Spatial Decision Intelligence for Sustainable Cities: A Causal GeoAI Framework for Equitable Land Value Capture and Investment Planning in Turkish Metropolises

Okan YILMAZ and Mehmet ALKAN, Türkiye

SUMMARY

Public infrastructure investments and planning interventions in urban areas generate unearned increments in land values. The public capture of these increments forms the basis of sustainable urban financing. However, the effectiveness of Türkiye's Land Value Capture (LVC) instruments remains contested, as a substantial share of the planning-induced land value uplift accrues to landowners, resulting in significant resource leakage. This leads to the concentration of land rent in certain private interests and highlights the critical need for a rational, data-driven mechanism to efficiently and equitably recapture the value created by public actions. To address this institutional and technical gap, the study discusses a hybrid Causal GeoAI decision-support framework designed to transition LVC from a reactive taxation tool to a proactive planning instrument. The proposed methodology integrates Machine Learning (ML) for mass valuation rather than traditional appraisal approaches and addresses the use of Explainable Artificial Intelligence (XAI) for transparency/legal defensibility. Crucially, the study proposes a Causal Machine Learning approach to isolate the specific 'treatment effect' of public impacts on land values through counterfactual analysis (CATE). The framework also incorporates spatial statistical tools to validate the heterogeneous distribution of value appreciation and scientifically delimit value capture zones. Finally, to ssynthesise economic rationality with social justice, a Multi-Criteria Decision Making (MCDM) mechanism is proposed that evaluates investment scenarios not only based on financial returns but also based on spatial justice and risk parameters.

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1. INTRODUCTION

In rapidly surbanising metropolises, public infrastructure investments—ranging from transportation networks to green spaces and social amenities—generate inevitable positive externalities within the urban fabric, leading to significant land value uplift. This 'unearned increment,' accrued by landowners without any direct contribution of labour or capital, solely because of public planning decisions and expenditures, presents a critical opportunity for sustainable urban financing. However, the equitable recapture of this value remains a significant challenge, particularly in developing economies like Türkiye, where it is not fully soperationalised due to persistent institutional and technical constraints.

The public appropriation of this economic surplus—referred to in the literature by various concepts such as 'development value,' 'planning gain,' or 'surplus value'—constitutes the foundation of Land Value Capture (LVC) mechanisms. In its most concise definition, LVC is a fiscal instrument designed to mobilise the value generated by public interventions to finance subsequent public investments (Goytía and Cristini, 2020; Hart, 2020). Approached by Gielen and Tasan-Kok (2010) through the dual perspectives of cost recovery and value capture, the fundamental rationale of this approach is to contribute to social welfare by preventing the benefits generated by infrastructure and services—whose costs are borne by society as a whole—from accumulating exclusively within private property interests (OECD and PKU-Lincoln Institute Center, 2022). Although implementation modalities vary according to national administrative systems (Suzuki *et al.*, 2015), LVC instruments are generally classified into 'recurring' tools, such as property taxes, and 'non-recurring' tools tied to development rights or specific infrastructure decisions (Halleux *et al.*, 2022). Specifically, the taxation of value uplifts resulting from discrete public decisions lies at the core of the relationship between strategic planning and investment financing, which forms the focal point of this study.

An examination of land management practices in Türkiye reveals a structural inefficiency in capturing the rent generated by the planning system for the public. Although the widely ussed Land Readjustment (LR) instrument is successful in securing raw land for public use, it remains insufficient to provide the financing for the infrastructure and facilities to be constructed on these areas. Similarly, the recently enacted Value Increment Share (VIS) mechanism has narrowed its focus to private-sector-driven, block-based increases in development rights (upzoning). This situation creates a vulnerability in which the substantial value uplift generated by the public's own strategic investments remains untaxed, paving the way for significant leakage of public resources into private ownership. Consequently, while the costs of

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surbanisation are borne by the public, the economic benefits generated by planning accrue to private interests.

