

Frameworks for Adaptive Smart Urban Systems: A Bibliometric Analysis and Systematic Literature Review

Gary Reyes ^{1,2,3,4,5,*} , Roberto Tolozano-Benites ⁴ , Jorge Reyes ², Laura Lanzarini ³ , Waldo Hasperué ³ , Dayron Rumbaut ^{1,4,5} , Julio Barzola-Monteses ^{1,2}  and Carlos George-Reyes ^{4,5} 

- ¹ Artificial Intelligence Research Group, Campus Durán, Universidad Bolivariana del Ecuador, Km 5.5 vía Durán Yaguachi, Duran 092405, Ecuador; drumbautr@ube.edu.ec (D.R.); jjbarzola@ube.edu.ec (J.B.-M.)
 - ² Facultad de Ciencias Matemáticas y Físicas, Universidad de Guayaquil, Cda. Universitaria Salvador Allende, Guayaquil 090514, Ecuador; jorge.reyess@ug.edu.ec
 - ³ Instituto de Investigación en Informática (LIDI) , Centro CICPBA, Facultad de Informática, Universidad Nacional de La Plata, Buenos Aires CP1900, Argentina; laural@lidi.info.unlp.edu.ar (L.L.); whasperue@lidi.info.unlp.edu.ar (W.H.)
 - ⁴ Campus Durán, Universidad Bolivariana del Ecuador, Km 5.5 vía Durán Yaguachi, Duran 092405, Ecuador; rtolozano@ube.edu.ec (R.T.-B.); cegeorger@ube.edu.ec (C.G.-R.)
 - ⁵ Instituto Latinoamericano de Futuros de la Educación, Universidad Bolivariana del Ecuador, Duran 092406, Ecuador
- * Correspondence: gxreyesz@ube.edu.ec

Abstract

The sustained growth of urban areas has increased the complexity of managing services, infrastructure, and mobility, creating a need for advanced technological solutions capable of responding dynamically to rapidly changing environments. In this context, adaptive smart urban systems have emerged as an innovative alternative that integrates artificial intelligence (AI) to optimize real-time decision making. This study presents a systematic literature review and bibliometric analysis of 64 scientific articles focused on the frameworks underpinning these systems. The methodology applied is based on the selection and critical analysis of indexed scientific publications, enabling the identification of predominant approaches such as machine learning, deep learning, multi-agent systems, and reinforcement learning. The findings reveal a strong convergence between AI, the Internet of Things (IoT), and Big Data, as well as significant limitations in terms of interoperability, data governance, and scalability. It is concluded that, while the advances are promising, the consolidation of these systems requires a comprehensive approach that combines technological innovation, appropriate regulation, and social sustainability.

Keywords: smart cities; adaptive artificial intelligence; urban systems; machine learning; smart infrastructure



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1. Introduction

Contemporary cities face growing challenges associated with digital transformation and the accelerated process of urbanization, which has emerged as one of the most significant phenomena of the 21st century. Population growth, territorial expansion, and the rising demand for urban services have created highly complex environments, characterized by shifting dynamics and strong interdependence among systems. This scenario calls for the development of technological solutions that are not only efficient and scalable but also capable of continuously adapting to changing conditions and uncertain contexts.

In this context, the concept of adaptive smart urban systems has emerged; these systems are distinguished by their ability to integrate multiple data sources, analyze them in real time, and autonomously adjust their behavior. These systems represent a significant evolution from traditional approaches to urban management, as they incorporate continuous learning mechanisms that allow them to progressively improve their performance across different operational scenarios.

An adaptive framework is defined as an architectural structure or conceptual model that incorporates mechanisms for continuous learning, real-time feedback, and the ability to autonomously adjust to dynamic changes in the urban environment. Unlike static systems based on predefined rules, adaptive frameworks use artificial intelligence techniques (such as machine learning, reinforcement learning, or multi-agent systems) to modify their behavior in response to changing conditions in the city, progressively improving their performance and responsiveness.

Artificial intelligence plays a fundamental role in these types of systems by providing advanced tools for pattern modeling, behavior prediction, and the optimization of complex processes. Unlike conventional approaches, which are based on static rules, AI-driven adaptive models enable the creation of dynamic systems that evolve based on data and the environment, facilitating more accurate and context-aware decision making [1–4].

However, the implementation of these solutions faces multiple limitations from both a technological and organizational perspective. Among these are limited interoperability between platforms, the difficulty of integrating with existing infrastructure, and the heterogeneity of data sources. Added to this are regulatory and ethical considerations, such as privacy protection, algorithmic transparency, and urban data governance, which significantly influence their adoption [5,6].

Smart urban systems are characterized by the convergence of various emerging technologies, including the Internet of Things (IoT), cloud computing, big data analytics, and edge computing. These technologies enable the capture, processing, and analysis of information in real time, facilitating the management of urban domains such as transportation, energy, security, and governance. Consequently, they promote the development of more efficient, sustainable, and resilient urban environments [3,4,7,8].

Within this framework, the purpose of this article is to analyze, through a systematic literature review, the main frameworks used in the design and implementation of adaptive smart urban systems. In particular, it seeks to identify the predominant artificial intelligence techniques, examine emerging technological trends, and analyze the structural challenges that influence their adoption in different urban contexts.

To this end, the methodology is based on the collection, selection, and critical analysis of scientific articles indexed in recognized academic databases, which allows for the identification of predominant approaches such as machine learning, deep learning, agent-based systems, and hybrid artificial intelligence models.

Despite the progress made, the implementation of adaptive smart urban systems continues to face significant structural challenges. Among these are scalability issues, limited interoperability between heterogeneous systems, the complexity of data management and governance, as well as the economic and technological constraints specific to each urban context. These limitations highlight the need to critically analyze existing frameworks, evaluating their capabilities, limitations, and potential for adaptation [5,8,9].

In this regard, this study proposes a systematic review aimed at identifying, classifying, and analyzing the main frameworks used in the development of adaptive smart urban systems, as well as at establishing a comprehensive overview of emerging trends and the structural guidelines necessary for their effective implementation, thereby contributing to the advancement of knowledge in the field of smart cities.

This study aims to answer the following research questions:

RQ1: What are the predominant frameworks and artificial intelligence techniques used in adaptive smart urban systems?

RQ2: What are the main technological trends and patterns identified through bibliometric analysis in this field?

RQ3: What are the key structural challenges and limitations for the effective implementation of these frameworks in different urban contexts?

2. Previous Work

Over the past decade, research on smart urban systems has experienced sustained growth, driven by the increase in the urban population and the growing complexity of public service management. Various studies agree that traditional models are insufficient to address issues such as congestion, energy consumption, and environmental sustainability. In this context, the integration of digital technologies and the intensive use of data have emerged as fundamental pillars of urban transformation [3,7,10,11].

The concept of the smart city has evolved from approaches focused on technological infrastructure toward more holistic models that incorporate governance, sustainability, and citizen participation. In this sense, a smart city is defined not only by the availability of technology, but by its ability to transform data into efficient and adaptive decisions [12–14]. This paradigm shift has driven the conception of urban systems as dynamic and interconnected ecosystems.

In this context, artificial intelligence has established itself as one of the primary tools for urban management. Various studies demonstrate its usefulness in predicting, optimizing, and automating services, particularly in areas such as transportation, energy, and security [1,8,9,15–17]. However, although these approaches have demonstrated high effectiveness, many of them have limitations in terms of adaptability to highly dynamic environments.

Regarding the techniques employed, supervised machine learning continues to be widely used due to its predictive capabilities in structured scenarios. However, its reliance on labeled data limits its application in complex urban contexts where information is heterogeneous and ever-changing [18–20].

Unsupervised learning has made it possible to identify hidden patterns in large volumes of urban data, facilitating spatial segmentation and behavioral analysis. Despite their exploratory utility, these methods often lack interpretability and control in decision making [21–25].

Deep learning has expanded analytical capabilities in the processing of complex data, particularly in computer vision and temporal analysis applications. However, its high computational cost and low explainability pose significant challenges for its implementation in real-world urban environments [26–29].

In terms of infrastructure, architectural frameworks integrate technologies such as IoT, cloud computing, and data analytics to enable the continuous capture and processing of urban information. While these models allow for scalability, they have limitations related to latency and dependence on connectivity [30–33].

As an alternative, edge computing has emerged as a solution that allows data to be processed close to its source, improving response times and reducing the load on centralized systems. However, its implementation poses challenges in terms of coordination and resource allocation [34–36].

An emerging trend is the development of adaptive urban systems capable of adjusting their behavior in real time through continuous learning mechanisms. These systems repre-

sent an evolution beyond static models; however, their implementation still faces limitations related to technological integration and the availability of real-time data [4,37,38].

In the field of urban mobility, numerous studies have focused on optimizing traffic flow through predictive models and intelligent control systems. Although these approaches have demonstrated improvements in transportation efficiency, their performance can be affected by the variability of the urban environment [4,26,39].

Significant challenges remain, such as a lack of interoperability, the absence of common standards, and the difficulty of integrating heterogeneous systems [5,40,41]. Furthermore, economic factors and operational constraints hinder the scalability of these solutions in real-world contexts [9,42,43].

Finally, issues such as privacy, cybersecurity, and transparency in decision making have become increasingly important, driving the development of approaches based on explainable artificial intelligence and data governance [44–46].

In summary, while the literature shows significant progress in the development of smart urban systems, there are still major limitations in terms of adaptability, integration, and scalability. These gaps justify the need for a systematic review aimed at identifying more robust and adaptive approaches to managing complex urban environments.

