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Towards long-term urban analytics: The convergence of smart cities, big data and urban policy

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Abstract
Big data analytics has revolutionized the field of urban research and planning by introducing more efficient real-time data mining and pattern recognition methods. These technologies, as part of the new smart urbanism strategy, promote more evidence-based urban management practices and support smart cities in achieving greater efficiency in their decision-making processes. This paper explores the potential value of big data analytics in urban policy making and planning and its limitations. First, the article constructs a framework for analyzing cities based on the theory of complex adaptive systems as a key component in the practice of new smart urbanism. The article goes on to explore the tension between the dynamic nature of high-frequency data and the long-term structural challenges of cities. By citing specific big-city data cases, the article identifies epistemological and practical-level challenges to using high-frequency data for strategic analysis, and makes recommendations on how urban analytics can be used to guide long-term urban policy.

Keywords: Big data, smart city, complex adaptive systems theory, urban policy

Introduction

With the acceleration of global urbanization, cities are facing increasingly complex challenges, including population growth, unequal resource distribution, environmental pollution, and traffic congestion. To effectively address these challenges, cities require more refined and intelligent management. The concept of a smart city emerged, integrating information and communication technology (ICT) and internet technology to achieve efficient and sustainable urban services. Big data, as the core driving force behind the construction of smart cities, provides unprecedented data support and analytical capabilities for urban management.

The development of big data analysis technology enables the fields of urban research and planning to utilize real-time data mining and pattern recognition methods, thereby gaining a deeper understanding of the dynamic processes of urban operations. These technologies not only improve the efficiency of urban management but also promote evidence-based decision-making, making policy formulation more scientific and precise. However, despite the enormous potential of big data in urban policy formulation, it still faces tensions between data dynamics and long-term structural challenges in cities, as well as challenges at the cognitive and practical levels.

Against this backdrop, this study aims to explore how to combine big data analysis technology with urban policy formulation and planning, constructing an urban analysis framework based on complex adaptive system theory. This framework will be an important part of the practice of new smart urbanism, helping urban managers better understand and respond to the dynamics and complexity of cities. By in-depth analysis of high-frequency data, this study will reveal the cognitive and practical challenges in urban policy formulation and propose corresponding strategies and suggestions to guide long-term urban policy formulation.

The importance of this study lies in that it not only provides theoretical support and practical guidance for the construction of smart cities but also has strategic significance for achieving sustainable urban development. Through this study, we can better understand the role of big data in urban policy formulation and how to overcome its limitations, thereby creating a more livable, efficient, and intelligent urban environment for urban residents.

1. Theoretical interpretation

The application of Complex Adaptive Systems (CAS) theory in urban research provides a new perspective and method for understanding and dealing with the dynamics and complexity of cities as open complex giant systems [1]. Cities are seen as systems composed of various interacting elements, including individuals, enterprises, government agencies, etc., which adapt and organize themselves in a constantly changing environment, thus forming the complexity and diversity of cities.

In terms of enhancing urban resilience, the theory emphasizes that the adaptability of micro-subjects is the foundation of the macro-system's resilience. Individuals and organizations within the urban system enhance the overall response and recovery capabilities of the city through adaptive behaviors. Researchers have applied CAS theory to the planning, construction, and management practices of resilient cities, focusing on urban vulnerable elements, understanding key processes and interactions, and developing the ability to deal with the structure and interaction of elements. In terms of urban planning and design, urban planners use CAS theory to understand and design more adaptive and flexible urban structures. By simulating the self-organizing process of cities, planners can design urban forms that can respond to future changes. In the comprehensive analysis of urban problems, CAS theory provides a framework for analyzing various urban issues, such as traffic congestion, environmental pollution, social inequality, etc. These issues are seen as the result of internal interactions within the system and need to be solved through systematic methods. In terms of urban policy formulation, policymakers can use CAS theory to design and evaluate the long-term impact of policies. By understanding the dynamics and non-linear characteristics of urban systems, policies can be more flexible and adaptive to cope with the changing urban environment. In terms of urban network analysis, urban networks are seen as complex adaptive systems, and researchers have established an integrated analysis framework for urban network resilience, analyzing the connectivity, redundancy, and modularity of urban networks to assess and enhance the resilience and efficiency of urban networks. In the design of smart cities, under the background of smart cities, CAS theory is used to design intelligent systems that can evolve and update autonomously. These systems can respond adaptively to external disturbances, achieving autonomous evolution and intelligent enhancement of the system.

