Big Data-Driven Research on Optimizing Municipal Infrastructure Maintenance and Management

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Keywords: Big Data; Municipal Infrastructure; Maintenance Management; Predictive Modeling; Decision Support; Smart Cities

Abstract: With the accelerating pace of urbanization, municipal infrastructure has become increasingly vital in ensuring urban operations and residents' quality of life. Traditional maintenance and management models commonly suffer from information silos, delayed responses, and inefficient resource allocation, failing to meet the demands of modern, refined urban governance. The emergence of big data technology offers new approaches and tools for intelligent municipal infrastructure management. This paper systematically explores optimization pathways for municipal infrastructure maintenance and management from a big data-driven perspective. The study first clarifies the application logic of big data in infrastructure management, emphasizing the critical role of data collection, integration, and sharing in enhancing management efficiency. It constructs a predictive and preventive maintenance model based on big data analysis, proposing a shift from “reactive repair” to “proactive prevention” through machine learning and lifecycle prediction. and explores the value of decision support systems in optimizing resource allocation, enhancing emergency response, and aiding management decisions. While big data technology can effectively advance the scientific and intelligent maintenance and management of municipal infrastructure, challenges remain in data standardization, privacy protection, and cross-departmental coordination. This research provides theoretical support and practical reference for smart city development.

1. Introduction

Municipal infrastructure, serving as the core support system for urban operations, encompasses road transportation, water supply and drainage, power and energy, communication networks, and public service facilities. Its operational status directly impacts urban safety, sustainable development levels, and residents' quality of life[1]. With accelerated urbanization, infrastructure faces challenges including accelerated aging, rising maintenance costs, and frequent emergencies. Traditional management models, often reliant on periodic inspections and reactive repairs, suffer from information delays, slow response times, and inefficient resource allocation[2]. These limitations hinder the ability to meet modern cities' demands for efficient, precise, and sustainable management.

The rapid advancement of big data technology presents new opportunities to address these challenges[3]. Through multi-source data collection, integration, and real-time analysis, city managers can gain broader and deeper insights into infrastructure operational status and potential risks. Sensors and IoT devices enable real-time monitoring of road cracks, pipeline pressure, or bridge stress conditions; remote sensing and geographic information systems facilitate dynamic monitoring of large-scale infrastructure performance; while public feedback and historical maintenance data further enrich data sources. This data provides robust support for full lifecycle facility management, enabling predictive maintenance and intelligent decision-making[4].

The application of big data in municipal infrastructure management not only significantly enhances maintenance efficiency and reduces operational costs but also enables proactive prevention by predicting potential risks, thereby minimizing losses from emergencies. Simultaneously, data-driven management optimization improves cross-departmental coordination efficiency, driving the transformation of urban governance from experience-driven to science-based decision-making. Currently, big data-driven municipal infrastructure management remains in an exploratory phase,

  DOI: 10.25236/icacel.2025.115

constrained by factors such as insufficient data standardization, inadequate information-sharing mechanisms, and privacy and security risks. These challenges hinder its broader adoption and application[5].

This paper explores optimization pathways for municipal infrastructure maintenance and management from a big data-driven perspective. Specifically, the research will examine the overarching logic of integrating big data with infrastructure management, analyze its application mechanisms, and focus on data acquisition and integration, predictive and preventive maintenance models, as well as the construction of management optimization and decision support systems[6]. This will lead to the formulation of strategies and outlooks for advancing municipal infrastructure management optimization. This study aims to provide theoretical support and practical references for smart city development and sustainable urban growth.

