The Future of Civil Engineering in Smart Cities: A Bibliometric Analysis

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Abstract
The emergence of smart cities, powered by technologies such as artificial intelligence, big data, and the Internet of Things, is transforming civil engineering practices. This study conducts a bibliometric analysis of 1,852 publications (1999–2024) from the Web of Science to examine the evolving relationship between smart city development and civil engineering. The analysis identifies three developmental phases—conceptual emergence, institutional expansion, and digital convergence and reveals how civil engineering research aligns with global policy shifts, particularly in China and the European Union. Key findings highlight the growing emphasis on system integration, AI-driven infrastructure management, green construction, and equitable urban services. The results suggest that policy frameworks significantly influence civil engineering innovation and technology adoption. To support sustainable and intelligent urban development, future research should prioritize the development of interoperable platforms, improved data governance mechanisms, and infrastructure planning strategies that incorporate environmental and social equity considerations.
Keywords: Smart Cities, Civil Engineering, Digital Twin, Internet of Things (IoT), Sustainability

Introduction
The fourth industrial revolution, which is characterized by developments in artificial intelligence, big data, and the Internet of Things, has led to a significant paradigm shift in various sectors (Lee et al., 2018). In this era, intelligence has emerged as a central theme, prompting advancements in fields such as smart homes, smart transportation, smart construction, and smart cities(Appio et al., 2019). These developments have garnered significant attention from researchers and developers worldwide. Notably, smart cities have emerged as a pivotal development strategy for numerous nations, exemplified by China's release of the smart city development implementation plan as a foundational strategy for national advancement.

Civil engineering, as a crucial component of the primary industry, is grappling with substantial industrial transformation challenges in alignment with contemporary trends. Statistical analysis reveals architecture, engineering and construction (AEC) as one of the least efficient industries(Liu et al., 2019). The pursuit of enhanced productivity has concomitantly engendered challenges in maintaining employment levels in the civil engineering sector, and the conventional civil engineering industry, predicated on repetitive tasks, has proven inadequate in addressing the demands of contemporary construction projects. The inherent and extrinsic challenges confronting civil engineering in the current era have assumed an urgent nature.

From a civil engineering perspective, the urban landscape constitutes a large engineering system that includes various engineering infrastructures. Smart cities refer to technologically advanced urban centers that seamlessly integrate modern technology, aiming to establish a comprehensive interconnection between people and technology. However, the traditional civil engineering paradigm can no longer meet the needs of smart city construction. For example, a large number of sensors are needed in smart cities to collect data and make analytical decisions.

Despite the increasing intersection between smart cities and civil engineering, there remains a lack of systematic understanding of how smart city development is transforming the civil engineering field. Most existing studies are fragmented, often focusing on specific technologies or case studies without providing a comprehensive, long-term perspective. To address this gap, the present study conducts a bibliometric analysis of 1,852 publications from the Web of Science (1999–2024) to examine research trends, thematic evolution, and policy influences at the nexus of smart cities and civil engineering. This method is well-suited to uncover broad patterns and shifts across disciplines, offering a data-driven approach to track the field's transformation over time. The study aims to identify key research phases, reveal the impact of global policy agendas, and provide insights that can guide future infrastructure planning, technological innovation, and sustainable development within the context of digital urbanization.

Literature Review
Smart Cities and Their Impact on Civil Engineering
The concept of smart cities has evolved significantly since the 1990s, originating from early projects like the California Smart Communities initiative and U-City strategies in Korea and Japan (Anttiroiko, 2013). Over time, the smart city paradigm has expanded into a holistic model integrating digital technologies to improve sustainability, mobility, governance, and urban resilience (Appio et al., 2019). Cities such as Songdo, Singapore, and Barcelona have implemented large-scale smart systems to optimize resource use, public service delivery, and infrastructure performance (Yang, 2020; Sipahi & Saayi, 2024).

Civil engineering plays a central role in enabling these developments. Smart infrastructure—such as sensor-enabled roads, intelligent buildings, and adaptive drainage systems—requires civil engineers to rethink conventional workflows and adopt digital tools (Kim et al., 2017). In particular, the integration of monitoring systems, automation platforms, and decision-support tools has extended the scope of civil engineering beyond physical construction toward system-level optimization and lifecycle management. However, despite

this progress, many cities continue to implement smart initiatives in silos, often lacking technical interoperability and cross-sector coordination (Kasznar et al., 2021).

Comparative Analysis of Key Technologies in Smart Civil Infrastructure
Several core technologies—namely the Internet of Things (IoT), Building Information Modeling (BIM), and Artificial Intelligence (AI)—are driving the transformation of civil engineering in smart city contexts.