3. Methodology

3.1. Research Approach

This study adopts a qualitative, descriptive, and analytical approach based on a systematic literature review and bibliometric analysis, following the PRISMA 2020 guidelines.

This approach allows for a structured and critical examination of existing knowledge on adaptive smart urban systems, facilitating the identification of predominant trends, artificial intelligence techniques, technological frameworks, and the main challenges associated with their implementation. Unlike purely quantitative studies, this methodology prioritizes the interpretative analysis of scientific evidence, enabling not only the description of the state of the art but also the detection of patterns, relationships, research gaps, and opportunities for future work. Furthermore, it supports the comparison of different frameworks and architectures proposed in the smart cities domain, contributing to a more comprehensive understanding of the phenomenon.

This review followed the PRISMA 2020 guidelines. The completed PRISMA 2020 checklist is provided as Supplementary File S1, The PRISMA flow diagram is provided as Figure 1.

3.2. Search Strategy

The search strategy was designed to ensure the collection of relevant, up-to-date, and methodologically sound literature. The Scopus database was selected due to its broad coverage and international recognition.

The search was conducted on 15 April 2026. The complete search string used is shown below.

Boolean operators (AND, OR) were applied. The search was restricted to articles and conference papers published between 2012 and 2026, in English language.

This query initially retrieved 2528 records. The detailed search parameters are summarized in Table 1.

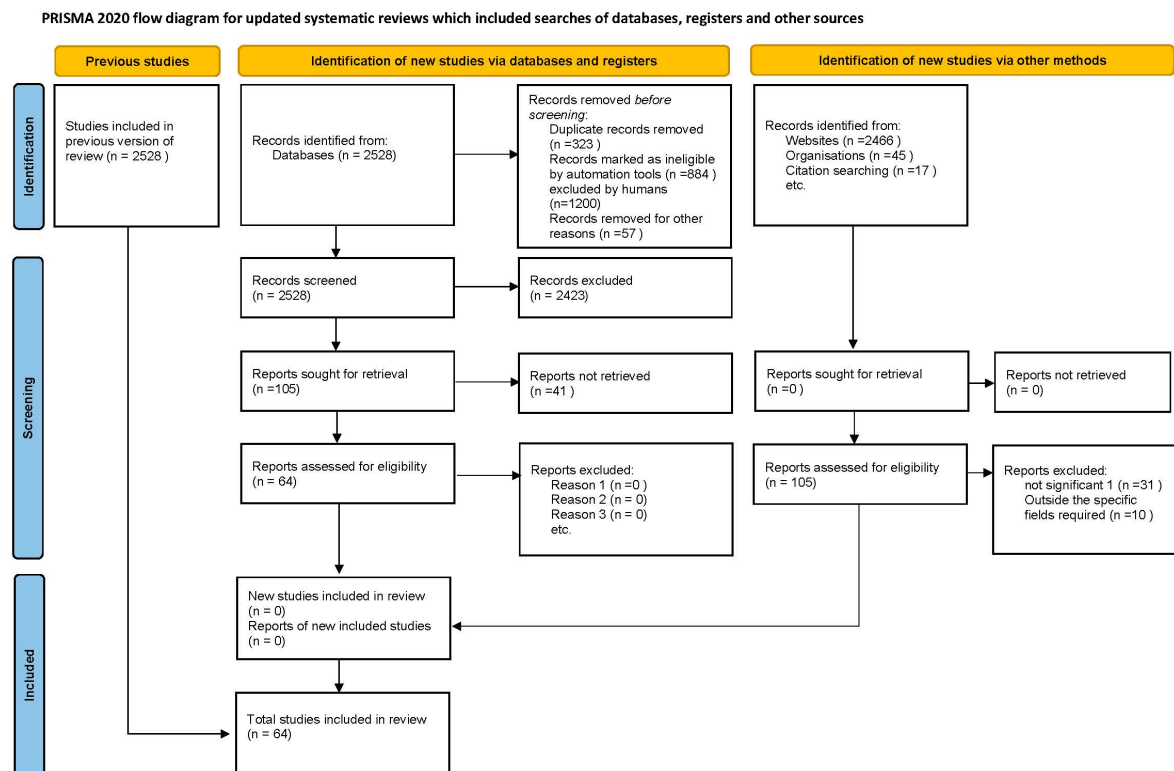


Figure 1. Prisma flow diagram of the study selection process.

Table 1. Search strategy used in the systematic review.

Element	Description
Database	Scopus
Search string	TITLE-ABS-KEY(("smart cit*" OR "smart urban*" OR "smart city") AND (adapt* OR "adaptive") AND ("artificial intelligence" OR "machine learning" OR "deep learning" OR "reinforcement learning" OR "multi-agent system*" OR AI OR ML) AND (framework* OR architecture* OR model* OR system*))
Operators	AND, OR
Time period	2012–2026
Document Type	Articles and conference papers
Language	English
Initial Results	2528 records
Date of search	15 April 2026

3.3. Study Selection Process

The study selection process was conducted in accordance with the PRISMA 2020 guidelines, which ensured the transparency, traceability, and reproducibility of the methodological procedure.

- **Screening:** Titles, abstracts, and keywords were independently screened according to the predefined inclusion and exclusion criteria. Duplicate records were removed using automated tools followed by manual verification. Studies unrelated to the urban context or not involving artificial intelligence as a core component were excluded during this stage. After screening, 105 potentially relevant studies remained for full-text assessment.

- **Eligibility:** The full texts of the 105 remaining studies were assessed against the pre-defined eligibility criteria. During this stage, 41 studies were excluded. Among them, 31 studies were excluded because they were not sufficiently relevant to the objectives of this review or did not adequately address the defined research questions. The remaining 10 studies were excluded because they were outside the scope of adaptive smart urban systems integrating artificial intelligence.
- **Inclusion:** A total of 64 studies satisfied all eligibility criteria and were therefore included in the final systematic literature review.

During the eligibility phase, a thorough review of the full text of the selected studies was conducted. At this stage, criteria such as thematic relevance, methodological quality, scientific contribution, and applicability to smart urban systems were evaluated. Following this analysis, 64 articles were finally selected, constituting the study's final sample, as shown in Table 2.

Table 2. PRISMA-Based Study Selection Process

Phase	Description	Number
Identification	Records retrieved from databases	2528
Screening	Filtering by title, abstract, and keywords	105
Eligibility	Full-text evaluation	64
Inclusion	Final studies selected	64

3.4. Inclusion and Exclusion Criteria

To ensure the consistency and objectivity of the selection process, inclusion and exclusion criteria were defined in advance.

Inclusion Criteria:

- Publications between 2012 and 2026.
- Studies indexed in Scopus.
- Research focused on smart cities or urban systems.
- Studies incorporating artificial intelligence techniques.
- Publications proposing models, architectures, or frameworks for adaptive smart urban systems.
- Articles and conference papers written in English.

Exclusion Criteria:

- Duplicate records.
- Studies without application or relevance to urban environments.
- Publications not focused on artificial intelligence or adaptive systems.
- Documents without full-text access.
- Studies that did not meet minimum standards of methodological rigor or scientific contribution.

3.5. Quality Assessment

Given the high heterogeneity of the selected studies—which include conceptual frameworks, simulation-based models, prototypes, and real-world implementations—a standardized methodological quality assessment tool (e.g., CASP or MMAT) was considered unsuitable for this review, as these instruments are primarily intended for qualitative, quantitative, or mixed-method empirical studies rather than engineering and computer science frameworks.

Instead, a structured qualitative appraisal was conducted using predefined operational criteria specifically developed for this review. Each included study was evaluated according to the following criteria:

- Clarity of the proposed framework or architecture.
- Methodological transparency, including sufficient description of the research approach and implementation process.
- Validation strategy, classified as conceptual proposal, simulation, prototype, or real-world implementation.
- Relevance to adaptive smart urban systems and the integration of artificial intelligence techniques.
- Scientific contribution, reflected in the novelty and applicability of the proposed solution.

These criteria were applied to support the study selection and comparative analysis rather than to generate an overall methodological quality score. Only studies meeting all predefined eligibility and appraisal criteria were retained in the final review. The operational appraisal criteria adopted in this study are summarized in Appendix B.

The absence of a standardized critical appraisal instrument is acknowledged as a limitation of this review and should be considered when interpreting the findings.

Each criterion was independently verified during the full-text screening phase. Studies that did not satisfy the predefined appraisal criteria (e.g., insufficient methodological transparency, lack of framework description, or limited thematic relevance) were excluded from the final dataset prior to evidence synthesis.

3.6. Data Extraction and Analysis

For each selected study, relevant information was systematically extracted, including framework name, main technologies used, application domain, year of publication, country/context, type of implementation, and key contributions.

The bibliometric analysis was performed using VOSviewer software (version 1.6.20). Details of the bibliometric procedure (keyword cleaning, thresholds, clustering method, etc.) are described in Section 3.12.

3.7. Materials and Methods

The final sample consisted of 64 scientific articles, which provide an up-to-date overview of the state of the art in adaptive smart urban systems. The analysis was conducted by integrating a systematic review, a comparative analysis, and a thematic classification.

The studies were organized based on the artificial intelligence techniques used, the application domains—such as transportation, energy, or security—and the type of architecture proposed. This organization allowed us to structure the information in a coherent manner and facilitated its subsequent analysis.

3.8. Data Structure

For each selected study, a systematic process of extracting relevant information was carried out. The main attributes analyzed included the name of the framework, the technologies used, the type of architecture, the application context, the region of implementation, the year of publication, and the associated technological standards.

