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Theoretical Insights into Artificial Intelligence Applications in Human Geography and Spatial Management (GeoAI)

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Abstract:

Purpose: *The aim of this article is to explore and preliminarily classify the theoretical potential of Artificial Intelligence (AI) in human (socio-economic) geography and spatial management. The study highlights key areas where AI methodologies intersect with geographical analysis, focusing on their conceptual implications.*
Design/Methodology/Approach: *This paper presents a descriptive review, employing a scoping literature review based on repositories, observation, and case study analysis. A comprehensive tabular compilation of the main areas of AI applications in human geography has been developed.*
Findings: *From the perspective of artificial intelligence technology implementation outcomes, it is necessary to distinguish between two areas of AI applications: scientific (analytical) and pragmatic - applied, although they remain interconnected. Achieving the objective required a broad perspective on the internal structure of human geography as a science (division into subdisciplines) and its pragmatic counterpart - spatial management and planning. The literature review of GeoAI applications in the socio-economic context revealed that cities and future city concepts constitute a major domain for various AI methods implementation.*
Practical Implications: *The findings of this study are primarily theoretical, offering a foundation for further exploration of AI applications in human geography and spatial management. While the research does not propose immediate practical solutions, it provides a conceptual framework that could guide future studies and inspire methodological advancements in the field.*
Originality value: *The paper addresses theoretical issues. The content can serve as a foundation for lectures or as a reference for other publications in this field.*

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1. Introduction

Artificial intelligence (AI) is a broad and multifaceted field encompassing various approaches, technologies, and problem-solving methods. The acronym AI is currently associated, due to startups financially supported by Big Tech players (Microsoft, Google, Amazon, Meta, Apple, etc.) and other entities, with interactive large language models (LLMs) such as ChatGPT, Gemini, Claude, and other less known models. These commercial solutions are available through subscription or in limited versions practically to everyone.

It is important to note that AI has been present for many years in analytical work related to geography, both physical and human. Technological advancement opens up opportunities for broader implementation of artificial intelligence methods, thus increasing the efficiency and quality of obtained conclusions, which enhances their utility in decision-making and expands knowledge about the geographical environment.

2. Literature review

According to Corea (2019), understanding AI requires awareness of the fundamental approaches used in AI. These include:

- Search and Optimization – search and optimization techniques that enable finding and improving problem solutions.
- Embodied Intelligence – systems responding to physical environment, crucial in robotics.
- Machine Learning (ML) – algorithms learning from data, used in predictions, classification, and pattern recognition.
- Probabilistic Methods – decisions based on probability under conditions of uncertainty.
- Knowledge-based Systems – knowledge management for decision-making.
- Logic-based Approaches – mathematical logic rules for precise decision-making systems.

Based on these approaches, various artificial intelligence technologies and algorithms have been developed, finding applications across different fields. These technologies include:

Evolutionary Algorithms – algorithms that employ mechanisms like biological processes, such as selection and mutation, to optimise problem solutions.

Ambient Computing – technology enabling AI interaction with the user's environment and adaptation to environmental context. Ambient computing allows systems to respond to varying environmental conditions.

Distributed Artificial Intelligence – where different AI components collaborate in a distributed system. This technology enables high scalability and is used in extensive networks and applications.

Autonomous Systems – systems operating without human intervention. Such systems are used in autonomous vehicles, robotics, and various applications requiring independent decision-making.

Artificial Neural Networks (ANN) – which imitate human brain structure and are used for pattern recognition, image processing, and natural language processing.
Probabilistic Programming – enables modelling of uncertainty and predicting outcomes in situations where complete information is difficult to obtain.

Decision Networks – help in modelling decision-making processes, taking into account preferences and environmental constraints.

Computer Vision – technology allowing AI to understand and interpret digital images, applied in object recognition, motion detection, and image analysis.

Natural Language Processing (NLP) – enables computers to understand, process, and generate natural language, finding applications in chatbots, translations, and voice assistant systems.

Robotic Process Automation (RPA) – business process automation technology that enables routine tasks to be performed using software "robots". RPA is applied in administrative and operational tasks.

Expert Systems – utilise expert knowledge and decision rules to support users in decision-making. They are applied in areas requiring specialist knowledge.
Inductive Logic Programming – combines logic and machine learning, enabling the creation of rule-based models.

All these technologies support the implementation of specific AI functions, and ultimately their operation can be reduced to basic problem-solving competencies. This division encompasses five key competencies:

Communication – function related to enabling AI interaction with users, primarily achieved through natural language processing. AI systems using NLP can understand and generate text, finding applications in chatbots, translations, and voice assistants.