IoT and Real-Time Monitoring
IoT provides real-time data acquisition for infrastructure performance and environmental monitoring, which enables predictive maintenance and emergency response (Yaqoob et al., 2017). Applications include smart grids, structural health monitoring, and intelligent transportation systems. However, challenges such as fragmented data standards, security risks, and high deployment costs remain unresolved (Gauthier et al., 2018).

BIM as a System Integration Platform
BIM has evolved from a 3D modeling tool to an integrative platform supporting the entire infrastructure lifecycle. Modern BIM systems allow for interoperability with GIS, IoT, and energy simulation tools, offering significant benefits in planning, construction, and maintenance (Jang et al., 2021). Nonetheless, technical limitations persist, particularly in semantic interoperability and real-time synchronization between design and operational data.

Artificial Intelligence and Predictive Optimization
AI techniques such as deep learning, reinforcement learning, and data classification have been applied to optimize energy consumption, traffic flow, and infrastructure health prediction (Kulkarni et al., 2025). These technologies enable a shift from reactive to predictive civil infrastructure management. However, issues such as algorithmic transparency, explainability, and domain-specific validation continue to hinder wide-scale engineering adoption.

Technology Convergence and Gaps
Although each technology brings unique value, their combined application in civil engineering remains limited due to disconnected development pathways, inconsistent policy support, and lack of integrated standards (Tuli et al., 2024). This suggests the need for unified frameworks that merge digital functionality with physical infrastructure systems to ensure scalability, governance, and long-term impact.

Policy Frameworks: Enablers and Constraints
National and regional policy frameworks have been instrumental in shaping smart city agendas. A chronological review reveals three phases:

Conceptual Emergence (1999–2013): Early policies such as Korea's U-City and the EU's i2010 strategy emphasized ICT infrastructure and digital service delivery (Anttiroiko, 2013). These policies laid the groundwork but had limited interaction with civil engineering practices.

Institutional Expansion (2014–2019): This period marked the operationalization of smart cities, with policies emphasizing cross-sector data sharing and infrastructure digitization. China's "New-Type Smart City Development White Paper" and Singapore's Smart

Nation vision reflected a strategic push toward urban digital governance (Wu et al., 2018; Sipahi & Saayi, 2024).

Digital Convergence and Resilience (2020–2024): Catalyzed by the COVID-19 pandemic, governments began integrating smart infrastructure into emergency response, health services, and mobility systems (Al-Humairi & Kamal, 2021). The deployment of digital twins and metaverse platforms further extended the role of civil engineering into virtualized planning and simulation (Qadir & Fatah, 2023). However, these developments also exposed vulnerabilities in data governance, privacy, and cybersecurity, raising new regulatory and ethical challenges (Tuli et al., 2024).

While these policy shifts have accelerated innovation, they often remain technologically deterministic and fail to address deeper integration with engineering codes, standards, and professional practice.

Summary and Research Gap

This review shows that smart cities are reshaping civil engineering through the convergence of digital infrastructure, emerging technologies, and national policy agendas. However, existing studies tend to focus on isolated cases or technologies, lacking a holistic and longitudinal analysis of how these trends have evolved in parallel.

To address this knowledge gap, the present study applies bibliometric analysis to systematically map the thematic evolution, research hotspots, and policy influences at the intersection of smart cities and civil engineering. By doing so, it aims to provide a comprehensive overview of technological trajectories and strategic priorities shaping the future of civil engineering in digitally enabled urban environments.

Materials and Methods

Data Collection

The present survey was conducted in accordance with the PRISMA framework, which illustrates the results of the literature search and article selection process (Liberati et al., 2009), as demonstrated in Figure 1. The PRISMA checklist delineates the protocol that was utilised to select the collection of articles for the systematic literature review. Its utilisation is intended to ensure that the selection process is replicable and transparent. The present study searched for articles from the Web of Science core database from 1999 to 2024. The WoS core collection comprises over 21,100 peer-reviewed journals, conference proceedings, and books, encompassing 250 subject areas including natural sciences, social sciences, and arts and humanities. The WOS core collection is widely regarded as the most comprehensive interconnected data collection platform for scientific publications (Li et al., 2018). The database employs rigorous journal selection criteria (e.g. impact factor, editorial quality) to ensure the inclusion of only high-impact journals, thereby preventing low-quality literature from compromising the analysis outcomes.