This structuring enabled the creation of a comparative database, which served as input for subsequent analysis.

3.9. Data Analysis

The analysis of the information was conducted using a qualitative, interpretive, and comparative approach. In this regard, the studies were classified by theme, the predominant techniques—such as machine learning, deep learning, multi-agent systems, and reinforcement learning—were identified, and the main emerging technological trends were analyzed.

In addition, the limitations and challenges reported in the literature were evaluated, providing a comprehensive overview of the current state of research.

3.10. Identification of Problems

Based on the analysis of the selected studies, various structural problems affecting the implementation of adaptive smart urban systems were identified. Among the main challenges are limited interoperability between heterogeneous systems, scalability issues, dependence on high-quality data, and the complexity of integrating multiple technologies.

These challenges are associated with factors such as the lack of common technological standards, the coexistence of heterogeneous infrastructures, budgetary constraints, and technological gaps between different regions.

3.11. Classification of Frameworks

The studies were classified according to their predominant technological approach, identifying architectures based on the Internet of Things, adaptive systems driven by artificial intelligence, solutions supported by edge computing, and models oriented toward urban sustainability.

The application of the PRISMA model, together with the qualitative analysis conducted, ensures the validity, reliability, and reproducibility of the study. The results obtained form the basis for the analysis presented in the following section.

3.12. Bibliometric Analysis Derived from the Systematic Review

Based on the results obtained from the systematic literature review, a bibliometric analysis was conducted with the aim of identifying the main research trends, emerging topics, the temporal evolution of scientific output, and the conceptual relationships among the most representative keywords in the field.

This analysis complemented the qualitative selection of studies with a quantitative perspective.

The analysis covered the period from 2012 to 2026. It was performed using VOSviewer software (version 1.6.20). The procedure included the following steps:

- Extraction of bibliographic metadata from the Scopus database.
- Cleaning and standardization of keywords: unification of singular and plural forms, correction of spelling variants, and elimination of generic terms.
- Definition of minimum occurrence thresholds (keywords appearing at least 3 times).
- Use of the full counting method.
- Application of the Louvain clustering algorithm with a resolution parameter of 1.0 for the identification of thematic clusters.
- Generation of co-occurrence networks, overlay visualizations for temporal trends, and density maps.

This methodology allowed for a robust identification of research patterns, keyword clusters, and the evolution of scientific production in the domain of adaptive smart urban systems.

4. Results

4.1. Results of the Selection Process

The systematic review process identified a total of 2528 initial records, obtained using the search strategy defined in the Scopus database. Subsequently, through an initial screening process based on a review of titles, abstracts, and keywords, duplicates and studies unrelated to the urban context or not involving the application of artificial intelligence were eliminated, reducing the sample to 105 potentially relevant articles.

In a second phase, corresponding to the eligibility analysis, the selected documents were read in full, and their thematic relevance, methodological rigor, and scientific contribution were evaluated. As a result, studies that did not meet the established criteria were excluded, ultimately yielding a sample of 64 scientific articles that form the basis of the analysis.

This process is summarized in Table 2, which provides a structured overview of the progressive reduction in studies through the phases of the PRISMA model.

4.2. Bibliometric Analysis of the Dataset

4.2.1. General Description

The analyzed dataset consists of the 64 selected articles, which represent a significant sample of the current state of research on adaptive smart urban systems. These studies cover the period from 2012 to 2026, demonstrating a progressive evolution of the field.

Overall, there is a high number of authors per paper, reflecting a strong collaborative component in the research. Furthermore, the presence of international co-authorship indicates that the development of solutions for smart cities is an area of global interest.

4.2.2. Annual Scientific Output

An analysis of scientific output reveals an upward trend in the number of publications, particularly in recent years. This growth is directly related to advances in technologies such as artificial intelligence, the Internet of Things (IoT), and urban data analytics.

A notable increase is observed starting in 2023, reaching its peak in 2025, which suggests that this area is becoming established as a priority line of research.

Figure 2 shows a clear upward trend in scientific production, with a significant acceleration starting in 2023 and reaching its peak in 2025. This growth reflects the increasing interest in adaptive technologies driven by advances in AI and IoT, as well as the post-pandemic focus on resilient urban systems.

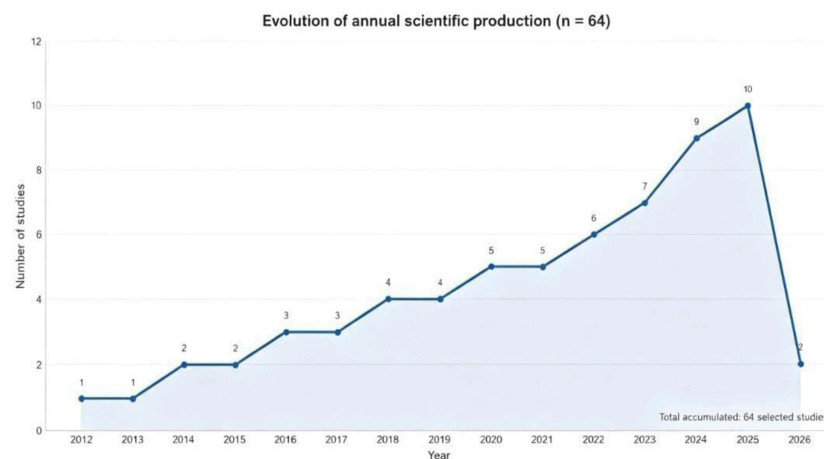


Figure 2. Trend in Annual Scientific Output from 2012 to 2026

4.2.3. Analysis of Sources and Authors

An analysis of the sources reveals that most of the studies come from high-impact indexed journals and international conferences, which guarantees the scientific quality of the selected works.

As for the authors, a diverse distribution is observed, with no dominant concentration, indicating that the field is expanding and has multiple active contributors. This diversity fosters the development of multidisciplinary approaches to creating smart urban solutions.

4.2.4. Keyword Frequency

The keyword analysis identified the most representative terms in the literature. Among the most frequent are:

- Smart city
- Artificial intelligence
- Internet of things
- Machine learning
- Sustainability

These terms clearly reflect the technological and data-driven approach that characterizes modern smart urban systems.

4.2.5. Keyword Co-Occurrence Network

The co-occurrence network shows the relationships between the main concepts used in the literature. It reveals that the term “smart city” acts as a central node, establishing strong connections with artificial intelligence, IoT, and sustainability.

This demonstrates that current research is based on the integration of multiple technologies to solve complex urban problems.

The co-occurrence network (Figure 3) reveals that “smart city” acts as the central hub, strongly connected with “artificial intelligence”, “Internet of Things”, and “sustainability”. This confirms the interdisciplinary and technological convergence that characterizes the field.

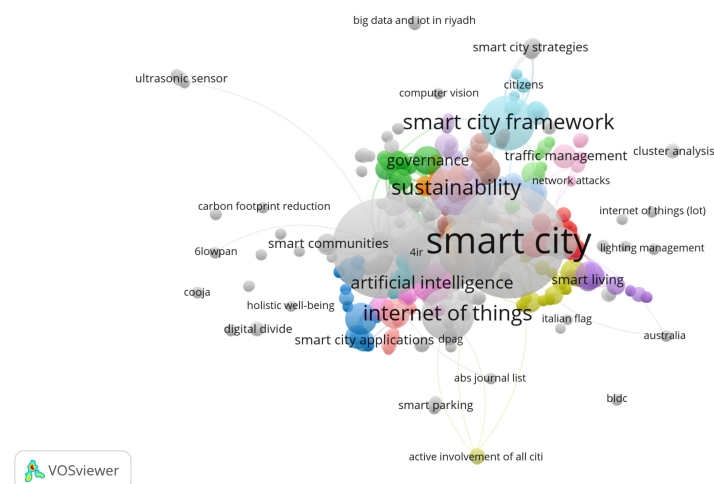


Figure 3. Clusters Based on the Domains Studied

4.2.6. Thematic Grouping

Cluster analysis made it possible to identify different lines of research within the domain studied. Among the main thematic groups are:

- IoT-based infrastructure
- AI-driven analytics
- Sustainability-oriented systems
- Urban governance and management

These clusters reflect the multidimensional nature of smart urban systems, where technological, social, and environmental aspects converge.

Cluster analysis identified four main research lines: IoT-based infrastructure, AI-driven analytics, sustainability-oriented systems, and urban governance. These clusters highlight the multidimensional nature of adaptive smart urban systems, as shown in (Figure 4),

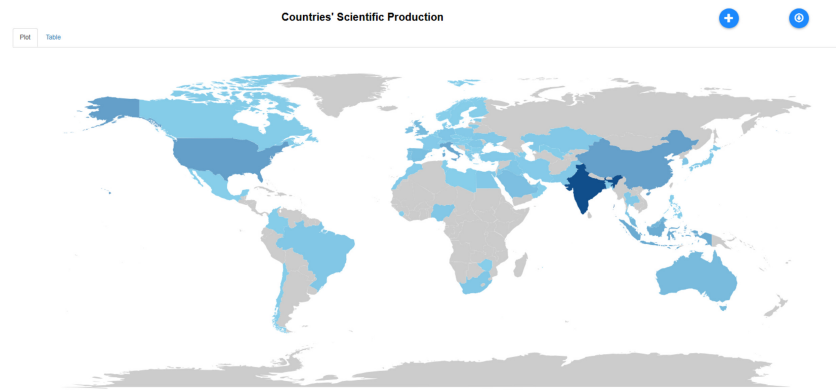


Figure 6. Regional Distribution of Research.

