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**Research paper**

# Digital twin technology supporting urban public space renewal

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**Abstract:** Urban public space, as a core component of the urban, is an important carrier for the residents' quality of life, social interaction and cultural inheritance. With the deepening of urbanization, urban public space is facing unprecedented challenges, including aging space, single function, environmental degradation, and mismatch with residents' needs, etc. This paper comprehensively discusses the application of digital twin technology in urban public space renewal, and systematically analyzes its core role in enhancing the function of public space, promoting the optimization of resource allocation, and reinforcing the ability of predictive analysis from the theoretical framework to specific countermeasures. Through the introduction of genetic algorithm and ARIMA model, the technical support of complex resource allocation and future trend prediction is shown; and the successful application and significant effect of digital twin technology in actual projects are demonstrated with the examples of The Bund in Shanghai and Marina Bay Gardens in Singapore. In addition, a detailed assessment of data security, technical compatibility, public participation and cost-effectiveness is made, and targeted countermeasures and recommendations are proposed.

**Keywords:** digital twin, spatial renewal, urban public space

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# 1. Introduction

In the 21st century, when globalization and urbanization are accelerating in parallel, urban public space, as a core component of the urban fabric, is not only a window for displaying the city's image, but also an important carrier for the residents' quality of life, social interaction and cultural inheritance. With the deepening of urbanization, urban public space is facing unprecedented challenges, including aging space, single function, environmental degradation, and mismatch with residents' needs, etc., which urgently require us to re-examine and optimize the planning and management strategies of urban public space. In this context, digital twin technology, with its unique technical advantages, provides a new perspective and solution for the renewal and transformation of urban public space [1].

As a shared stage of urban life, the function and form of urban public space are directly related to the vitality of the city and the well-being of its residents. However, rapid urban expansion is often accompanied by over-commercialization of public space, destruction of natural ecology, and loss of community culture, resulting in degradation of the function of public space, monotonous landscapes, and declining environmental quality.

Digital twin technology is a comprehensive platform that integrates advanced technologies such as Internet of Things, big data, cloud computing and artificial intelligence, which realizes real-time interaction and data synchronization between the physical world and the digital world by creating an accurate mapping of the physical world in virtual space. In the field of urban planning and management, the application of digital twin technology enables city managers to look at urban space from a new perspective, realizing real-time monitoring, dynamic simulation, predictive analysis and optimized decision-making for the urban environment.

This technology can not only significantly improve the science and efficiency of decision-making, but also enhance the resilience and sustainability of the urban system [2], the specific application model is shown in Fig. 1.

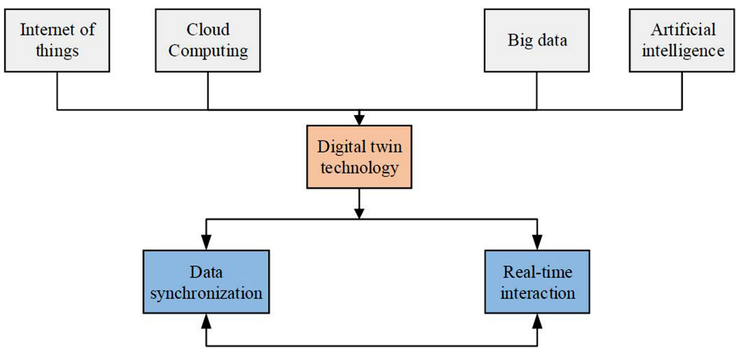


Fig. 1. Digital twin application model

This study focuses on exploring the application of digital twin technology in addressing the challenges faced by urban public spaces, particularly in enhancing their functionality, sustainability, and adaptability. The central research problem is to investigate how digital twin technology can be effectively utilized to revitalize and transform urban public spaces, ensuring they meet the evolving needs of modern cities and their inhabitants [3,4].

To achieve our research objectives, we employ a combination of theoretical analysis and case studies. The methodology includes literature review, comparative analysis, and empirical evidence from successful applications. We will analyze the technical requirements of digital twin technology in urban public space renewal, explore how digital twins can assist in the innovative design and optimization of public space, assess the environmental impact of renewal projects, and examine how the digital twin platform can facilitate public participation in the renewal process [5]. By combining these methodologies, this study seeks to provide a comprehensive understanding of how digital twin technology can be effectively applied to address the challenges faced by urban public spaces, thereby contributing to their intelligent renewal and sustainable development [6].