In order to identify all publications related to this field, the following query was defined: TS=(("smart city" OR "smart cities" OR "intelligent city" OR "digital city" OR "urban intelligence")) AND TS=(("civil engineering" OR "construction engineering" OR "infrastructure" OR "structural engineering" OR "geotechnical engineering")). TS is an

acronym for topic, denoting the searching of words mentioned in the title, abstract, and keyword list. The query was developed following exploratory trials. Initially, the search was limited to "smart city", which yielded a limited number of articles. To enhance the scope, "smart cities", "intelligent city", and "digital city" were incorporated into the search, along with "civil engineering", "construction engineering", and "infrastructure". Inclusion Criteria: (1) Time frame: 1999–2024, to capture the emergence and evolution of smart city–civil engineering research. (2) Language: English only, to ensure consistency in bibliometric analysis. (3) Document types: Research articles and review articles; conference papers, editorials, and non-peer-reviewed content were excluded. (4) Search fields: "Topic" field (TS) covering title, abstract, and keywords.

The search yielded 1922 documents, which were then filtered based on exclusion criteria, with a cutoff date of 2024. The final inclusion criterion was limited to articles and literature review articles, resulting in the exclusion of two non-English articles, leaving 1852 documents for further analysis. The data were exported in BibTex format, filtered, and then inspected.
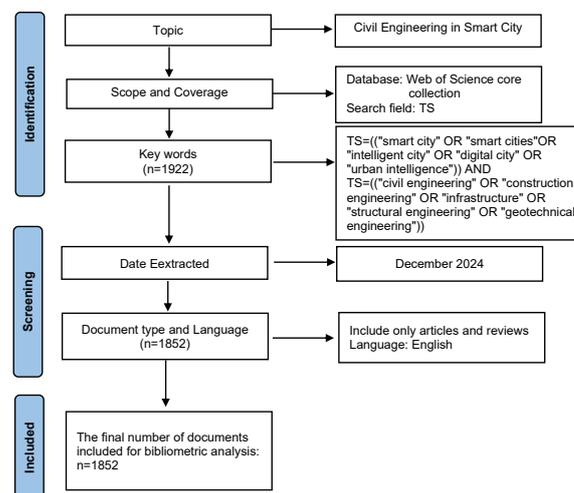

Figure 1. PRISMA Framework

Data Analysis
Bibliometric analysis was conducted using the Bibliometrix R package (version X.X), which enables the automation of statistical and network-based bibliometric workflows (Aria & Cuccurullo, 2017).

To ensure semantic consistency: All author keywords and Keywords Plus were converted to lowercase.Synonyms (e.g., "IoT" and "internet of things") were manually merged.Plural/singular and spelling variants were normalized.

A co-occurrence matrix was generated, where nodes represent keywords and edges represent their co-occurrence frequency across documents. A frequency threshold of ≥5 occurrences was applied to filter low-frequency terms, which reduces noise and enhances cluster interpretability (Callon et al., 1983).

The co-word network was subjected to Louvain modularity-based community detection, a widely used algorithm for identifying thematic clusters in large networks (Blondel et al., 2008). Louvain clustering maximizes the modularity score (Q), which quantifies the strength of division of the network into modules. It is computationally efficient and well-suited for large-scale, sparse bibliometric graphs.

The clusters were then visualized using thematic maps, where:
X-axis = centrality (degree of connection to other topics)
Y-axis = density (internal cohesion of cluster)

Thematic quadrants are interpreted as:

Motor themes (high centrality + high density)
Basic themes (high centrality + low density)
Niche themes (low centrality + high density)
Emerging/declining themes (low centrality + low density)

This dual-metric representation facilitates both structural and evolutionary insight into the intellectual organization of the field.

Results
The present study's data set encompasses literature from 1999 to 2024, encompassing a total of 1,852 documents from 432 diverse sources, including journals and books, thus illustrating the continuous development of the intersection of smart cities and civil engineering on a global scale. As illustrated in Figure 2, the average annual growth rate reached 25.68%, reflecting the sustained increase in research enthusiasm in this field. The annual publication trend is closely related to key policies and technological breakthroughs (e.g., the popularization of 5G, the Internet of Things, and digital twin technology), providing substantial data support for the future transformation of intelligent civil engineering. The comprehensive analysis in this study extracted a total of 2080 Keywords Plus and 6104 author keywords, thereby reflecting the extensive range and diversity of research topics in this field. These topics encompass multiple dimensions, including digital twins (an advanced digital technology that uses virtual models to map the state of physical entities in real time to achieve monitoring, prediction, and optimization management), smart materials, resilient cities (referring to urban systems that improve disaster resistance and recovery capabilities through smart technologies), and green construction, among others. The extant literature is predominantly composed of articles, numbering 1,682, with 170 reviews, indicative of a substantial corpus of original research in the field, complemented by a significant body of summary and comprehensive work.