Overall, the results of the bibliometric analysis show that research on adaptive smart urban systems is in a phase of growth and consolidation. The combination of artificial intelligence, the Internet of Things (IoT), and distributed architectures has enabled the development of increasingly sophisticated solutions for urban management.

Persistent challenges related to technological integration, interoperability between systems, and the need for sustainable and scalable approaches have also been identified, which is consistent with the findings of recent studies [3,8,40].

The geographic distribution of the selected studies reveals a marked concentration in Europe (38%), Asia (32%), and North America (18%). This uneven distribution highlights a significant research gap in developing countries and resource-constrained urban environments, emphasizing the need for further studies that address the unique challenges and requirements of these underrepresented regions.

These findings form the basis for the comparative analysis of the frameworks, which is presented in the following sections.

4.3. Classification of Frameworks for Smart Urban Systems

Based on a detailed analysis of the 64 selected articles, different approaches to the design and implementation of frameworks for smart urban systems were identified. These approaches were grouped according to their technological orientation, architecture, and functional purpose, allowing for the establishment of a structured classification that facilitates an understanding of the current state of the field.

The proposed classification is organized into four main categories:

- Internet of Things (IoT)-based architectures
- Artificial intelligence-driven frameworks
- Distributed architectures (edge/fog computing)
- Approaches focused on sustainability and governance

4.3.1. Relevant Research on Internet of Things (IoT)-Based Architectures

IoT-based frameworks form the technological foundation of most smart urban systems. These approaches are characterized by the integration of sensor devices, communication networks, and data collection platforms that enable real-time monitoring of various variables in the urban environment. The reviewed studies show an evolution from traditional IoT architectures—focused on data capture and transmission—toward hybrid approaches that incorporate artificial intelligence, digital twins, Zero Trust security, and intelligent cyber-physical systems.

In these models, the architecture is typically structured in multiple layers, including perception (sensors), communication (networks), processing (cloud or edge platforms),

and application (urban services). This organization facilitates the continuous acquisition of data and its subsequent analysis for decision making. Table 3 summarizes the main frameworks identified within this category, listing their name, authors, year, country or context of presentation, and main contribution.

Table 3. IoT- and AIoT-based frameworks for smart urban systems.

Framework	Authors	Year	Country/Context	Main Contribution
Hybrid AI-IoT Framework with Digital Twin Integration for Predictive Urban Infrastructure Management in Smart Cities	Alourani, Alam, Ali, Khan, and Samal	2026	International	Integrates IoT, artificial intelligence, and digital twins to anticipate failures and optimize predictive maintenance of urban infrastructure [7].
AIoT for Real-Time Traffic Analysis and Optimization	Gupta and Kohli	2025	International	Uses sensors and connected devices along with intelligent algorithms to analyze traffic in real time, optimize urban mobility, and reduce traffic congestion [4].
TwinSnake: A ZTN-Orchestrated Architecture for Secure AIoT Model Training with Digital Twins and Bio-Inspired Snake Learning in Smart Cities	Islam, Karimipour, and Gadekallu	2025	China, IEEE	Combines digital twins, bio-inspired learning, and Zero Trust Networking principles to protect the data used in AIoT model training [36].
Implementing Smart Cyber-Physical Systems in Industrial and Urban Applications: A Practical Approach	Mathew, Chaudhry, Upreti, Farooqui, and Radhakrishnan	2025	International	Integrates sensors, IoT devices, and intelligent processing mechanisms to connect the physical environment with computational systems in urban and industrial applications [30].
The Convergence of Artificial Intelligence and the Internet of Things for Next-Generation Smart Systems	Swetha et al.	2026	International	Analyzes the convergence of AI and IoT to build autonomous, efficient urban systems capable of dynamically responding to changing conditions [31].

An analysis of these frameworks shows that the role of the IoT is no longer limited to urban sensor deployment. In the most recent proposals, the data captured by sensors becomes input for predictive models, smart maintenance systems, adaptive mobility platforms, and security mechanisms for model training. In this regard, the hybrid AI-IoT framework with digital twin integration represents a clear transition toward AIoT architectures, where urban infrastructure can be simulated and evaluated before actual failures occur [7]. Complementarily, IoT applied to traffic gains value when combined with algorithms capable of processing data in real time and generating optimization actions [4].

TwinSnake broadens the discussion to the security of AIoT ecosystems, emphasizing that urban adaptability requires protecting the data used to train intelligent models [36]. Intelligent cyber-physical systems underscore the importance of connecting physical objects, sensors, and computational processing to achieve continuous interaction between the city and its digital platforms [30]. Finally, the AI-IoT convergence can be interpreted as a structural trend toward a new generation of urban systems that are more autonomous and context-aware [31]. Taken together, these frameworks show that the main strength of IoT architectures is their ability to generate real-time urban data; however, their limitations continue to relate to interoperability, security, data quality, and dependence on robust connectivity infrastructures.

4.3.2. Relevant Research on Artificial Intelligence

A second category consists of frameworks focused on using artificial intelligence as the core of the system. These approaches incorporate machine learning algorithms, deep learning, explainable artificial intelligence, and multi-agent systems to analyze urban data and generate adaptive responses. Unlike traditional models, these systems not only

collect information but are also capable of predicting urban events, optimizing resources, automating decisions, and dynamically adapting to changes in the environment.

Applications within this category include public services, smart transportation, urban infrastructure, land-use planning, and algorithmic transparency. Table 4 presents the main AI-driven frameworks identified in the review, listing their name, authors, year, country or context, and main contribution.

Table 4. AI-driven frameworks for smart urban systems.

Framework	Authors	Year	Country/Context	Main Contribution
SmartCityPredict: An AI and Machine Learning Framework for Enhancing Urban Service Efficiency Through Real-Time Data Analytics	Koduri et al.	2025	International	Proposes an architecture based on AI and machine learning to transform urban data into predictions and recommendations aimed at improving the efficiency of public services [20].
SmartCityNext: Leveraging AI and Machine Learning for Responsive and Efficient Urban Services	Saritha et al.	2025	India	Presents a smart platform to dynamically analyze urban needs and adapt services to changing environmental conditions [15].
An AI-Driven Intelligent Transportation System: Functional Architecture and Implementation	Huszkak, Simon, Bokor, Tizedes, and Pekar	2024	Hungary	Describes a functional architecture implemented to optimize urban mobility, traffic management, and real-time decision making [19].
AI-Driven Decision-Making Architectures for Future-Ready Smart Urban Infrastructures	Rathod et al.	2025	India	Proposes an architecture to automate decision making in smart urban infrastructures through the analysis of complex scenarios [8].
Explainable AI for Future Smart Cities: Architectures, Applications, and Challenges	Khader and Abu Al-Haija	2025	Jordan	Introduces explainable artificial intelligence to increase transparency, trust, and understanding of algorithmic decisions in smart cities [44].
Conceptualization of an Integrated Multi-Agent Framework for Innovative Urban Planning	Tepjit	2025	Thailand	Proposes a multi-agent framework in which intelligent agents interact to analyze urban scenarios and support city planning [37].

An analysis of these frameworks shows that artificial intelligence is used as a layer of reasoning capable of transforming large volumes of urban data into actionable knowledge. SmartCityPredict and SmartCityNext reflect this approach by employing machine learning and real-time analytics to improve the efficiency and responsiveness of urban services [15,20]. In the field of mobility, AI-based smart transportation architecture demonstrates a more concrete application, tied to a specific geographic context, where algorithms support traffic management and real-time decision making [19].

AI-driven decision-making architectures extend the scope of these systems to urban infrastructures prepared for future scenarios, in which automation enables a response to complex operational conditions [8]. However, the growing autonomy of these models requires mechanisms for transparency and trust; therefore, explainable artificial intelligence becomes a key component for understanding the reasoning behind the decisions generated by algorithms [44]. Finally, multi-agent approaches provide a distributed perspective for urban planning by allowing multiple intelligent agents to interact, evaluate scenarios, and support more flexible decision-making processes [37]. Taken together, these results show that AI has evolved from applications focused solely on prediction to more complex architectures geared toward decision making, algorithmic transparency, and the automation of urban processes.

4.3.3. Relevant Work on Distributed Architectures: Edge and Fog Computing

The growth of real-time applications has driven the development of distributed architectures, particularly those based on edge computing, fog computing, Edge AI, federated

learning, and 5G networks. These frameworks aim to reduce latency and improve processing efficiency by executing analytical tasks close to the data source.

Unlike centralized cloud models, these architectures enable local data processing, real-time response, reduced network traffic, and greater system resilience. Table 5 summarizes the main distributed frameworks identified in the review.

Table 5. Distributed, edge, and federated frameworks for smart urban systems.

Framework	Authors	Year	Country/Context	Main Contribution
Federated Edge Intelligence: Enabling Privacy-Preserving AI for Smart Cities and IoT Systems	Sheelam	2024	International	Combines edge computing and AI to process data close to the source, reduce centralization, and preserve the privacy of urban information [35].
Federated Learning-Based Edge Intelligence for IoT	Uddin, Shankar, and Islam	2025	International	Integrates federated learning and edge intelligence to train distributed models without transferring raw data to central servers [34].
Federated Learning Shaping the Future of Smart City Infrastructure	Verma, Kishor and Galletta	2024	International	Explores federated learning as a mechanism to improve scalability, collaboration among entities, and decentralized management of urban data [32].
Optimizing Smart City Infrastructure Using 5G Edge AI with Adaptive Multi-Agent Reinforcement Learning	Dhatchayani et al.	2025	India/global	Integrates 5G, Edge AI, and multi-agent reinforcement learning to optimize urban infrastructure and respond in real time to dynamic events [28].
Blockchain-Integrated Federated Learning for Privacy-Preserving Artificial Intelligence and Sustainable Smart City Infrastructure	Balaji et al.	2026	India/global	Combines blockchain and federated learning to strengthen privacy, traceability, and trust in distributed urban ecosystems [48].