In summary, the theory of complex adaptive systems provides a theoretical framework for urban research to understand and deal with the complexity of cities, which helps to enhance the resilience of cities, optimize urban planning and design, comprehensively analyze urban problems, formulate flexible urban policies, and design smart city systems. Through these applications, CAS theory helps to achieve sustainable urban development and improve the quality of life of urban residents.

2. The tension between high-frequency data and long-term urban challenges

The tension between the dynamics of high-frequency data and the long-term structural challenges of cities refers to the interaction and influence between short-term, rapidly changing data (such as traffic flow, energy consumption, social media activity, etc.) and long-term, relatively stable structural issues (such as urban planning, economic development, social equity, etc.) in urban data analysis and policy-making [2].

2.1. The dynamics of high-frequency data

High-frequency data, as an emerging urban data analysis tool, refers to datasets that can be collected and updated in real-time or near real-time at a very high frequency. This data typically comes from various sensors, monitoring devices, mobile applications, and social media platforms within the city, providing instantaneous information about urban traffic flow, energy consumption, public safety incidents, environmental quality, and commercial activities. Due to its rapid update speed and large volume, high-frequency data can capture and reflect the dynamic changes in urban activities in detail, even revealing patterns and trends in urban operations.

For urban managers, the characteristics of high-frequency data provide unprecedented insights, allowing them to monitor urban operations more precisely and respond promptly to various emergencies, such as traffic congestion, natural disasters, or public health crises. Additionally, high-frequency data can assist researchers and planners in analyzing urban operational patterns and predicting future development trends, enabling more scientific and forward-looking decisions in urban planning, traffic management, and environmental governance. By optimizing resource allocation, high-frequency data helps improve the efficiency of urban services and response times, enhances urban resilience, promotes sustainable development, and ultimately improves residents' quality of life. Therefore, high-frequency data has become an indispensable part of the construction and management of smart cities.

2.2. Long-term structural challenges of cities

Long-term structural challenges of cities refer to a series of deep-seated issues that persistently affect urban operations and the quality of life for residents during the urban development process. These challenges typically include, but are not limited to, rapid urbanization, housing shortages, aging infrastructure, environmental pollution, and social inequality. The acceleration of urbanization leads to resource scarcity, increased carbon emissions, and overburdened infrastructure, while also giving rise to transnational economic growth and new urban forms, such as polycentric megacities. The issue of housing shortages is becoming increasingly severe globally, with estimates suggesting that the number of people lacking adequate housing could rise to 3 billion by 2030. The problem of aging infrastructure involves insufficient financial investment in public infrastructure, leaving many economically weaker developing countries facing severe public investment budget constraints.

Environmental pollution issues have intensified with urban expansion and population growth, forcing cities to confront significant social problems such as environmental degradation and economic recession. Social inequality manifests in the context of urbanization and megacities, where resource scarcity, social fragmentation, and inequalities related to gender and race urgently need to be addressed. The resolution of these issues requires long-term planning and sustained policy support rather than short-term emergency measures [3]. They often involve complex socio-economic factors and the coordination of multiple stakeholders, necessitating in-depth analysis and comprehensive consideration. For instance, urban renewal projects require collaboration and democratic voting among government, community, and investors to ensure the rights and interests of all parties are safeguarded from the outset. Furthermore, enhancing urban resilience and optimizing the spatial layout and functional configuration of cities are also crucial aspects of addressing these challenges.

2.3. Tension

The tension here refers to the contradiction and conflict between the immediacy and dynamics of high-frequency data and the continuity and stability of long-term structural challenges in cities. While high-frequency data can provide immediate insights, it may not be sufficient to reveal the trends and patterns of long-term urban development. On the other hand, addressing long-term structural challenges requires a deep understanding of urban dynamic changes, while the rapid fluctuations of high-frequency data may complicate long-term planning and policy-making. This tension reflects a cognitive and practical challenge in urban data analysis: how to integrate short-term, rapidly changing data with the long-term development goals and policies of cities.

The immediacy of high-frequency data demands that urban managers respond quickly and make decisions to address emergencies and daily management issues. However, this rapid response may conflict with the solutions to long-term structural challenges, which typically require more in-depth analysis, planning, and sustained policy support. For example, real-time traffic data can help managers alleviate immediate traffic congestion but may not provide sufficient information for the long-term planning of urban traffic infrastructure.