Figure 2. Main Information

Annual Scientific Production and Trends
According to the data retrieved from the Web of Science core database (1999–2024), the annual scientific production is shown in Figure 3. The number of publications in this field shows a clear three-stage development trend:
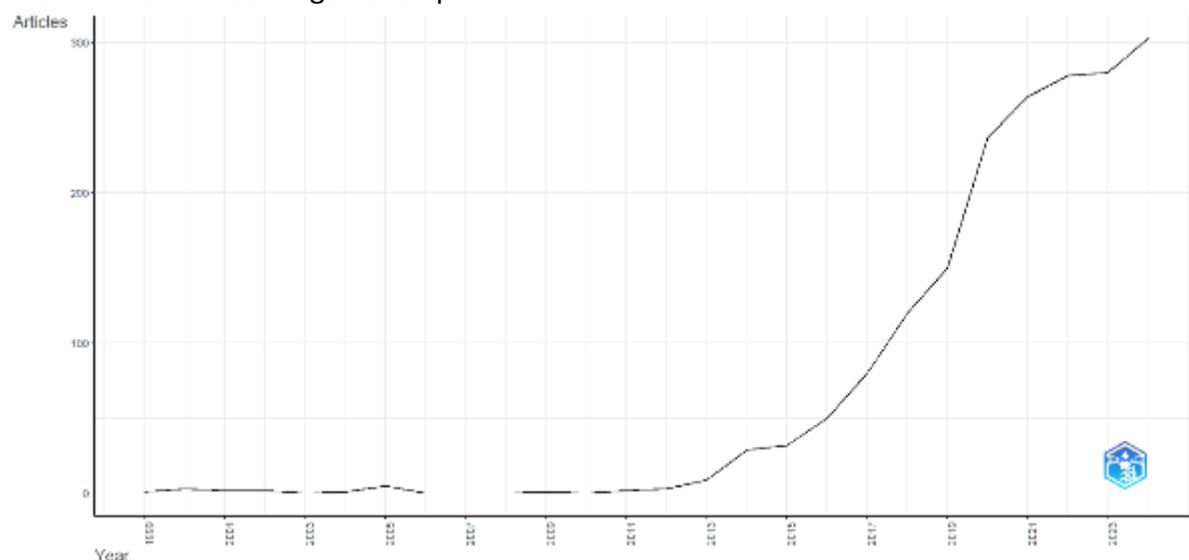

Figure 3. Annual Scientific Production

(1) Slow start-up phase (1999–2013)
From 1999 to 2013, the total volume of literature produced was minimal, with an annual publication rate of less than 10 articles (e.g., only one article in 1999 and nine articles in 2013). This phase indicates that while the intersection of smart cities and civil engineering was in its nascent stages, the research perspectives remained dispersed, and the technologies and theories were underdeveloped.

(2) Explosive growth phase (2014–2019)
Beginning in 2014, the number of articles increased rapidly, reaching 29 in 2014, slightly increasing to 32 in 2015, and then gradually increasing to 150 in 2019. This turning point is closely related to the promotion of the concept of smart cities worldwide, related policies (such as the implementation of China's smart city strategy)(Wu et al., 2018), and the rise of new generation information technologies (such as the Internet of Things, 5G, and digital twin technology). Concurrently, the academic community has begun to direct greater attention

toward the utilization of advanced technologies to transform civil engineering and achieve intelligent and sustainable urban infrastructure development.

(3) Continuous expansion stage (2020–2024)
Since 2020, there has been an exponential increase in the number of literature publications, reaching 237 in 2020 and steadily climbing to 303 in 2024. This surge in publications signifies the pressing need for intelligent monitoring systems, emergency response mechanisms, and eco-friendly urban infrastructure development in the aftermath of the global COVID-19 pandemic(Al-Humairi & Kamal, 2021). It also mirrors the increasing commitment of nations to augment their investment in promoting intelligent transformation. To better understand this development trend, we add key events and background, see Table 1.