This study aims to make significant contributions to the field of urban planning and management by providing a comprehensive framework for the application of digital twin technology in urban public space renewal [7]. Our findings will offer actionable insights for urban planners, policymakers, and stakeholders, enabling them to leverage digital twin technology more effectively to create vibrant, sustainable, and inclusive public spaces. Additionally, the research will contribute to the broader academic discourse on smart city technologies and their role in addressing contemporary urban challenges [8, 9].

## 2. Relevant studies

In the cutting-edge field of urban public space renewal, the innovative application of digital twin technology is gradually demonstrating its far-reaching impact and revolutionizing urban planning and design [10, 11]. Through the construction of digital mapping of public space, this technology not only empowers urban planners with unprecedented insight and decision-making ability, but also provides a scientific basis and practical path for optimizing spatial layout, enhancing environmental aesthetics, and intelligently configuring facilities [12, 13]. The essence of digital twin technology lies in its ability to simulate and evaluate every update option that may be implemented in the real world first in a highly simulated virtual environment, greatly reducing the cost and risk of the traditional trial-and-error method. For example, in Singapore, as a country in the forefront of smart city construction, the government of Singapore conducted an in-depth analysis and prediction of urban parks through the application of digital twin technology, accurately simulated the density of pedestrian flow, light intensity, and temperature changes in different time periods, and then guided the optimization of the layout of the park's sitting areas, walking paths, and vegetation, which significantly improved the efficiency of the use of public space and the comfort of the residents [14]. The practice of digital twinning is not only a demonstration of digital twinning, but also an example of digital twinning. This practice not only demonstrates the potential of digital twin technology in improving the quality of the physical environment of public space, but also emphasizes its important role in promoting the green and sustainable development of cities. In addition, some European cities, such as Copenhagen, are actively utilizing digital twin technology for the renewal of urban squares. By integrating real-time traffic data, climate information and public feedback, Copenhagen's urban planning team is able to dynamically adjust the multifunctionality of the plaza to ensure optimal use of the space, whether for daily access, festivals or emergency evacuation [15]. This data-driven and flexible management strategy lays a solid foundation for building the continued adaptability and resilience of public spaces.

Meanwhile, scholars at home and abroad have also conducted extensive research on the application of digital twin technology in urban public space renewal. For example, it is pointed out in their study that digital twin technology can help planners better understand complex urban systems through high-precision modeling and simulation, and make more scientific and reasonable planning decisions on this basis [16]. Literature has explored how to use digital twin technology for urban microclimate regulation, especially how to reduce the urban heat island effect by optimizing the greening layout in hot summer [17].

Overall, although the application of digital twin technology in the field of urban public space regeneration is still in the exploratory stage, the great potential it shows has attracted extensive attention from both the academic and practical communities. Future research needs to further explore how to more closely integrate digital twin technology with urban planning practice, especially in how to solve the problems of data privacy protection, user participation enhancement, and the establishment of cross-departmental collaboration mechanisms in the application of the technology, so as to ensure that this technology can better serve the sustainable development of cities.

# 3. Overview of urban public space renewal

The domain's knowledge status embraces advanced optimization and forecasting in urban public space renewal, with Genetic Algorithms and ARIMA models as key tools for data-driven planning to improve functionality and sustainability [18].

The proposed algorithm, merging Genetic Algorithms and ARIMA, addresses urban renewal's need for efficient resource allocation and trend forecasting, offering a decision-support tool for planners to optimize public spaces and meet community needs.

## 3.1. Importance and function of public space

Urban public spaces are vital for social interaction, economic vitality, environmental quality, cultural heritage, and resident well-being. They foster community cohesion, attract commercial investment, improve the urban microclimate, preserve history, and promote active lifestyles. Flexible designs enhance resilience against urban challenges like climate change [19].

## 3.2. Genetic algorithms in complex resource allocation

Genetic Algorithm (GA), as a global optimization method based on the principle of biological evolution, shows unique advantages in solving complex, multi-objective optimization problems such as urban public space resource allocation. It searches the solution space efficiently and seeks the optimal resource allocation scheme by simulating the biological evolution process such as natural selection, heredity and mutation. The following will introduce the application of genetic algorithm in public space resource allocation in detail, combined with specific cases and formulas, to explore its working principle and practical value in depth [20, 21]. The application framework of genetic algorithm in resource allocation is specifically shown in Fig. 2.