Moreover, the dynamics of high-frequency data may lead policymakers to focus excessively on short-term issues while neglecting more fundamental long-term urban problems, such as urban planning, social equity, and environmental protection. This bias can complicate long-term planning and policy-making, as they must find a balance between rapidly changing data and the slowly evolving urban structure.

Therefore, understanding and addressing this tension requires urban managers and policymakers to possess critical thinking skills, enabling them to identify and integrate the relationship between short-term data and long-term trends, as well as to make informed decisions between rapid responses and long-term planning. This not only involves technical challenges but also the strategic challenge of aligning the value of big data with the goals of sustainable urban development.

3. Challenges of high-frequency data strategic analysis: A case study of Yanbu city in Saudi Arabia

Yanbu, a vibrant city in Saudi Arabia, is in the midst of rapid urbanization, facing a unique set of challenges and opportunities. The case of Yanbu provides an ideal analytical material to observe and explore the application of high-frequency data in the actual urban environment.

3.1. Smart Yanbu industrial city

In the early 1970s, the name Yanbu was virtually unknown on maps, and there was no entity called the Royal Commission of Yanbu [4]. However, a royal decree by the Saudi king in 1975 changed all that; Yanbu Industrial City was officially established and managed by the Royal Commission. After 40 years of development, Yanbu has risen to become the world's third-largest oil refining center, processing over 1.1 million barrels of crude oil daily, with an annual industrial output of 131 million tons. Additionally, Yanbu boasts the largest oil transportation port on the Red Sea and a major petroleum liquefaction facility.

With the advancement of rapid industrialization, the urban landscape of Yanbu has also been transformed, showcasing the city's rapid development with its well-planned urban layout, wide streets, ample public spaces, and lush parks. However, with the city's prosperity, a series of challenges have emerged. Insufficient network bandwidth has begun to restrict the internet needs of the government, businesses, and residents, affecting work efficiency and online entertainment experiences. A large number of heavy vehicles, required for the operation of refineries, docks, and warehouses, frequently travel, with overloading and speeding issues not only increasing road maintenance costs but also raising the risk of traffic accidents. The surge in private cars has made public parking management extremely difficult. The high cost of urban road lighting is also a significant expense. The surge in construction and domestic waste has sometimes even exceeded the capacity for timely removal. Safety issues in densely populated areas and the safety hazards of a large number of underground industrial facilities due to lack of monitoring are all issues that Yanbu needs to face and resolve.

Saudi Arabia's "Vision 2030" provides a transformation opportunity for the Royal Commission of Yanbu, which is committed to building Yanbu Industrial City into a smart city to address current challenges. They have released the "Smart Yanbu Industrial City Vision," aiming to synchronize with the country's development goals and improve the quality of life for residents through smart city technology. This vision sets a series of specific targets, including ensuring that all national transformation projects reach a 100% implementation rate, achieving a smart city annual revenue of over 66 million US dollars, reducing the average response time for incidents to less than 7 minutes, controlling the number of annual traffic accidents to below 1,200, increasing the fiber optic coverage rate in Yanbu Industrial City to over 59%, providing free Wi-Fi coverage in public places exceeding 70%, reducing public lighting costs by 30%, improving garbage collection efficiency by 30%, and lowering road maintenance costs by 20%. The achievement of these goals will mark significant progress in the intelligent management and services of Yanbu, bringing a more convenient, safer, and more environmentally friendly living environment for residents [5].

The construction of Smart Yanbu Industrial City is a phased process, divided into three main development stages. In the Smart City 1.0 phase, the focus is on building the city's infrastructure, including urban broadband networks and cloud computing facilities, aiming to achieve comprehensive interconnectivity in the city. Entering the Smart City 2.0 phase, the focus shifts to the development of specific urban applications, covering safety, intelligent public services, and environmental protection, among other areas, aiming to create a perceptive urban environment. The Smart City 3.0 phase is dedicated to improving the construction of the city platform, including the urban management platform and smart community portals, with the goal of building a highly intelligent and autonomously operated advanced city. Through the gradual implementation of these three stages, Smart Yanbu Industrial City will gradually achieve a comprehensively smart urban development vision, from basic construction to intelligent applications.

