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Advancing Data-Driven Decision-Making in Smart Cities through Big Data Analytics: A Comprehensive Review of Existing Literature

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Governments and cities are increasingly launching smart city (SC) schemes to address the challenges posed by rapid urbanization and population growth in municipalities. Smart cities utilize data from various sources within a metropolis to enhance urban development, promote qualitative lifestyles, and focus on economic and environmental sustainability. Big data analytics (BDA) plays a crucial role in collecting and analyzing vast amounts of data from SC infrastructures, enabling

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effective management and implementation of smart city initiatives. BDA helps explore data collected through Internet of Things (IoT) devices and sensors, identifying trends, and making appropriate changes, ultimately making smart cities more efficient, sustainable, and beneficial for their inhabitants. However, big data in SC also presents potential risks and challenges related to urban security and the well-being of residents.

The literature review examines various research approaches, techniques, algorithms, and architectures proposed to address the challenges of handling big data in smart cities. Urbanization's growing trend is causing challenges in managing basic amenities and resources in urban areas, necessitating innovative solutions to ensure efficient functioning and improved quality of life for citizens. Previous research has highlighted the significance of big data analytics in driving smart city decision-making, yet many smart city big data initiatives have faced difficulties in implementation. To overcome these challenges, researchers have explored techniques like artificial intelligence, machine learning, data mining, and deep learning, as well as architectures encompassing layers of instrumentation, middleware, and application for end-users. Additionally, researchers have emphasized the importance of selecting appropriate sensors for efficient data collection and explored low-cost smart traffic systems to improve urban traffic management. Overall, this review synthesizes insights from nine scholarly papers, shedding light on approaches to handling big data challenges in smart cities.

Keywords: Smart city; big data analytics; urbanization; data mining; machine learning; IoT; sensor networks; urban planning; sustainability; smart traffic systems.

1. INTRODUCTION

According to Shahat Osman and Elragal [1], governments and cities launch smart city (SC) schemes to manage the challenges of urbanization growth that are fast evolving and population viscosity in municipalities. Hence, the notion of an SC is a contemporary technique for urban development that involves gathering, dissecting, analyzing, and exchanging data across various environments within a metropolis or city [1]. Consequently, SC initiatives promote qualitative lifestyles in cities focusing on economic and environmental sustainability [1]. The effectual collection and analysis of big data from SC infrastructures are vital to gain invaluable insights into an effective management system and execution of SC endeavors [2]. Big data analytics (BDA) is crucial in exploring data collected through IoT devices and sensors to recognize tendencies and make appropriate changes [3]; it can make SC more effectual, maintainable, and advantageous for people [4]. Although the danger of data breaches persists [5]; the probable risks linked with big data in SC pose constant challenges that require thorough consideration to improve urban security and prioritize the welfare of its inhabitants [6]. This literature review examines the approaches, techniques, algorithms, and architectures proposed in various research to handle big data challenges in smart cities.

2. BACKGROUND OF THE PROBLEM

Urbanization is a growing trend, causing severe demographic shifts, with over 68% of the global population projected to live in cities by 2050; hence, this inrush to the cities is causing traffic, pollution, crime, congestion, resource distribution, fiscal difficulties, housing, traffic, and crime creating a need for more innovative solutions to keep them running efficiently [7]. Also, the surge in population in these urban areas is resulting in complexities in managing basic amenities and resources such as water, electricity, transportation, public education, accommodation, security services, and improved health services to guarantee the city's continuous running and people's welfare [8]. The resolutions to the challenges of SC lie in data gathering through various urban activities to enable the maximization of resource distribution and effective governance [9]; therefore, managing large amounts of unstructured data collected from IoT devices, sensors, public and social networks, and has become necessary because cities are metamorphosis into the data-rich digital ecosystem [7].

2.1 Previous Attempts to Examine the Issue of Smart Cities and Big Data Analytics

Barham and Daim [10] emphasized the extent to which cities worldwide are adopting smart city undertakings to improve the citizens' lives, enhance infrastructure efficiency, and foster practical urban planning. However, the success of these endeavors strongly depends on big data analytics. However, based on past scholarly research, more than 50% of smart cities big data schemes failed or were aborted, adding to the lingering management issue of urbanization [10]. Smart city initiatives are expensive and demanding to manage, and many of these cities work on lean budgets; thus, it is becoming tough to leverage big data to build smart cities [10].

