDBI (Normalized Difference Built-up Index), and NDWI

(Normalized Difference Water Index) makes it possible to automatically detect changes in land cover.

For example, a decrease in NDVI over a five-year period for a specific site may indicate a reduction in green vegetation or a land-use change in favor of construction. This approach is particularly effective for large, highly urbanized agglomerations [16,17].

GIS analytics allows not only recording the fact of changes but also analyzing their spatial patterns.

Using density functions, heat maps, clustering, or spatial autocorrelation (e.g., Moran's Index), it is possible to identify zones with the highest change intensity, their asymmetry, and their relationships with other indicators — socio-economic, demographic, and transportation. This is especially relevant for planning areas targeted for renovation, rehabilitation, or revitalization [12,14].

Within scenario-based change analysis, forecasting functions based on trends are used. The application of machine learning methods (classifiers, decision trees, neural networks) with historical GIS data makes it possible to predict probable directions of territorial transformation. For example, the system may indicate that a peripheral site with high transport accessibility and medium building density has a high probability of changing its designation from agricultural to residential use within the coming years [18,19].

An equally important component of analysis is the assessment of changes in social and environmental aspects. This includes studying the effects of residential densification on green space preservation, noise levels, lighting conditions, and temperature regimes (urban heat island effect). Based on such change models, decision-makers can justify measures for ecosystem conservation, the planning of new social infrastructure facilities, and zoning adjustments in line with the actual needs of residents [13,16].

Thus, change analysis in the urban space using GIS is both a technical data comparison procedure and a complex system for interpreting urban development dynamics. It enables the realization of a strategic vision of transformations, the identification of conflict zones, the avoidance of planning errors, and the formation of an adaptive urban management policy in the context of sustainable development.

2.6 GIS for Urban Development Management

Today, land resources are considered both a spatial foundation for the placement of infrastructure facilities and a multifunctional natural and economic asset with social, environmental, and financial value. In the urban context, land assessment encompasses the analysis of land use designation, functional zoning, legal status, market value, and development potential [11,12].

The essence of land assessment lies in determining its suitability for specific activities and identifying the most effective ways of use. In cities, this process is more complex than in rural areas, as it must account for the interaction of various factors: building density, transport accessibility, engineering service availability, environmental characteristics, social infrastructure, and population needs. GIS technologies serve as a core tool for integrating these factors, providing spatial analytics and data visualization [13,14].

Modern methods for assessing urban land resources include:

- Economic assessment, which determines the normative and market value of land parcels.
- Environmental assessment, which considers soil quality, pollution levels, and ecosystem services.
- Urban planning assessment, based on the analysis of functional zoning and master plans.

GIS enables the integration of these approaches into a unified system, modeling relationships between factors and predicting the impact of planned changes [15].

A particularly important task is evaluating the efficiency of land use, which helps identify underutilized areas, development or redevelopment reserves, and zones with chaotic or improper land use. Spatial analysis methods are applied for this purpose — such as building density mapping, transport accessibility analysis, and identifying zones with low floor area ratios (e.g., industrial areas that have lost functionality) [12,16].

Urban land data is collected from multiple sources: the State Land Cadastre, the Urban Planning Cadastre, zoning plans, real estate market statistics, and remote sensing data. Satellite imagery and aerial photography enable the automatic detection of land cover changes, identification of new objects, and assessment of the condition of green spaces or vacant plots suitable for development [4,7].

In modern cities, value-based zoning is increasingly applied, where territory is divided into zones according to indicators such as cost, functional purpose, investment attractiveness, and environmental safety.

In this context, GIS functions as an analytical platform that automates calculations, creates cartographic models, and generates forecast scenarios for land resource use [13,15].

An important component is the assessment of urbanization impacts on land conditions, particularly identifying soil degradation, building densification, and the reduction of green space. By analyzing multi-temporal GIS data, it is possible to determine which areas have undergone the most significant changes and develop measures for reclamation or restoration. Increasingly, the potential use of underground space (e.g., for utilities or parking facilities) is also analyzed, which is becoming relevant in densely populated cities [16,18].

Thus, the assessment of urban land resources in a GIS environment is a complex process that integrates analytics, economic and environmental indicators, legal considerations, and predictive modeling. It supports informed decision-making, improves the efficiency of urban land use, and provides a foundation for the sustainable development of the urban environment [11,14,17].

Control over the development of urban infrastructure is a strategic area of territorial management aimed at ensuring the rational, balanced, and sustainable functioning of the city as a unified socio-technogenic organism. In this context, Geographic Information Systems (GIS) provide spatio-temporal monitoring, analytics, and visualization of changes occurring within the infrastructural framework of urban territories [11,12].

The infrastructure of a modern city includes transportation networks, engineering utilities (water supply, sewerage, electricity supply, gas supply, district heating), social facilities (schools, hospitals, administrative buildings), as well as technical zones, energy complexes, and public service systems. Controlling the development of this complex system involves continuous monitoring of its changes, operational efficiency, compliance with regulations, and alignment with forecasted development scenarios [13,14].

GIS in this process provides a multi-parameter environment for collecting, storing, analyzing, and interpreting information on the spatial distribution of infrastructure facilities, their technical condition, load levels, capacity reserves, accident rates, and future expansion plans. This makes it possible to record the actual state and detect imbalances between urban development and infrastructure provision, unnecessary duplication of functions, or excessive loads on systems [12,15].

Special importance is given to monitoring construction and reconstruction of infrastructure facilities, which in GIS is implemented by overlaying current data (from the urban planning cadastre, permit registries, satellite or UAV imagery) onto the base model of the city. This allows tracking compliance with urban planning documentation, detecting unauthorized or illegal construction, and verifying that actual land use matches its designated purpose [14,16].

For analyzing infrastructure provision, geospatial accessibility modeling methods are applied, including the construction of isochrones, calculation of service areas, and analysis of territorial coverage by critical infrastructure facilities. For example, using such models makes it possible to identify neighborhoods that are outside the acceptable reach of medical or educational institutions and, based on this, to make decisions on the need for constructing new facilities [15,17].

Integration with network system data and smart meters opens opportunities for dynamic monitoring of loads on utility networks. In a GIS environment, these data can be visualized as thematic layers showing water, electricity, and heat consumption at the level of individual buildings, blocks, or neighborhoods. Such functionality allows timely identification of critical load points or drops in efficiency, which in turn influences decisions on modernization or reconstruction [12,18].

An important area of control is also the assessment of infrastructure compatibility when planning new developments, particularly in densely built-up areas. Using GIS models makes it possible to analyze whether the existing utility infrastructure can meet the demands of new buildings, whether the design capacity will be exceeded, and whether new communication lines, power grids, sewer systems, etc., will be required. In this way, GIS supports decision-making on the feasibility of construction in specific locations [16,19].

Control over infrastructure development in modern cities cannot be achieved without integrating spatial data with legal, economic, and environmental information. For example, a water supply network reconstruction project must consider sanitary protection zones, protected area boundaries, restrictions according to the land cadastre, as well as budget constraints and the priorities of municipal programs. GIS provides a platform that integrates these aspects into a unified analytical environment [11,15,18].

3 APPLIED ASPECTS OF USING GEOGRAPHIC INFORMATION TECHNOLOGY TOOLS FOR SOLVING URBAN MANAGEMENT TASKS

3.1 Application of GIS in Urban Planning and Design

Analysis of urban land use is one of the main areas of urban planning and spatial monitoring, allowing for the assessment of the structure of territorial development, the degree of efficiency in the use of land resources, the identification of zoning conflicts, and the forecasting of possible scenarios for the transformation of urban space. In modern conditions, this analysis is impossible without the use of geographic information systems, which make it possible to integrate, visualize, and analytically process multicomponent spatial and attribute data [11,12].

Urban land is usually classified according to its functional use: residential development, industrial zones, public and business centers, engineering and transport infrastructure, public land, green zones, special-purpose land, as well as reserve and temporarily unused areas (appendix A.1). Spatial structuring of this information in GIS enables the creation of thematic layers that allow for quantitative and qualitative analysis of land use, both for the city as a whole and within individual neighborhoods, blocks, or functional zones [13].

One of the most important tasks of the analysis is to determine the land use structure, which makes it possible to assess the share of each usage category in the overall balance of the city's land.

This analysis is the basis for further management decisions: for example, if the share of green areas is less than 15% in a densely populated district, there is a need to expand recreational infrastructure. Conversely, an excessive share of industrial land in the city center may indicate outdated functional planning that requires revitalization [12,14].

GIS technologies make it possible to identify conflicts in land use that arise from discrepancies between actual land use and established regulations, functional zoning, legal status, or the master plan. For example, in GIS it is possible to automatically detect cases of residential development located in engineering communication zones, illegal expansion of commercial facilities, or unauthorized occupation of public land [15,16].

Land use analysis also allows for the assessment of change dynamics using multitemporal data—particularly satellite images, aerial photographs, and cadastral archives.

With modern tools, it is possible to detect processes such as infill development, reduction of green areas, changes in the structure of industrial territories, transformation of waterfronts, or the redevelopment of former industrial sites. This analysis is extremely important for detecting unauthorized activities or forecasting infrastructure loads [14,17].

In current practice, an approach to evaluating land use efficiency is increasingly applied, based on indicators such as building density, functional saturation coefficients, intensity of land use, and the availability of related infrastructure. For example, spatial analysis can help identify underutilized areas in the central part of the city that are suitable for redevelopment, or reserve land with potential for social housing or parks [13,15].

GIS analysis also includes the assessment of spatial equity in land access, which involves studying how evenly green areas, healthcare facilities, educational institutions, or recreational spaces are distributed across different city districts. Identifying such imbalances may be a reason to revise urban planning policy or to implement socially oriented development programs [11,18].

Thus, the analysis of urban land use based on GIS is not only an inventory of territories but also multidimensional analytics covering legal, functional, social, and environmental aspects. Its results form the basis for strategic and tactical decision-making in the fields of urban planning, land management, infrastructure development, and regional policy [12,14,17].