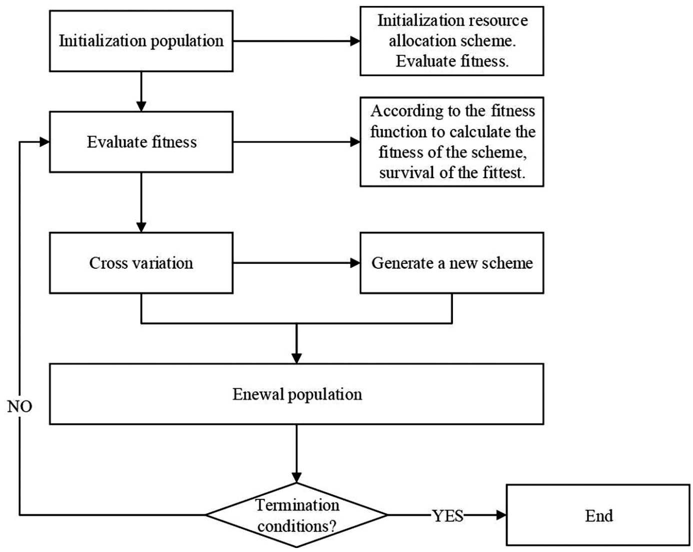


Fig. 2. Framework for the application of genetic algorithms in resource allocation

First, the resource allocation problem is transformed into a form suitable for genetic algorithm processing. Taking the allocation of greening resources in public space as an example, the greening proportion of each area can be encoded as a binary string, such as $x_i = [b_1, b_2, \ldots, b_m]$, where $b_k$ represents the binary value of the $k$-th bit and m is the encoding length. During initialization, an initial population of a certain size is randomly generated to ensure broad coverage of the solution space. We use a fitness function to evaluate the quality of each solution, which directly affects the search orientation of the algorithm. Considering multi-objectives such as cost, aesthetics, and eco-efficiency, the fitness function can be designed as Eq. (3.1).

$$F(x) = w_1 C(x) + w_2 B(x) + w_3 E(x) \tag{3.1}$$

where *C(x)* is the total cost, *B(x)* is the aesthetics score, *E(x)* is the eco-efficiency index, and $w_1, w_2, w_3$ is the weight of each objective, which needs to be adjusted according to the actual situation. We used a roulette wheel selection method, where individuals with a high degree of adaptation have a greater chance of being selected to reproduce the next generation. We use single-point crossover, randomly selecting a crossover point and exchanging part of the chromosomes of the two parents, e.g. Eq. (3.2) [20].

$$x_i^{(c1)} = \begin{cases} x_1[i] & \text{if } i \le P \\ x_2[i] & \text{otherwise} \end{cases} \tag{3.2}$$

The values of certain loci are then changed with some probability to introduce new genetic diversity, e.g. Bit Variants as Eq. (3.3).

$$x_{\mathrm{i}} = \begin{cases} 1 - x_i & \text{with probability } P_m \\ x_i & \text{otherwise} \end{cases} \tag{3.3}$$

A genetic algorithm is used to optimize resource allocation for an urban park's greening, balancing cost, ecological efficiency, and aesthetics. Each solution is a binary string representing greening proportions across 10 park areas. Objectives are weighted and the algorithm iterates to find the optimal greening scheme. The process and final solution offer visual reports to aid decision-making.

## 3.3. Application of ARIMA model in forecasting

For optimizing urban public space resource allocation using Genetic Algorithm (GA), parameters are finely tuned. With 10 park areas, encoding length $m = 10$, population size 50, and equal weights 1/3 for cost, aesthetics, and eco-efficiency. Roulette wheel selection favors fitter solutions, while crossover rate 0.8 and mutation rate 0.01 maintain diversity and prevent premature convergence. Running for $G = 100 - 500$ generations ensures comprehensive solution exploration [21].

The modeling steps in this paper are shown in Fig. 3. ARIMA model-based forecasting of public space renewal projects mainly utilizes historical time-series data of the projects, such as past monthly cost overheads and visitor volume records, which need to be meticulously cleaned and pre-processed to ensure data quality [22].

