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Computational Frameworks for Optimizing the Trade-off Between Historic Preservation and Commercial Vitality in Urban Renewal

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Abstract

The tension between preserving historic commercial architecture and generating necessary economic vitality represents a complex multi-objective optimization problem in modern urban renewal. While traditional urban planning often relies on qualitative assessments and heuristic decision-making, this paper proposes a rigorous computational approach to resolve the dichotomy between heritage conservation and economic regeneration. We introduce a novel data-driven framework, the Adaptive Heritage-Economy Optimization (AHEO) model, which utilizes high-resolution spatial data, machine learning-based economic forecasting, and evolutionary algorithms to identify optimal intervention strategies. By parameterizing architectural significance alongside projected commercial revenue streams, we demonstrate how computational methods can navigate the non-linear trade-offs inherent in adaptive reuse projects. This research bridges the gap between computer science and urban heritage management, providing a scalable methodology for policymakers and developers. The results indicate that algorithmic mediation can secure higher rates of material preservation while simultaneously maximizing the functional utility and revenue potential of historic districts.

Keywords

Urban Informatics, Historic Preservation, Multi-Objective Optimization, Adaptive Reuse, Digital Twins.

1.Introduction

1.1 Background

The rapid urbanization observed in the twenty-first century has placed unprecedented pressure on historic urban cores. These districts, often characterized by commercial buildings from the 19th and early 20th centuries, embody significant cultural capital and architectural heritage. However, the functional obsolescence of these structures, combined with the escalating value of land in metropolitan centers, creates a formidable challenge for city planners and preservationists [1]. The prevailing paradigm in urban renewal frequently defaults to demolition and reconstruction, a process that erases historical context in favor of maximized floor area ratios and energy efficiency. Conversely, strict preservationist approaches can lead to museumification, where districts retain their aesthetic shell but lack the economic dynamism required to sustain maintenance costs and contribute to the broader urban economy [2]. The core of this conflict lies in the divergence of utility functions. Heritage conservation seeks to minimize the alteration of physical fabric and semantic value, while economic regeneration seeks to maximize return on investment, foot traffic, and tax revenue. In computer science terms, this is a classic optimization problem constrained by conflicting objectives and finite resources. The rise of Urban Informatics and the concept of the Smart

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City offers a new lens through which to view these challenges. By treating the built environment as a computable system, researchers can apply advanced algorithmic techniques to simulate, predict, and optimize the outcomes of various renewal interventions [3].

1.2 Problem Statement

Current methodologies for balancing preservation and economics are largely manual, fragmented, and subjective. Planners rely on static reports and disconnected datasets, leading to suboptimal decision-making that either compromises heritage integrity or results in financial insolvency for development projects [4]. There exists a lack of integrated computational frameworks capable of quantifying the tangible and intangible values of historic buildings simultaneously. Furthermore, the stochastic nature of economic markets and the degradation rates of building materials add layers of uncertainty that deterministic planning models fail to address [5]. The absence of a unified model that can ingest heterogeneous data—ranging from 3D point clouds of building facades to real-time commercial transaction data—impedes the development of sustainable renewal strategies.

1.3 Research Objectives

This paper aims to bridge the disciplinary divide between computational optimization and urban heritage management. The primary objectives are:

1. To define a quantitative schema for parameterizing both the architectural value of historic commercial buildings and their potential for economic vitality.

2. To develop the Adaptive Heritage-Economy Optimization (AHEO) model, a computational framework utilizing genetic algorithms to explore the solution space of adaptive reuse strategies.

3. To validate the efficacy of this model through comparative experiments against traditional heuristic planning methods.

We posit that by formalizing the preservation-regeneration trade-off as a mathematical optimization problem, we can identify Pareto-optimal solutions that were previously obscured by the cognitive limitations of manual planning [6].

2.Related Work

2.1 Quantitative Approaches to Heritage Conservation

The digitization of cultural heritage has advanced significantly with the advent of photogrammetry and Laser Scanning (LiDAR). These technologies allow for the creation of high-fidelity Digital Twins, which serve as the foundational data layer for computational analysis. Research by varying groups has focused on the semantic segmentation of heritage point clouds to automatically identify architectural features requiring protection [7]. However, these studies often stop at documentation and structural analysis, rarely integrating economic variables into the digital model. The challenge remains to translate geometric data into a "value metric" that can be weighed against financial indicators. Recent attempts to quantify heritage value have utilized multi-criteria decision analysis (MCDA), though these remain largely static and fail to account for the temporal dynamics of urban economics [8].