In a modern city, where spatial processes are characterized by high dynamics, multiple factors, and interdependence, effective decision-making is possible only under conditions of digital territory analysis, scenario visualization, and multilevel monitoring. It is GIS that makes it possible to implement these functions within an integrated analytical environment [11,12].

GIS as a decision support system combines three key components: the informational, which ensures data collection and processing; the analytical, which implements modeling, simulation, and spatial analysis algorithms; and the visualization component, which transforms complex information into a form accessible for perception by managers, designers, and the public. On this basis, decisions are made that take into account not only technical factors but also socio-economic, legal, and environmental considerations [13,14].

One of the leading areas of GIS application in decision support is urban planning, where the system provides analysis of development density, accessibility, functional zoning, and the development potential of territories (appendix A.2). Decisions regarding the placement of new infrastructure facilities, changes in land use designation, neighborhood renovation, or preservation of natural areas can be made based on spatial analysis, including isochrone accessibility models, density analysis, conflict zoning, and more [12,15].

Another important example is risk and hazard vulnerability analysis, particularly in the context of the safety of critical infrastructure facilities, flood zones, seismic risks, or thermal anomalies. GIS allows modeling of potential emergency scenarios and determining optimal response routes, evacuation plans, and locations for emergency services. Such tools are actively used by municipal authorities and civil protection services [14,16].

An important function of GIS is multicriteria territory assessment. For example, when selecting a land plot for a new social facility (school, hospital, park), GIS makes it possible to take into account dozens of factors—from proximity to residential areas and transport accessibility to the condition of engineering networks and the environmental background (appendix A.3). Such an assessment is implemented through weighted overlay algorithms, the analytical hierarchy process, and other decision-making methods [13,17].

GIS platforms also support transparent and interactive management—particularly through the implementation of web maps, public geoportals, and citizen participation e-services. This makes it possible to involve the population in discussing development projects, monitoring problems, and providing feedback. Such practices are part of the concept of "smart governance"—digital governance based on open data and public dialogue [11,16].

Modern decision support systems also implement scenario-based and predictive modeling. For example, GIS can be used to assess the impact of implementing a new master plan on traffic flows, power system loads, land use, and changes in noise or air pollution levels. The results are presented in the form of interactive maps, diagrams, and 3D models, making them accessible for joint discussion among experts and authorities [15,18].

Therefore, GIS as a decision-making support tool in urban management is not just a technical visualization environment but a full-fledged platform for strategic analysis, modeling, forecasting, and ensuring communication among all participants in the urban planning process. Its application improves the quality of management decisions, helps reduce risks, optimizes resource use, and ensures sustainable urban development [12,14,17].

3.2 GIS for Environmental Monitoring in Urban Areas

Assessing the environmental condition in urban areas is one of the most urgent tasks for sustainable territorial development. Under conditions of increasing anthropogenic pressure on urbanized areas, the need for comprehensive monitoring of the ecological situation and timely detection of negative trends becomes particularly important. In this context, Geographic Information Systems (GIS) serve as an integrated platform for the collection, storage, analysis, modeling, and visualization of spatially oriented environmental data [11,12].

Within GIS analysis, environmental condition assessment is carried out through the multifactor interpretation of data covering various environmental components:

atmospheric air, soils, water resources, green spaces, noise levels, radiation background, thermal anomalies, and other indicators. The use of remote sensing (RS) of the Earth, mobile environmental monitoring, and stationary observation posts ensures regular data updates and enables rapid response to changes [13,14].

One of the main directions is air quality monitoring. Data from Sentinel-5P (TROPOMI) and MODIS satellites, combined with ground-based sensors and GIS analytics, allow the detection of concentrations of nitrogen oxides (NO_2), ozone (O_3), carbon dioxide (CO_2), and particulate matter (PM2.5/PM10). Visualization of these data in the form of thematic layers and heat maps makes it possible to identify zones of elevated pollution, which often correlate with transport arteries, industrial zones, or densely built-up residential districts [15,16].

An equally important component is the assessment of green space conditions, implemented through index-based processing of satellite images (NDVI, SAVI, EVI). These indices provide a quantitative evaluation of the area, density, and condition of vegetation cover, help identify degradation of green zones, and assist in planning urban greening with regard to thermal comfort, noise reduction, and pollutant absorption. GIS also enables the comparison of vegetation cover dynamics over several years to detect areas of critical green space reduction [12,17].

GIS technologies also make it possible to assess noise pollution levels. Based on modeling of traffic flows, building typology, noise sources, and barrier objects, GIS creates spatial noise background models (appendix B.1). This makes it possible to identify zones exceeding permissible noise levels, which is important for zoning residential areas and for locating kindergartens, hospitals, recreational facilities, and similar sensitive sites [14,18].

Urban heat island (UHI) GIS models are also actively implemented, based on infrared imagery or satellite observations (e.g., Landsat 8/9 TIRS). They make it possible to identify areas with elevated surface temperatures caused by building density, absence of greenery, and high traffic intensity. These models support decision-making for priority greening, installation of reflective roof coatings, or modification of road surface materials [16,19].

Assessment of soil and water conditions within a city is also carried out based on spatial analysis. Using the results of environmental sampling integrated into GIS, maps of contamination by heavy metals, petroleum products, nitrates, and pesticides are modeled. It is also possible to spatially reproduce changes in the hydrological regime: location of pollution sources, condition of small rivers, and localization of flooding zones. This makes it possible to improve the level of environmental safety and to make effective decisions regarding the renaturalization of water bodies or the localized remediation of soils [17,20].

GIS makes it possible not only to analyze the current state of the environment but also to conduct scenario forecasting, simulating the consequences of implementing various urban planning decisions or changes in climatic conditions. For example, it is possible to model how a 20% reduction in park area will affect surface temperature or what consequences densification of development will have for air quality in a specific neighborhood [12,15].

Thus, GIS technologies serve as a powerful tool for objective environmental assessment in urban space, allowing the integration of traditional monitoring methods with high-precision spatial models. Their use provides an integrated vision of the environmental condition of the territory, supports decision-making, and promotes the implementation of sustainable urban development principles [11,13,17].

Urban Resource Management. Management of natural resources within the urban environment requires consideration of numerous factors: resource scarcity, high concentration of anthropogenic loads, spatial heterogeneity of the environment, and rapid change dynamics. In this case, GIS provides an effective environment for data integration, situation modeling, forecasting consequences, and supporting decisions related to the conservation, distribution, and rational use of resources in cities [11,12].

One of the main tasks of GIS in this area is the inventory and monitoring of the condition of resources — land, water, forest, and energy. In particular, cities carry out spatial accounting of green zones, water bodies, water supply sources, areas with environmental protection status, and recreational territories potentially suitable for restoration. With GIS, it is possible to automatically generate maps of resource use, perform multi-layer zoning, model loads, and identify conflict zones [13,14].

Resource management requires not only recording the current state but also assessing risks associated with depletion, pollution, or inefficient use. GIS allows for risk modeling by analyzing the combination of geofactors (relief, hydrology, soils), socio-economic characteristics (population density, infrastructure load), observation data, and permissible load norms. For example, in assessing the state of water bodies or green spaces, it is possible to identify degradation zones or areas at risk of disappearance that require urgent ecological intervention [14,15].

Environmental impact modeling is becoming increasingly relevant — the assessment of how planned changes in the urban environment (new construction, reconstruction, installation of engineering networks) will affect the state of the environment. GIS technologies make it possible to build impact scenarios: for example, calculating the increase in the number of motor vehicles and the associated deterioration in air quality, increased noise levels, reduction of vegetation cover, and changes in the thermal balance. It is also possible to assess cumulative impacts, when different sources (transport, industry, dense development) overlap in the same area and intensify environmental stress [12,16].

Thanks to spatial analysis in GIS, it is possible to localize environmentally vulnerable zones such as flood-prone areas, landslide-prone slopes, areas with excessive air or soil pollution, and territories with reduced biodiversity (appendix B.2). For this purpose, multi-temporal satellite imagery, data from monitoring stations, field surveys, and land cover classification algorithms (e.g., supervised classification, random forest) are used [13,17].

A separate area is the integration of GIS with environmental impact assessment tools, which allows environmental factors to be taken into account at an early stage of project planning. Using input data on relief, hydrography, wind rose, building density, and existing restrictions, it is possible in GIS to model the impact zone of an object, determine the areas of noise propagation, emissions, changes in surface water flow, and so on. This increases the environmental justification of decisions and reduces the risks of social conflict [15,18].

GIS is also a tool for ecosystem-based planning, which is based on the concept of balanced development and preservation of the ecological functions of territories. In this case, urban environment planning considers not only the technical feasibility of construction but also the importance of natural elements — green corridors, drainage systems, and ecosystem services. GIS models make it possible to identify ecosystem services (e.g., recreation, air purification, moisture retention) and to develop spatial strategies for their preservation [11,16,19].

3.3 Spatial Analysis for Urban Infrastructure Optimization

Urban road planning is one of the most complex components of territorial development, as it combines engineering, socio-economic, environmental, and spatial aspects. In modern conditions, where the dynamics of urbanization and building density complicate traffic flows, effective management of road infrastructure is possible only with the implementation of digital technologies, in particular Geographic Information Systems (GIS). GIS provides comprehensive analysis of the spatial characteristics of the network, accessibility of facilities, route efficiency, traffic congestion modeling, identification of "bottlenecks," and the creation of reconstruction scenarios [17].

Functional zoning of urban roads is the foundation for their efficient design. The urban street network consists of main roads of citywide importance (primary and district), collector streets, local access roads, and pedestrian infrastructure. Each road category has different engineering loads, capacity, permissible speed, parking conditions, and maintenance requirements [14].