An analysis of these frameworks reveals a growing trend toward decentralized architectures that seek to minimize latency, improve citizens' privacy, and increase the resilience of smart urban systems. In this regard, proposals based on edge computing and edge intelligence reduce dependence on central servers by processing information on devices close to the source of data generation [34,35]. Federated learning, in turn, extends this logic by enabling the collaborative training of models without moving the original data, which promotes scalability and cooperation among multiple urban stakeholders [32].

The incorporation of 5G and multi-agent reinforcement learning accelerates the response to dynamic events, especially in urban infrastructures that require low latency and continuous adaptation [28]. The integration of blockchain adds an additional layer of traceability and trust, which is particularly relevant when distributed urban systems use sensitive data or AI models shared among different entities [48]. This approach is especially useful in critical applications such as traffic control, security monitoring, and emergency management; however, it introduces new challenges related to distributed management, data synchronization, and the maintenance of multiple nodes.

4.3.4. Relevant Works on Sustainability- and Governance-Oriented Approaches

A set of frameworks was identified that integrate technological aspects with social, environmental, and governance dimensions. These approaches seek not only to optimize the city's operations but also to ensure its long-term sustainability. This category includes models that incorporate energy efficiency, emissions reduction, citizen participation, transparency in decision making, ethical data management, climate resilience, and public dissemination of urban information.

Table 6 presents the main sustainability- and governance-oriented frameworks identified in the review.

Table 6. Sustainability- and governance-oriented frameworks for smart urban systems.

Framework	Authors	Year	Country/Context	Main Contribution
Smart City Digital Twin Framework for Real-Time Multi-Data Integration and Wide Public Distribution	Adreani, Bellini, Fanfani, Nesi, and Pantaleo	2024	Italy	Integrates multiple urban data sources in real time using digital twins and facilitates the public distribution of information for city management [1].
Assessing Data Governance Models for Smart Cities	Bozkurt, Rossmann, Pervez, and Ramzan	2025	Europe	Compares data governance models and evaluates their ability to address regulatory, ethical, and operational requirements of European smart cities [5].
SORA-ATMAS: Adaptive Trust Management and Multi-LLM Aligned Governance for Future Smart Cities	Antuley et al.	2026	International	Introduces adaptive trust management and governance aligned with multiple large language models (LLMs) to strengthen the reliability of smart urban systems [49].
Green Transportation Planning for Smart Cities: Digital Twins and Real-Time Traffic Optimization in Urban Mobility Networks	Lis and Madziel	2026	Poland	Uses digital twins and real-time traffic optimization to improve urban mobility and reduce the environmental impacts of transportation [38].
AIoT at the Frontline of Climate Change Management: Enabling Resilient, Adaptive, and Sustainable Smart Cities	Banciu and Florea	2026	International	Analyzes the use of AIoT to strengthen urban resilience, climate adaptation, and sustainability in the face of environmental phenomena [9].
Harnessing AI for Sustainable Smart Cities: Impact, Innovations, and Use Cases	Soni and Taneja	2026	International	Examines AI applications aimed at energy efficiency, resource optimization, and reducing environmental impacts [43].
The Green City: Sustainable and Smart Urban Living Through Artificial Intelligence	Satpathy, Nayak, and Jain	2025	International	Highlights the potential of AI to improve resource management, the efficiency of public services, and sustainable urban development [42].

An analysis of these frameworks reveals a gradual transition from approaches focused exclusively on technology toward comprehensive models that integrate sustainability, data governance, and urban resilience. Frameworks based on digital twins enable the dynamic representation of urban infrastructure and support both operational management and the public communication of information [1]. In the case of transportation, the combination of digital twins and real-time optimization helps reduce environmental impacts and improve the efficiency of mobility networks [38].

Data governance emerges as a cross-cutting theme, as it defines the conditions under which urban data can be collected, shared, audited, and used ethically. In this regard, the governance models evaluated for European smart cities provide relevant regulatory and operational criteria [5], while SORA-ATMAS extends this discussion to adaptive trust management and the alignment of systems based on multiple LLMs [49]. Furthermore, approaches focused on climate change and sustainability show that the convergence of AIoT and AI can strengthen urban resilience, optimize resources, and promote more sustainable urban lifestyles [9,42,43]. These frameworks reflect an evolution of the smart city concept toward a more comprehensive approach, in which technology serves as a means to improve quality of life, environmental sustainability, and institutional trust.

4.3.5. Justification of the Proposed Classification

The proposed classification organizes the frameworks into four main categories: (1) Internet of Things (IoT)-based architectures, (2) Artificial intelligence-driven frameworks, (3) Distributed architectures (edge/fog computing), and (4) Approaches focused on sustainability and governance.

This categorization was developed inductively through a thematic analysis of the 64 selected studies, considering the predominant technological core and primary contribution reported in each work. It builds upon and extends previous classifications in the smart city literature. While earlier works such as [3] and other systematic reviews, Ref. [40] have emphasized technical layers or self-adaptation mechanisms, our framework explicitly incorporates sustainability and governance as a distinct dimension, reflecting the growing importance of ethical, social, and environmental aspects observed in publications from 2024 to 2026.

Frameworks were assigned to the category that best represents their main technological focus and contribution, as identified in the original studies. We acknowledge that many solutions present hybrid characteristics. For example, blockchain-integrated federated learning approaches combine distributed processing with strong governance and privacy elements. In such cases, they were classified under the dominant dimension while noting their multidisciplinary contributions in the corresponding analysis. Although the categories are not mutually exclusive, this structure provides an analytically useful lens to identify predominant trends, technological convergences, and research gaps.

To further clarify the current state of development and better understand the gap between theory and practice, the identified frameworks were also classified according to their level of maturity and practical application, as shown in Table 7,

Table 7. Distinction between types of frameworks for adaptive smart urban systems

Type	Description	Examples in This Review
Conceptual	Theoretical models or architectures without practical implementation	Many AI-driven frameworks and early proposals
Simulation-based	Models tested through simulation, digital twins, or virtual environments	Digital Twin traffic optimization framework
Prototype	Functional prototypes tested in controlled or pilot environments	Several Edge AI and federated learning proposals
Real-world implementation	Frameworks deployed and validated in actual urban contexts	CityAI (Hungary), Snap4City (Italy)

This dual classification (technological orientation and maturity level) reveals that, despite the rapid growth in publications, real-world implementations remain limited. Most frameworks are still at conceptual or simulation stages, which limits the generalizability of findings and highlights the need for more empirical validation in diverse urban contexts. Overall, the results obtained lead to the conclusion that the current trend is toward the integration of multiple technologies, automation based on artificial intelligence, distributed processing, and the incorporation of sustainability and governance criteria.

This classification provides a solid conceptual foundation for the development of new models of adaptive smart urban systems, as well as for identifying opportunities for future research.

4.3.6. Classification Rules

To ensure consistency in the classification of frameworks, the following coding rules were established and applied by two independent reviewers:

- Each framework was assigned to the category that best represented its main technological contribution or core component.
- Hybrid frameworks (e.g., AIoT or digital twins with edge computing) were classified according to their predominant approach, while acknowledging their multidisciplinary nature in the text.

- Categories are not mutually exclusive; overlap is recognized and discussed.
- Coding was performed independently by two researchers. Inter-rater agreement was calculated, reaching over 80% initially, with final consensus reached through discussion.

4.3.7. Summary of the Classification

In summary, the proposed classification shows that smart city frameworks have evolved from isolated technological structures toward complex, adaptive, and multidimensional ecosystems, as shown in Table 8.

Table 8. Comparative Evaluation Matrix of Frameworks for Adaptive Urban Systems.

Framework/Category	AI	IoT/Edge	Sustainability	Real-World Implementation
CityAI	High	Medium	Medium	Yes (Hungary)
Snap4City	Medium	High	High	Yes (Italy)
Digital Twin Traffic Optimization	Medium	High	High	Yes (Poland)

4.4. Identified and Implemented Frameworks

Among the 64 reviewed studies, three frameworks were selected for a more in-depth analysis due to their successful real-world implementations and their representation of different categories within the proposed classification:

- **CityAI:** Represents artificial intelligence (AI)-driven frameworks applied to intelligent transportation systems, supporting data-driven decision making for urban mobility.
- **Snap4City:** Exemplifies Internet of Things (IoT)-based platforms with a strong emphasis on data integration, interoperability, and urban data governance.
- **Digital Twin Traffic Optimization Framework:** Illustrates sustainability-oriented approaches that leverage digital twin technology to optimize urban traffic management and mobility.

These frameworks were selected because they demonstrate practical applicability in real urban environments, particularly within European cities, provide validated implementation outcomes, and serve as representative examples of the principal categories identified through the systematic literature review.

4.4.1. Artificial Intelligence-Driven Frameworks

Within this category, one framework was identified that has an application associated with a specific geographic context. These types of architectures are characterized by their use of artificial intelligence algorithms as a central element for analyzing urban information, optimizing processes, and generating adaptive responses to changes in the environment.

Project: *An AI-Driven Intelligent Transportation System: Functional Architecture and Implementation*

- **Framework implemented:** CityAI.
- **Implementation:** Applied in an urban context in Hungary, Europe, as a smart architecture geared toward the management and optimization of Intelligent Transportation Systems (ITS).