Reasoning – AI's ability for logical thinking and drawing conclusions. Through expert systems and probabilistic programming, AI can analyse complex situations and make decisions based on logic and inductive reasoning.

Knowledge – area related to information storage and management. Systems such as decision networks and advisory systems store knowledge that AI can use for decision-making and generating recommendations.

Perception – function involving understanding and interpreting sensory data, such as images and sounds. Computer vision and robotics allow AI systems to interpret the surrounding world, recognise objects, analyse movements, and adapt to environmental changes.

Planning – the ability to plan actions and predict future states. Technologies such as autonomous systems and optimization algorithms enable AI to create complex plans that are executed to achieve a designated goal.

The precursor to technologies now referred to as Artificial Intelligence (AI)—often complex language models—are Artificial Neural Networks (ANNs). These models are inspired by biological nervous systems and can perform information processing tasks such as data classification and pattern recognition. An ANN consists of simple processing nodes, whose operation depends on the network's structure and the strength of its connections (synaptic weights).

Like biological neural networks, ANNs acquire knowledge through a learning process, with weights serving as the storage mechanism for this knowledge. Each neuron sums input signals and processes them through an activation function, which generates either excitatory or inhibitory outputs. These networks learn from data by adjusting their internal parameters to improve performance on specific tasks, such as prediction and classification. ANNs are, de facto, the foundation for many of today's advanced AI technologies.

The evolution of ANNs has led to the development of various architectures, including feedforward and convolutional networks, which are widely used in fields such as artificial intelligence and data analysis (Korytkowski, 2024; Qamar and Ali Zardari, 2023). Neural networks are not an invention; they originated in the 1940s. McCulloch and Pitts (McCulloch and Pitts, 1943) developed the first mathematical model of an artificial neuron, initiating the development of neural networks. Later, Rosenblatt (Rosenblatt, 1958) invented the perceptron, one of the first implementations of an artificial neuron. During the 1980s and 1990s, Hinton, LeCun, and Bengio significantly advanced deep learning methods (LeCun *et al.*, 2015).

Computational methods have also been employed in geography for many years, including genetic algorithms, cellular automata, expert systems, smart systems, and artificial life, which were developed in the 1980s (Openshaw and Openshaw, 1997; Tikunov, 1990). Integrating various types of information system technologies—such as GIS, expert systems, and artificial neural networks—can help mitigate the limitations of each system, particularly enhancing the intelligence level of geographic information systems.

The limitations of conventional geographic information systems (GIS) highlight three critical elements for integration with next-generation, more intelligent systems (Fischer, 1994):

- The concept of fuzzy logic,
- Advanced spatial analysis and modelling modules using conventional tools and/or AI technologies,
- AI technologies and spatial expert systems (SES), particularly artificial neural networks (ANNs).

Artificial neural networks (ANNs) excel at handling imprecise data, making them effective for solving complex problems where establishing clear rules is challenging. With their parallel processing capabilities, ANNs find applications in diverse fields such as engineering, finance, and spatial data analysis, including satellite data. They facilitate the classification, interpretation, and modelling of spatial information, supporting the approximation of complex physical processes.

Despite the division of geography into physical and human branches, both benefit from AI-based tools, finding common ground in spatial determinism (determinismus geographicus). This shared foundation underscores the versatility and adaptability of AI technologies across various geographical domains.

Determinism in the context of natural settings refers to the assumption that natural phenomena significantly influence or shape social, economic, and environmental behaviors, ultimately guiding human activity.

The following sections explore the key aspects of this concept. The influence of natural conditions and environmental changes affects human behavior, which is evident in the modifications of human actions and their geographic imprint (Ernste and Philo, 2009).

On the other hand, human activity, often referred to as anthropopression, carries both negative and positive connotations. In a negative sense, it involves environmental stress and degradation caused by human actions (Obolewicz *et al.,* 2022). Conversely, in a positive context, it encompasses environmental protection, reclamation, and renaturalisation efforts, which also manifest spatially.

A unifying theme for the application of AI methods in geography is captured under the term GeoAI. This emerging field represents the integration of artificial intelligence techniques into spatial analysis, enhancing the understanding and modelling of complex interactions between natural and human systems.

3. GeoAI

GeoAI, or geospatial artificial intelligence, is an interdisciplinary field that combines AI techniques with geospatial data and processes (Ouchra *et al.*, 2023; Usery *et al.*, 2022). It integrates approaches from computer science, statistics, engineering, and geographic disciplines to analyze and model spatial and temporal patterns. Applications of GeoAI extend to diverse fields, including urban planning, public health, environmental management, and defense (Chauhan and Shekhar, 2021).