GIS enables the creation of classification layers of the road network by functional types, linked to spatial coordinates. This results in a structured database for analyzing network density, connectivity, and hierarchy. According to European standards (such as Sustainable Urban Mobility Plan — SUMP models), planning should include the creation of transport corridors that provide continuous and rational connections between districts [11].

One of the central concepts in road planning is transport accessibility — the time and effort required to reach a particular facility or area. Using GIS tools, such as service area analysis, buffer analysis, and isochrone generation, it is possible to determine the efficiency of transport coverage. This makes it possible to plan public transport placement, identify service disparities, and make decisions on new stops or roads [12].

For example, in QGIS or ArcGIS Network Analyst, accessibility maps to schools, hospitals, or administrative facilities can be created, taking into account time of day, type of transport (pedestrian, car, bus), average speed, traffic density, etc. Such models make it possible to assess the level of infrastructural equity — i.e., providing residents with transport regardless of their place of residence [11].

Optimization of transport routes in urban conditions is a task that requires flexible adaptation to traffic changes, emergencies, seasonality, and other factors. GIS technologies make it possible to automate the search for the shortest or fastest routes, taking into account restrictions such as weight limits for freight transport, closed streets, one-way traffic, etc. [11].

Classical methods — Dijkstra's algorithm, A*, or transport models based on graph theory — allow such calculations to be implemented. At the same time, base data such as OpenStreetMap can be enriched with attributes of road surface, width, and operating conditions, increasing model accuracy. The results of the analysis can be used to design public transport routes and optimize routes for special vehicles (ambulances, fire engines, waste collection), freight transport, and utility services.

Using spatial analysis in GIS, it is possible to determine the intensity of use of individual road segments, particularly through GPS tracking data, flow sensors, mobile network data, etc. (Google Traffic, Waze, etc.). The spatial distribution of load is displayed on thematic layers in the form of heat maps, which make it possible to identify excessively congested segments. This serves as the basis for planning lane expansions, adjusting traffic light cycles, creating bypass routes, or implementing restricted traffic zones.

For example, in cities with high levels of private vehicle use, it is advisable to implement flexible traffic schemes with priority for public transport, cyclists, and pedestrians. At the same time, GIS analysis allows the modeling of the effects of such changes before they are implemented, minimizing the risk of ineffective planning [16].

When designing new roads, it is essential to take into account urban parameters and natural conditions: relief, hydrographic network, soil conditions, the presence of green areas, or protected zones. GIS tools make it possible to integrate layers of the digital elevation model, geological maps, hydrology data, and protected area boundaries. This helps avoid construction in risk-prone zones — landslide areas, flood-prone areas, and environmentally sensitive territories [11].

In addition, the planning process considers the environmental impact of road construction — noise levels, air pollution, and reduction of green spaces. GIS-based analysis includes modeling the impact on adjacent areas and developing environmental mitigation measures, such as noise barriers, landscaping, and the creation of ecological corridors.

Public facilities are elements of social infrastructure that shape the city's functioning. These include administrative, educational, healthcare, cultural, commercial, sports, and religious institutions that meet the needs of the population and ensure comfortable living within the urban environment. Their planning is an important part of the city's spatial development strategies.

Geographic Information Systems make it possible to analyze the placement of public facilities in the context of [19]:

- building density;
- population size;
- demographic characteristics;
- transport accessibility;
- engineering infrastructure provision.

Based on such data, optimal service areas are defined (for example, service radii of clinics, kindergartens, or schools), and "white spots" — territories with insufficient coverage by social infrastructure facilities — are identified.

In ArcGIS or QGIS, choropleth maps of population density, layers with service radii, and accessibility maps are created, enabling the calculation of the need for new facilities and the justification of their placement [16].

When analyzing service provision, it is necessary to consider not only the existence of a facility but also its functional capacity. For example, if the standard for 1,000 residents requires one outpatient clinic, but in a neighborhood with 3,000 residents there is only a small facility that can serve five visitors at a time, the area is effectively underserved.

GIS methods make it possible to create layers with weighting coefficients (for example, accessibility × capacity factor), perform cluster analyses, and calculate service provision indices. For instance, in Kyiv and Lviv, accessibility indices to schools and medical institutions were created with a building-by-building reference, which made it possible to precisely identify deficit zones and propose optimal locations for new facilities [19].

Integration with census data is also of particular value, allowing the spatial representation of the social structure of the population (age, gender, economic status). This makes it possible to locate public facilities according to their intended purpose — for example, building additional kindergartens in areas with a high proportion of young families or opening outpatient clinics where elderly residents are concentrated [19].

Recreational areas — parks, squares, embankments, botanical gardens, sports grounds — are essential for ensuring quality of life in the city. Green spaces regulate the microclimate, reduce noise levels, promote biodiversity, enhance the aesthetics of the urban environment, and contribute to the physical and psychological health of the population.

GIS analysis allows [11]:

- determining the area of green zones as a percentage of the total area of the settlement;
- calculating the average distance to the nearest green zone for each residential building;
- identifying spatial gaps in access to recreational areas;

- modeling greening scenarios for districts with excessive building density.

In cities such as Barcelona, Vienna, and Lublin, the concept of the “15-minute city” has been implemented, where every resident has access to green areas within a 15-minute walking distance. GIS serves as the basis for building accessibility zones, determining service radii, and setting priorities for greening in such concepts [10].

In GIS environments, it is possible to create comfort zone heat maps that take into account total insolation, tree shade availability, humidity, noise, and fine particulate matter concentration — providing a comprehensive assessment of a space in terms of its ecological suitability for recreation.

Planning public facilities in the 21st century is closely linked to energy efficiency, environmental safety, and resilience to climate change. For example, when designing schools or hospitals, it is extremely important to consider [20]:

- prevailing wind directions;
- noise levels;
- natural lighting;
- shading from neighboring buildings;
- proximity to emission sources or industrial facilities.

GIS enables 3D insolation analysis, creation of noise pollution layers, and microclimate analysis. The results are integrated into BIM systems or modeling environments (such as ArcGIS Urban, CityEngine), allowing the design of engineering and environmentally optimized facilities.

Modern technologies also make it possible to build digital twins of public infrastructure facilities that combine GIS components with real-time sensor data, including energy consumption, temperature, traffic, etc. [11].

Assessment of the need for new public facilities is carried out through spatial demand forecasting, based on demographic, socio-economic, mobility, and statistical indicators. In GIS, this is implemented through [11]:

- creating maps of future population density;
- modeling birth/aging forecasts;
- analyzing migration flows;

- merging heterogeneous data (open data, cadastre, mobile operators, social networks).

For example, if demographic forecasts indicate an expected increase in the youth population in the northwestern sector of the city, a GIS model can propose a scenario for locating an additional high school, taking into account transport accessibility, existing infrastructure, and available land reserves.

In the future, the application of machine learning combined with GIS will make it possible to build self-learning models for locating public services based on dozens of parameters — from topography to social preferences. Thus, planning ceases to be merely an engineering task and transforms into a complex analytical process focused on future needs.

3.4 Innovative Technologies in GIS for Urban Management

UAVs, at the current stage of technological development, have become an effective tool for collecting spatial data in the urban environment. Their use significantly increases the efficiency, accuracy, and flexibility of geoinformation support for processes of managing urban infrastructure, territorial planning, monitoring the condition of buildings, technical inspection of facilities, and rapid response in emergency situations [21,22].

UAVs perform aerial photography, laser scanning, thermography, and hyperspectral sensing. The main advantage of their use is the ability to obtain highly accurate and highly detailed images in a very short time, which is especially important for the dynamic urban environment, where objects change quickly, and standard geodetic methods often do not provide the necessary mobility [23,24].

The processes of using UAVs in urban conditions include several stages:

1. Flight mission planning, taking into account the configuration of buildings, airspace regulations, the presence of restricted flight zones (for example, near critical infrastructure or airports), weather conditions, and safety factors.

2. Calibration and adjustment of equipment, including cameras, laser scanners, or thermal sensors, depending on the purpose of the survey — topographic mapping, inspection of building heat loss, inventory of green spaces, etc.

3. Flight execution, during which data is collected using GNSS navigation, inertial systems, as well as stabilization methods and route adherence.

4. Office processing, including photogrammetric alignment, generation of orthophotos, digital terrain models (DTMs) and digital surface models (DSMs), creation of 3D models, vectorization, and analytical processing in a GIS environment [22,25].

In urban management practice, UAVs are used for:

- monitoring the condition of infrastructure (roofs, facades, bridges, overpasses) without involving high-rise workers, significantly reducing costs and risks [26];
- updating topographic and cadastral maps, especially in areas with active construction or destroyed infrastructure (after disasters or hostilities);
- assessing the condition of green spaces, analyzing tree canopies, vegetation density, monitoring pests and diseases in urban ecosystems [23];
- controlling the implementation of construction works, recording progress dynamically, enabling the creation of a digital timeline of project implementation;
- estimating the volumes of waste and detecting violations in urban quarries, solid waste landfills, or illegal dumps, where it is important to quickly obtain accurate digital models [25].

Modern integrated platforms allow combining UAV data with satellite imagery, data from public services (such as OpenStreetMap or property registries) in a single GIS environment. This improves the accuracy of decision-making, automates analysis processes, and facilitates the creation of digital twins of urban objects.

However, the use of UAVs in the city also has certain limitations: these include regulatory barriers, the need to comply with data privacy laws, risks associated with flying in built-up areas or near power lines, and the important issue of standardizing data formats and ensuring their compatibility with municipal information systems [26,27].

In the context of transforming cities into "smart" cities, UAVs are considered one of the elements of an intelligent observation ecosystem, with the ability for rapid response, automatic routing, online processing, and integration into artificial intelligence systems, opening new horizons for urban planning and spatial analysis [24,27,28].

Urban development processes, the growing infrastructure complexity of cities, and the need for decision-making based on multidimensional information have driven the development of next-generation spatial technologies — three-dimensional modeling and integration of geographic information systems with building information modeling (BIM). In synergy, these two directions provide the foundation for the concept of the "digital twin of the city", enabling effective planning, analysis, and management of the urban environment at a qualitatively new level [21,22].

