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Geoinformation Modelling of Urban Underground Real Estate Use Scenarios Based on Game Theory

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SUMMARY

A methodological approach to geoinformation modelling of urban underground real estate use scenarios based on game theory has been developed. The proposed approach is aimed at reconciling the economic, urban-planning, engineering, safety, and public interests of the main stakeholders involved in underground space development, including municipal authorities, investors, residents, and utility infrastructure operators. The information framework of the study comprises cadastral and urban-planning data, information on underground utility networks, geological and hydrogeological conditions, transport accessibility, building and population density, real estate values, investment costs, and the demand for protective structures. The methodological approach includes the development of a geoinformation database, spatial analysis of influencing factors, indicator normalization, determination of stakeholder payoff functions, construction of a strategy matrix, and identification of an equilibrium scenario based on the Nash equilibrium. The alternative underground real estate use scenarios considered include underground parking, a dual-purpose protective structure, a commercial and service facility, a transport and logistics facility, and a multifunctional underground complex. The modelling results provide spatial zoning of the territory according to priority underground space use scenarios and identify compromise solutions that balance private and public interests. The practical significance of the approach lies in its potential application to support managerial decision-making, justify investment choices, reduce spatial conflicts, and improve the efficiency of urban underground space use.

Keywords: Underground real estate; Urban underground space; Geoinformation modelling; Game theory; Nash equilibrium; Scenario analysis; Decision support.

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Introduction

The shortage of available land, increasing development density, and growing pressure on urban infrastructure enhance the importance of underground space as a resource for accommodating transport, parking, commercial, engineering, and protective facilities. Its efficient use requires the coordination of urban-planning, engineering, economic, and safety-related decisions, as well as appropriate spatial data management (Peng et al., 2021). Urban underground real estate comprises spatially defined underground structures and volumes with established boundaries, functional purposes, engineering characteristics, and economic value. It includes parking facilities, pedestrian passages, metro stations, utility tunnels, shelters, logistics facilities, and multifunctional structures. Their use is determined by the 3D configuration of space, geological and hydrogeological conditions, the location of utility networks, and interaction with above-ground development.

Geoinformation technologies enable the integration of data on underground facilities, the geological environment, transport, buildings, population, and urban-planning constraints. Authors (Liu et al., 2022) applied voxel modelling and three-dimensional visualization, researchers (Yang et al., 2024) used comprehensive assessment of geological and environmental factors, while authors (Hao et al., 2024; Nesterenko et al., 2025) employed the analytic hierarchy process and fuzzy evaluation to assess underground space suitability. However, most studies focus primarily on technical and spatial conditions, while insufficiently considering the interests and behaviour of stakeholders involved in urban development. Decisions concerning underground real estate use depend on the interaction between municipal authorities, investors, local communities, and utility infrastructure operators, whose objectives often differ.

Game theory makes it possible to formalize their strategies, payoffs, conflicts, and compromise solutions. Its effectiveness in land-use planning and stakeholder behaviour modelling has been demonstrated by authors (Abolhasani et al., 2023; Han et al., 2024). Nevertheless, the integration of game-theoretic models with spatial GIS data for selecting underground real estate use scenarios remains insufficiently developed. **The aim of this study** is to develop a methodological approach to geoinformation modelling of urban underground real estate use scenarios based on game theory in order to reconcile economic, urban-planning, engineering, safety, and public interests.

Method and Theory

A methodological approach combining the development of a 3D geodatabase, spatial multi-criteria analysis, and game theory is proposed for modelling urban underground real estate use scenarios. The research workflow, from the collection of input data to the identification of an equilibrium scenario and cartographic visualization of the results, is presented in Figure 1.

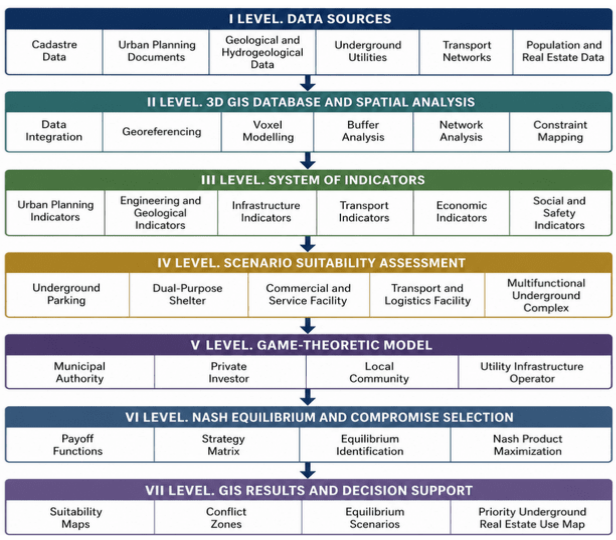

Figure 1. *Conceptual Framework for GIS-Based Game-Theoretic Modelling of Urban Underground Real Estate Use Scenarios*