2.2 Techniques for Handling Big Data in Smart Cities

The advancements in sensing, digital, and communication technologies are creating the possibility of successfully managing smart cities to overcome the challenges of demographic shifts and demands [8]. Accordingly, these technological improvements fuel the evolution of big data and the continuous advancement in smart cities using artificial intelligence (AI), machine learning, automated vehicles, and robotics, resulting in a substantial increase in the volume of exploitable big data [9]. Alahakoon et al. [7] identified AI and machine-learning techniques for smart city big data analytics. Also, Estrada et al. [11] found that machine learning and deep learning are two effective techniques used to categorize data and pinpoint data patterns.

2.3 Algorithms for Handling Big Data in Smart Cities

According to Shahat Osman and Elragal [1], there are various types of algorithms for big data analytics, such as data mining, machine learning, AI, and deep learning. The algorithms function differently, unlike the standard data analysis statistical techniques; hence, these algorithms are efficient in managing unstructured and structured data and extracting qualitative and quantitative parameters [1]. Psomakelis et al. [4] also introduced the Map-Reduce algorithm, which functions on Map and Reduces the concept. The Map-Reduce algorithm uses mathematical algorithms to assign and allocate tasks within multiple systems leveraging the capability of a distributed computing ecosystem [4]. Badidi et al. [8] also identified five big data analytics algorithms for smart cities: Ant Colony Optimization, Throttled, Artificial Bee Colony, Particle Swarm Optimization, and Round-Robin.

2.4 Architectures for Handling Big Data in Smart Cities

Kousis and Tjortjis [12] described smart city architecture using three hierarchical layers: instrumentation layer, service-oriented middleware layer, and application layer for end users. The instrumentation layer incorporates a distributed sensor grid in the network that collects real-time data such as temperature, humidity, weather, photos, videos, and sounds [12]. The service-oriented middleware layer employs data mining, cloud computing, and indexing services to manage vast data storage, real-time analysis, and processing to make decisions and support the functioning of smart city applications [12]. The application layer for end users furnishes tailored services for diverse domains and fosters direct interchange to boost user experience in smart cities [12].

3. LITERATURE REVIEW

The literature review analyzes various SC and BDA problems and gaps identified in several scholarly articles with big data handling approaches in SC, including techniques, algorithms, and architectures. The review synthesizes information from 9 peer-reviewed scholarly papers, broadly examining the issue and shedding light on scholarly attempts to address it.

3.1 Limited Focus on the Capabilities of Big Data Analytics in Enhancing Smart City Decision-Making

According to Shahat Osman and Elragal [1], a smart city is a sophisticated network of related systems involving various stakeholders, from planners to citizens, and BDA has become a valuable mechanism to enable databased decision-making in SC [1]. However, the problem shows the existence of concentrated efforts on technical aspects or smartening specific SC domains instead of focusing on existing research on the capabilities of BDA and SC [1]. The research question explores how BDA facilitates data-driven decision-making enablers in SCs, thus furnishing significant layout considerations for BDA frameworks founded on empirical backgrounds [1]. The data analysis integrated two computational approaches: data analytics deep learning neural networks and fuzzy logic, along with BDA algorithms such as machine learning, AI, data mining, and deep learning. The research also employs a three-layer architecture comprising the platform, security, and data processing layers [1]. The methodology has two approaches - The first is a systematic literature review of newly published papers to examine the correlation between BDA structures and SC to pinpoint similar characteristics. The second methodology uses an established framework utilizing industry software packages for analysis, following the action design research (ADR) approach [1]. The qualitative data analysis involved assessing 26 articles to pinpoint domain-independent BDA frameworks within the context of SC in the healthcare environment. It also incorporates using a BDA framework in a healthcare ecosystem to examine patients' feedback and satisfaction [1]. The study's outcome showed the capability of the BDA framework to boost decision-making and improve the quality of healthcare in SC [1].