The primary technical challenge underlying this financial imbalance is the inability to isolate the pure impact of a public intervention on real estate values. Traditional hedonic price models and spatial econometric methods often attempt to explain complex urban dynamics through linear relationships, which are inadequate for disentangling the causal impact of an investment from extraneous market noise. Because policymakers cannot empirically measure the exact value appreciation generated by a specific intervention, such as a metro station or technical infrastructure upgrade, they struggle to determine a fair 'betterment levy' or tax rate. This limitation inevitably forces LVC policies into either over-sgeneralised static formulas or complete dysfunction. To address this institutional and technical gap in Türkiye, this study discusses the potential of a hybrid Causal GeoAI framework that integrates machine learning with spatial decision-support systems. Within this scope, the study investigates data-driven solutions to isolate the heterogeneous value uplift induced by public interventions and to synthesise these insights through Multi-Criteria Decision-Making (MCDM) processes. The objective is to identify optimal investment locations that smaximise financial returns for the public while simultaneously upholding spatial equity. Ultimately, the study examines opportunities to transform urban planning from a passive regulatory tool into an active, strategic investment management model capable of self-financing.

2. THE CHALLENGE OF VALUE ASSESSMENT AND THE MACHINE LEARNING OPPORTUNITY IN TÜRKİYE

Lacking a centralissssed and standardised database, the real estate valuation system in Türkiye is characterised by structural fragmentation, often referred to as a 'multi-valued' market structure. Official records for a single property frequently exhibit a plurality of disconnected and inconsistent price labels, including the assessed tax value, the declared value for title deed fees, the expropriation value, and the actual market value. In particular, the significant discrepancy between declared tax base values and market realities creates a serious crisis of confidence about which data benchmark public authorities should use when implementing LVC policies. The absence of reliable and up-to-date reference value data constitutes the primary institutional barrier to the equitable taxation of value uplift. This situation undermines the applicability of LVC instruments and paves the way for legal disputes between property owners and the administration. Beyond the conflicts arising from the disparate treatment of property value across different contexts, the determination of the value uplift itself further exacerbates these disputes. For instance, infrastructure contribution fees are calculated by prorating public expenditures against the total tax value of properties, rather than assessing the actual value added to the real estate by the infrastructure. Regarding block-based zoning plan amendments, the relevant Regulation mandates the preparation of valuation reports by at least two licensed valuation companies for each specific parcel, assessing values both prior to (ex-ante) and following (ex-post) the plan amendment. However, the valuation methodology required for these assessments, as stipulated in Article 11 of Law No. 2942, is strictly bound to traditional

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valuation methods. This article enforces a conventional, expert-oriented approach, mandating the Sales Comparison Approach for urban plots, the Income Capitalisation Approach for agricultural land, and the Cost Approach for structures.

The operational constraints inherent in the static and manual nature of traditional valuation methods, coupled with the data chaos resulting from the multi-valued market structure, constitute the primary rationale for the transition from parcel-based valuation to data-driven mass appraisal systems within the Turkish spatial planning system. As Grover (2016) posits, when many properties require assessment, a Mass Appraisal System must be implemented sutilising standardised processes, data, attributes, and algorithms. Specifically, diverse public interventions—such as ensuring the principle of equivalence required for the transition to a value-based system in LR processes, the equitable distribution of betterment levies in urban regeneration projects, and the accurate calculation of value uplift arising from planning amendments or public investments—necessitate a holistic and rapid valuation infrastructure rather than disconnected, fragmented processes. Parametric regressions employed in Mass Appraisal models are predominantly based on hedonic regressions, such as multiple linear regression (Narula, Wellington,. However, the fundamental hedonic price model relies on simple regression via Ordinary Least Squares (OLS) estimation; consequently, its capacity to capture the spatial heterogeneity and dependence inherent in spatial data is limited (Chi and Zhu, 2019). In this context, ML algorithms offer a strategic advantage over traditional statistical models due to their capacity to learn non-linear, complex relationships and spatial interactions within the real estate market. By processing large datasets, Mass Appraisal Models applicable to thousands of parcels can minimisse human bias in the valuation process while providing administrations with the speed and scalability needed for the effective implementation of LVC policies. However, although ML models yield superior predictive performance compared to hedonic models, they often function as 'black boxes' that provide only price predictions without revealing the intrinsic relationships and interactions between inputs (property attributes) and outputs (property price). This opacity renders them non-transparent and unexplainable (Wan and Lindenthal, 2023). To mitigate concerns regarding the black box nature of ML models, Explainable Artificial Intelligence (XAI) tools can be utilised. While Global methods explain the average effect of features on predictions, Local methods focus on interpreting individual predictions (Iban, 2022; Gunes, 2023).This ensures that model predictions can be clearly articulated to taxpayers, policymakers, and courts, thereby significantly contributing to transparency and legal defensibility.