3D modeling in GIS creates volumetric representations of urban infrastructure objects — buildings, roads, engineering networks, terrain, and green spaces — based on spatially coordinated data. Unlike traditional 2D maps, three-dimensional models provide a multi-parameter depiction of objects, taking into account height, volume, orientation, material composition, and functional purpose. This is particularly important for tasks such as:

- modeling building density and insolation;
- analyzing shadow zones and the visual impact of new structures;
- planning evacuation routes in emergency situations;
- designing energy-saving solutions at the block and neighborhood levels [23,24].

Various technologies are used to create 3D models: UAV aerial photography, laser scanning, mobile mapping, photogrammetry, satellite elevation models, as well as digital cadastre data. The data is stored in formats that support volumetric geometry (CityGML, 3D Tiles, OBJ, IFC) and integrated into environments such as ArcGIS Pro, QGIS, Bentley, Autodesk Infraworks, etc. [25].

The use of 3D models significantly improves visualization and perception of urban space when discussing projects with the public, developing zoning plans, assessing traffic flows, and reconstructing cultural heritage sites (appendix B.3).

Building Information Modeling (BIM) provides detailed structural, geometric, engineering, and operational information about buildings and structures, from the design stage to decommissioning. Unlike GIS, which focuses on context — territory, spatial relationships, and interactions between objects — BIM details the object down to the level of a construction element (wall, slab, utility line), often without geographic reference at early stages [26].

Integrating GIS and BIM combines the "macro" and "micro" levels of city data, creating a holistic digital model of the environment. The main advantages of integration are:

- combining geospatial context (GIS) with construction-level detail (BIM) allows analysis of how a specific object impacts surrounding infrastructure — transportation, water supply, environment;
- facilitating urban planning analysis: for example, modeling how a structure will affect the city skyline or how drainage will change as a result of densification;
- enabling lifecycle management of objects, including maintenance, repairs, energy efficiency, and regulatory compliance;
- creating digital twins, enabling real-time monitoring of object condition by integrating data from IoT sensors, drones, and satellites [27,28].
- Technologically, integration is achieved through format conversion (IFC to GDB or CityGML), middleware (FME, ArcGIS GeoBIM), or platforms that directly combine both domains — Autodesk BIM360 with ArcGIS GeoBIM, Bentley OpenCities Planner, Trimble Cityworks.

The general trend in infrastructure planning, urban development, “smart cities,” asset management, and climate change adaptation is toward the growing role of such integrated models, which are already in use in Europe, Asia, and the USA in national infrastructure platforms (for example, Digital Twins UK, Singapore Virtual City) [30].

4 METHODS OF ARTIFICIAL INTELLIGENCE AND NEURAL NETWORK MODELING IN MUNICIPAL GIS

4.1 Theoretical Foundations of Neural Networks and Artificial Intelligence

In modern urban management, there is a growing need to enhance the intelligence of information and analytical processes, particularly in the areas of territorial, infrastructure, environmental, transportation, and resource management. Consequently, geographic information systems (GIS) are increasingly being integrated with artificial intelligence (AI) technologies, opening new horizons for the automated analysis of large volumes of spatial data.

AI enables the development of new approaches to understanding urban processes, optimizing management decisions, and predicting changes in the urban environment [31].

Artificial intelligence, as a field of scientific research, encompasses the creation of systems capable of intelligent activities, including perception, processing, analysis, learning, planning, and decision-making.

Within geospatial analytics, particular importance is given to AI subfields such as machine learning, deep learning, computer vision, and neural modeling methods, which allow for the processing of complex, structured, and unstructured geodata. The foundation of deep learning lies in artificial neural networks—computational models that emulate the functioning of biological neural structures in the brain. These consist of elements (neurons) that transmit signals through weighted connections and adapt their behavior in response to training [31,32].

The architecture of an artificial neural network typically includes an input layer, one or more hidden layers, and an output layer. Each neuron receives values from the previous layer, performs operations such as a weighted sum and an activation function (e.g., ReLU, sigmoid, tanh), and passes the result onward. Thanks to their multi-layered structure, neural networks can detect complex non-linear relationships between input geodata and the system's responses—an ability that is highly relevant when classical statistical or logical methods prove insufficient [32].

In municipal GIS, neural networks are applied to tasks such as object recognition in satellite imagery, land use classification, building change prediction, traffic load analysis, green area degradation detection, 3D reconstruction of urban spaces, and anomaly detection in utility networks. Different architectures are employed for each of these domains. For instance, Convolutional Neural Networks (CNNs) work effectively with raster data and are widely used in the processing of satellite and aerial imagery. These models consist of convolutional layers that detect spatial features, pooling layers that reduce dimensionality, and dense layers for classification. They enable automated image segmentation, the recognition of buildings, roads, water bodies, and trees, and the detection of changes in urban structures by comparing images from different time periods [32].

Another type, Recurrent Neural Networks (RNNs), is designed for processing sequential data. They are used to forecast traffic flows, energy consumption, air pollution levels, and water supply or sewage dynamics. The most advanced models in this category—Long Short-Term Memory (LSTM) and Gated Recurrent Units (GRU)—are capable of "remembering" important elements in time series while ignoring insignificant fluctuations. This allows municipal services to forecast peak loads on engineering systems, determine the need for flow regulation, or take preventive measures [32].

Graph Neural Networks (GNNs) form yet another promising class of models. Unlike CNNs or RNNs, they operate on graph structures, which are ideally suited for describing urban networks—transportation, communication, utility, and social systems. In such networks, nodes represent objects (e.g., intersections, buildings, utility network nodes), while edges represent their relationships. GNNs can not only classify individual nodes or predict their states but also model the dynamics of the entire network, identify critical nodes, and forecast the consequences of failures or reconstructions [32,33].

Generative neural networks, including GANs (Generative Adversarial Networks) and Variational Autoencoders (VAEs), are used to create new cartographic materials, reconstruct missing image fragments, simulate urban development, or generate alternative planning scenarios.

For example, GAN models can synthesize missing parts of orthophotos based on adjacent areas or generate new hypothetical building layouts in accordance with spatial constraints and architectural regulations.

An essential process in the operation of a neural network is training—the gradual adjustment of the weights of connections between neurons to minimize the error between predicted and actual values. Typically, this is accomplished using the backpropagation algorithm combined with optimization methods such as Stochastic Gradient Descent, Adam, or RMSprop. The choice of loss function is another critical factor, as it determines how the system responds to errors. For example, cross-entropy is used for classification tasks, while mean squared error is common for regression problems [33].

For effective training, it is crucial to have a sufficient amount of high-quality spatial data with appropriate structure, attributes, and metadata. In GIS environments, this involves both open sources (OpenStreetMap, Sentinel, Landsat) and local municipal databases.

To ensure consistency, data preprocessing methods are applied: normalization, georeferencing, projection transformations, and noise removal. The data is then split into training, validation, and test sets.

After training, the model's accuracy is evaluated using metrics such as precision, recall, F1-score, and AUC-ROC (fig. 4.1). If the performance is acceptable, the model is integrated into the municipal GIS environment via APIs, web services, or plugins for desktop applications such as QGIS or ArcGIS [33].

In global practice, there are already a number of successful examples of applying such technologies. For instance, in the city of Helsinki, CNNs are used for automated detection of roof types in buildings to assess the potential for solar energy production. In Barcelona, graph neural networks are applied to optimize urban transport, while in

Singapore they are used for real-time forecasting of loads on utility networks. In Ukraine, pilot projects utilizing neural networks for detecting changes in urban development or analyzing green zones are actively being implemented in cities such as Kyiv, Lviv, and Kharkiv [34].