2. Overview of Big Data-Driven Municipal Infrastructure Maintenance and Management

Municipal infrastructure serves as the core support system for urban operations, encompassing diverse facilities such as roads, bridges, drainage networks, and water/power supply systems[7]. Its operational status directly impacts the normal functioning of urban services. Traditional maintenance and management models primarily rely on periodic inspections and experiential judgments, which suffer from issues like delayed responses, resource wastage, and low maintenance efficiency[8]. Against the backdrop of continuously expanding urban scales and accelerating facility aging, these traditional approaches struggle to meet modern urban management demands for efficiency, precision, and sustainability. The fusion of multi-source infrastructure data can be expressed mathematically as shown in Equation 1:

$$D_{fused} = \sum_{i=1}^{n} w_i D_i, \quad \sum_{i=1}^{n} w_i = 1 \qquad (1)$$

The emergence of big data technology offers new pathways for municipal infrastructure maintenance and management[9]. Through the collection and analysis of massive, multi-source, real-time data, city administrators can gain a more comprehensive understanding of facility operational status and potential risks. Sensors, IoT devices, and remote sensing technologies enable real-time acquisition of structural health data for roads, bridges, and pipeline networks[10]. Historical maintenance records, inspection data, and public feedback further enrich information sources, providing robust data support for management decisions.

Building upon data integration and analysis, big data technology enables predictive maintenance and intelligent decision-making. Through machine learning, predictive analytics, and risk assessment models, potential failures can be identified and facility lifecycles forecasted, shifting from traditional reactive repairs to proactive prevention. This data-driven management approach not only significantly enhances maintenance efficiency and reduces operational costs but also lowers the probability of emergencies, thereby boosting overall urban resilience. To evaluate the overall condition of a facility, we define a weighted Facility Health Index as given in Equation 2:

$$FHI_j = \frac{\sum_{k=1}^{m} \alpha_k S_{jk}}{\sum_{k=1}^{m} \alpha_k}, \quad j = 1,2,...,N \qquad (2)$$

Big data also optimizes resource allocation and management processes in municipal infrastructure. Leveraging decision support systems and visualization platforms, administrators achieve cross-departmental information sharing, rapid incident response, and evidence-based maintenance strategies. This data-driven model provides the technological foundation for smart city development, progressively shifting urban management from experience-based practices toward scientific and intelligent approaches—thus ensuring robust support for sustainable urban development. The relationship between infrastructure Health Index and Maintenance Cost is illustrated in Figure 1:

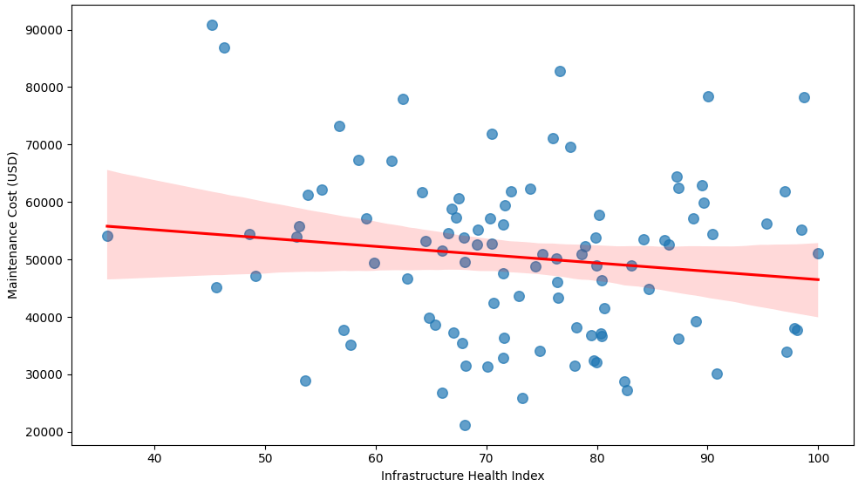

Figure 1 Relationship between Health Index and Maintenance Cost

3. Application Mechanisms of Big Data in Municipal Infrastructure Management

The application mechanisms of big data in municipal infrastructure management can be understood across three levels: data acquisition and integration, predictive and preventive maintenance models, and management optimization with decision support systems. Through the collection and integration of multi-source data, managers can establish comprehensive, dynamic infrastructure information databases, providing a solid foundation for subsequent analysis. Predictive models based on big data analytics and machine learning can identify potential failures in advance, enabling a shift from reactive repairs to proactive prevention, thereby enhancing facility safety and operational efficiency; With the aid of management optimization and decision support systems, urban management departments can scientifically allocate resources, respond swiftly to emergencies, and leverage visualization and intelligent platforms for decision-making support, thereby advancing the intelligent and scientific management of infrastructure. These three mutually reinforcing aspects constitute the core mechanism of big data-driven optimization in municipal infrastructure management.