Because an equitable LVC strategy requires establishing a causal link in value appreciation rather than merely predicting value, approaches capable of moving beyond correlation to measure the isolated impact of public interventions emerge as a methodological necessity in the discourse on the fair distribution of urban rent. Although traditional ML methods can generate high-accuracy predictions based on correlations within datasets, they disregard the complex cause-and-effect relationships inherent in the data generation process. This lack of focus renders traditional models inadequate in predicting how outcomes change when a system is subjected to external intervention. In contrast, Causal ML aims to complement the predictive power of traditional models with the capacities for understanding, intervention, and spersonalisation

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(Lechner, 2023). While prediction-oriented machine learning methods, such as Random Forest, focus on sminimising total error, they fail to clearly distinguish the impact of a public facility from other environmental and structural variables. Causal ML algorithms overcome these limitations by adaptively partitioning the data, estimating how the investment impact differentiates from parcel to parcel in a data-driven and heterogeneous manner through the Conditional Average Treatment Effect (CATE) (Miller, 2020; Rehill, 2025; Sverdrup, Petukhova and Wager, 2025). Whereas traditional methods succeed only in explaining observed data, Causal ML, which focuses on analysing the potential outcomes of an intervention, can answer questions such as *'What would have happened if this investment had not been made?'* or *'How would the result change if it were located elsewhere?'* by utilising counterfactual analysis tools (Feuerriegel *et al.*, 2024). This capability can assist in the strategy of generating realistic scenarios during the planning phase of public investments and managing rent fairly before it even accrues. Figure 1 shows the predictive outputs of a model used in classification and regression analyses compared to a Causal ML model.
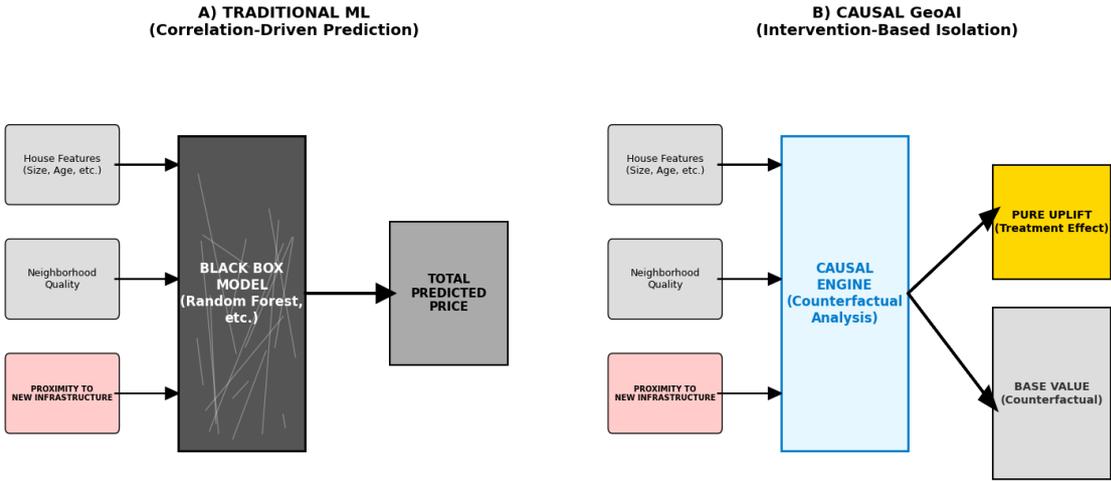

Fig. 1: Task specificity of causal ML models

3. SPATIAL VALIDATION AND PROACTIVE SCENARIO GENERATION

LVC mechanisms often implement fixed tax rates or sstandardised betterment levies based on the assumption that a public intervention generates a homogeneous effect across the entire study area (Lu *et al.*, 2014). However, urban reality is defined by spatial non-stationarity; the value uplift generated by a metro station or green space is not uniformly distributed but is instead shaped by local accessibility barriers, topography, and the existing urban fabric. Disregarding this heterogeneity results in severe spatial injustice, in which property owners in high-impact

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zones contribute less than their fair share, while those with limited access bear disproportionate financial burdens.