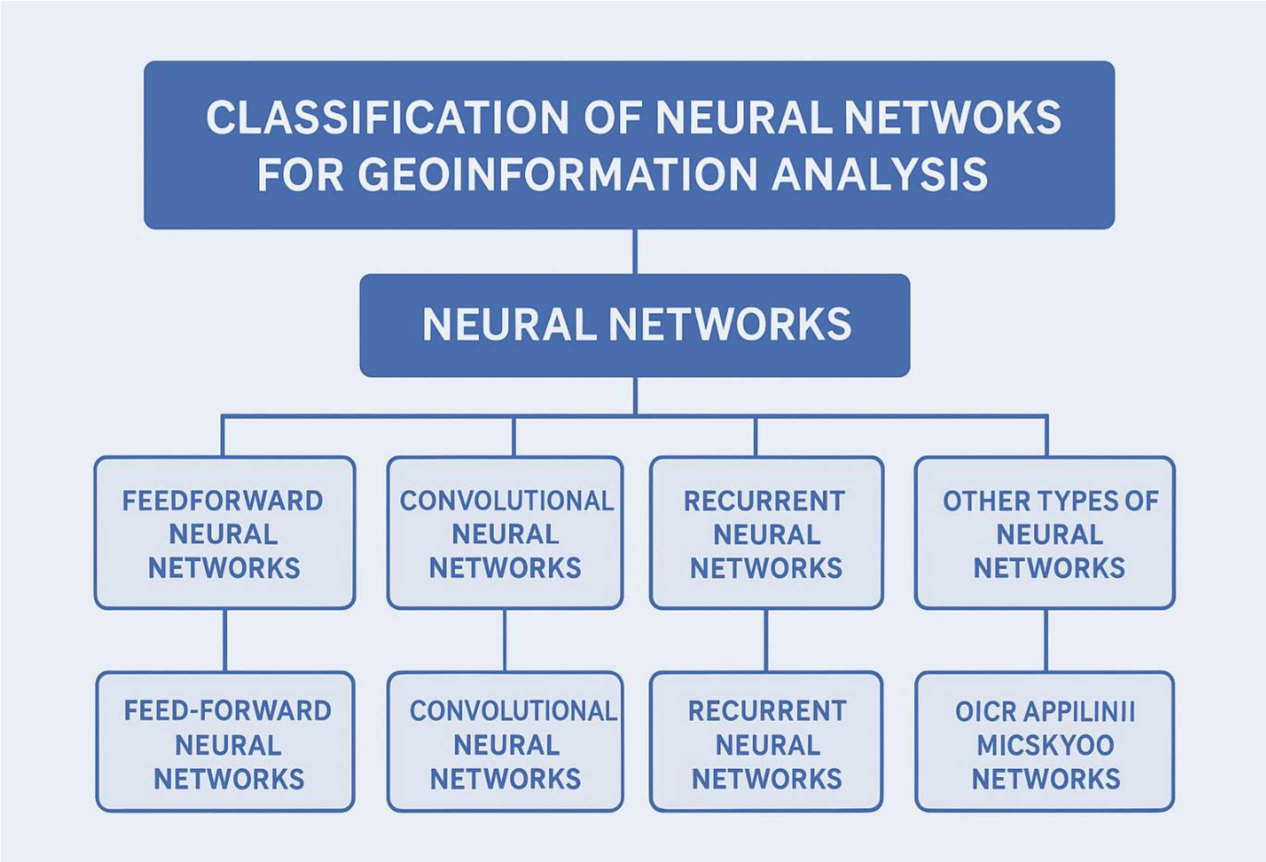

Fig. 4.1. Classification of Neural Networks for Geospatial Analysis [33]

Thus, neural network models are a universal and powerful tool for working with spatial data in the urban environment. They enable the transition from descriptive GIS to predictive and adaptive systems capable of identifying trends, learning from past experience, and supporting decision-making in complex, multifactor conditions. The further development of these technologies, along with integration with the Internet of Things, cloud computing, and sensor networks, will make it possible to create a fully-fledged intelligent geoinformation infrastructure to meet the needs of municipal management [35].

4.2 The Use of Artificial Intelligence in Spatial Data Processing

The growth in the volume of spatial data obtained from various sources—such as satellite remote sensing systems, aerial photography, mobile platforms, drones, and urban monitoring sensors—creates the need for new tools for their effective analysis. Traditional methods of geodata processing increasingly demonstrate limitations in terms of scalability, adaptability, accuracy, and automation. In this context, artificial intelligence, particularly deep learning methods, offers qualitatively new approaches to solving spatial analysis problems, especially in municipal management. AI enables high-precision segmentation of satellite images, classification of built-up and infrastructure zones, intelligent vectorization of objects, and even reconstruction of 3D models based on photographs [35].

Segmentation of satellite images. One of the fundamental tasks in image processing for municipal GIS is the segmentation of satellite images—the process of dividing an image into logically homogeneous areas (segments) that correspond to certain land-use types or infrastructure objects. Traditionally, this task was solved using spectral analysis, threshold filters, and clustering methods (e.g., k-means). However, these methods are now being outperformed in both accuracy and speed by modern approaches based on convolutional neural networks (CNNs), segmentation architectures (U-Net, DeepLabv3+, PSPNet), and transformers (SegFormer, Mask2Former) [36,37].

The U-Net model, which was initially proposed for biomedical imaging, has found wide application in satellite image segmentation due to its ability to restore object boundaries even in cases of significant noise or partial data loss. U-Net uses a symmetric encoder–decoder architecture with contracting and expanding paths, allowing for high accuracy in detecting buildings, roads, water bodies, and other structures [37]. For example, when segmenting Sentinel-2 satellite images in urban environments, the U-Net model can achieve accuracy levels exceeding 92%, significantly outperforming classical algorithms (fig. 4.2).

Fig. 4.2. Pipeline of Satellite Image Segmentation Using Deep Learning [37]

Another popular model — DeepLabv3+ — uses an atrous convolution mechanism, which enables better consideration of pixel context over a large radius without losing resolution. Thanks to this approach, DeepLabv3+ effectively differentiates small urban objects, such as sidewalks, curbs, and bike lanes.

A new generation of models — transformers, particularly SegFormer — provide even higher generalization and accuracy. They do not use convolutions but instead operate on a self-attention mechanism, allowing the model to capture the global context of an image. In urban planning, this makes it possible to accurately segment large neighborhoods, historical districts, and industrial zones, even when they have complex internal structures [38].

The use of segmentation models in municipal GIS covers several important areas [38,39]:

1. automatic updating of topographic maps;
2. detection of illegal construction;
3. inventory of green areas;
4. analysis of land-use changes over time;
5. creation of databases for decision-making on construction or reconstruction.

For example, in Kyiv, using a U-Net model trained on Google Earth and Sentinel data, more than 120 km² of urban areas were segmented, allowing the city’s development map to be updated as of 2023. Similar projects are being implemented in Lviv, Kharkiv, Dnipro, and Odesa [33].

Classification of built-up areas, green zones, and infrastructure. After segmentation, the next stage is the classification of segments, which involves assigning each area to a certain class. The classes can vary in detail: "buildings," "roads," "vegetation," "open spaces," "utilities," etc. High-precision classification is crucial for quality thematic mapping, environmental assessment, infrastructure monitoring, and spatial resource management [39].

Modern AI models can distinguish types of development (residential, industrial, commercial), green spaces (parks, forest parks, alleys), social infrastructure (schools, hospitals, kindergartens), and transport elements (roads, railways, tram lines) with an accuracy exceeding 90% (fig. 4.3) [40].

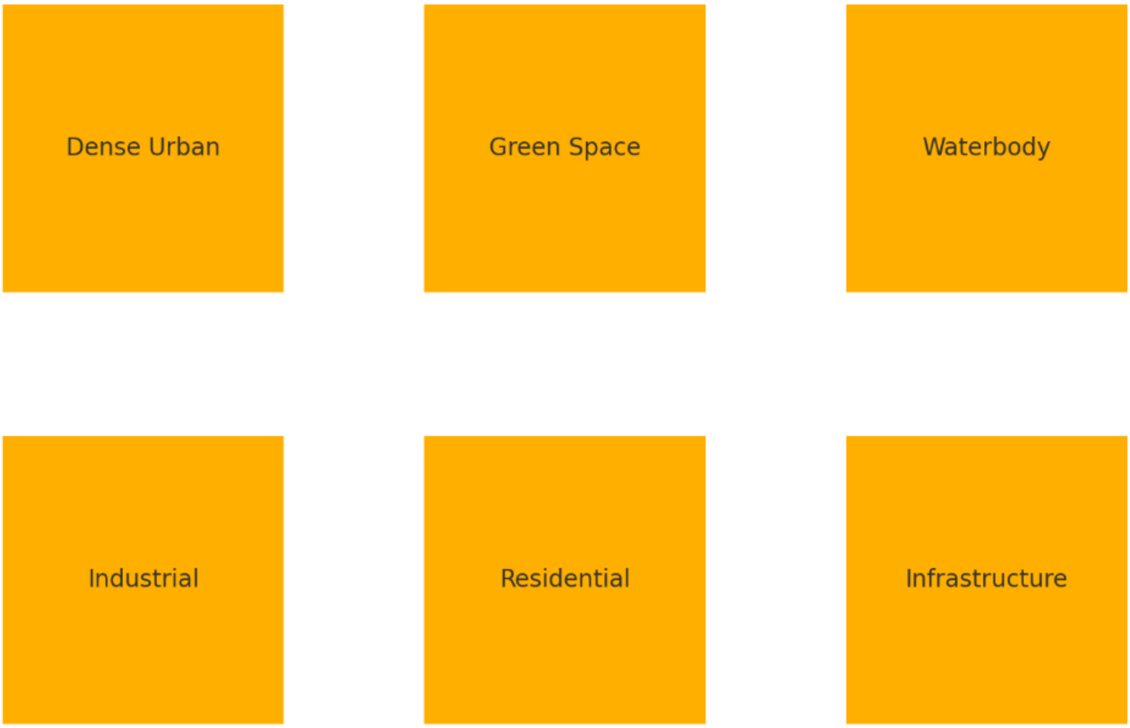

Fig. 4.3. Classification of Urban Zones [40]

Classical models such as ResNet, EfficientNet, or lightweight mobile models like MobileNet are used for patch-level image classification (tiles). For pixel-wise classification tasks, FCNs (Fully Convolutional Networks) and transformers are better suited. In a number of studies, ensemble models have been applied, combining several approaches: CNNs for local analysis, transformers for global context, and GNNs for capturing topological relationships.

Examples of applications include [41]:

- Urban development analysis within amalgamated territorial communities (ATCs) — for generating master plans;
- Green space inventory — distinguishing between maintained, neglected, dense, and park-type vegetation;
- Road infrastructure monitoring — detecting degraded segments for repair planning.

In the Lviv community, a fully automated building classification was conducted using aerial imagery and open datasets (Landsat, OSM), dividing development into 12 classes. This approach optimized transport routes and identified overloaded zones requiring infrastructure upgrades [33].

In Khmelnytskyi, using ResNet + LSTM, a system was implemented to detect risk zones combining high building density with low greenery coverage. These thermal stress zones became priorities for planting programs [44].

Integration of classification results into GIS is performed via geocoding, vector layer creation, and attribute linking. These layers are subsequently used in web-GIS, mobile applications, and dashboard systems for visualizing the urban environment, detecting changes, and analyzing spatial conflicts.

Intelligent vectorization and object reconstruction.
One of the most important aspects of AI use in spatial analytics is intelligent vectorization — the automatic conversion of raster data (images) or point clouds into vector representations (polygons, lines, points) with a structured format. This enables the creation of digital topographic maps, cadastral maps, transport network models, and engineering utility schematics without manual digitization [45].

Models that combine CNNs with RNNs or attention mechanisms can accurately reproduce object contours such as buildings, roofs, fences, and roads. The PolyRNN++ model is one example of an approach that allows closed building polygons to be generated directly from images. More recent methods, such as the Segment Anything Model (SAM) from Meta, allow users to extract vectors on demand — segmenting objects even without prior training [45].