The information framework includes cadastral and urban-planning data, information on buildings, transport and underground utility infrastructure, geological and hydrogeological conditions, population, real estate values, traffic flows, and the location of protective structures. The data are transformed into a common coordinate reference system, checked for topological consistency, and integrated into a geoinformation database. Underground space is represented as a set of cadastral parcels with specified depth intervals or as voxels, which makes it possible to account for the relative positions of structures, foundations, utility networks, and geological layers.

Geoinformation processing includes geocoding, vectorization, buffer and network analysis, spatial overlay of thematic layers, transport accessibility assessment, and the identification of urban-planning and technical constraints. For each spatial unit, a set of urban-planning, engineering-geological, infrastructure, transport, economic, social, and safety indicators is established. After indicator normalization, the spatial suitability index for each scenario j is determined as follows:

$$\boldsymbol{S_{ij} = \sum_{k=1}^{m} w_{kj}\, z_{ik}} \tag{1}$$

where S_{ij} is the suitability of the i-th spatial unit for implementing scenario j; z_{ik} is the normalized value of the k-th indicator; w_{kj} is its weighting coefficient; and m is the number of indicators.

Five scenarios were considered: an underground parking facility, a dual-purpose protective structure, a commercial and service facility, a transport and logistics facility, and a multifunctional underground complex. Indicator weights are determined separately for each scenario according to its functional purpose. The participants in the game-theoretic model are the municipal authority G, private investor I, local community C, and utility infrastructure operator O. Benefits, costs, and risks are assessed for each participant:

$$\boldsymbol{U_{pij} = \alpha_p B_{pij} - \beta_p C_{pij} - \gamma_p R_{pij}} \tag{2}$$

where U_{pij} is the payoff of participant $p$from implementing scenario $j$in spatial unit i; B_{pij}, C_{pij}, and R_{pij} denote the benefits, costs, and risks, respectively; and α_p, β_p, and γ_p are their significance coefficients.

$$\boldsymbol{U_p(a_p^*, a_{-p}^*) \geq U_p(a_p, a_{-p}^*)},$$

according to which no participant can increase their payoff by unilaterally changing their strategy. If several equilibrium solutions exist, the compromise scenario is determined by maximizing the Nash product:

$$\boldsymbol{N_{ij} = \prod_{p=1}^{n} (U_{pij} - d_p)} \tag{3}$$

where d_p - is the minimum acceptable payoff level for participant.

As a result, technically feasible, economically viable, and strategically stable scenarios are identified for each spatial unit. The GIS environment is used to generate suitability maps, identify zones of conflicting interests and areas with equilibrium solutions, and produce a final map of priority urban underground real estate use.

Results

The proposed approach was tested using six model functional-spatial zones of Kharkiv, denoted as Z_1–Z_6. These zones represent the central business district, a transport interchange hub, a densely built-up residential area, a peripheral logistics area, a public-commercial centre, and a residential area with a shortage of protective structures. For each zone, normalized suitability indices for five scenarios were calculated within the range from 0 to 1, and the equilibrium scenario was determined based on the results of game-theoretic modelling (Table 1).

Table 1. *Results of Scenario Suitability Assessment and Game-Theoretic Equilibrium Selection*

Model zone	***(S_P)***	***(S_S)***	***(S_C)***	***(S_T)***	***(S_M)***	***Scenario with maximum suitability***	***Equilibrium scenario***
(Z_1) – Central business zone	*0.84*	*0.61*	*0.93*	*0.73*	*0.91*	*Commercial and service facility*	*Multifunctional underground complex*
(Z_2) – Transport interchange zone	*0.76*	*0.68*	*0.82*	*0.94*	*0.90*	*Transport and logistics facility*	*Transport and logistics facility*
(Z_3) – High-density residential zone	*0.93*	*0.91*	*0.62*	*0.66*	*0.88*	*Underground parking*	*Dual-purpose shelter*
(Z_4) – Peripheral logistics zone	*0.71*	*0.49*	*0.58*	*0.92*	*0.75*	*Transport and logistics facility*	*Transport and logistics facility*
(Z_5) – Public-commercial centre	*0.78*	*0.63*	*0.94*	*0.74*	*0.92*	*Commercial and service facility*	*Multifunctional underground complex*
(Z_6) – Residential zone with shelter deficit	*0.56*	*0.96*	*0.45*	*0.52*	*0.81*	*Dual-purpose shelter*	*Dual-purpose shelter*

