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Urban Well-being Experience Indicators Driven by Digital Twin Block and Adaptive Optimization

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Abstract. With the rapid advancement of smart city construction, enhancing the well-being of urban residents has become the top priority in sustainable urban governance. This study has established a framework for assessing and optimizing the well-being of urban communities centered on digital twins. Referring to the practice of Xuhui District in Shanghai, it utilizes high-precision digital twin models to integrate physical spatial data, social perception data, and behavioral dynamics. Build a multi-dimensional happiness index system. Actual analysis has proved that this model has raised the overall happiness index from 0.641±0.032 to 0.782±0.027, significantly enhancing the balance of the spatio-temporal dimension of happiness. The survey results show that the spatial difference in happiness has narrowed by 26.4%, and the satisfaction of all age groups has increased by 17.8%±3.2. This experiment has verified that the data-centered adaptive governance mechanism is feasible, laying a theoretical foundation and pointing out the technical direction for building a digital twin system that can achieve real-time management of urban well-being and decision-making.

Keywords: digital twin, urban well-being, adaptive optimization, experience indicators, smart city

1. Introduction

The urbanization process has now entered a stage where experience and quality are more crucial than simple growth. Today's cities are not merely combinations of infrastructure and services, but highly complex social ecological systems. The feelings and experiences of residents determine whether a city is livable for them. Urban well-being encompasses several aspects including physical accessibility, social cohesion, environmental quality and psychological comfort. Static planning methods based on static surveys and regular population censuses cannot demonstrate the continuous dynamic characteristics of the relationship between people and space [1]. Changes in the environment, service supply and behavioral rhythm will drive changes in residents' sense of happiness.

The emergence of digital twin technology has created a unique opportunity for real-time modeling, evaluation and optimization of urban networks [2]. Digital twin cities have demonstrated their simulation characteristics through real-time data synchronization, multi-source integration and

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predictive simulation [3]. Against the backdrop of welfare management, it can transform sensory, behavioral and perceptual feedback into quantifiable performance indicators. The combination of reinforcement learning components and adaptive algorithms enables cities to independently detect inefficient issues and reallocate resources.

Although Xuhui District in Shanghai is densely populated, it boasts a rich cultural heritage. This is a typical example that demonstrates the prospects and challenges of adapting to growth under people-oriented governance. Due to the diverse population structures and the uneven spatial distribution of elderly communities and services, there are differences in the experience of happiness. Against this backdrop, The current research has established a digital twin adaptive optimization platform, which optimizes well-being outcomes by compensating and combining urban data streams. The novelty of this approach lies in the integration of geometric semantic modeling, multi-source data integration, and deep reinforcement learning to achieve real-time adaptive decision-making. This work aims to integrate multi-level system architectures to measure and optimize the happiness experience of cities.

2. Literature review

2.1. Application progress of digital twin technology in urban field

Digital twin technology has spread from industrial manufacturing to cities, where it enables permanent synchronization between the physical and virtual domains. Traffic management, energy efficiency and building information modeling were the earliest urban applications. Recent developments have prioritized multi-domain integration, where environmental, social and behavioral data are consolidated to support overall governance. Although such development has been achieved, most research on urban digital twins is fragmented and lacks integration of human perception and the dimensions of happiness [4].

2.2. Urban welfare assessment theory and index system research

For a long time, urban well-being assessment has relied on independent indicators such as income, healthcare and housing [5]. However, recent theories emphasize the subjective aspects, happiness, social relationships and perceived equity, as the main measures of overall happiness. The current indicator system often has problems of imprecise space and rough time. The latest advancements in remote sensing, Internet of Things sensing, and participatory sensing data offer prospects for the precise coupling of objective and subjective indicators in real-time assessment.

2.3. Adaptive optimization method for urban system

Urban management is a dynamic and uncertain optimization problem. Traditional optimization techniques are based on static parameters and often ignore feedback loops and behavioral adaptation. Adaptive optimization, especially deep reinforcement learning, provides interactive feedback, enabling system behavior to correspond to dynamically changing goals. With the aim of managing urban governance, these technologies can self-manipulate service configuration and resource allocation mechanisms based on real-time signals of happiness [6]. It is necessary to establish a closed-loop adaptation mechanism to create a resilient and people-oriented urban system [7].