3.1 Data Acquisition and Integration

Data sources for municipal infrastructure management are extensive, encompassing physical sensors, IoT devices, remote sensing imagery, Geographic Information Systems (GIS), historical operation and maintenance records, and public feedback. Physical sensors and IoT devices enable real-time monitoring of facility operational status—such as road cracks, bridge stresses, and sewer network pressures—providing managers with highly timely, firsthand data. Remote sensing imagery and drone inspections facilitate macro-level monitoring of large-scale infrastructure, proving particularly valuable in areas difficult to inspect on-site.

Historical maintenance records and inspection data provide crucial long-term trend information for infrastructure management. This data not only reflects a facility's service life, repair history, and failure frequency but also serves as the foundation for constructing facility health indices and lifespan prediction models, enabling predictive maintenance. Combined with public feedback data—such as information from city apps, hotlines, and social media—it supplements managers' perception of facility conditions, offering particular advantages in rapidly identifying sudden issues. The probability of infrastructure failure based on key features can be modeled using logistic regression, as illustrated in Equation 3:

$$P\left(\text{Failure}_j\right)=\frac{1}{1+e^{-\left(\beta_0+\sum_{i=1}^{p}\beta_i x_{ji}\right)}} \tag{3}$$

During multi-source data integration, heterogeneity, fragmentation, and inconsistency pose major challenges. Data from different sources may exhibit format discrepancies, temporal inconsistencies, or missing values, necessitating data cleansing, standardization, and fusion processing. By establishing unified data platforms or databases, managers can effectively integrate structured and unstructured data to achieve dynamic monitoring and management across the entire infrastructure lifecycle.

Ensuring data availability and security is equally critical in establishing a data management system. This requires developing data collection standards, implementing permission management mechanisms, and establishing data security and privacy protection policies to guarantee reliability and compliance throughout data collection, transmission, storage, and usage. Through a robust data acquisition and integration system, municipal infrastructure management can establish a comprehensive, accurate, and sustainable data foundation, providing essential support for predictive maintenance and intelligent decision-making.

3.2 Predictive and Preventive Maintenance Models

In traditional municipal infrastructure management, maintenance activities primarily focus on reactive repairs, leading to delayed responses and resource wastage. The introduction of big data technology enables predictive and preventive maintenance. By analyzing facility operational data, historical failure records, and environmental factors, managers can build predictive models to identify potential risks and possible failure points in advance, thereby shifting from reactive maintenance to proactive prevention. The remaining useful life of a facility component can be estimated by the degradation model presented in Equation 4:

$$\mathrm{RUL}_j = \frac{T_{max,j} - T_{current,j}}{\gamma_j}, \quad (4)$$

Predictive models typically leverage machine learning, statistical analysis, and life cycle assessment methodologies. Techniques such as regression analysis, neural networks, or random forest algorithms can forecast trends in facility conditions like road cracks, bridge stresses, and pipeline leaks. Integrating historical data with real-time monitoring enables dynamic model calibration, enhancing prediction accuracy and reliability. This approach empowers managers to scientifically schedule maintenance plans, minimizing the impact of sudden failures on urban operations. Figure 2 shows the predicted Failure Probability of infrastructure components plotted against their Remaining Useful Life, with criticality levels highlighted:

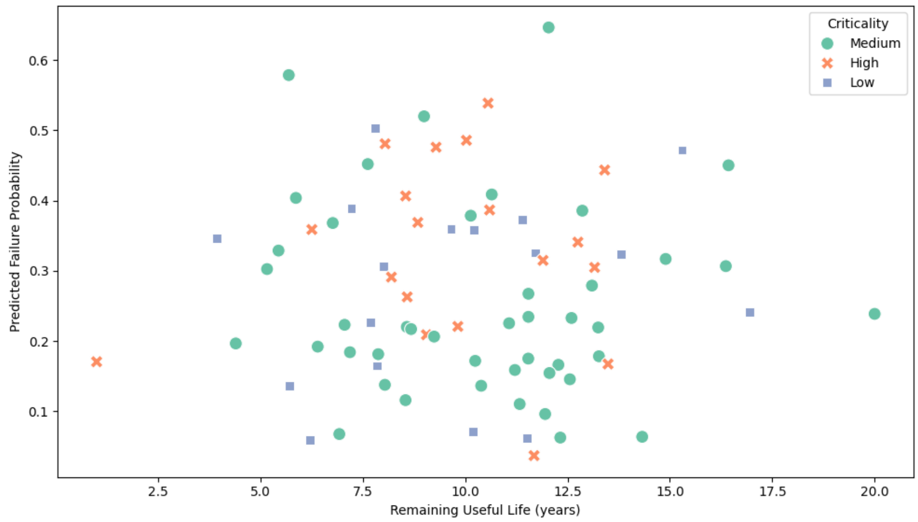

Figure 2 Predictive Failure Probability vs. Remaining Useful Life

The core of predictive maintenance models lies in optimizing resource allocation and repair strategies. By quantitatively assessing risk levels, usage intensity, and criticality across different facilities, managers can prioritize maintenance tasks for high-risk or key infrastructure, rationally allocating human, material, and financial resources. This approach not only reduces overall operational costs but also enhances the overall safety and reliability of the city's infrastructure systems.

Predictive and preventive maintenance models can also integrate deeply with decision support systems to achieve intelligent maintenance management. Visualizing predictive results on management platforms assists decision-makers in establishing scientific inspection frequencies, repair plans, and emergency protocols. Through continuous optimization of model algorithms, the system can self-learn and adjust during operation, continually improving prediction accuracy and maintenance efficiency, thereby providing robust technical support for smart city development.

3.3 Management Optimization and Decision Support Systems

The application of big data technology in municipal infrastructure management extends beyond data collection and predictive maintenance to encompass the construction of management optimization and decision support systems. By integrating multi-source data, predictive models, and operational experience into intelligent management platforms, these systems enable comprehensive monitoring of facility conditions and efficient decision-making, thereby enhancing resource utilization and management standards. Optimal allocation of maintenance resources under budget constraints can be formulated as the optimization problem shown in Equation 5:

$$\min_j C=\sum_{j=1}^{N} c_j x_j, \quad \text{s.t.} \quad \sum_{j=1}^{N} r_j x_j \le R_{total}, \; x_j \in \{0,1\} \tag{5}$$

Management optimization primarily manifests in the scientific allocation of resources, task scheduling, and maintenance strategies. By leveraging big data analytics, the system quantitatively assesses maintenance priorities, risk levels, and historical failure patterns across different facilities, enabling optimal distribution of human, material, and financial resources. The system dynamically adjusts maintenance plans based on real-time monitoring data, enhancing flexibility and response speed to emergencies. Through such optimization, urban infrastructure management achieves maximum efficiency within limited resources.

Decision support systems serve as the core tool for intelligent management. Through visualization platforms, administrators gain intuitive oversight of infrastructure operational status, potential risks, and repair progress. The system provides simulation forecasting and solution optimization capabilities, delivering scientific foundations for emergency response, long-term planning, and policy formulation. Combined with AI algorithms, it automatically generates maintenance recommendations and risk alerts, enabling semi-automated or fully automated decision support that significantly boosts management efficiency.

Management optimization and decision support systems also foster cross-departmental collaboration and information sharing. Through unified data platforms, different departments can access real-time infrastructure operation information, coordinate maintenance tasks and emergency responses, and achieve holistic optimization of urban management. As technology advances, future management systems will become more intelligent and adaptive, continuously optimizing decisions in dynamically changing urban environments to provide robust support for smart city development.