For zones Z_2, Z_4, and Z_6, the scenarios with the highest suitability indices coincided with the equilibrium solutions. In the transport-oriented zones $Z_2$and Z_4, priority was assigned to the transport and logistics facility, with suitability indices of 0.94 and 0.92, respectively. For zone Z_6, which is characterized by a shortage of shelters, the dual-purpose protective structure was identified as the optimal scenario, with an index of 0.96. In zones Z_1, Z_3, and Z_5, the game-theoretic model changed the decisions obtained solely on the basis of the maximum suitability index. For the central and public-commercial zones, a multifunctional underground complex was selected instead of a commercial and service facility, as it combines commercial, parking, public, and protective functions. In the densely built-up residential zone Z_3, a dual-purpose protective structure was identified as the equilibrium solution instead of an underground parking facility, as it provides greater public and safety-related benefits. With the minimum acceptable payoff set at $d_p = 0.20$, the Nash product for the equilibrium scenarios ranged from 0.122 to 0.154. The highest value was obtained for the multifunctional underground complex in zone Z_1, indicating the most balanced reconciliation of the interests of the municipal authority, investor, local community, and utility infrastructure operator.

Thus, in three of the six zones, the equilibrium solution did not coincide with the scenario having the highest spatial suitability. This confirms the feasibility of combining geoinformation-based multi-criteria assessment with game theory. The spatial distribution of the identified scenarios is presented in Figure 2.

Conclusions

A methodological approach to geoinformation modelling of urban underground real estate use scenarios has been developed, combining 3D representation of underground space, multi-criteria assessment, and game theory. The proposed approach takes into account urban-planning, engineering-geological, transport, economic, social, and safety indicators, as well as the interests of municipal authorities, investors, local communities, and utility infrastructure operators. Based on the testing results, priority underground space use scenarios were identified for six model zones of Kharkiv. In zones Z_2, Z_4, and Z_6, the equilibrium solutions coincided with the scenarios of maximum spatial suitability. For zones Z_1, Z_3, and Z_5, game-theoretic modelling changed the initial selection in favour of multifunctional underground complexes and dual-purpose protective structures, which provide a more balanced combination of economic, public, and safety-related benefits.

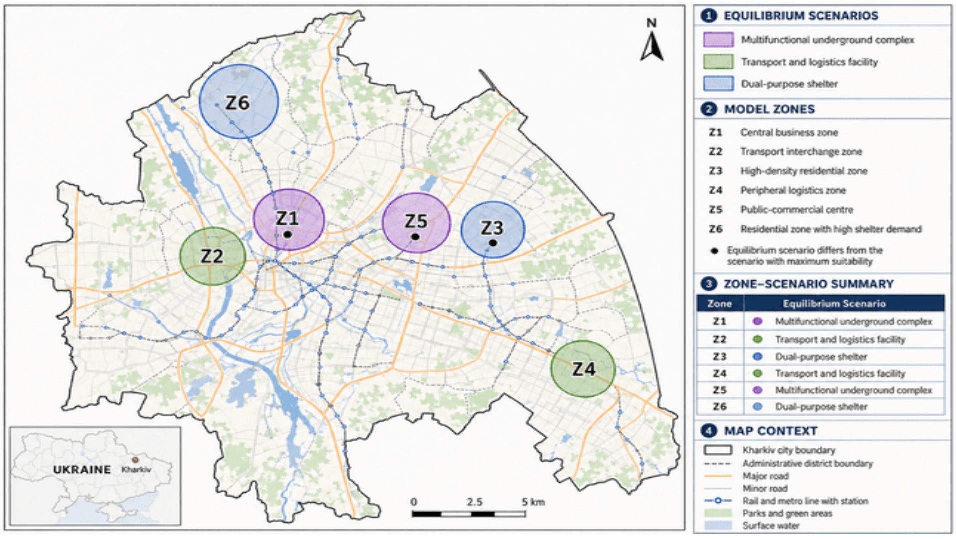

Figure 2. *Spatial Distribution of Equilibrium Scenarios for Urban Underground Real Estate Use*

The practical significance of the results lies in the potential application of the proposed approach to spatially justify the functional purposes of underground facilities, identify zones of conflicting interests, assess investment decisions, and support urban planning. The integration of GIS and game theory makes it possible to identify not only the most suitable but also strategically stable scenarios for urban underground real estate use.

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