The *CityAI* framework, developed by Huszak, Simon, Bokor, Tizedes, and Pekar in 2024, integrates technologies such as artificial intelligence, machine learning, functional architectures for urban transportation management, and data processing mechanisms geared toward decision making.

The proposed architecture enables the collection, processing, and interpretation of information related to urban mobility, using computational models capable of analyzing the behavior of the transportation system and generating useful insights to improve its operation. Through the application of intelligent techniques, the framework seeks to adapt to changes in the urban environment and provide data-driven solutions to optimize traffic-related processes.

One of the most significant aspects of this framework is its implementation in a specific geographic setting, which demonstrates the applicability of artificial intelligence within real-world mobility systems. Unlike purely conceptual proposals, *CityAI* presents a functional architecture in which intelligent models are integrated with transportation management to transform urban data into useful information for vehicle planning and operations.

This framework represents a significant contribution to the development of solutions focused on analyzing mobility patterns, optimizing traffic, and enabling smart urban transportation planning. Its implementation highlights the importance of combining artificial intelligence, data processing, and digital infrastructure to address the current challenges facing smart cities.

4.4.2. Approaches Focused on Sustainability and Governance

Within this category, a framework focused on smart urban information management was identified, in which digital technologies are used as tools to strengthen sustainability, governance, and decision making within urban environments. These approaches are characterized by the integration of different data sources, digital platforms, and information management mechanisms with the aim of improving the operational efficiency and transparency of public services.

Unlike frameworks focused exclusively on data processing or the optimization of specific processes, these models incorporate a comprehensive perspective in which technology serves as a support for urban planning, efficient resource management, and the generation of data-driven knowledge.

Project: *Smart City Digital Twin Framework for Real-Time Multi-Data Integration and Wide Public Distribution*

- **Framework implemented:** Snap4City.
- **Implementation:** Applied in Italy as a smart city-oriented architecture for the integration, management, and distribution of urban information using digital technologies.

The *Snap4City* framework, developed by Adreani, Bellini, Fanfani, Nesi, and Pantaleo in 2024, is an open-source, integrated IoT platform architecture designed to manage the entire urban data lifecycle. The framework enables the collection, indexing, processing, and distribution of information from multiple sources, facilitating the creation of dynamic digital representations of the urban environment.

The architecture integrates technologies such as digital twins (*Digital Twin*), the Internet of Things (IoT), smart urban data management, and digital platforms for the public distribution of information. Through this integration, the framework enables the centralization of heterogeneous data generated by different urban systems, providing tools for the visualization, analysis, and monitoring of variables relevant to city management.

A key feature of *Snap4City* is its ability to combine information from various systems within a single platform, thereby improving interoperability among urban services and facilitating data-driven decision-making processes. Its implementation in Italy demonstrates the practical application of digital architectures geared toward the development of smart cities and the efficient management of urban resources.

This framework represents a significant contribution to sustainability and governance approaches because its purpose is not limited to the technological processing of information;

rather, it seeks to strengthen urban administration through mechanisms of integration, transparency, and access to data. Although it is not directly focused on identifying traffic congestion using artificial intelligence, it provides a relevant technological infrastructure for future smart mobility systems that require the integration of data from sensors, connected devices, and urban platforms.

Project: *Green Transportation Planning for Smart Cities: Digital Twins and Real-Time Traffic Optimization in Urban Mobility Networks*

- **Implemented framework:** Digital twins (DT) with real-time traffic optimization systems.
- **Implementation:** Applied in Poland within the context of sustainable urban transportation planning and mobility network optimization.

The framework developed by Lis and Madziel in 2026 proposes an architecture based on the integration of digital twins, microsimulation, and real-time information processing to improve urban transportation management. The proposal combines digital models capable of representing the actual conditions of the mobility system with analytical mechanisms designed to evaluate scenarios and optimize the operation of road networks.

The architecture uses a dynamic Adaptive Flow Measurement (AFM) logic, which interacts with data from IoT sensors to enable real-time Software-in-the-Loop (SiL) simulation processes. This integration makes it possible to analyze traffic behavior, identify potential congestion scenarios, and evaluate optimization strategies before implementing them in the physical environment.

The framework integrates technologies such as digital twins (*Digital Twin*), Intelligent Transportation Systems (ITS), real-time traffic optimization, digital urban modeling, and sustainable mobility systems. Through this combination of technologies, the model generates a dynamic representation of the transportation system, facilitating data-driven decision making and improving the ability to respond to changes in traffic conditions.

A key feature of this framework is its preventive approach to traffic congestion, as it uses simulations and digital models to anticipate system behavior before implementing changes to infrastructure or mobility strategies. This makes it possible to evaluate alternatives aimed at increasing operational efficiency, reducing environmental impacts, and improving the sustainability of urban transportation.

This framework represents a significant contribution to approaches focused on sustainability and governance, as it combines advanced digital technologies with objectives related to energy efficiency, resource optimization, and smart mobility planning. Although it does not focus directly on GPS trajectory clustering algorithms, its architecture is relevant to intelligent transportation systems that require the integration of urban data, computational models, and real-time analysis for traffic congestion management.

4.4.3. Comparison of the Identified Frameworks

A comparison of the identified frameworks shows that intelligent systems applied to urban environments do not rely on a single technology, but rather are evolving toward integrated architectures capable of combining different approaches to address the complexity of modern cities. Each framework analyzed has specific characteristics depending on its primary objective, the technologies used, and its level of integration with urban transportation management, as shown in Table 9.

Table 9. Comparison of the Identified and Implemented Frameworks

Framework	Approach	Main Technologies	Contribution to Smart Transportation
CityAI	Artificial Intelligence applied to Intelligent Transportation Systems (ITS)	Artificial Intelligence, Machine Learning, data processing, and functional architectures for urban transportation	Enables the analysis of mobility information, the generation of insights from urban data, and the improvement of operational transportation management through intelligent models.
Snap4City	Intelligent urban data management and governance	Digital Twin, Internet of Things (IoT), integration of multiple data sources, and digital urban information platforms	Facilitates the integration, processing, and distribution of urban data, providing a technological infrastructure for the efficient administration of smart cities.
Digital Twin (DT)-Based Framework for Real-Time Traffic Optimization	Traffic Optimization and Sustainable Mobility	Digital Twins, IoT, Microsimulation, Adaptive Flow Measurement (AIM), and Software-in-the-Loop (SiL)	Enables dynamic representation of the transportation system, evaluation of mobility scenarios, and optimization of traffic conditions through real-time simulation.

Frameworks based on the Internet of Things (IoT) represent the initial layer within smart ecosystems, as they enable the continuous acquisition of information through sensors, connected devices, and monitoring systems. In the context of urban transportation, these technologies facilitate the collection of variables related to traffic flow, infrastructure conditions, vehicle location, and travel patterns. However, the massive generation of data requires additional mechanisms capable of processing and transforming this information into useful knowledge for decision making.

Artificial intelligence-oriented frameworks, such as the CityAI model, represent an evolution toward systems capable of interpreting large volumes of information and generating adaptive responses to changes in the urban environment. These models incorporate machine learning and computational analysis techniques to identify patterns, optimize processes, and improve the management of Intelligent Transportation Systems. Their main strength lies in their ability to transform historical data and real-time data into useful information for transportation planning and operations.

Distributed architectures based on edge computing, fog computing, and federated models complement these approaches by enabling information processing to take place closer to the data source. This is essential in smart mobility applications, where rapid response times and reduced latency are critical factors for analyzing dynamic traffic conditions. Additionally, these models help improve aspects related to security, privacy, and computational efficiency.

Studies related to digital twins (*Digital Twin*) show a trend toward the creation of dynamic virtual representations of urban systems. Frameworks such as Snap4City and digital twin-based models using microsimulation demonstrate that these technologies enable the integration of heterogeneous information, the representation of real-world environmental conditions, and the evaluation of scenarios before implementing changes to physical systems. In the field of transportation, these capabilities make it possible to analyze optimization strategies, simulate vehicle behavior, and improve sustainable mobility planning.

The comparison conducted reveals that technological evolution within smart cities does not occur through the replacement of one approach with another, but rather through the progressive integration of different paradigms. Each framework contributes a specific capability within the urban ecosystem: IoT enables the capture of information; artificial

intelligence enables the analysis of patterns and the generation of predictions; distributed architectures provide efficient processing; while digital twins and governance models enable the strategic representation, management, and use of information.

This integration is particularly relevant for systems designed to identify areas of traffic congestion, as these systems require combining different sources of information, such as GPS trajectories, urban sensors, historical records, and real-time data. The combined application of artificial intelligence techniques, spatiotemporal analysis, and digital architectures enables the development of models capable of identifying mobility patterns, detecting recurring behaviors, and supporting traffic management decisions.

Future intelligent transportation systems are moving toward hybrid architectures where different technologies work in a complementary manner. The combination of data capture via the IoT, processing using artificial intelligence, trajectory analysis, and appropriate information management mechanisms represents a highly promising approach for improving our understanding of urban mobility and developing more efficient, sustainable, and adaptive solutions to today's transportation challenges.

5. Discussion

The results obtained in this study show that the development of smart urban systems has evolved significantly in recent years, establishing itself as a multidisciplinary field driven by the convergence of emerging technologies. The sustained growth in scientific output identified in the bibliometric analysis confirms that smart cities have become a central focus of research, in line with recent studies that highlight their relevance to the digital transformation of urban environments [3,10,43].