A closely related concept, with a broader scope, is computational geography (Longley et al., 1998), which focuses on the use of computational methods to address geographical questions and challenges. Both fields reflect the increasing constructive interaction between advanced computational techniques and geographical sciences, opening new avenues for understanding complex spatial interactions.

Computational geography is a data-driven transformation of geography, aiming to understand the mechanisms underlying geographical forms and processes through the simulation of complex geographical phenomena and the intensive use of data. It aligns with the evolving field of computational social sciences (Lazer *et al.*, 2009).

GeoAI, on the other hand, focuses on developing spatial intelligence in machines to enhance the understanding of geographical phenomena and Earth science processes (Gao, 2020). While computational geography emphasises data and simulation to model and analyse dynamics, GeoAI leverages artificial intelligence to extract, interpret, and model geospatial patterns, creating a synergy between machine intelligence and geographical inquiry.

Emerging research areas in GeoAI include geospherical representation learning, spatiotemporal prediction, environmental monitoring, and semantic analysis of geotextual data. The unique challenges of GeoAI stem from the specific characteristics of geospatial data, such as spatial autocorrelation and the geometric nature of information, which require fundamentally different AI algorithms.

As the volume of geospatial data and applications continues to grow exponentially, GeoAI is expected to drive mutual advancements in both artificial intelligence and geospatial sciences. This synergy will not only improve the efficiency and accuracy of geospatial analyses but also expand the frontiers of AI through its adaptation to complex problems.

Among other things, GeoAI supports administration in city modeling, resource analysis and infrastructure forecasting. In natural resource management, it enables invasive species detection, raw material monitoring and tree stand analysis. In public safety, it forecasts events, optimizes emergency responses, and identifies damage.

In insurance, it analyzes the impact of events and classifies damages, and in construction, it improves project management and hazard identification.

4. Applications of GeoAI in Human Geography and Spatial Management

The first area of application of AI or GeoAI will be Monitoring and modeling changes in space. This is the identification of geographic conditions - physical, environmental changes occurring at different rates - This has long been done by remote sensing (e.g., LIDAR, radar, visible light, and invisible range techniques) to support environmental monitoring and sozology.

Reviewing thousands of photographs their comparison over time is a labor-intensive process, partially automated in photogrammetric processing and the use of raster graphics and GIS programs. Neural networks and learning algorithms allow for improved automation, greater productivity, and accuracy (Ouchra *et al.,* 2024).

Classification of information and data extraction are pivotal areas that benefit from AI integration. Through remote sensing, AI can automatically derive insights from geospatial data, such as identifying buildings, roads, green spaces, and other features in imagery. Data extraction converts raster data into vector formats, assigning attributes to point, line, or polygon objects. This process supports the creation of precise databases, such as tree maps, road infrastructure inventories, or analyses of land degradation. AI further aids in monitoring environmental changes, including vegetation succession, forest cover alterations, and the impacts of climate change, integrating these insights seamlessly into spatial analyses

Spatial-Social Analysis. This interdisciplinary approach combines data analysis methods with spatial and social contexts. It employs advanced techniques, such as cluster analysis (e.g., k-means or DBSCAN algorithms) (Starczewski *et al.,* 2020), enabling the identification of areas with similar characteristics based on datasets. Machine learning, both supervised and unsupervised, also plays a pivotal role by allowing the classification of regions based on selected features, such as demographics or infrastructure accessibility.

Additionally, the analysis of social data, including information derived from social media, is gaining importance, enabling the study of human behaviours and preferences in specific locations. Analytical platforms such as KNIME and Orange offer modules for such studies, utilising NLP-based tools (e.g., Geotagging/Geoparsing). Applications of spatial-social analysis include examining inequalities in access to public services, analysing socio-demographic structures, and identifying marginalised areas requiring intervention in public policies.

Optimising space usage and planning is a crucial aspect of urban management, supported by advanced data analysis technologies. Among the methods used are multi-criteria analyses (MCA) enhanced by artificial intelligence, which enable the consideration of multiple variables in decision-making processes. Spatial regression and predictive models, such as *Random Forest* and *XGBoost*, are also widely applied, allowing for the prediction of changes in spatial development.

Optimisation algorithms are used in planning the locations of new investments, identifying optimal solutions based on predefined criteria. Applications of these methods include determining the placement of critical facilities such as hospitals, schools, or logistics centres, urban development planning, and spatial management, including areas for construction, green spaces, and technical infrastructure. They also facilitate the creation of spatial development scenarios that incorporate social, economic, and environmental variables, supporting efficient space management and improving quality of life.