Table 1
Key Events and Background

Year	Number of Publications	Key Events and Background
1999	1	The concept of smart cities emerged, with only sporadic exploratory studies (e.g., initial discussions on digital city management).
2004	1	South Korea and Japan launched the U-Korea and U-Japan national strategic plans, initiating national-level smart city layouts.
2005	5	The EU launched the "i2010" strategy, promoting pan-European digital city development.
2009	1	IBM proposed the "Smarter Planet" concept, sparking initial academic interest in urban intelligence.
2013	9	Breakthroughs in IoT technology and smart city pilot projects (e.g., Barcelona) drove interdisciplinary research.
2014	29	The U.S. deployed the "Array of Things" project, using urban sensors to monitor air quality and traffic flow in real-time.
2016	50	China released the "New-Type Smart City Development White Paper," leading to a surge in global smart city investments.
2017	80	Singapore introduced five strategic national smart city initiatives, emphasizing infrastructure integration to drive digital nation development.
2020	237	The COVID-19 pandemic accelerated digitalization, making smart infrastructure (e.g., contactless transportation, remote monitoring) a research hotspot.
2024	303	Metaverse and digital twin technologies matured, transforming civil engineering into a "hyper-intelligent infrastructure" era, integrating virtual and physical spaces.

It is evident that the substantial growth observed after 2014 is closely aligned with the implementation of smart city policies in China and the European Union. Following 2019, the advent of 5G and AI technologies has catalyzed the refinement of research methodologies. Following 2020, the growth rate of publications decelerated (annual average growth <10%), yet research topics exhibited a shift toward sustainability (e.g., carbon-neutral buildings) and social equity (e.g., smart service coverage of low-income communities). In particular, the Metaverse platform (An immersive digital space that integrates technologies such as virtual reality (VR) and augmented reality (AR), where users can socialize, work, entertain themselves

and achieve a deep integration of digital life and real life.) is proposed to cover a large amount of urban infrastructure, personnel and operational data (Qadir & Fatah, 2023). Insufficient security protection may result in the illegal acquisition or misuse of sensitive data. Addressing these concerns necessitates the development of effective methodologies for integrating advanced technologies, such as the Metaverse and quantum computing, into the existing civil engineering framework(Tuli et al., 2024). This integration must be done in a manner that ensures privacy protection in smart infrastructure, particularly with regard to the boundary between urban monitoring systems and personal data. The solution to these challenges is pivotal in determining the future of civil engineering and smart infrastructure.

Theme Evolution: Intelligent Technology Path for Civil Engineering
A comprehensive analysis of "topic evolution" was conducted to elucidate the developmental trajectory from conceptual exploration to deep integration in the intersection of smart cities and civil engineering. This analysis was informed by retrieval data and field evolution trends, in conjunction with the results of annual publication trend analysis. The initial exploration period (1999-2013) was characterized by a paucity of literature, with research concentrating on concept introduction, basic network technology, and preliminary intelligent applications of civil engineering. The subsequent rapid growth period (2014-2019) witnessed a marked increase in literature, driven by the promotion of relevant policies and emerging technologies (such as the Internet of Things and wireless sensor networks) starting from 2014. This period also saw a diversification of themes. The period between 2020 and 2024, known as the "maturity and deepening period," has seen a significant increase in the publication of literature. Since 2020, the research content has expanded beyond technical foundations to include in-depth explorations of system management, security protection, blockchain, and the specific applications of artificial intelligence in civil engineering. Given the paucity of literature in the initial exploration period (1999–2013), this paper focuses on the thematic evolution analysis of the rapid growth period (2014–2019) and the maturity and deepening period (2020–2024).

Rapid Growth Period (2014–2019)
The thematic map is a tool that divides keywords into four quadrants according to betweenness centrality and closeness centrality (see Figure 8).

Motor Themes: These keywords have both high centrality and high density. They are frequently cited in the field and are of high importance. They also have a perfect internal structure.

Basic Themes: high centrality, low density, usually the basic theories and methods of the field, although they have strong connections with other themes, their own development is relatively scattered.

Niche themes: low centrality, high density, focus on a certain niche field, in-depth internal research but weak connection with the overall field.

Emerging or Declining Themes: low centrality, low density, may be new trends that have just emerged or directions that are gradually being eliminated.

Motor Themes

The initial keyword analysis of the research paper on the Internet of Things (IoT) and Big Data in smart cities reveals the predominant themes of "motor," "Internet," "management," "cities," "framework," "challenges," "IoT," "architecture," "security," and "big data." This cluster underscores the pivotal role of the Internet of Things (IoT) and Big Data in smart cities, particularly in the domains of urban management, architecture, and data security. The high prevalence of the term "challenges" signifies that the development of smart cities is still encumbered by numerous challenges, including data governance, system interconnection, and security risks. The term "framework" is indicative of the researchers' current focus on the development of an efficient smart city technology framework for integrating data and optimizing resource allocation. From 2014 to 2019, the Internet of Things (IoT) and Big Data emerged as significant technical foundations for the intelligentization of civil engineering in smart cities. Research in this area has centered on the utilization of these technologies in infrastructure management, smart transportation, and urban governance.