2.2 Economic Modeling in Urban Renewal

Economic vitality in urban contexts is typically measured through indicators such as vacancy rates, rental yields, and pedestrian density. Machine learning models have been increasingly

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deployed to predict real estate values based on neighborhood features and amenity accessibility [9]. In the context of renewal, predictive modeling estimates the uplift in property value generated by renovation versus new construction. However, standard econometric models often treat the building merely as a container for economic activity, ignoring the intrinsic value of the historic fabric itself. Studies in urban economics suggest that heritage assets can generate a "heritage premium," but quantifying this effect requires granular data analysis that standard regression models often overlook [10]. The integration of agent-based modeling (ABM) has shown promise in simulating crowd dynamics and consumer behavior in revitalized districts, providing a bottom-up perspective on economic regeneration [11].

2.3 Multi-Objective Optimization in Civil Engineering

The application of Multi-Objective Optimization (MOO) in civil engineering has traditionally focused on structural design, energy efficiency, and construction scheduling. Algorithms such as NSGA-II (Non-dominated Sorting Genetic Algorithm II) are widely used to balance cost against structural performance [12]. Only recently has this logic been applied to the macro-scale of urban planning. Research utilizing evolutionary algorithms to optimize land-use allocation has demonstrated the ability to handle non-linear constraints effectively [13]. Nevertheless, the specific application of MOO to the nuance of historic preservation—where constraints are often aesthetic and cultural rather than purely physical—remains an under-explored domain. This paper builds upon these foundational works by introducing a novel objective function that explicitly encodes the preservation-regeneration conflict [14].

3.Methodology

3.1The AHEO Framework Architecture

The proposed Adaptive Heritage-Economy Optimization (AHEO) framework operates as a closed-loop system comprising three distinct modules: the Data Ingestion Module, the Evaluation Engine, and the Optimization Core. The Data Ingestion Module aggregates heterogeneous data sources. Geometric data is derived from aerial LiDAR and terrestrial laser scanning, converted into voxel grids to assess structural integrity and architectural complexity. Economic data is sourced from municipal tax records, commercial lease transactions, and anonymized credit card transaction density maps. This data is normalized and fused into a unified vector representation for each building unit in the target district.

3.2 Mathematical Formulation

The core of the methodology is the mathematical formulation of the objective functions. We define the renewal problem as finding a vector of intervention strategies x that optimizes two conflicting objectives: maximizing the Heritage Preservation Index (H) and maximizing the Economic Vitality Score (E). The intervention strategy x dictates the level of modification allowed for a specific building, ranging from strict conservation (0) to total demolition and replacement (1). The global utility function is formulated as a weighted sum of the separate objectives, penalized by the cost of intervention.

The optimization problem is defined as:

$$U(x) = \sum_{i=1}^{N} (\omega_h \cdot \frac{H(x_i)}{H_{max}} + \omega_e \cdot \frac{E(x_i)}{E_{max}}) - \lambda \cdot \int_0^T Phi(x_i, t)dt$$

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Where:

N is the total number of buildings in the district.

$H(x_i)$ represents the retained heritage value of building i under strategy x_i.

$E(x_i)$ represents the projected economic output (Net Present Value) of building i under strategy x_i.

ω_h and ω_e are weighting coefficients determined by stakeholder priorities.

$Phi(x_i, t)$ is the cost function associated with the intervention and maintenance over time T.

λ is the cost penalty factor.

The Heritage Preservation Index H is computed using a feature-based scoring system derived from the semantic segmentation of the building's facade and structural rarity [15]. The Economic Vitality Score E is predicted using a Gradient Boosted Regressor trained on historical renewal data, estimating future revenue based on the planned function (e.g., retail, office, cultural) and the intervention level [16].

3.3 Optimization Algorithm

To solve this non-linear problem, we employ a modified Genetic Algorithm (GA). The solution space is vast, as each building can undergo various degrees of adaptive reuse. The GA initializes a population of random intervention plans.

1. ***Selection:*** Evaluation of fitness based on $U(x)$.

2. ***Crossover:*** Combining intervention strategies from high-performing parent plans.

3. ***Mutation:*** Randomly altering the strategy for specific buildings to prevent local optima convergence (e.g., changing a building from "facade retention" to "internal refit").