3.2 Development of Low-Cost Smart Traffic Systems for Future Smart Cities

According to Sharif et al. [2], Smart Traffic System (STS) helps shape the future of SC; however, developing an STS to improve the quality of public traffic management is costly. The problem is the necessity for low-cost STS for future smart cities and an infrastructure yielding qualitative public traffic management service [2]. The approach employs Internet of Things (IoT) technology to rapidly gather public traffic data. This is achieved through the utilization of cost-effective vehicle-detecting sensors strategically placed at 500-meter intervals along roadways [2]. These sensors produce continuous streams of real-time data, which are then utilized for Big Data Analytics (BDA) purposes [2]. The architecture incorporates BDA for handling the streaming data by applying an easy traffic management algorithm for implementation in the traffic system [2]. The author did not state the research questions. However, the methodology ensured the big data gathering using low-cost vehicle-detecting sensors and transmission quickly through IoT technology because of providing solutions via a predictive analytics model [2]. In this quantitative data analysis, the authors utilized BDA to study the real-time streaming traffic data using predictive analytics to analyze traffic density with appropriate resolutions [2]. The study's outcome showed enhanced qualitative traffic control, better traffic management for SC, and travelers' flexibility using advanced sensors and BDA [2].

3.3 Managing Urban Data for Improved City Policies and Urban Issues

Cesario [13] confirmed that urban cities continually forge more considerable and significant volumes of data, whose examination can furnish predictive, descriptive, and prescriptive models as practical support to build data-driven SC systems. Thus, BDA and machine learning algorithms are responsible for advancements in urban issues and policies [13]. The problem is managing the large volumes of data cities' ecosystems generate and improving city policies and urban issues. The techniques are big data analysis and machine learning algorithms, with architecture using three actual case studies to illustrate the application of data analysis procedures to solve SC problems [13]. This research method contains three case studies to furnish innovative resolutions for SC problems. Hence, the quantitative data research first uses a crime forecasting algorithm incorporating spatial examination and auto-regressive models utilizing Chicago crime data. The second explores the discovery of mobility hotspots and trajectory patterns using GPS data from Beijing taxis, and the third offers a strategy to recognize spatiotemporal predictive epidemic patterns using mobility and infection data tested on actual COVID-19 data [13]. The outcome offered evidence proving that BDA models can successfully support SC managers in handling challenges and improving urban networks [13,14,15].

3.4 Challenges of Big Data in Smart City

Amović et al. [6] explored adopting digital technologies like IoT, cloud computing, and open data in SC to overcome impediments associated with the conventional model and sharing of geospatial data. The problem shows the need for more existing answers to the lack of suitable storage and management for large amounts of SC data; however, the existing solutions to address the issue rely on data visualization instead of storage capacities that allow exhaustive data administration [6]. The author did not state the research questions; nonetheless, they suggested an IoT technique for SC, which entails collecting a considerable volume of data through multiple sensors [6]; also, the architecture is an open and interoperable end-to-end IoT architecture based on the OGC SensorThings API and Apache Spark to provide scalability and tolerance for MapReduce algorithms, which are essential in the management of big data database [6]. The methodology used the GAMINESS management system that runs on Apache Spark's big data framework to manage and analyze data challenges in SC [6]. In this quantitative data analysis, the authors implemented the GAMINESS management system using the Apache Spark big data platform; hence, specialized UDTs were developed for managing geospatial data, allowing the integration of geospatial information into the framework using Map Reduce algorithms, which transcend conventional RDBMS from the perspectives of five V parameters [6]. The outcome shows that the developed model can exchange data irrespective of the approach or data structure applied to the Apache Spark data framework schema [6].

3.5 Data Management for Efficient Service Delivery in Smart Cities

In their study, Badidi et al. [8] showed that demographic growth in urban areas is tantamount to basic amenities challenges. However, they explored the possibilities of using advances in sensing, communication, and digital technologies to resolve the issues of these challenges. The problem is managing the challenge of vast amounts of data generated by various city technologies to better the lives of its citizens to get basic amenities [8]. The authors did not provide research questions. Nonetheless, the technique in the article adopted edge and fog computing as emerging paradigms to manage big data storage and analysis in SC [8]. Hence, the architecture illustrates the structure of a fog-based data pipeline with specific algorithms used in the fog-based data pipeline. The method reviewed existing literature on service delivery models in SC, and the qualitative data analysis reconsidered the extant literature on fog computing-based solutions using healthcare, intelligent transportation systems (ITS), and smart grids [8]. The outcome reveals that data processing and analytics must rely on strong and highly scalable messaging applications, solid software machines for data stream processing, and scalable data storage solutions [8].