Emerging or Declining Themes

The predominant keywords and clusters pertain to "middleware," encompassing "middleware," "semantic web," "ontology," and "vision." This theme centers on the integration of semantic technology to enhance the data integration capabilities of smart cities, with a focus on the "semantic web" and "ontology." The concept of "middleware" underscores the necessity to establish data interaction and communication between disparate smart city technology systems. While it may be considered an emerging technology between 2014 and 2019, it is plausible that it will be superseded or transformed due to the gradual predominance of big data and AI. The roles of semantic web and ontology in smart city intelligent technology are currently bridging, but it is conceivable that they will be supplanted by more advanced AI and large-scale data mining technology in the future.

Basic Themes

The main keywords and clusters are Systems, including systems, infrastructure, city, impact, technology, and policy. This theme emphasizes the construction of smart infrastructure and the impact of intelligent technology on urban systems. The inclusion of "policy" as a core word indicates its crucial role in the development of smart cities, especially in terms of smart infrastructure investment, legislation, and technical specifications. At this stage, urban smart infrastructure has become the basic support for the development of smart cities. The imminent advancements in digital twins and AI technology promise to further expand the scope of this research direction.

Niche Themes

The primary keywords and clusters in this domain include Air Pollution, encompassing air pollution, electric vehicles, CO_2 emissions, and fuel consumption. This cluster underscores environmental concerns such as air pollution, electric vehicles, and carbon emissions, signifying an emerging focus among civil engineering researchers on the integration of smart transportation and low-carbon infrastructure. The co-occurrence of "electric vehicles" and "CO2 emissions" signifies that research in this domain is shifting beyond mere urban environmental concerns, beginning to explore the impact of low-carbon transportation technology on sustainable development. The pursuit of environmental sustainability has emerged as a pivotal consideration for the intelligent advancement of civil engineering,

paving the way for future research that may further integrate AI optimization, green construction, and smart transportation.
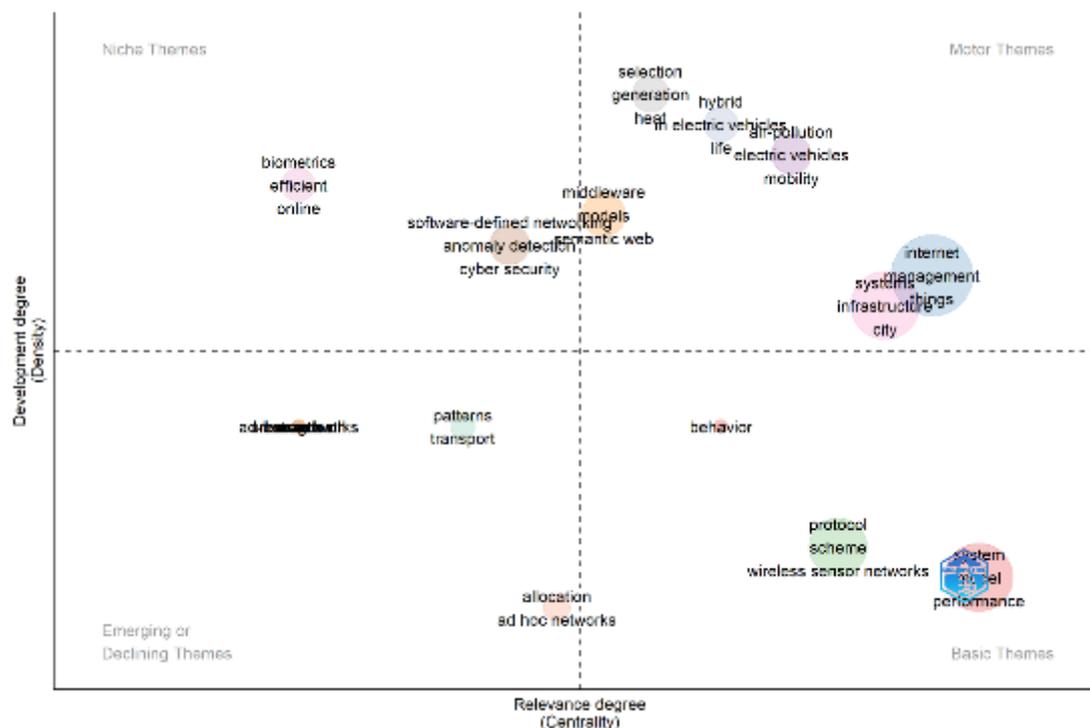

Figure 4. Thematic Map （2014–2019）

Maturity and deepening period (2020–2024)

Motor Themes

The representative cluster, entitled "Management," encompasses a range of subjects pertinent to urban administration, including management challenges, urban planning, systems, models, infrastructure, intelligent management tools (e.g., big data, optimization, frameworks, design), and artificial intelligence and decision support (e.g., artificial intelligence, smart cities, prediction, classification).