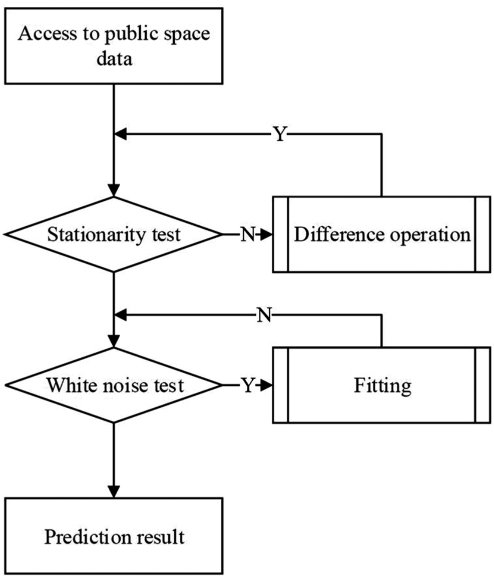


Fig. 3. ARIMA model modeling steps

If the series is not smooth, differentiation is required until the series is smooth. The mathematical expression for differencing is as follows: $Y_t = X_t - X_{t-1}$, where $Y_t$ is the differenced series and $X_t$ is the observation of the original time series in period t. The difference is then applied to the data. Based on the autocorrelation (ACF) and partial autocorrelation (PACF) plots of the differenced series, p (order of the autoregressive term), d (number of differencing, known), and $q$ (order of the moving average term) in the ARIMA model are determined. The model is selected by considering the balance between the complexity of the model and the prediction accuracy, and the optimal parameters are usually determined by the AIC or BIC information criterion. The general form of the ARIMA($p$,$d$,$q$) model is: $\Phi(B)(1-B)^d X_t = \Theta(B)a_t$ where B is the backward shift operator, $\Phi(B)$ and $\Theta(B)$ are the AR and MA polynomials, respectively, and $a_t$ is the white noise sequence. For the AR part, we have Eq. (3.4) [23].

$$\Phi(B)X_t = \phi_1 X_{t-1} + \phi_2 X_{t-2} + \ldots + \phi_p X_{t-p} \tag{3.4}$$

For the MA part, we have: $\Theta(B)a_t = \theta_1 a_{t-1} + \theta_2 a_{t-2} + \ldots + \theta_q a_{t-q}$. We estimate the model parameters $\phi_1, \phi_2, \ldots, \theta_1, \theta_2, \ldots$, which minimize the residual sum of squares, using methods such as great likelihood estimation (MLE) or least squares (OLS). The specific formulas for parameter estimation depend on the estimation method used, but the core idea is to optimize the model parameters so that the model residuals conform to the white noise characteristics [24].

The applicability and predictive accuracy of the model is assessed through residual analysis (to check whether the residuals are random and free of autocorrelation), $Q$-statistic test (to check whether the residuals follow a normal distribution), and the model's prediction error (e.g., mean square error MSE). If the model is not satisfactory, return to step 2 to adjust the parameters or model structure. Once the model is confirmed to be valid, the trained ARIMA model can be used to forecast key metrics for a certain period of time in the future, with the forecasting formula based on the ARIMA model structure defined earlier. For example, for a one-step forecast, the formula simplifies to Eq. (3.5).

$$\hat{X}_{t+1} = \hat{\mu} + \sum_{i=1}^{p} \hat{\phi}_i X_{t+1-i} + \sum_{j=1}^{q} \hat{\theta}_j a_{t-j} \tag{3.5}$$

where $\hat{X}_{t+1}$ is the forecast, $\hat{\mu}$ is the constant term, $\hat{\phi}_i, \hat{\theta}_j$ is the estimated coefficients, and $a_{t-j}$ is the residual estimate from the prior period. Ultimately, these prediction results can directly serve project management decisions, such as budget planning and resource allocation, providing data-driven insights for the efficient operation and optimization of public space renewal projects.

# 4. Application examples to explore

## 4.1. Shanghai bund digital twin smart transformation project

Digital twin technology manages urban public spaces by collecting real-time and periodic data, filtering anomalies and irrelevance, and processing via time series analysis, image recognition, and sentiment analysis. This enables real-time insights and predictive analytics, optimizing decision-making and integrating multiple data sources. The Bund in Shanghai deployed sensors and cameras, built a digital twin model using BIM, optimized space and crowd management, and established a real-time monitoring system for facilities, enhancing visitor satisfaction and sustainability.

To effectively apply digital twin technology in urban public space management, data collection and processing parameters must be defined. This includes structured sensor data (e.g., temperature, pedestrian flow) and unstructured data (e.g., CCTV images, social media posts). Data is collected in real-time and periodically, with filtering for anomalies and relevance. Processing involves time series analysis, image recognition, and sentiment analysis, enhancing decision-making and ensuring public spaces are vibrant, sustainable, and meet community needs.