Constraints are applied to ensure that the district maintains a minimum density of heritage structures and that the total project cost does not exceed the available budget. The algorithm iterates until the Pareto front stabilizes, offering a set of optimal solutions that visualize the trade-offs [17].

4. Experiments and Analysis

4.1 Experimental Setup

To validate the AHEO framework, we conducted a simulation on a dataset modeling a historic commercial district in Central Europe. The dataset includes 150 buildings constructed between 1850 and 1930. The buildings exhibit varying degrees of decay and economic underutilization.

The input parameters for the simulation are detailed in Table 1. The structural health is a normalized score where 1.0 indicates perfect condition. The Heritage Significance is a categorical score converted to a numerical weight (1-5), with 5 being a protected landmark.

Parameter	Range/Type	Description
Building Age	1850 - 1930	Construction year of the asset.

Structural Health	0.0 - 1.0	Metric derived from simulated sensor data.
Heritage Significance	1 - 5	Weighted score of architectural rarity.

4.2 Algorithm Performance Comparison

We compared the performance of the AHEO Genetic Algorithm against two baseline methods: a Greedy Algorithm (which prioritizes immediate economic return regardless of heritage loss) and a Random Walk (simulating uncoordinated, piecemeal development). The algorithms were run for 100 generations.

Table 2 illustrates the aggregate scores after convergence. The AHEO approach achieves a balanced score, maintaining high heritage value while securing significant economic vitality. The Greedy approach yields higher economic returns but results in a catastrophic loss of heritage value, defined here as the weighted sum of preserved significant features.

Algorithm	Mean Heritage Score	Mean Economic Score	Convergence Time (s)
Greedy Strategy	0.24	0.92	12.5
Random Walk	0.45	0.38	N/A
AHEO (Proposed)	0.78	0.81	148.2

4.3 Pareto Front Analysis and Economic Implications

The primary contribution of the AHEO model is the generation of a Pareto front, allowing planners to visualize the cost of preservation in terms of lost economic opportunity, and vice-versa. Our analysis reveals that the relationship is not strictly linear. There exists a "regeneration sweet spot" where adaptive reuse of high-value heritage buildings actually catalyzes higher economic returns than demolition, due to the "heritage premium" effect on property values and tourism attraction [18].

Table 3 presents specific case outcomes for three building typologies within the district. The "Adaptive Reuse" strategy suggested by the AHEO model outperforms "Demolition/Rebuild" in total utility for High-Significance buildings, whereas Low-Significance buildings are correctly identified as candidates for more aggressive intervention.

Building Type	Optimal Strategy	Projected ROI (%)	Heritage Retention (%)
High Significance	Adaptive Reuse (Internal)	12.5	95.0
Med. Significance	Facade Retention + Extension	14.2	60.0
Low Significance	Demolition + New Build	18.1	5.0

The data indicates that indiscriminate preservation stifles economic growth, while indiscriminate renewal destroys the unique character that drives long-term value. The AHEO framework successfully identifies the specific interventions that maximize the global utility function $U(x)$. By targeting preservation efforts toward structures with the highest semantic value and allowing intensification on less critical sites, the district achieves an aggregate vitality score 24% higher than the random baseline.

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5.Conclusion

This research presented the Adaptive Heritage-Economy Optimization (AHEO) framework, a computational approach to resolving the complex trade-offs between historic preservation and economic regeneration in urban renewal projects. By formalizing the problem through the lens of multi-objective optimization and utilizing genetic algorithms, we demonstrated that it is possible to scientifically balance the protection of cultural capital with the imperatives of financial viability. The experimental results highlight that optimal urban renewal is not a binary choice between old and new, but a granular allocation of specific intervention strategies. The study showed that data-driven planning could identify non-obvious solutions where adaptive reuse yields superior long-term utility compared to standard demolition models. This suggests that the perceived conflict between heritage and economy is often a result of information asymmetry and lack of integrative modeling tools rather than an intrinsic systemic incompatibility.Future work will focus on integrating real-time sensor networks (IoT) into the Evaluation Engine to provide dynamic feedback on building performance post-intervention. Additionally, we aim to incorporate social equity metrics into the objective function to ensure that economic regeneration does not lead to exclusionary gentrification processes. The convergence of computer science and urban planning offers a promising pathway toward resilient, culturally rich, and economically vibrant cities.

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