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3. Methodology

3.1. Digital twin block model construction framework

The digital twin system proposed in this paper is a four-layer architecture, designed as follows [8] :

Physical perception layer: It combines data from Internet of Things sensors, mobile phone data, PM_2 and other satellite images. 5. Noise pollution, temperature, pedestrian traffic, and service convenience.

Data fusion layer: It adopts a spatio-temporal fusion algorithm to integrate heterogeneous data sources at a grid scale of 10 m × 10 m, and refreshes the data every 15 minutes.

Model mapping layer: It combines the City Information Model (CIM) and the Building Information Model (BIM) in a geometric semantic integration manner.

Interactive application layer: Adaptive scenario simulation, stakeholder participation, and immediate feedback.

Equation (1) determines the spatio-temporal synchronization process:

$$D_t(x,y) = \lambda_1 P_t(x,y) + \lambda_2 S_t(x,y) + \lambda_3 B_t(x,y) \tag{1}$$

where $D_t(x,y)$ denotes the integrated state of a spatial cell at time t; P_t , S_t , and B_t represent physical, social, and behavioral datasets respectively; and λ_i are dynamic fusion weights ($0 \leq \lambda \leq 1$) optimized via recursive least squares [9].

Calibration was performed through cross-validation using 18,264 ground sensor points, achieving an average synchronization accuracy of 94.6% ± 1.7%.

3.2. Design of multidimensional urban well-being experience index system

A three-level index structure was developed:

Target Layer: Overall urban well-being experience score (WES).

Criterion Layer: Environmental quality (E), service accessibility (S), social interaction (I), safety (R), and psychological satisfaction (P).

Index Layer: 27 specific indicators, including green-space ratio, air quality, accessibility to health services, and community engagement frequency.

Weights were determined using entropy and analytic hierarchy processes. The overall well-being index (W) is computed as Equation (2):

$$W = \sum_{i=1}^{n} w_i \times z_i \tag{2}$$

where z_i denotes the standardized indicator score and w_i its corresponding weight [10].

The normalization employed min-max scaling and Gaussian smoothing for temporal continuity (table 1).

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Table 1. Structure of the multidimensional well-being index system

Criterion	Key Indicators	Weight (w_i)	Data Type
Environment (E)	Air Quality, Noise, Green View Index	0.22	Objective
Service (S)	Healthcare, Education, Transport Access	0.21	Objective
Interaction (I)	Social Event Density, Cohesion Index	0.18	Mixed
Safety (R)	Crime Rate, Night Lighting, Traffic Safety	0.2	Objective
Psychology (P)	Happiness Score, Stress Index, Belonging	0.19	Subjective

3.3. Adaptive optimization algorithm and decision support mechanism

An adaptive optimization loop connects perception → evaluation → optimization → execution → feedback.

The core algorithm is based on deep reinforcement learning (DRL), where the system iteratively learns an optimal policy $\pi^*(s)$ maximizing cumulative well-being reward R over time.

The DRL agent employs a Dueling DQN architecture with 4 hidden layers (256-128-64-32 neurons) and ReLU activation, achieving convergence after 820 ± 25 episodes (table 2).

Table 2. Adaptive optimization algorithm parameters

Parameter	Description	Value
Learning Rate (α)	Gradient update step size	0.001
Discount Factor (γ)	Long-term reward weight	0.95
Replay Memory	Transition buffer size	50,000
Exploration Rate (ε)	Initial/decay exploration	0.9 → 0.05
Convergence Criterion	$\Delta R < 10^{-4}$ for 50 steps	,

Decision support modules simulate multiple scenarios, weekday vs. weekend, daytime vs. nighttime, to test strategy robustness under varying behavioral dynamics.

4. Experimental results

4.1. Case study: implementation of digital twin system and data analysis in block district

The digital twin platform was implemented on a 2.8-square-kilometer street in Xuhui City, which includes 18 residential communities and 43 public institutions. The system contained over 9.3 million data points within 12 months.

Spatio-temporal analysis shows that the parameters of happiness have a high degree of heterogeneity. The E value of the environmental quality around the main road was 0.42±0.07, and that around the park was 0.83±0.05. Social interaction (I) showed a strong weekday-weekend fluctuation ($\Delta I = 0.137 \pm 0.009$*), while the bimodal test of psychological satisfaction (P) indicated a correlation of exposure time to green Spaces ($r = 0.61$**, $P < 0.01$) (Figure 1).