This subject constitutes the fundamental management theme in the context of smart cities, with research endeavours encompassing urban governance, system optimization, infrastructure intelligence, and big data-driven decision support. Intelligent management and architecture optimization stand as pivotal research directions in this era.

Future trends: The deep integration of technologies such as intelligent traffic management, energy optimization, intelligent building management, and digital twin systems will continue to promote the development of this topic.

Basic Themes

The representative cluster is "internet," which encompasses core technologies such as the Internet of Things (IoT), Internet, wireless sensor networks, blockchain, and protocols. Within the "internet" cluster are sub-clusters including data security and privacy, which encompasses security, privacy, attacks, and authentication; and smart infrastructure, which includes cloud, edge computing, and unmanned aerial vehicles (UAVs).This theme provides the underlying technical support for smart cities, involving the Internet of Things, data security, cloud

computing, and blockchain technology, and constitutes the technical cornerstone of the entire field.

The term "Internet" is more frequently mentioned, indicating the significance of network infrastructure in the smart city architecture. Future trends: The integration of technologies such as 5G, blockchain + Internet of Things, cloud-edge collaborative computing, and AIoT (artificial intelligence + Internet of Things) will further promote the development of smart cities.

Niche Themes

The representative cluster is "performance", including intelligent computing: reinforcement learning, deep learning; environmental disaster management: air pollution, sustainable cities, energy consumption. Policy and social impact: governance, policy, equity. The application of artificial intelligence in urban management has deepened, mainly reflected in automated scheduling, intelligent energy consumption optimization, environmental monitoring and other aspects. Research on sustainable development has increased, especially on topics such as carbon neutral city construction and green energy. Policy and governance have become the focus, emphasizing how smart city construction can achieve fair and inclusive development.

Emerging or Declining Themes

Keywords such as "neural networks" and "damage detection" are representative of the subject matter. Emerging technologies encompass augmented reality, big data analytics, and unmanned aerial vehicles. Sustainable development includes green infrastructure, renewable energy, and low-carbon cities. The application of artificial intelligence (AI) in structural health monitoring has garnered significant attention. This subject is exploratory in nature, and it should be noted that certain technologies are not yet fully mature and are still in the experimental stage. However, they possess considerable potential value. Research related to "augmented reality" has begun to emerge, and when combined with BIM and digital twins, it may promote the development of intelligent construction and virtual monitoring. The ongoing strengthening of sustainable development policies may further catalyse research related to green cities and low-carbon infrastructure. However, certain single technologies (e.g., the application of augmented reality in buildings) may encounter challenges due to their limited application scenarios.
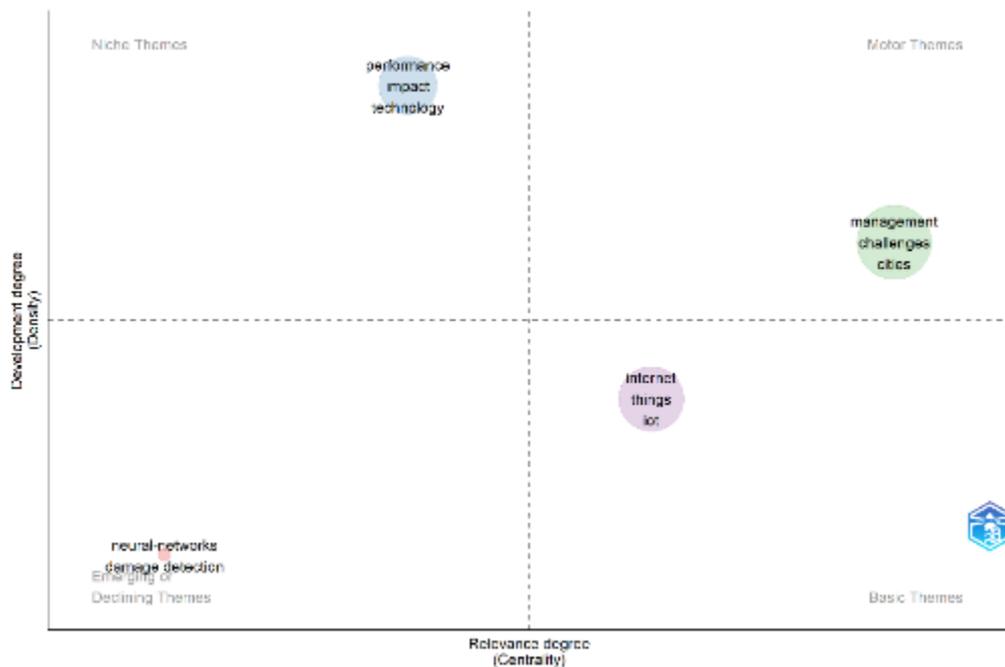
Figure 5. Thematic Map (2020–2024)