3.6 Importance of Choosing Appropriate Sensors in Smart Cities Big Data Analytics

Estrada et al. [11] designed a practical and comprehensive technique for SC using sensors and data analysis crafted to interpret phenomena; thus, the appropriate sensor area denotes a pivotal facet for proper data Big Data collection. The problem of choosing appropriate sensor areas for big data gathering in SC is challenging [11]. The author did not state the research questions; however, the suggested technique utilizes data developed by sensors to collect data in real-time within a hot-zone space to enhance the precision and efficacy of big data gathering for sensor placement [11]. The research architecture consisted of four steps to calculate the most appropriate georeferenced places for sensors and visualization using the Guadalajara Metropolitan Zone in Mexico as the case study focusing on air quality monitoring using sensors in ten different sites within twenty years [11]. The algorithm leverages the available information to design a frequency matrix that perfectly aligns with the territorial adjacency matrix.

Additionally, it employs machine learning techniques and training data to evaluate the optimal placement of new sensors in the specified hot zones [11]. The method incorporated data analysis, algorithms, machine learning methods, and real-time sensor relocation based on the planned hot zones to maximize the sensor placement and enhance the comprehensive data-gathering procedure for observing phenomena in SC [11]. The authors analyze data developed by sensors as a vital element of the proposed method to recognize meaningful data tendencies within hot zones [11]. The study's outcome confirms that the efficacy and precision of sensor placement for data gathering in SC are practical and can improve decision-making [11].

3.7 Challenges in Designing, Developing, and Deploying Sensors in Smart City Planning

Enlund et al. [9] accentuated that SC builds its system on gathering data for effective governance. The problem emphasized by the authors is the challenges and intricacies required in designing, developing, and deploying sensors in SC planning [9]. The authors did not state specific research questions; nevertheless, they asked questions on how the sensors can add to the development of SC [9]. The technique engaged innovative participatory strategies to handle the diversity of peoples' needs in municipalities collaborating with designers, engineers, scholars, and geographers [9]. The algorithm is unstated, but the architecture used functioning sensors and their conceptualizations of space for analysis [9]. The approach employs a participatory design method to explore how the diverse requirements of individuals can play a role in developing a pleasant and safe urban environment. This study takes Norrköping, Sweden, as its focal point, aiming to grasp the diverse nature of sustainable city planning and spatial arrangements [9]. The research is a mixed method where the authors analyzed data by blending the qualitative case study of various best practices on SC and quantitative analysis of secondary data on air quality, sound, and mobility in the SC scenario [9]. The outcome accentuates the significance of apprehending how sensor technology impacts the design of SC and how the visibility of sensor technology can make urban cities inhabitable for humankind [9].

3.8 Managing Diverse Unstructured Data in Smart Cities Big Data Analytics

Alahakoon et al. [7] emphasized how the emerging information revolution necessitates the management of vast amounts of unstructured data due to the increasingly populated ecosystem by IoT devices and sensors that are intelligent and able to transmit information to each other. However, the newly created digital environment has produced volumes of volatile and multifarious data; thus, the problem is the need to quickly and resourcefully handle numerous diverse unstructured data in the emerging information revolution using standard AI and machine learning techniques with unsupervised learning [7]. The architecture offered a packet of adaptive self-building AI in dynamic SC spaces and an algorithm with a capacity for self-building AI [7]. The authors did not provide research questions. However, the methodology used self-building AI and unsupervised learning to facilitate data processing in a dynamic SC ecosystem to establish the significance of self-building AI using video surveillance, IoT, and motion identification systems [7]. The quantitative data analysis is from video surveillance, IoT, and motion identification systems; thus, the outcomes showed the successful speed and capability of self-building AI in IoT, video surveillance, and motion identification systems in handling numerous diverse unstructured data in the emerging information revolution using standard AI and machine learning techniques with unsupervised learning [7].