To render heterogeneous data actionable for decision-makers, it is essential to verify whether predicted value uplifts are random or reflect structural spatial clusters. It necessitates the employment of Spatial Autocorrelation and Hotspot Analysis tools not merely as statistical validation steps, but as fundamental instruments for delineating value capture zones. By statistically confirming where high-value uplifts cluster and where they dissipate, public administrations can ground tax boundaries on scientific evidence rather than arbitrary administrative lines. This validation process transforms the 'black box' predictions of AI into legally defensible and spatially verified zones, providing the objective foundation required to justify betterment levy implementations against potential legal challenges.

In the current state, urban administrations struggle to usse value uplifts as a proactive pre-financing instrument; instead, they operate in a reactive manner that typically targets partial cost recovery after investment completion (e.g., contribution fees) or trails market values (e.g., periodic property tax assessments). This study discusses the transition to a proactive planning approach, in which value-propagation parameters are simulated prior to investment. The proposed Causal GeoAI framework enables the execution of counterfactual queries on the trained model. Technically, this process operates by virtually manipulating the distance variable (d_{ij}), which serves as the treatment variable: when planners alter the coordinates (x,y) of a proposed facility, the model recalculates access matrices for all parcels and instantaneously generates the estimated total value surface for each scenario. Beyond mere location, the distance decay coefficients—which vary depending on the type of intervention (e.g., green spaces, development restrictions)—can also be simulated to sanalyse the breadth of the impact area and the spatial boundaries of LVC potential. This technical capability evolves the role of the planner from a passive observer trailing market responses into an active strategist who optimises the financial structure and site selection of investments by testing various parameter combinations. This approach aligns with the vision of transforming planning from a static regulatory tool into a dynamic Planning Support System capable of forecasting outcomes (Geertman and Stillwell, 2020).

4. STRATEGIC DECISION-MAKING: SYNTHESISING VALUE AND EQUITY

Although the CATEs generated by the Causal GeoAI model offer public authorities the potential to visualise the financial return of an investment, urban planning cannot be reduced solely to economic maximisation. Decision-makers are often compelled to strike a balance between multidimensional and frequently conflicting objectives. Directing investment to the region promising the highest value uplift (and thus maximum tax collection) may enhance financial efficiency; however, this approach risks exacerbating existing inequalities by further enriching already developed areas, thereby undermining spatial equity. Similarly, selecting the lowest-cost land may conflict with accessibility or environmental sustainability goals. Consequently, there is a need for a holistic decision-support mechanism wherein machine

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learning outputs are treated not as direct decisions, but as inputs to be evaluated alongside other critical criteria such as risk, cost, and social benefit.