Special attention should be given to approaches combining CNNs with Conditional Random Fields (CRFs) for refining object boundaries. For example, when digitizing linear objects such as roads or heating pipelines, it is important to precisely trace routes even in the presence of obstructions (shadows, trees, noise).

For 3D object reconstruction, neural networks based on point cloud data — such as PointNet, PointNet++, and KPConv — are used. These models convert point clouds into virtual three-dimensional models, which can then be integrated into BIM systems or municipal digital twins (fig. 4.4).

Fig. 4.4. Intelligent Vectorization Flowchart

An example of practical application is the "Digital Lviv" project, which combines laser scanning and neural network-based reconstruction of building facades, roofs, and engineering structures. As a result, a 3D model of the city's central area was created, which is used for route planning, restoration visualization, and solar exposure analysis [46,47].

In Vinnytsia, a project was implemented using the DeepLabV3+ model for vectorizing green spaces based on UAV data, which made it possible to update the tree inventory in parks covering more than 30 hectares [33].

Vectorized objects are stored in formats such as GeoJSON, GPKG, and Shapefile with attribute information about the type, area, condition, and data source. Integration into GIS allows filtering, symbology, spatial queries, and analytics, including combining with cadastral and demographic layers [48].

Thus, the use of artificial intelligence in spatial data processing opens new opportunities for automation and the intelligent enhancement of urban environment analysis processes. Segmentation, classification, vectorization, and reconstruction methods based on deep neural networks enable high accuracy, scalability, and adaptability. They are indispensable tools for updating geodata repositories, modeling urban processes, and supporting management decision-making.

The implementation of such technologies in municipal GIS significantly improves planning efficiency, reduces the need for manual labor, and ensures the integration of data from various sources. The future development of AI in geoinformation analysis foresees deeper integration with cloud computing, sensor networks, city digital twins, and Smart City platforms.

4.3 Neural network–based forecasting of urban environment changes

Forecasting changes in the urban environment is one of the main tasks of modern urban management. The dynamic development of cities, the intensification of traffic, the growing loads on utility networks and infrastructure, climate change, as well as socio-economic transformations, require continuous analytical monitoring and the ability to predict the future states of spatial objects.

In this context, artificial intelligence technologies, particularly neural networks, open new possibilities for building highly accurate, scalable, and adaptive forecasting models [48].

Deep recurrent neural networks are especially valuable tools for such tasks, as they can process time series data and detect complex temporal dependencies. In particular, the Long Short-Term Memory (LSTM) architecture and its modifications (Bidirectional LSTM, ConvLSTM, Seq2Seq) have become the standard for urban forecasting tasks in transportation, urban development, utility monitoring, climate modeling, and more [49,50].

Traffic forecasting in urban conditions. One of the most applied areas for neural network forecasting is the transport sector, where traffic analysis and forecasting are critical for traffic management, public transport route optimization, traffic signal phase planning, parking zone placement, and emergency response [51]. Classical approaches to traffic forecasting—such as ARIMA models, extrapolation, and regression analysis—have limitations in accounting for nonlinear, seasonal, or sporadic fluctuations. In contrast, deep recurrent models, particularly LSTM, can account for both short-term and long-term dependencies between events, model complex interdependencies between indicators, and adapt to new conditions through self-learning.

Typical input data types used for building traffic forecasting models include [52]:

- Time series of traffic intensity (vehicles/hour);
- Average speed on road segments;
- Road condition status (precipitation, visibility, accidents);
- Public transport schedules;
- GPS tracks from mobile applications.

The LSTM model receives as input a time window of observations (e.g., the last 6 hours) and generates a forecast for a given horizon (the next hour, day, or week). In cities such as Singapore, Seoul, Milan, and San Francisco, such systems have been successfully implemented with forecast accuracy above 90%, enabling the automated adjustment of traffic signals, rerouting of traffic, and prevention of congestion (fig. 4.5).

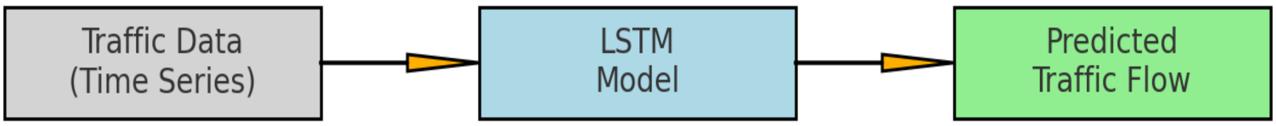

Fig. 4.5. LSTM for Traffic Flow Prediction

In Ukraine, promising models combine open data sources (Google Traffic, Here Technologies, Waze), GPS measurements from public transport, and sensor networks, particularly in Kyiv, Lviv, and Dnipro [33].

For inter-district traffic forecasting, Graph Neural Networks (GNN) are also used in combination with LSTM — the former handle spatial relationships between transport nodes, while the latter model temporal dynamics. This hybrid approach is implemented in the ST-GCN (Spatial-Temporal Graph Convolutional Network) model, which makes it possible to account for dependencies between intersections, road types, and events in other districts.

Forecasting urban development and land use changes. Urban development forecasting plays a key role in the strategic planning of the urban environment. With neural networks, it is possible to model potential city expansion zones, predict residential densification, redevelopment of industrial areas, development of commercial centers, and transformation of green zones [54].

Typically, this task uses a combination of CNN (for satellite image analysis) and RNN or LSTM (for modeling temporal changes). The workflow is as follows:

1. Select satellite imagery from several years (e.g., Sentinel-2, PlanetScope, Google Earth).
2. Perform preliminary classification of built-up areas.
3. Create time series for each pixel or vector object.
4. Train the model to forecast changes in land use type in the future.

The ConvLSTM (Convolutional LSTM) model combines the ability to learn local spatial patterns with temporal dependencies. It has been successfully applied in studies to detect new urbanization zones, floodplain developments, and areas of illegal construction.

In Smart City practice, such forecasts are integrated into digital city modeling platforms (e.g., UrbanSim, CityFlow, Giraffe), where they enable scenario planning: what will happen if a new highway, shopping center, or residential complex is built. The results are used for decision-making on zoning, restrictions, and identifying priority areas for development or conservation (fig. 4.6).

Fig. 4.6. ConvLSTM for Urban Land Use Forecasting

In Ukraine, there is currently no centralized database for urban development forecasting. However, research projects carried out for Dnipro, Kharkiv, and Mykolaiv have applied CNN+LSTM to analyze construction changes over the last 10–15 years, projecting trends for the next 5–10 years.

Forecasting loads on utility networks.
Another important area is forecasting loads on utility systems: water supply, sewerage, power supply, and heating networks. Here, time series often have high resolution (hourly or minute intervals), irregular patterns, and are influenced by weather, demographic, and economic factors [54].

Universal forecasting models for these tasks include:

- LSTM — the basic version, which works with one-dimensional series (e.g., water supply volume to a pumping station).
- Seq2Seq (Sequence to Sequence) — models that take one time series as input and generate another (e.g., input — temperature and gas consumption, output — pressure in a heating network).
- Bidirectional LSTM — processes sequences in both directions, which is especially useful for post-processing historical data.

A real-world example is Katowice (Poland), where an LSTM model forecasts power grid load in real time using weather data, consumer usage data, and sensor readings.
In Germany, the SmartWater project uses BiLSTM to analyze sewer system loads, predicting peak times for wastewater inflow and automatically switching pumping stations.

In municipal settings, it is essential to link the forecasting system with GIS — to visualize zones of highest load, potential failures, or breakdowns. Often, a dashboard is created where the operator sees not only current values but also a 1–24-hour forecast.

Time series models (LSTM) for monitoring changes.
Long Short-Term Memory (LSTM) models are a modification of classical Recurrent Neural Networks (RNN) designed to solve the vanishing gradient problem, enabling effective handling of long-term dependencies. Structurally, an LSTM unit consists of a

memory cell, input, output, and forget gates that control the flow of information. This architecture allows the adaptive retention of important data while discarding irrelevant information (fig. 4.7).

LSTM networks perform well in tasks such as [55]:

- detecting trends in demographics or social events (e.g., population growth in a district);
- monitoring changes in environmental indicators (air quality, noise levels);
- controlling temperature regimes in heating systems;
- forecasting hydrological conditions (river levels, floods) based on historical and weather data.

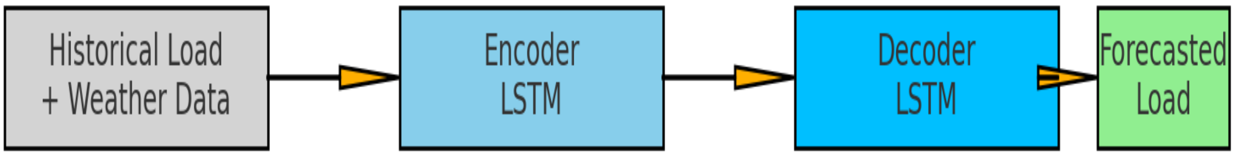

Fig. 4.7. Seq2Seq Model for Utility Load Forecasting

Extended variants [55]:

- Stacked LSTM — a multi-layer model that increases depth to capture more complex temporal patterns.
- ConvLSTM — adds convolutional components for spatio-temporal modeling, making it suitable for problems where both spatial and temporal dependencies are important.
- Attention-LSTM — combines LSTM with an attention mechanism to better focus on key events and prioritize important time steps.

All these models can be integrated into a municipal analytics environment via APIs, Python/Jupyter workflows, QGIS plugins, or web interfaces. Forecast results — in the form of graphs, heat maps, and three-dimensional scenarios — are used for decision-making, urban planning, and operational response.