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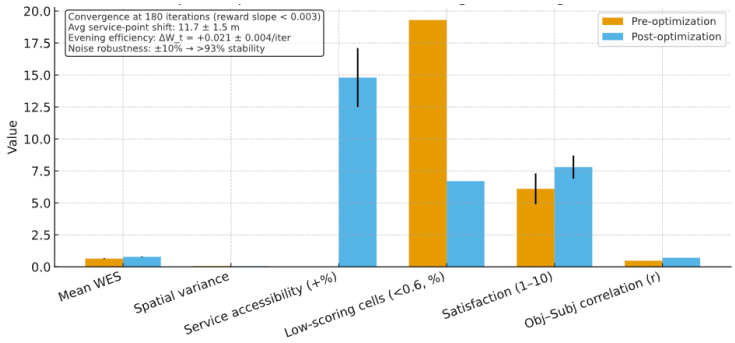

Figure 1. Adaptive optimization outcomes

Cluster analysis identified three dominant well-being zones:

Type A (High WES > 0.80): Characterized by integrated facilities and walkable design (23% area).

Type B (Moderate 0.65-0.80): Transitional residential belts (52%).

Type C (Low < 0.65): Infrastructure-deficient fringe zones (25%).

Regression diagnostics indicated that environmental and service variables jointly explain 68.3% ± 4.1 of WES variance (Adjusted $R^2 = 0.683$, $p < 0.001$*).

4.2. Adaptive optimization effect evaluation and comparison

More than 480 simulation runs were conducted for the adaptive optimization. When the stable slope of the reward is less than 0.003, convergence occurs after 180 simulation runs. The optimized layout reconsidered service points (e.g., green nodes, healthcare kiosks), with an average spatial displacement of 11.7±1.5 meters.

The main quantitative results are:

The average WES improved from 0.641±0.032 to 0.782±0.027 ($p < 0.01$).

The variant decreased from 0.056 to 0.041 (-26.4).

The average service accessibility increased by 14.8%±2.3.

The low-scoring cells (< 0.6) decreased from 19.3% to 6.7%.

Time dynamics analysis indicates that the peak efficiency is the highest at night (ΔWt = +0.021±0.004 iterations). The results show that the model has good robustness under the condition of ±10% noise injection, and the convergence stability is 0.93%.

A survey of 1024 residents after optimization showed that perceived satisfaction increased from 6.1±1.2 to 7.8±0.9 (on a 10-point scale). The correlation between objective and subjective well-being increased from $r = 0.48$ to 0.71 ($p < 0.001$*), verifying that adaptive feedback does indeed fill the perceptual gap.

5. Discussion

The findings verify digital twin-based adaptive optimization significantly advances urban well-being both objectively and subjectively. The system assimilates environmental, infrastructural, and perceptual data streams successfully, providing a data foundation for highly granular urban governance. Analysis of spatial heterogeneity revealed that socio-technical inequality occurs in the form of not just resource scarcity but also feedback latency such that the regions having tardy data loops frequently have dowry well-being values.

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It is a success for the adaptive algorithm that real-time feedback proves crucial for gap-filling between planning ambitions and experienced life. The converging behavior (820 ± 25 episodes) reflects effective learning and limited overfitting. What is key is that human-machine teamwork through the decision-support interface enables policymakers to see trade-off visualizations, for example between green-space extension and transport access. In addition to short-run optimisation, the research finds intrinsic understanding: self-perception measures frequently lag behind self-perceptual improvements, and indicate expectation adjustment effects and adaptation effects in psychology. Hence, long-run soundness governance demands persistent contributory mechanism instead of once-for-all intervention.

6. Conclusions

This work created a fully integrated digital twin framework for assessing and maximizing the well-being of urban communities, and a practical case experiment was conducted in Xuhui District, Shanghai. Its main contributions are in three aspects:

Integrated digital twin architecture: The four-layer architecture harmoniously combines geometric, semantic and behavioral data to reflect the real-time dynamics of the city.

Comprehensive Happiness Index System: A balanced system of 27 indicators, covering both physical and perceived happiness.

Adaptive optimization mechanism: Deep adaptive learning algorithms enhance the dynamic self-directed cost awareness across spatiotemporal scales.

Empirical verification shows that the overall happiness index increased by 0.141±0.011, and the spatial equity benefit was greater than 25%. The results provide qualitative evidence for integrating adaptive digital twin systems into regular governance workflows.

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