The fourth category, *Mobility and spatial behaviour analysis*, focuses on studying how people move and interact with space using spatial and technological data. Trajectory modelling plays a key role among the applied methods, utilising GPS data to track and analyse movement paths of individuals or vehicles. Another widely used approach is spatial network analysis, employing tools such as Space Syntax or transport graphs to study the structure and functionality of urban spaces, including transport connections and accessibility.

Big Data analysis from geotagged sources, such as social media, provides additional insights into user behaviours and preferences in specific locations. Applications of these methods include urban traffic modelling, population flow analysis, spatial consumption patterns, and public transport optimisation. These approaches enable better alignment of infrastructure with residents' needs, supporting smart city management and resource allocation.

Table 1. *Areas (detailed) of GeoAI applications in human geography and spatial management*

No	Area of Applications in Geography	Data Type	Primary Activity	Benefits	Examples
Monitoring and modeling changes in space					
1.	Economic Geography	Economic, statistical, regional, and geolocated economic data	Trend analysis, predictive modeling, identification of optimal locations	Economic development forecasts, facilitation of location decision-making	Regional development and economic dynamics (*Sztuczna Inteligencja i Inteligentna Geolokalizacja w Systemie GIS*, 2021)
2.	Physical / Urban Geography	Satellite imagery, spatial data, and GIS information	Classification and extraction of spatial data	Accurate classification of land cover	Land cover changes, urbanization, and environmental shifts (Golenia et al., 2015; Wen & Li, 2022)

3.	Climate Geography / Spatial Management	Climate, economic, and spatial datasets	Analysis of impacts, effect modeling, and prediction	AI models (e.g., CMIP6) increase prediction accuracy	NOAA (ML) forecasting the impacts of sea level rise (Tiwari et al., 2023)
4.	Environmental Geography, Management	Satellite images, sensor data	Image processing and change detection	Timely identification of environmental changes and appropriate response. Crisis management	Environmental transformations, pollution, and ecological degradation
Spatial-Social Analysis					
5.	Social Geography / Societal Geography / Spatial Management	Demographic, geolocated, social, economic, and infrastructure data (VGI - Volunteered Geographic Information)	Processing and analysis of large data sets, modeling and forecasting public service demand	Precise migration forecasts and understanding of causes, optimization of public resource allocation	AI recommendations from WorldPop (O'Riordan, 2024), provision of public services, and social development planning (Sui et al., 2013)
6.	Population Geography, Demography	Demographic data and census records	Modeling and forecasting demographic changes	Better socio-economic planning and policy-making	Population structure, demographic changes (Petrova & Lapina, 2020)
Optimising space usage and planning					
7.	Urban Geography, Spatial Management	Spatial (GIS), traffic data, socio-economic data + VGI	Demographic change modeling and forecasting	Optimization of urban space planning and processes	Smart City in Singapore (Łopusiewicz, 2019)
Mobility and spatial behaviour analysis					
8.	Transport Geography, Urban Planning	GPS datasets, traffic flow information, and telecommunications data	Analysis and modeling of traffic dynamics	Enhancing transport planning, mitigating congestion, and improving safety	Mobility of residents, development of transport infrastructure (ITS, 2021)
9.	Tourism Geography	Tourist preference data, demographic data, destinantions, spatial data	Analysis of behaviors and forecasting tourism trends	Adjusting tourism offerings to meet tourists' needs and addressing overtourism challenges	Tourist traffic, tourism development in the region (García & Grilló, 2023; Zhou, 2023).

Source: *Own elaboration.*

Geostatistical data analysis is an important area of AI applications in socio-economic research. AI supports the processing of large datasets, such as demographic, economic, and environmental data, assigned to administrative units (countries, regions, municipalities) or analytical units (e.g., FUAs – Functional Urban Areas in Europe).

AI enables the modeling of socio-economic phenomena, considering temporal and spatial variability. Big Data analyses, including data from mobile technologies and GPS, allow for the study of residents' activities and their movements.

5. Conclusions

GeoAI, as applied to human geography and spatial management, utilizes a range of data and methods from physical geography and remote sensing. The scope of analyses in human geography and AI can be observed across various levels, from the global to the local scale, and even down to specific places (placemaking). A city − metropolitan areas − serves as a unique microcosm for AI applications. Urbanized areas are characterized by significant intensity and dynamics, not only in terms of objects and land cover changes but also in various urban processes.

These processes have a spatial dimension and are crucial for the efficient functioning of the territorial urban system. In this perspective, the city is composed of two interdependent spheres: the social sphere and the territory. The development of AI tools can significantly enhance day-to-day city management. This is supported by the areas of AI applications identified in this article (Table 1).

Moreover, AI support methods in these areas can be categorized into approaches focused on immediate responses to changes in cities, as well as their strategic and planning use, including the realization of the Smart City vision.

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