Summary of Theme Evolution Evolution

By analyzing the topic evolution diagrams of the two stages of 2014-2019 and 2020-2024, we can summarize the following main trends and evolution characteristics:

The Shift from Technical Foundation to System Integration

During the rapid growth period (2014-2019), researchers mainly focused on using the Internet, the Internet of Things, and related communication technologies to lay the foundation for smart city construction. The core themes of this stage are mainly concentrated on keywords such as "system", "model", and "performance", reflecting the exploration and initial application of basic technologies (such as networks, sensors, protocols, etc.). With the surge in the number of literatures, these technical topics have gradually formed driving topics, providing solid theoretical and practical support for the entire field.

Management and Performance Optimization become the Core Driver

After entering the maturity and deepening period (2020-2024), the research focus has gradually expanded from single technology applications to overall system management and performance optimization. Keywords such as "performance", "impact", "technology", "smart city", "innovation" and "management" have increased significantly in frequency during this stage, indicating that research not only focuses on the technology itself, but also explores how to optimize the operation of urban systems and civil engineering infrastructure through scientific management, policy support and intelligent decision-making. The complexity of smart city construction requires interdisciplinary integration and collaboration, and this trend is fully reflected in the management and performance optimization topics.

The rise of Intelligent Detection and Artificial Intelligence Applications

In the mature stage, topics such as neural networks and damage detection began to gradually emerge, reflecting the deepening application of artificial intelligence technology in the field of structural health monitoring and automatic detection. Although these topics are

specialized or marginal in the entire knowledge network, they are of great significance in actual engineering operation and maintenance and provide advanced technical means for realizing the full life cycle management of infrastructure.

Sustainable Development and Green Intelligence become the Future Development Direction
Another significant trend is the gradual rise of environmental and sustainability issues. Keywords such as "climate-change", "sustainability", "sustainable cities", "renewable energy" and "air-pollution" all have a high frequency of occurrence in the mature stage, indicating that the global attention to green construction, low-carbon cities and the use of renewable energy is increasing. This trend reflects that while pursuing efficient management, smart city construction is paying more and more attention to ecological environment protection and sustainable development.

Conclusions
This study conducted a comprehensive bibliometric analysis of 1,852 publications spanning 1999 to 2024 to investigate how smart city development is influencing civil engineering. The results reveal a clear thematic evolution from foundational technologies such as IoT and BIM to more complex system integration involving AI, digital twins, and sustainability considerations. While progress has been made, significant challenges remain, including fragmented digital platforms, inadequate standardization, and limited attention to social equity in infrastructure development.

For Civil Engineers:
Upskill in digital competencies: Engineers should enhance their proficiency in BIM, AI-driven analytics, and digital twin tools to remain relevant in smart infrastructure planning and maintenance.
Adopt lifecycle thinking: Emphasize performance monitoring, predictive maintenance, and long-term sustainability over traditional short-term construction goals.
Foster interdisciplinary collaboration: Work more closely with data scientists, urban planners, and IT professionals to bridge technical and urban system gaps.

For Policymakers:
Develop standardized data governance frameworks: Establish clear protocols for open data, cybersecurity, and interoperability to enable scalable digital infrastructure.
Support inclusive infrastructure planning: Ensure smart technologies address the needs of marginalized or underserved communities.
Incentivize green infrastructure: Introduce funding and regulatory mechanisms that prioritize climate-resilient, low-carbon civil engineering projects.

For researchers, future efforts should focus on adapting smart city concepts to the needs of emerging economies, where infrastructure development often faces resource and governance constraints. Advancing explainable AI in engineering applications is also critical to ensuring transparency and trust in automated decision-making. Moreover, the ethical dimensions of integrating digital technologies—such as digital twins and data-driven governance—into public infrastructure warrant deeper investigation. These priorities highlight the need for interdisciplinary research that combines technical innovation with social responsibility and contextual relevance.

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