## 4.2. Digital twin ecosystem management in gardens by the bay, Singapore

Gardens by the Bay, Singapore uses digital twinning technology for ecosystem management, simulating plant growth and water quality for scientific decision-making. IoT enables real-time monitoring and automatic adjustment of irrigation and shading, while AR apps enhance visitor education. Digital twin management platforms improve operations and reduce labor costs.

# 5. Experimental evaluation

## 5.1. Technical standards and compatibility issues

The level of public awareness and participation is an important indicator of the project's social impact. Table 1 demonstrates the results of the public questionnaire, which reflects the current level of public awareness of digital twin technology and their willingness to participate. Table 1 evaluates the level of public awareness of digital twin technology and their willingness to participate by collecting data through the public questionnaire. The results show that although there is a certain level of understanding of digital twin technology (45%), there is still much room for improvement, especially in stimulating the public's interest in submitting suggestions for improvement (58% awareness corresponds to 78% willingness to participate) and participating in the AR experience (82% awareness corresponds to 89% willingness to participate), which demonstrates a strong willingness of the public to participate. Online interactive platforms are less frequently used, but the public has expectations for such platforms, suggesting that enhanced promotion and optimized user experience can effectively increase public participation.

Table 1. Public awareness and participation survey

| Type of issue | Cognizance (%) | Willingness to participate (%) |
|---|---|---|
| Digital twin understanding | 45 | 67 |
| Improving the willingness to submit proposals | 58 | 78 |
| AR experience Interest | 82 | 89 |
| Frequency of use of online interactive platforms | 30 | Looking forward to the upgrade |

Figure 4 reveals a strong demand for "technology education popularization" and "personalized experience customization" in digital twin technology, with privacy and data security being top concerns. There's also a call for "cross-platform compatibility" and "real-world simulation applications." The public shows interest in participating in digital twin community building. Digital twin models have proven effective, with notable improvements in urban public spaces, smart buildings, manufacturing, healthcare, and agriculture, including reductions in incidents, energy consumption, and waste, as well as increases in satisfaction and productivity.

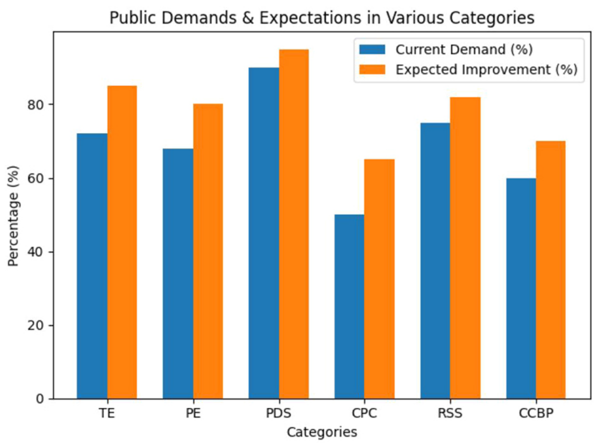


Fig. 4. Specific needs and desired areas of enhancement in the field of digital twin technology by the public

The experimental results demonstrate the effectiveness of digital twin models across various applications. In urban public spaces, there was a 15% reduction in incidents, a 20% decrease in energy consumption, and a 30% increase in positive feedback on social media. Smart buildings saw a 25% reduction in energy bills, a 10-year extension in the lifespan of building systems, and a 90% occupant satisfaction rate. Manufacturing plants experienced 99.5% machine availability, a 15% reduction in raw material waste, and 95% defect-free products. Healthcare facilities reported a 20% reduction in readmission rates, a 10% decrease in waiting times, and a 15% decrease in medication errors. Agricultural fields achieved a 30% increase in wheat yield, a 25% reduction in water usage, and a 20% decrease in pesticide use.

## 5.2. Resource inputs and cost-benefit analysis

Resource inputs and cost-benefit analysis are key considerations for project sustainability. Table 2 summarizes the major resource inputs compared to the expected long-term benefits. This table compares the project's major resource inputs with expected benefits, providing a quantitative analysis of the project's economic viability. Hardware construction and software development and maintenance are the major capital expenditures, but the expected long-term benefits far outweigh the current inputs, with projected payback periods of 3 years and 2.5 years, respectively, indicating a good return on investment for the project.