In this context, the integration of MCDM systems must be approached as a strategic necessity to synthesise AI-based value uplift data (LVC maximisation) with the normative values of the planning discipline (equity, risk, public interest). MCDM methods are employed to identify the optimal option among multiple, often conflicting criteria (Fei, Lu and Feng, 2020; Torkayesh, Malmir and Rajabi Asadabadi, 2021). The divergence point among MCDM methods lies in how the problem is modeled, how criteria are handled, and the mathematical approaches used for resolution. When criteria can be structured hierarchically, the Analytic Hierarchy Process (AHP) is a suitable method that utilises pairwise comparisons to minimise subjective judgments and ensure consistency (Kutlu Gündoğdu et al., 2021). Best-Worst Method (BWM) provides convenience to the decision-maker by comparing the best and worst criteria against each other when they are identified, thereby simplifying the pairwise comparison process. TOPSIS ranks decision alternatives by measuring their distance to the ideal solution (highest value for each criterion) and the negative-ideal solution (lowest value) (Torkayesh, Malmir and Rajabi Asadabadi, 2021). The diversity of MCDM methods offers the capability to evaluate alternatives in alignment with the specific nature of the policy problem. Such a methodological synthesis provides decision-makers with a dynamic negotiation platform where weights can be adjusted according to political priorities, rather than imposing a single optimum. Thus, the model evolves from a rigid calculator pointing solely to the parcel yielding the highest rent into a flexible policy instrument capable of navigating between revenue maximisation and spatial justice scenarios, serving the pursuit of multidimensional solutions. Figure 2 visualises the multi-criteria decision processes of an exemplary site selection mechanism.
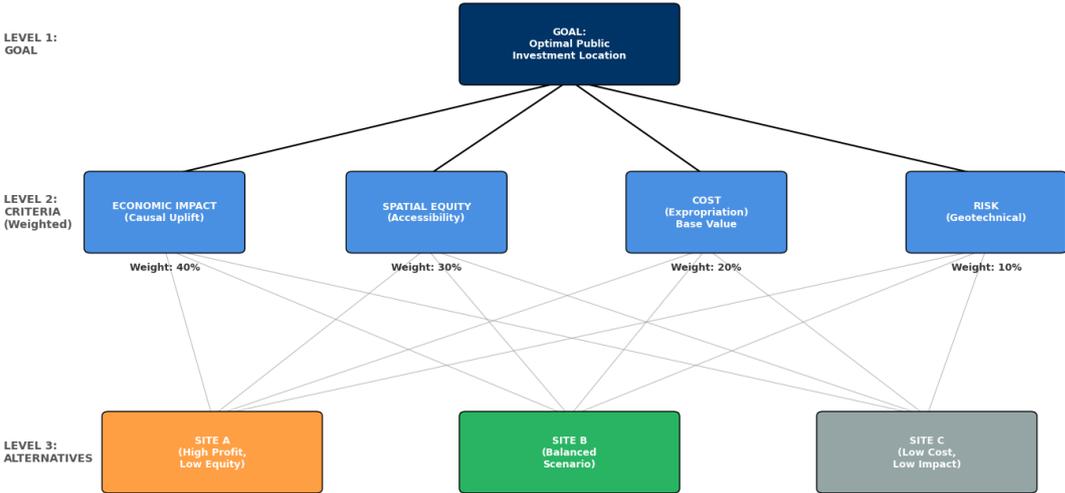

Fig. 2: A workflow for an instance site selection decision

5. CONCLUSION

In rapidly urbanising metropolises, the fair and effective recapture of value uplift generated by public interventions stands as one of the most critical components of sustainable urban financing. By discussing the operational constraints, data fragmentation, and inadequacies in establishing causality links faced by current LVC mechanisms in Türkiye, this study proposes a novel decision-support framework based on Causal GeoAI. The theoretical and methodological discussions conducted underscore the potential advantages of transitioning from traditional static and expert-oriented valuation approaches to dynamic, data-driven systems. However, this transformation represents not merely a change in technological tools, but a paradigm shift. With the proposed framework:

- Through Machine Learning and XAI tools, value assessment is elevated from an opaque process to a transparent foundation that is legally defensible and explicable to taxpayers and the judiciary.
- By isolating the pure treatment effect generated by public interventions, taxation boundaries are grounded in scientifically proven impact zones rather than arbitrary assumptions.
- Urban administrations are transitioning from a reactive position—attempting to measure results post-investment—to a proactive stance that manages investment financing, site selection, and social impacts through ex-ante simulations.

Consequently, the integration of Causal GeoAI and MCDM holds the potential to transform urban planning from the mere organisation of physical space into a strategic management model that is self-financing, prioritises spatial equity, and optimises public resources. For developing economies like Türkiye, this model can help convert urban rents from a vehicle for speculative gain into a public resource dedicated to sustainable urban development. Naturally, assessing the theoretical, technological, and political suitability of this proposed framework for the Turkish Land Administration System warrants further comprehensive research and multi-stakeholder studies.

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