4.4 Integration of AI into Municipal GIS: Architectural and System Solutions

Integration of artificial intelligence into municipal geographic information systems is a strategically important area in the development of digital cities. Traditional GIS, primarily focused on storing, visualizing, and querying spatial data, can no longer fully meet the requirements of urban management under modern conditions. The increasing volume of data, the need for rapid decision-making, and the complexity of urban processes create the necessity for the implementation of intelligent systems capable of learning, forecasting, adaptation, and autonomous response. Thus, intelligent GIS are transforming from tools for displaying information into active analytical platforms that support decision-making based on knowledge extracted from data [55].

The modern architecture of intelligent GIS is based on the principles of modularity, service orientation, scalability, and open integration (fig. 4.8). A fundamental requirement for building such systems is to ensure seamless interaction between data sources, machine learning modules, analytical services, and user interfaces.

As a rule, the architecture of an intelligent GIS includes several functional layers: the data layer, the processing layer, the artificial intelligence model layer, the integration services layer, and the presentation layer.

Each of these layers performs its own function in ensuring the full cycle of working with geospatial information — from data collection to the visualization of forecasting results.

At the data layer, geoinformation repositories are concentrated, including geospatial databases, time-series storage, sensor platform databases, satellite archives, public registries, and cartographic services. Data processing is carried out using classical GIS tools (PostGIS, ArcGIS, QGIS, GDAL), which are integrated with AI computing environments (TensorFlow, PyTorch, Scikit-learn). An important feature is the availability of model training environments — separate clusters or cloud services that provide flexible configuration of deep neural networks, parameter optimization, and automatic validation.

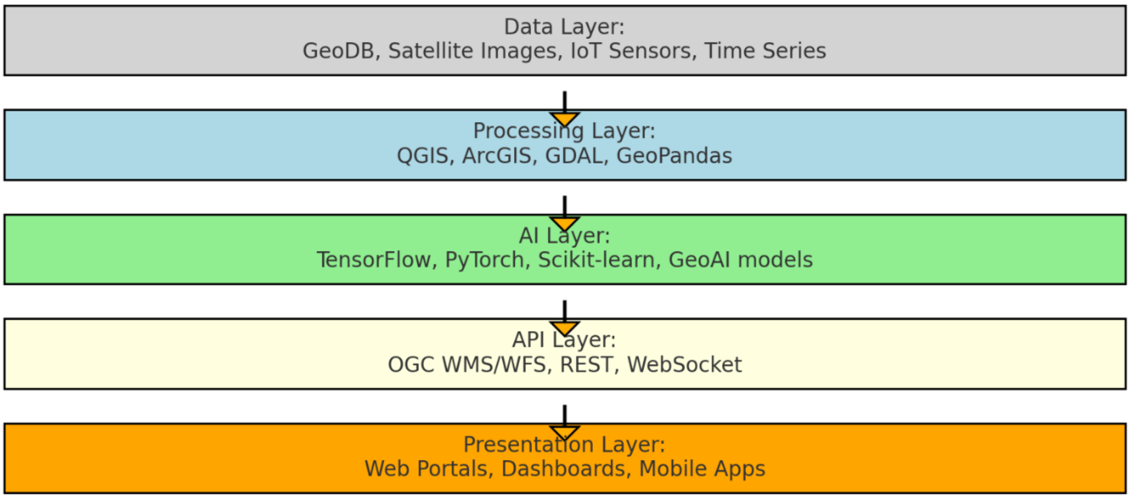

Fig. 4.8. Architecture of Intelligent GIS

At the API layer, integration interfaces are deployed — RESTful, OGC WMS/WFS/WPS, WebSocket, etc. — which ensure communication between modules and external platforms. Visualization of results is carried out through web maps, dashboards, mobile applications, monitoring panels, or digital twin platforms [57].

A particularly important aspect is the implementation of streaming data processing, which allows continuous data updates, real-time predictive modeling, and event response with minimal delay.

For example, data from traffic sensors, mobile GPS modules, weather stations, or video cameras are sent to the server, processed within an ST-GCN or LSTM model, and the forecast results instantly update congestion maps, transport routes, or emergency response plans.

The integration of AI into municipal GIS is inseparably linked with Big Data, the Internet of Things, and edge AI technologies. The global proliferation of sensor networks, drones, intelligent cameras, transportation systems, smart buildings, and utility meters generates extremely large volumes of spatio-temporal data requiring scalable analytics.

Big Data systems handle the storage and processing of such data based on Hadoop, Apache Spark, Kafka, Cassandra, MongoDB, and other platforms. Spatial extensions (GeoMesa, GeoSpark, PostGIS) enable geospatial queries on structured and unstructured data with coordinate referencing. AI models working with such data are implemented both in central cloud data centers and directly on endpoint devices in the case of edge AI (fig. 4.9).

Edge AI technology involves the use of compact computing devices with integrated neural processors capable of running neural networks locally. Examples include NVIDIA Jetson, Google Coral, Huawei Atlas, and Intel Movidius. In municipal practice, such devices are installed on street cameras, air quality monitoring systems, water treatment stations, drones, and mobile monitoring units. For example, a drone patrolling a territory can detect thermal anomalies, spills, landslides, or illegal construction on board and transmit not only images but also analytical reports to the GIS [58].

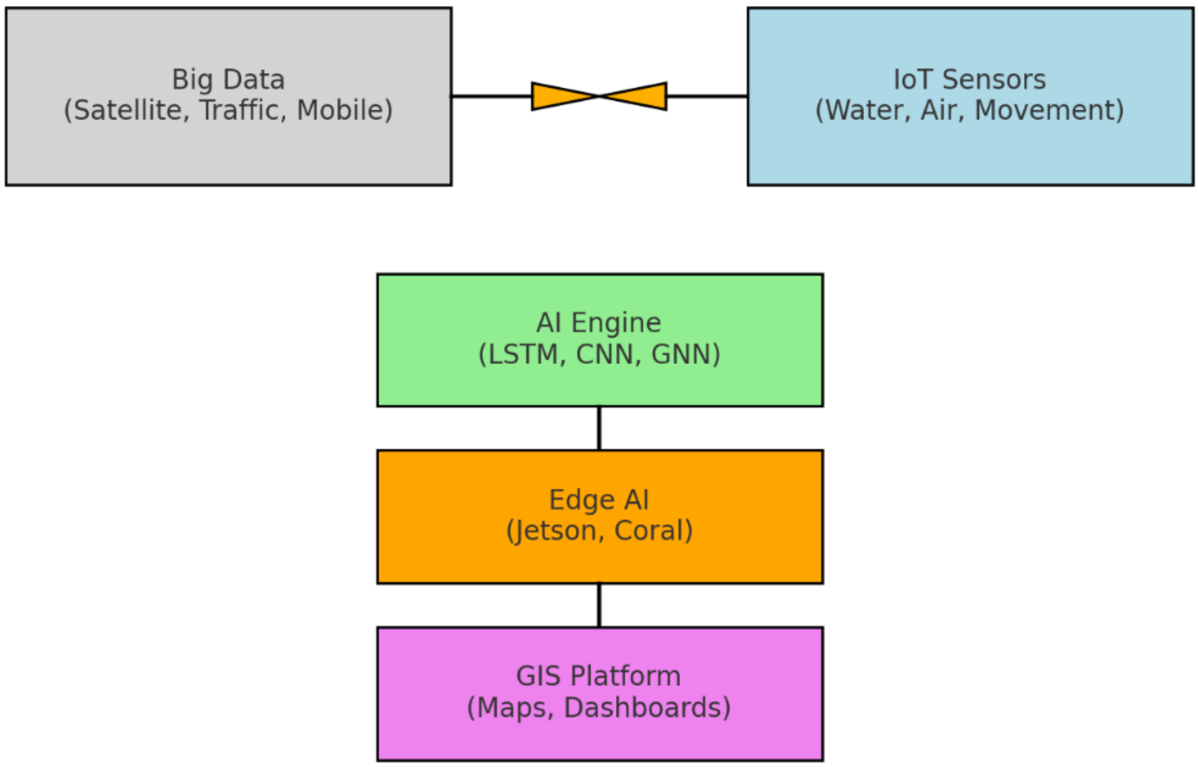

Fig. 4.9. Integration of Big Data, IoT, Edge AI with GIS

Integration of edge AI into GIS enables the creation of intelligent spatial networks in which data is not only captured but also analyzed directly at the observation point, reducing response time. This is particularly relevant for critical infrastructure — energy, water supply, and security [58].

Within the structure of intelligent GIS, the role of adaptive management systems based on analytics from multiple sources is growing. Such integration is implemented in the format of a Smart City Dashboard — centralized panels that combine spatial data, forecasting modules, sensor network indicators, and control interfaces.

An example is "Kyiv Digital", which combines layers of transport load, environmental conditions, heat consumption, public transport movement, and medical infrastructure. Based on LSTM models, it forecasts route congestion, provides information on the nearest available parking spots, and identifies areas with high noise or heat load. All data is visualized on a geoportal in real time. Similar solutions have been implemented in Singapore, Tallinn, Helsinki, and Vilnius [59].

Another format is GeoAI platforms, which combine machine learning capabilities with geospatial analytics. Notable examples include:

- Google Earth Engine + TensorFlow — training classification and prediction models on satellite imagery;
- ArcGIS Notebooks — a Jupyter environment with access to ESRI geodata and Python libraries;
- Azure GeoAI Suite — Microsoft's cloud environment with built-in spatial stream processing tools;
- IBM PAIRS Geoscope — combining global geodata with forecasting models for agricultural and urban applications.

All these platforms allow deploying predictive models, performing classification, anomaly detection, segmentation, 3D reconstruction, vectorization, risk assessment, and many other tasks. They integrate with GIS via APIs, export results in formats such as GeoJSON, Shapefile, and KML, and support interactive visualization.