Although previous reviews have addressed smart urban systems and their frameworks [3,40], this study offers a distinct contribution by focusing specifically on adaptive frameworks that incorporate continuous learning and real-time decision-making mechanisms. In addition, it combines a systematic literature review with a comprehensive bibliometric analysis, proposes a structured classification into four categories supported by a comparative matrix, and includes real-world implementation examples. Thus, this work addresses new research questions and provides both theoretical and practical insights for the advancement of the field.

One of the most significant findings concerns the predominance of hybrid architectures that integrate multiple technologies, particularly the Internet of Things, artificial intelligence, and distributed computing. This result aligns with what has been reported in the literature, which indicates that current urban solutions require integrated approaches to address the complexity of modern urban systems [7,8,47]. In this regard, the classification proposed in this study reinforces the idea that frameworks should not be analyzed in isolation, but rather as interdependent components within broader technological ecosystems.

The analysis also reveals that, although IoT-based architectures remain fundamental, their effectiveness depends largely on the quality of the underlying infrastructure. Issues such as interoperability between devices, technological heterogeneity, and the management of large volumes of data continue to pose critical challenges. These findings are consistent with studies highlighting the need to establish common standards and improve integration among urban platforms [5,46].

The adoption of distributed architectures such as edge and fog computing reflects a direct response to the limitations of centralized cloud models, particularly in applications that require low latency and real-time processing. However, their implementation introduces new complexities related to the management of distributed nodes and data synchronization, suggesting the need for further research into efficient coordination and control mechanisms in decentralized environments [32,34].

Beyond the adoption of distributed architectures, cybersecurity emerged as another critical challenge for adaptive urban systems. Beyond basic protection, special attention must be paid to cyber-physical infrastructure, the integrity of real-time data, the prevention of malicious manipulation of AI models, and operational resilience against attacks. Future frameworks should incorporate AI-based anomaly detection, secure-by-design principles, and automated recovery mechanisms to ensure the continuity of critical urban services.

From a broader perspective, the findings also highlight growing concerns about non-technological aspects, such as sustainability, governance, and ethics in data use. This approach reflects an evolution in the concept of the smart city, which has shifted from a predominantly technological vision to a more comprehensive model focused on citizen well-being. In this context, recent research highlights the importance of incorporating principles of transparency, privacy, and citizen participation into the design of smart urban systems [40,50–52].

Data governance emerged as a fundamental cross-cutting component of adaptive urban systems. Beyond its conceptual importance, effective governance requires practical mechanisms to address data ownership, informed citizen consent, algorithmic transparency, accountability, and compliance with regulatory frameworks such as the General Data Protection Regulation (GDPR) and equivalent local legislation. The most robust frameworks integrate governance principles through privacy-by-design approaches, ensuring transparency, data protection, and fairness in the management of urban information. Future research should explore hybrid governance models that combine public regulation with emerging technologies such as blockchain to enhance data traceability, trust, and citizen confidence.

However, the review also reveals significant limitations in the existing literature. Most of the studies analyzed were conducted in urban settings in countries with a high level of technological development, which limits the generalizability of their results to cities with limited resources. Furthermore, the diversity of methodological approaches and the absence of standardized criteria make it difficult to directly compare the proposals and objectively evaluate their performance.

These limitations highlight the need to direct future research toward the development of low-cost, scalable frameworks that can be adapted to contexts with infrastructure, budget, and technological maturity constraints, particularly in Latin America, Africa, and other developing regions. Furthermore, it is essential to establish common evaluation methodologies that allow for consistent comparison of solutions and facilitate their adoption in different urban settings.

Taken together, the results of this research suggest that the evolution of smart urban systems will be driven by greater technological integration, the use of artificial intelligence for automation and decision making, and the incorporation of principles of sustainability and governance. Achieving this goal will require overcoming technical, organizational, and ethical challenges, as well as strengthening collaboration among academia, industry, and public administrations.

6. Conclusions

This research enabled a systematic analysis of the state of the art in frameworks for adaptive smart urban systems, based on a bibliometric analysis and systematic literature review of 64 scientific articles selected according to the PRISMA guidelines. By applying the PRISMA model, we were able to refine an initial set of 2,528 records to a final sample of 64 relevant articles, thereby ensuring the quality, relevance, and methodological rigor of the study.

The results show that research on smart cities has experienced sustained growth in recent years, particularly since 2023, driven primarily by advances in technologies such as artificial intelligence, the Internet of Things, and distributed computing. This increase reflects global interest in developing innovative solutions to optimize urban management and improve quality of life in increasingly complex environments.

One of the main contributions of this study lies in the classification of the frameworks identified in the literature, which were grouped into four categories: IoT-based architectures, AI-driven models, distributed architectures, and approaches focused on sustainability and governance. This classification revealed that there is no single dominant approach, but rather a clear trend toward the integration of multiple technologies into hybrid architectures.

Furthermore, it was found that smart urban systems have evolved from models focused on data collection toward more advanced approaches that incorporate predictive analytics, automation, and adaptive capabilities. In this context, artificial intelligence plays a fundamental role by enabling data-driven decision making and the dynamic optimization of urban services.

However, the study also highlights the existence of significant challenges that limit the effective implementation of these systems. Among these are the lack of interoperability between platforms, scalability issues, reliance on high-quality data, data governance, cybersecurity, and the difficulty of implementation in cities with limited resources.

Based on these findings, it is concluded that the development of adaptive smart urban systems requires not only technological advances but also comprehensive approaches that take social, economic, regulatory, and ethical aspects into account. The adoption of common standards, the strengthening of digital infrastructure, and the incorporation of ethical principles will be key factors in ensuring the success of future implementations.

Future lines of research should focus on the validation of hybrid frameworks in real urban contexts, the development of low-cost and scalable solutions for emerging economies, and the strengthening of explainable AI, cybersecurity, and robust data governance models, with the aim of moving toward truly smart, resilient, and citizen-centered cities.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/info17080750/s1>, File S1: PRISMA 2020 Checklist [53].

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Appendix A. List of Studies Included

Table A1 presents the complete studies included in this systematic review. Each study is identified by an ID and linked to its corresponding reference number in the bibliography.

Table A1. Studies included (n = 64). Each study is identified by an ID and linked to its corresponding reference number in the bibliography.

ID	Year	Title	Source	Ref.
S1	2024	Smart City Digital Twin Framework for Real-Time Multi-Data Integration and Wide Public Distribution	IEEE Access	[1]
S2	2026	Hybrid AI-IoT Framework with Digital Twin Integration for Predictive Urban Infrastructure Management in Smart Cities	Computers, Materials and Continua	[7]
S3	2025	Optimizing Autonomous Vehicle Navigation Through Reinforcement Learning in Dynamic Urban Environments	World Electric Vehicle Journal	[39]
S4	2026	SORA-ATMAS: Adaptive Trust Management and Multi-LLM Aligned Governance for Future Smart Cities	Knowledge-Based Systems	[49]
S5	2022	Machine Learning for Urban Computing	Machine Learning and the City: Applications in Architecture and Urban Design	[18]
S6	2026	Blockchain Integrated Federated Learning for Privacy-Preserving Artificial Intelligence and Sustainable Smart City Infrastructure	Smart City Computational Paradigms: A Sustainable Approach	[48]
S7	2024	Quantitative Impact of Artificial Intelligence on Smart Cities: A Comparative Study Using Federated Learning	IET Conference Proceedings	[54]
S8	2026	AIoT at the Frontline of Climate Change Management: Enabling Resilient, Adaptive, and Sustainable Smart Cities	Climate	[9]
S9	2025	Artificial Intelligence in Urban Planning: Co-Word Analysis for Emerging Topics	Journal of Design and Built Environment	[21]

Table A1. Cont.

ID	Year	Title	Source	Ref.
S10	2025	Generative AI of Things for Sustainable Smart Cities: Synergizing Cognitive Augmentation, Resource Efficiency, Network Traffic, Cybersecurity, and Anomaly Detection for Environmental Performance	Sustainable Cities and Society	[47]
S11	2024	A Survey on Adaptive Smart Urban Systems	IEEE Access	[3]
S12	2025	Assessing Data Governance Models for Smart Cities: Benchmarking Data Governance Models on the Basis of European Urban Requirements	Sustainable Cities and Society	[5]
S13	2019	Reputation Management in Multi-Agent Systems Using Permissioned Blockchain Technology	Proceedings of the IEEE/WIC/ACM International Conference on Web Intelligence	[55]
S14	2019	Urban Intelligence: A Modular, Fully Integrated, and Evolving Model for Cities Digital Twinning	IEEE HONET-ICT International Conference on Smart Cities	[56]
S15	2024	Planning and Building Digital Twins for Smart Cities	Digital Twins for Smart Cities and Villages	[2]
S16	2026	Adaptive Infrastructure Intelligence: Integrated Urban Stormwater Management Framework for Climate-Resilient Cities	Journal of Hydrology	[57]
S17	2025	Advancements in Traffic Signal Control: A Review of Reinforcement Learning and Deep Learning Approaches	Lecture Notes in Networks and Systems	[26]
S18	2025	Optimizing Smart City Infrastructure Using 5G Edge AI with Adaptive Multi-Agent Reinforcement Learning	Proceedings of the International Conference on Visual Analytics and Data Visualization (ICVADV 2025)	[28]
S19	2025	Smart Cities and Social Equity: A Data Science Perspective on Urban Development	Journal of Applied Bioanalysis	[14]
S20	2025	AIoT for Real-Time Traffic Analysis and Optimisation	AIoT for Smart Transportation: Transforming the Future of Mobility	[4]
S21	2012	Approach for Defining Intelligent Systems Technical Performance Metrics	Performance Metrics for Intelligent Systems (PerMIS) Workshop	[6]
S22	2024	Recent Trends in Artificial Intelligence Applications for Smart Cities: A Review	Emerging Electrical and Computer Technologies for Smart Cities	[10]
S23	2024	An AI-Driven Intelligent Transportation System: Functional Architecture and Implementation	Infocommunications Journal	[19]

Table A1. Cont.