3.9 Identifying Suitable Data Mining Methods for Smart City

Kousis and Tjortjis [12] affirmed that SC unites individuals and places using innovative technologies such as IoT, big data, data mining, machine learning, and big data. Hence, the authors conducted exhaustive bibliometric research to review data mining technologies in the SC environment [12]. The issue is selecting appropriate data mining methods for supply chain (SC) research. Kousis and Tjortjis [12] outlined these research questions: 1) Major data mining techniques in SC context; 2) Determining interdisciplinary SC knowledge base and outlook; 3) Quantitative evolution of data mining in SC, considering publications and citations; 4) Conceptual structure of data technologies for SC; 5) Social network structure of the SC scientific community. The technique is a comprehensive bibliometric analysis to study and summarize relevant articles and best practices. The architecture used innovative technologies like IoT, big data, AI, data mining, machine learning, and big data to study every layer of the SC project, with much machine learning [12]. Also, the authors used many supervised and unsupervised machine learning algorithms and application layers in SC projects. The method employed qualitative and quantitative methods to study the subject, and the bibliometric research was conducted using R developed Biliometrix library [12]. The quantitative secondary data analysis is the comprehensive study of 197 papers published from 2013 to 2021, using bibliometric analysis to study the tendencies and patterns in the field of data mining for SC [12]. The study's outcome showed that data mining for SC is growing fast, gaining more popularity daily, and is efficient in BDA for SC [12].

4. RESEARCH QUESTIONS

The authors trying to answer the problems of BDA in SC crafted the following research questions. Shahat Osman and Elragal's [1] question examined the utilization of BDA as a tool for promoting data-driven decision-making in SC. Also, Kousis and Tjortjis's [12] questions addressed several research questions in their work, including identifying the primary decision-making techniques used in smart cities BDA. However, Amović et al. [6], Estrada et al. [11], Sharif et al. [2], Enlund et al. [9], Alahakoon et al. [7], Badidi et al. [8], and Cesario [13] did not provide research questions in their studies. The available research questions are as follows:

1. Can BDA effectively stand as a data-driven decision-making enabler in SCs? – [1].
2. Kousis and Tjortjis [12] research questions:
   a. Which are the main DM techniques used in the context of smart cities?
   b. Can the knowledge base for the interdisciplinary field of smart cities and their intellectual structure be identified?
   c. Does the field of DM for smart cities quantitatively evolve, specifically concerning the publication and citation counts?
   d. What is the conceptual structure of data technologies for smart cities?
   e. What is the social network structure of data technologies for the smart cities' scientific community?

5. METHODOLOGY

Several methodologies used by authors in the literature reviewed helped achieve favorable outcomes in confirming the significance of BDA in SC. Shahat Osman and Elragal [1] developed methodologies with two approaches using 26 articles to pinpoint domain-independent BDA frameworks within the context of SC. It. The initial is a systematic literature review of newly published papers to examine the correlation between BDA structures and SC to pinpoint similar characteristics, and the second methodology used an established framework utilizing industry software packages for analysis, following the action design research (ADR) approach. Amović et al. [6] methodology used the GAMINESS management system that runs on Apache Spark's big data framework to manage and analyze data challenges in SC. In their methodologies, Estrada et al. [11] incorporated data analysis, algorithms, machine learning methods, and real-time sensor relocation based on the planned hot zones to maximize the sensor placement and enhance the comprehensive data-gathering procedure for observing phenomena in SC.

In addition, the methodology used by Sharif et al. [2] ensured big data gathering using low-cost vehicle-detecting sensors and transmission quickly through IoT technology because of providing solutions via a predictive analytics model. Enlund et al. [9] methodology uses a participatory design technique to examine various people's needs can contribute to building a comfortable and secure urban space using Norrköping, Sweden, as a point of the study to comprehend the heterogeneity of SC planning and spatial formulations. Alahakoon et al. [7].

The methodology used self-building AI and unsupervised learning to facilitate data processing in a dynamic SC ecosystem to establish the significance of self-building AI using video surveillance, IoT, and motion identification systems.

Further, Badidi et al. [8] reviewed existing literature on service delivery models in SC. Kousis and Tjortjis [12] conducted a comprehensive study of 197 papers published from 2013 to 2021; the methodology employed supervised and unsupervised machine learning algorithms and application layers in SC projects. The method employed qualitative and quantitative methods to study the subject, and the bibliometric research was conducted using R developed Biliometrix library and Cesario's [13] research methodology contains three case studies to furnish innovative resolutions for SC problems.