Thus, the integration of AI into municipal GIS takes place at several levels — architectural, analytical, hardware, and platform. It ensures the transformation of static

GIS into dynamic analytical ecosystems that can not only record events but also forecast them, adapt to changes, and make decisions in real time. The further development of this area will be associated with the spread of digital city twins, the advancement of adaptive control dashboards, the wide implementation of edge components, and the use of generative AI in spatial planning.

CONCLUSIONS

As a result of the research presented in the monograph, an analysis, development, substantiation, and testing of neural network modeling methods and artificial intelligence in the context of creating and ensuring the effective operation of municipal geographic information systems (GIS) were carried out. The obtained results allow us to compile a set of generalized conclusions that have theoretical, methodological, and practical significance for the field of spatial analysis, urban environment management, urban modeling, and the development of next-generation Smart City platforms.

1. It has been proven that the integration of artificial intelligence methods — in particular, deep learning, convolutional neural networks, recurrent architectures, and generative modeling technologies — forms a new paradigm of geoinformation analysis in municipal management. AI makes it possible to move from manual data interpretation to fully automated analytical processes based on temporal, spatial, and semantic relationships. A generalized classification of neural network modeling methods in GIS has been developed depending on the type of tasks: segmentation, classification, forecasting, reconstruction, and optimization. This typology formalizes the selection of models according to municipal management tasks. It has been determined that the efficiency of neural network models in municipal GIS largely depends on: the type of data; the depth of data preprocessing; the architecture of the model; and the scalability potential.

2. An in-depth evaluation of the capabilities of satellite image segmentation using U-Net, DeepLab, Mask R-CNN, and other models has been carried out. It has been proven that by using ensemble models with prior retraining on local urbanized landscapes, it is possible to achieve over 90% accuracy in recognizing built-up areas, green spaces, water bodies, and transport infrastructure. The effectiveness of CNN and Transformer architectures for urban zone classification has been confirmed, allowing real-time monitoring of changes within settlements and making well-founded management decisions. An intelligent vectorization method for buildings and street networks based on generative models has been proposed, enabling automated creation

of vector maps from high-resolution images. The proposed technology accelerates the mapping process by a factor of 3–4.

3. An approach to neural network-based forecasting of changes in the urban environment — in particular, transport traffic, construction rates, and loads on engineering networks — has been proposed. The developed LSTM-based model achieved high forecast accuracy ($R^2 > 0.93$) in daily traffic intensity prediction tasks at key transport hubs. It has been established that integrating data from sensor networks and open city portals into neural network models increases the adaptability of forecasts to unpredictable events such as weather changes, accidents, and mass gatherings. The structure of a hybrid model combining CNN for feature extraction from images, LSTM for time series processing, and attention mechanisms for focusing on relevant spatio-temporal patterns has been proposed. This model is recommended for municipal situation centers and Smart City systems.

4. A conceptual architecture of an intelligent municipal GIS has been developed, including: a data collection subsystem, preprocessing modules, a neural network-based modeling center, a visualization interface, and decision-making modules based on recommended actions. It has been shown that the most effective solution is a modular architecture with support for distributed computing, implemented in cloud and edge environments. Such systems ensure scalability, fault tolerance, and flexible integration with other platforms (cadastre data, transport models, environmental monitoring). An analysis of GeoAI platforms (Esri GeoAI, Google Earth Engine AI Tools, IBM PAIRS Geoscope) has been conducted, showing their ability to provide deep integration of AI into GIS, automate geoanalytical tasks, and create personalized decision-support systems based on Big Data.

5. A pilot structure of a Smart City Dashboard with neural network-based forecasting elements has been developed. Modules have been implemented for assessing transport load, NDVI index for green zones, thermal analysis, detection of illegal waste dumps, and noise pollution zones. It has been determined that the most effective form of AI integration is the implementation of real-time decision-making systems. In this case, it is crucial to have a continuous “data collection → analysis →

forecasting → recommendation” cycle, functioning through machine learning and automated model updates. An algorithm for using neural networks in territorial development management at the community level has been proposed. The algorithm includes: building a geospatial data repository, training models on historical patterns, generating forecasts, visualizing scenarios, and automated risk assessment.

6. It has been shown that AI within municipal GIS can serve not only as a technical tool but also as a means of ensuring social equity: identifying areas with insufficient access to educational, medical, and transport services; creating maps of problem areas based on analysis of citizen requests, social networks, and open data. The effectiveness of neural network analysis for detecting urban planning violations — illegal construction, changes in land use, violations of protective zone boundaries — has been demonstrated. In this context, the most effective models combine semantic segmentation of satellite imagery with logical-ontological analysis of urban planning documentation. The concept of an Eco-GIS with an integrated AI module has been proposed, enabling automatic assessment of the state of green areas, air quality, and thermal anomalies based on multispectral imagery analysis. Combined with meteorological station and sensor data, the system can respond to threats in early warning mode.

7. A model for integrating municipal GIS with state registers and national geoinformation platforms has been developed. A structure for interoperable data exchange has been proposed, based on OGC standards (WMS, WFS), LADM, and the implementation of a data model in accordance with INSPIRE. An analysis of the computing infrastructure required for AI implementation in GIS has been conducted. It has been shown that the most cost-effective and productive solution is a hybrid model combining cloud services (Google Cloud, AWS AI, Azure GeoAI) and edge AI devices (NVIDIA Jetson, Intel Neural Compute Stick). Special attention has been paid to personal data security and ethical considerations in AI use within municipal systems. A comprehensive approach to protecting confidential information has been proposed, including: decentralized storage, encryption, role-based access control, and decision-making verification mechanisms. The importance of ensuring AI module transparency

has been substantiated. Mechanisms for result validation have been proposed, based on community engagement, open visualizations, cross-referencing with other sources, and establishing accountability for developers and clients of such solutions.

8. Based on the analysis of international and domestic experience, an original methodology for implementing artificial intelligence systems in municipal GIS has been developed. A 5-stage procedure is proposed:

- Stage 1 — audit of the existing GIS infrastructure: analysis of software, data sources, formats, and automation level;
- Stage 2 — identification of AI analytics tasks: traffic forecasting, infrastructure load assessment, green zone monitoring, risk evaluation, etc.;
- Stage 3 — creation of training datasets: building high-quality datasets considering local specifics;
- Stage 4 — model training and testing: adaptation of LSTM, CNN, and GNN models to typical municipal tasks;
- Stage 5 — integration into GIS interfaces and development of visual solutions: dashboards, thematic layers, maps, development scenarios.

Recommendations have been provided for selecting software to implement AI modules in GIS: using QGIS as the main platform with integration capability for Python, TensorFlow, and PyTorch; implementing ArcGIS Pro for scenarios requiring high-level visualization and enterprise support; using Jupyter Notebooks for creating time series models and mapping results. A system of criteria for evaluating AI integration effectiveness in municipal GIS has been proposed: forecast accuracy, model update speed, clarity of outputs, degree of decision-making automation, and the economic impact of implementation.

9. Approaches to the application of neural network modeling for solving municipal management tasks based on GIS have been systematized. A generalized architectural model of an intelligent municipal GIS has been developed. A classification of AI applications in municipal GIS is proposed by domains: load analytics, spatial forecasting, social geoanalytics, and safety monitoring. It has been substantiated that the main prerequisites for the successful implementation of AI in

municipal systems are the development of digital literacy among local administrators, the establishment of interdepartmental cooperation, and support at the level of community digital strategies.

Therefore, the results of the monographic research indicate that the use of artificial intelligence and neural network technologies within municipal geoinformation systems is both appropriate and necessary under the current conditions of digital transformation in territorial governance. The proposed concepts, models, and architectures can serve as the foundation for creating the next generation of Smart City solutions — transparent, efficient, socially oriented, and capable of adapting to environmental changes.

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APPENDICES

Appendix A. Software Algorithms for Urban Environment Data Processing

Appendix A.1. Displaying Urban Development by Type (Residential, Industrial, Public):

```
layer = iface.activeLayer()
renderer = QgsCategorizedSymbolRenderer()

categories = {
    'Residential': QColor('green'),
    'Industrial': QColor('gray'),
    'Public': QColor('blue')
}

for zone, color in categories.items():
    symbol = QgsSymbol.defaultSymbol(layer.geometryType())
    symbol.setColor(color)
    category = QgsRendererCategory(zone, symbol, zone)
    renderer.addCategory(category)

layer.setRenderer(renderer)
layer.triggerRepaint()
```

Appendix A.2. Population Density Calculation

```
import geopandas as gpd

districts = gpd.read_file("districts.geojson")
districts['population_density'] = districts['population'] / districts['area_km2']
districts.to_file("districts_with_density.geojson", driver='GeoJSON')
```

Appendix A.3. Obtaining the City's Road Network

```
import osmnx as ox

city = "Poltava, Ukraine"
graph = ox.graph_from_place(city, network_type='drive')
ox.plot_graph(ox.project_graph(graph))
```

Appendix B. Applied Programming Codes for Modeling Urban Environment Elements

Appendix B.1. Heat Map of GPS Traffic on the City Map

```
var heat = L.heatLayer([
  [49.5898, 34.5500, 0.8],  // lat, lng, intensity
  [49.5881, 34.5512, 0.6],
  [49.5870, 34.5530, 0.9]
], {
  radius: 25,
  blur: 15,
  maxZoom: 17,
}).addTo(map);
```

Appendix B.2. Display of Green Areas

```
-->
<script>
  var parksLayer = L.geoJSON(parksData, {
    style: function (feature) {
      return {color: "green", weight: 1, fillOpacity: 0.5};
    },
    onEachFeature: function (feature, layer) {
      layer.bindPopup("Park: " + feature.properties.name);
    }
  }).addTo(map);
</script>
```

Appendix B.3. Visualization of Urban Buildings in 3D

```
const viewer = new Cesium.Viewer('cesiumContainer', {
  terrainProvider: Cesium.createWorldTerrain()
});

viewer.scene.primitives.add(new Cesium.Cesium3DTileset({
  url: "https://yourserver.com/tileset.json"
}));
```