ID	Year	Title	Source	Ref.
S24	2025	TwinSnake: A ZTN-Orchestrated Architecture for Secure AIoT Model Training with Digital Twins and Bio-Inspired Snake Learning in Smart Cities	Proceedings of the IEEE International Conference on Cloud Computing Technology and Science (CloudCom 2025)	[36]
S25	2024	Smart Cities and Urban Sustainability with AI	The Convergence of Self-Sustaining Systems with AI and IoT	[12]
S26	2024	Artificial Intelligence-Infused Urban Connectivity for Smart Cities and the Evolution of IoT Communication Networks	Blockchain-Based Solutions for Accessibility in Smart Cities	[58]
S27	2025	Explainable AI for Future Smart Cities: Architectures, Applications, and Challenges	Explainable Artificial Intelligence for Trustworthy Decisions in Smart Applications	[44]
S28	2025	SmartCityPredict: An AI and Machine Learning Framework for Enhancing Urban Service Efficiency Through Real-Time Data Analytics	Proceedings of the 3rd International Conference on Cyber Resilience (ICCR 2025)	[20]
S29	2025	Pixel by Pixel: Constructing Smart Cities with AI Building Blocks	Generative AI for a Net-Zero Economy	[59]
S30	2015	Reputation Systems Evaluation Survey	ACM Computing Surveys	[60]
S31	2024	Adoption Intention of Artificial Intelligence Enabled Smart City Services from Citizens' Perspective	International Journal of Human Capital in Urban Management	[13]
S32	2026	Green Transportation Planning for Smart Cities: Digital Twins and Real-Time Traffic Optimization in Urban Mobility Networks	Applied Sciences	[38]
S33	2025	Blockchain Technology: Enabling Trust in Urban Systems	AI, Cybersecurity, and Next-Generation Mobility in Smart Cities	[61]
S34	2025	Implementing Smart Cyber-Physical Systems in Industrial and Urban Applications: A Practical Approach	Cognitive Cloud Computing: Building Intelligent Systems for Tomorrow	[30]
S35	2024	An Advance Review of Urban-AI and Ethical Considerations	Urban-AI 2024: Proceedings of the 2nd ACM SIGSPATIAL International Workshop on Advances in Urban-AI	[50]

Table A1. Cont.

ID	Year	Title	Source	Ref.
S36	2025	A Comprehensive Review on Urban Resilience via Fault-Tolerant IoT and Sensor Networks	Computers, Materials and Continua	[62]
S37	2024	Smart City Frameworks SWOT Analysis: A Systematic Literature Review	Frontiers in Sustainable Cities	[40]
S38	2025	Digital Twins for Climate-Responsive Urban Development: Integrating Zero-Energy Buildings into Smart City Strategies	Sustainability	[63]
S39	2022	Analysis of Suitable Frameworks for Artificial Intelligence Adoption in the Public Sector	IDIMT 2022: Digitalization of Society, Business and Management in a Pandemic	[41]
S40	2023	Unraveling the Processes and Challenges of Artificial Intelligence Implementation in the Swiss Public Sector: A TOE Framework Analysis	IDIMT 2023: New Challenges for ICT and Management	[64]
S41	2026	Combining AI with Urban Resilience Planning: A Bibliometric Analysis of Literature	City and Environment Interactions	[11]
S42	2025	AI-Driven Decision-Making Architectures for Future-Ready Smart Urban Infrastructures	Proceedings of the IEEE International Conference on ICT in Business, Industry and Government (ICTBIG 2025)	[8]
S43	2025	Cyber Resilient Smart Cities Through Big Data and Cryptography	AI, Cybersecurity, and Next-Generation Mobility in Smart Cities	[65]
S44	2025	Blockchain and Smart Cities: Co-Word Analysis and BERTopic Modeling	Smart Cities	[23]
S45	2024	The Smart Socially Innovative City Advancing in Italy	Proceedings of the European Conference on Knowledge Management (ECKM 2024)	[66]
S46	2025	SmartCityNext: Leveraging AI and Machine Learning for Responsive and Efficient Urban Services	Proceedings of the 3rd International Conference on Cyber Resilience (ICCR 2025)	[15]
S47	2025	Enhancing Flood Prediction Accuracy: A Hybrid Modeling Framework Integrating CNN, Random Forest, and Bayesian Regression	Proceedings of the 3rd International Conference on Inventive Computing and Informatics (ICICI 2025)	[67]
S48	2025	The Green City: Sustainable and Smart Urban Living Through Artificial Intelligence	Utilizing Technology to Manage Territories	[42]

Table A1. *Cont.*

ID	Year	Title	Source	Ref.
S49	2021	Truth or Dare? How Can We Influence the Adoption of Artificial Intelligence in Municipalities?	Proceedings of the Annual Hawaii International Conference on System Sciences (HICSS)	[68]
S50	2024	Federated Edge Intelligence: Enabling Privacy-Preserving AI for Smart Cities and IoT Systems	MSW Management	[35]
S51	2025	Artificial Intelligence in Urban Planning: A Bibliometric Analysis and Hotspot Prediction	Land	[22]
S52	2024	Modern Smart Cities and Open Research Challenges and Issues of Explainable Artificial Intelligence	Advances in Explainable AI Applications for Smart Cities	[69]
S53	2026	Harnessing AI for Sustainable Smart Cities: Impact, Innovations, and Use Cases	Artificial Intelligence (AI) for IT Energy Efficiency and Green AI for Environment Sustainability	[43]
S54	2026	The Convergence of Artificial Intelligence and the Internet of Things for Next-Generation Smart Systems	Navigating Cybersecurity and Privacy in the Evolution of Smart Urban Ecosystems	[31]
S55	2025	Conceptualization of an Integrated Multi-Agent Framework for Innovative Urban Planning	Procedia Computer Science	[37]
S56	2025	Reinforcement Learning for Traffic Signal Control: Advancing Efficiency Through Hybrid Exploration Strategies	Journal of Supercomputing	[27]
S57	2024	Explainable Artificial Intelligence for Urban Planning: Challenges, Solutions, and Future Trends from a New Perspective	International Journal of Advanced Computer Science and Applications	[45]
S58	2025	Federated Learning-Based Edge Intelligence for IoT	Edge Intelligence and Analytics for Internet of Things	[34]
S59	2024	Federated Learning Shaping the Future of Smart City Infrastructure	Federated Learning for Smart Communication Using IoT Application	[32]
S60	2023	A Thorough Examination of Smart City Applications: Exploring Challenges and Solutions Throughout the Life Cycle with Emphasis on Safeguarding Citizen Privacy	Sustainable Cities and Society	[46]
S61	2024	The Transformation and Challenges of Urban Geography Development in the Era of Artificial Intelligence	Acta Geographica Sinica	[70]
S62	2025	Digital Twin Technology in Smart Cities: A Step Toward Intelligent Urban Management	Energy Reports	[71]

Table A1. *Cont.*

ID	Year	Title	Source	Ref.
S63	2025	Smart Cities and Artificial Intelligence: Convergent Systems for Planning, Design, and Operations (2nd Edition)	Elsevier	[52]
S64	2023	Inclusion, Exclusion, and Participation in Digital Polis: Double-Edged Development of Poor Urban Communities in Alternative Smart City-Making	Springer Nature	[72]

Appendix B. Structured Qualitative Appraisal of Included Studies

To improve the methodological transparency of this systematic review, a structured qualitative appraisal was conducted using predefined operational criteria specifically designed for heterogeneous engineering and computer science studies. Due to the diversity of the included studies—ranging from conceptual frameworks to simulation-based models, prototypes, and real-world implementations—a standardized methodological appraisal tool (e.g., CASP or MMAT) was not considered appropriate.

Instead, the following operational criteria were applied during the screening and comparative analysis to ensure that the selected studies provided sufficient methodological information and were relevant to the objectives of this review. These criteria were intended to support study selection and evidence synthesis rather than to calculate an overall methodological quality score Table A2.

Table A2. Operational criteria used for the structured qualitative appraisal of the included studies.

Criterion	Operational Definition	Assessment
Framework description	The study provides a clear and sufficiently detailed description of the proposed framework or architecture.	Yes/No
Methodological transparency	The research methodology, implementation process, and analytical procedures are described with sufficient detail to enable understanding of the proposed approach.	Yes/No
Validation strategy	The proposed framework includes evidence of validation through a conceptual proposal, simulation, prototype, or real-world implementation.	Conceptual/Simulation/Prototype/Real-world
Thematic relevance	The study directly addresses adaptive smart urban systems and integrates artificial intelligence techniques aligned with the objectives of this review.	Yes/No
Scientific contribution	The study presents a clear methodological, architectural, or application-oriented contribution to the field of adaptive smart urban systems.	Yes/No

The operational criteria described above were systematically applied during the full-text assessment of all candidate studies. Rather than producing a numerical quality score, they were used to ensure methodological consistency, transparency, and sufficient reporting before inclusion in the final evidence synthesis. Consequently, only studies satisfying all predefined appraisal criteria were retained in the final dataset.

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