6. DATA ANALYSIS

Shahat Osman and Elragal's [1] data analysis involved assessing 26 articles to pinpoint domain-independent BDA frameworks within the context of SC. It also incorporates using a BDA framework in a healthcare ecosystem to examine patients' feedback and satisfaction. Also, Amović et al. [6] data analysis implemented the GAMINESS management system using the Apache Spark big data platform; hence, specialized UDTs were developed for managing geospatial data, allowing the integration of geospatial information into the framework using MapReduce algorithms, which transcend conventional RDBMS from the perspectives of five V parameters. Estrada et al. [11] analyzed data developed by sensors as a vital element of the proposed method to recognize meaningful data tendencies within hot zones.

Sharif et al. [2] utilized BDA to study the real-time streaming traffic data using predictive analytics to analyze traffic density with appropriate resolutions. Enlund et al. [9] analyzed data by blending the case study of various best practices on SC and quantitative analysis of secondary data on air quality, sound, and mobility in the SC scenario. Alahakoon et al. [7] analyzed data from video surveillance, IoT, and motion identification systems; thus, the outcomes showed the weight and possibility of self-building AI in IoT, video surveillance, and motion identification systems. Badidi et al. [8] data analysis reconsidered the extant literature on fog computing-based solutions using healthcare, intelligent transportation systems (ITS), and smart grids.

Further, Kousis and Tjortjis's [12] used bibliometric analysis to study the tendencies and patterns in the SC data mining field. Finally, Cesario's [13] data analysis first used a crime forecasting algorithm incorporating spatial examination and auto-regressive models utilizing Chicago crime data. The second explores the discovery of mobility hotspots and trajectory patterns using GPS data from Beijing taxis, and the third offers a strategy to recognize spatiotemporal predictive epidemic patterns using mobility and infection data tested on actual COVID-19 data.

7. CONCLUSION

The articles convey a common understanding of the significance of BDA in SC. However, research questions, methodologies, data analysis, problems, application domains, and architectural frameworks vary. Nevertheless, the article concentrates on using big BDA in the context of SC, although each discusses different aspects of BDA in SC. All the authors employ different techniques, architectures, and algorithms to process and analyze big data generated in SC systems, such as traffic, healthcare, IoT, and sensor data. Similarly, the analyses highlight the significance of leveraging advanced technologies like IoT, cloud computing, machine learning, and AI for BDA. In the attempt to solve the problem, some authors explicitly stated research questions, while others focused on problems or research objectives. Methodologies range from systematic literature reviews to case studies, bibliometric analysis, and quantitative and qualitative data analysis.

The authors did not state any clear hypothesis; however, the outcomes and conclusion of their data analysis answered research questions or supported the focus of their research. Shahat Osman and Elragal's [1] study's outcome within the SC's healthcare environment showed the capability of the BDA framework to boost decision-making using data. Amović et al. [6] research outcome shows that the developed BDA model can exchange data irrespective of the approach or data structure applied to the Apache Spark data framework schema, thereby boosting the efficiency of SC initiatives. Estrada et al. [11] study's outcome confirms that the efficacy and precision of sensor placement for data gathering in SC are practical and have the capabilities to improve decision-making. Sharif et al. [2] study's outcome showed enhanced qualitative traffic control, better traffic management for SC, and travelers' flexibility using advanced sensors and BDA.

Further, Alahakoon et al. [7] outcome showed the successful speed and capability of self-building AI in IoT, video surveillance, and motion identification systems in handling numerous diverse unstructured data. Enlund et al. [9] data analysis outcome accentuates the significance of apprehending how sensor technology impacts the design of SC and how the visibility of sensor technology can make urban cities inhabitable for humankind. Kousis & Tjortjis's [12] conclusion reveals that data mining for SC is growing fast and gaining more popularity daily. Finally, Cesario [13] data analysis outcome offered cases proving that BDA models can successfully support SC managers in handling challenges and improving urban networks Badidi et al. [8] outcome reveals that data processing and analytics must rely on strong and highly scalable messaging applications, solid software machines for data stream processing, and scalable data storage solutions.

COMPETING INTERESTS

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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