Table 2. Resource inputs and cost-benefit analysis

| **Input projects** | **Input costs ($ million)** | **Projected benefits ($ million)** | **Recovery cycle (years)** |
|---|---|---|---|
| Hardware construction | 500 | 1200 | 3 |
| Software development and maintenance | 300 | 900 | 2.5 |
| Personnel training | 100 | Enhancement of intangible assets | – |
| (grand) total | 900 | 2100 | – |

Personnel training is essential for implementing digital twin technology in urban public space management. Tailored training courses covering data science fundamentals, digital twin modeling, and advanced analytics tools are necessary. Workshops and hands-on exercises help participants effectively collect and utilize data. Regular refresher courses ensure ongoing skill development. A robust evaluation framework assesses digital twin effectiveness using performance metrics like prediction accuracy and sustainability impact. Regular audits and feedback mechanisms, such as user surveys, enable continuous improvement and system relevance over time. Countermeasures address technical and organizational challenges, including data integrity and resistance to change. An iterative upgrade process, driven by feedback loops and KPIs, ensures the digital twin evolves with changing needs, supporting sustainable and adaptive management practices.

## 5.3. Responses and recommendations

The research on the application of digital twin technology in urban public space renewal can put forward the following three countermeasures and suggestions:

(1) Data collection and analysis optimization.

Establish a perfect data collection system, including sensors, cameras and other devices, in order to capture various data of urban public space in real time and in a comprehensive way, such as the flow of people, traffic conditions, environmental parameters and so on. Use digital twin technology to simulate, analyze and predict the collected data in order to optimize the design and operation of public space. By simulating the effects of different scenarios, it can be evaluated before actual implementation, reducing input costs and risks.

(2) Multi-party participation in co-construction.

Establish a multi-party cooperation mechanism, including government departments, enterprises, communities and residents, to participate in the planning, design and implementation process of urban public space renewal. Using the visualization and interactive functions provided by digital twin technology, all parties can participate in discussions and decision-making in a more intuitive way, improve participation and consensus, and ensure that the renewal project meets the interests and needs of all parties.

(3) Strengthening user participation and experience design

Considering that urban public spaces are for citizens, user experience design should be strengthened and citizens should be actively invited to participate in the design and feedback on the use of the spaces. Utilizing the digital twin platform to conduct online research or virtual reality experience activities can allow more citizens to understand the renewal plan and give their opinions. In this way, more diversified opinions and suggestions can be collected to help the design team better understand the real needs of the public and thus optimize the design scheme. In addition, virtual tours can be provided through the platform so that users can experience the renewed public space before the actual construction is completed and adapt to the new environmental layout in advance.

(4) Continuous Iteration and Feedback Loop

Given that urban development is a dynamic process, the needs of urban public space will also change with time and environment. Therefore, when applying digital twin technology for public space renewal, a set of continuous iteration and feedback mechanisms should be established. This means not only focusing on the design and implementation at the initial stage of the project, but also continuously monitoring the use of the space after the completion of the project and continuously adjusting and optimizing it based on user feedback. By setting up a fixed evaluation cycle, data on the use of the space is collected regularly, its effectiveness is analyzed, and improvement measures are made accordingly. This closed-loop management approach helps to maintain the functionality and attractiveness of the public space so that it can serve the public in the long term and adapt to future urban development needs.

## 6. Conclusions

In the context of rapid urbanization and diversified social needs, the renewal and optimization of urban public space has become a key issue to improve the quality of urban life and promote sustainable development. This study explores the importance of multidimensional urban public space renewal, and focuses on the use of genetic algorithm for resource allocation optimization, ARIMA model for prediction analysis, and the innovative application of digital twin technology in planning, construction, and operation and maintenance. Through theoretical analysis, model introduction, and example analysis, this study systematically explains how modern technological tools can empower the renewal of public space and realize a more efficient, intelligent, and sustainable development path. It is found that the genetic algorithm is highly efficient in dealing with complex resource allocation problems in public space, and can find the optimal solution by considering multiple objectives such as cost, aesthetics, and ecological benefits, etc. The ARIMA model effectively improves the accuracy of predictive analysis, and helps decision makers to accurately grasp the trend of the time-series data of the public space renewal project, which can provide data support for the budget and resource planning. The introduction of digital twin technology improves the intelligence of project management from the early stage of design to the later stage of operation and maintenance, which not only optimizes the planning decision, but also enhances public participation and satisfaction, reflecting the great potential of technological innovation in the field of public space renewal.

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