4. Big Data-Driven Pathways for Municipal Infrastructure Maintenance and Management Optimization

In municipal infrastructure maintenance and management, big data technology not only transforms information acquisition and predictive maintenance models but also unlocks entirely new possibilities for optimizing management pathways. These pathways can be developed across three dimensions—technology, management, and policy—forming multidimensional, systematic enhancement strategies that propel urban infrastructure management toward intelligent and scientific approaches. Key optimization pathways manifest in the deep integration of data governance, artificial intelligence algorithms, and IoT technologies. By establishing a unified data platform, multi-source heterogeneous data can be integrated, cleaned, and standardized to ensure accuracy and usability. Leveraging big data analytics and machine learning algorithms enables real-time prediction of facility operational status and health assessments, supporting the formulation of scientific maintenance strategies. Concurrently, IoT technology facilitates real-time monitoring and remote management of facilities, creating a closed-loop system from data collection to decision execution, thereby enhancing management efficiency and response speed. To prioritize maintenance actions, we construct a Decision Support Index integrating health, failure probability, and criticality, as defined in Equation 6:

$$\mathrm{DSI}_j = \lambda_1 \frac{\mathrm{FHI}_j}{\max(\mathrm{FHI})} + \lambda_2 \frac{P(Failure_j)}{\max(P(Failure))} + \lambda_3 \frac{Criticality_j}{\max(Criticality)} \quad (6)$$

The optimization pathway emphasizes innovation in organizational structures and operational models. Establishing cross-departmental collaboration mechanisms enables different functional departments—such as transportation, water supply, energy, and urban management—to share infrastructure operation information, coordinate maintenance tasks, and enhance overall resource utilization efficiency. Through intelligent decision-making platforms and visualization tools, managers can dynamically adjust maintenance plans and emergency response protocols to optimize task scheduling and resource allocation. Additionally, establishing a performance- and risk-based management assessment system ensures effective implementation of management strategies.

The optimization pathway emphasizes institutional safeguards and regulatory guidance. First, policies promoting data openness and sharing should be advanced to break down information silos and foster cross-departmental, cross-system data interoperability. Robust data security and privacy protection mechanisms must be established to ensure public information and sensitive infrastructure data receive appropriate safeguards. Policy incentives and standardized norms can guide urban infrastructure management entities toward adopting big data technologies and intelligent management methods, thereby elevating the industry's overall capabilities. The optimization pathways in technology, management, and policy complement each other, collectively forming a big data-driven optimization system for municipal infrastructure maintenance and management. Implementing this system enables urban management to achieve predictive facility maintenance, scientific resource allocation, and intelligent decision-making. This provides robust support for smart city development and ensures sustainable urban growth alongside enhanced quality of life for residents.

5. Conclusion

This paper systematically explores optimization pathways for municipal infrastructure maintenance and management from a big data-driven perspective. Through analyzing data acquisition and integration, predictive and preventive maintenance models, and management optimization and decision support systems, the study reveals the critical role of big data technology in enhancing infrastructure management efficiency, reducing operational costs, and strengthening urban resilience. Multi-source data integration and real-time monitoring provide robust support for facility lifecycle management. Predictive maintenance models enable a shift from reactive repairs to proactive prevention, while intelligent management optimization systems enhance resource allocation efficiency and decision-making rigor, delivering systematic and intelligent solutions for urban infrastructure management. Several challenges persist in practical implementation. Standardization and sharing mechanisms for multi-source heterogeneous data remain imperfect, often leading to information silos and inefficient data utilization. Data security and privacy protection pose heightened demands on infrastructure management, necessitating robust technical and institutional safeguards. Cross-departmental collaboration and the widespread adoption of intelligent decision-making platforms continue to face organizational, technical, and financial constraints.

Future trends in municipal infrastructure management will increasingly rely on the deep integration of technologies such as big data, artificial intelligence, the Internet of Things, and digital twins. By continuously optimizing data governance systems, enhancing predictive model accuracy, and refining decision support systems—coupled with scientific policy guidance and institutional safeguards—urban administrators can achieve efficient, intelligent, and sustainable infrastructure management. As smart city development progresses, big data-driven infrastructure management models are poised to evolve into standardized, replicable practices that provide valuable references for other cities.

Big data technology offers novel concepts, tools, and pathways for municipal infrastructure maintenance and management. Its application not only enhances management efficiency and facility safety but also provides theoretical underpinnings and practical guidance for smart city development and urban sustainability. Efforts should continue to deepen technological innovation, refine management mechanisms, and strengthen policy support to fully unlock the potential of big data in urban infrastructure management.

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