3.2. Challenges in data usage in Yanbu's smart city construction

In the process of constructing Yanbu's smart city, the challenges of data usage are mainly reflected in three aspects. The first is the insufficiency in data collection work. In terms of breadth, Yanbu needs to expand the scope of data collection to cover all aspects of urban operations. This involves deploying more sensors and monitoring devices in the city's infrastructure, such as traffic monitoring, environmental monitoring, and energy management systems, to ensure the capture of real-time data from every corner of the city. In terms of accuracy, Yanbu City needs to improve the quality and performance of data collection equipment to ensure the accuracy of the collected data. This may require upgrading existing hardware and adopting more advanced data collection technologies to improve data accuracy and reliability. In terms of depth, Yanbu needs to strengthen in-depth data analysis to reveal the deep-seated patterns and trends in urban operations. This requires not only big data analysis technology but also artificial intelligence algorithms to process and analyze data, providing urban managers with deeper insights and decision support.

The second challenge in Yanbu's smart city construction is the lack of high-end talent in data analysis and processing. The construction and operation of a smart city require data scientists, engineers, and analysts who can interpret, process, and analyze data, transforming it into valuable insights and recommendations. However, Yanbu City may currently face a shortage of such professionals, limiting its ability to make data-driven decisions. To address this issue, Yanbu City may need to invest in education and training programs to cultivate local talent and attract international experts to participate in smart city projects [6].

The third challenge is the need for regulation in the management of data collection and usage processes. The construction of a smart city requires not only technological progress but also innovation and progress in organization and mechanisms. Yanbu City needs to establish a complete data governance framework, including data quality management, security, compliance, and the circulation and trading rules of data. This involves formulating clear data policies and standards, as well as establishing effective data management and supervision mechanisms to ensure the reasonable, safe, and efficient use of data. In addition, attention must be paid to data privacy and security issues to protect citizens' personal information from misuse or disclosure. Through these measures, Yanbu City can ensure the reasonable use of data while protecting the rights and interests of citizens.

4. Recommendations for guiding policy formulation through urban analysis

Urban analysis plays a crucial role in guiding long-term urban policies. Based on the use and analysis of data in smart cities, this paper offers relevant recommendations aimed at helping cities achieve more effective long-term planning and development.

4.1. Establishing a comprehensive data collection and management system

The foundation of urban analysis lies in data collection and management. Therefore, first and foremost, cities must establish a comprehensive data collection system that covers all key areas of the city, including but not limited to transportation, environment, energy, and public safety. This means deploying sensors and monitoring devices at key points in the city to collect and monitor the city's key performance indicators in real time. For instance, traffic cameras can monitor traffic flow, environmental sensors can detect air quality in real time, and smart meters can track energy usage. To ensure the accuracy and reliability of the data, cities should invest in advanced hardware and data processing technologies. This may include using high-precision sensors, high-speed data transmission networks, and powerful data processing servers. Additionally, adopting artificial intelligence and machine learning technologies can increase the level of automation in data processing, thereby improving the speed and accuracy of data analysis [1].

4.2. Cultivating and attracting data analysis talent

Data analysis is at the core of urban analysis. Cities need the capability to interpret and analyze the vast amounts of collected data to extract valuable information and insights. Therefore, cities must cultivate and attract professional talent in the field of data analysis. This can be achieved by collaborating with local higher education institutions to develop courses and training programs related to data analysis and data science. At the same time, cities should create an environment that attracts international talent, including offering competitive compensation, a good working environment, and career development opportunities. Furthermore, cities should encourage interdisciplinary collaboration, as urban analysis often requires knowledge from multiple fields such as urban planning, sociology, environmental science, and information technology. By establishing interdisciplinary teams, cities can better understand and address complex urban issues.

4.3. Regulating data management and usage processes

As the volume of data increases, the regulation of data management and usage processes becomes crucial. Cities need to establish a clear data governance framework to ensure the reasonable, safe, and efficient use of data. This includes setting data quality management standards to ensure the accuracy and completeness of data; implementing data security measures to protect data from unauthorized access and misuse; and complying with data compliance requirements to ensure that data collection and processing comply with relevant laws and regulations. In addition, cities should establish data circulation and trading rules to promote the sharing and utilization of data. This may include formulating data sharing agreements, establishing data trading platforms, and formulating data privacy protection policies. Through these measures, cities can ensure the reasonable use of data while protecting the privacy rights of citizens. At the same time, transparent data management and usage processes also help to improve public trust and acceptance of smart city projects.

Conclusion

This paper, through an in-depth analysis of the integration of smart cities, big data, and urban policy, explores how urban analysis can guide the formulation of long-term urban policies. The article first elaborates on the application of complex adaptive system theory in urban research and discusses the tension between the dynamics of high-frequency data and the long-term structural challenges of cities. Based on this, taking Yanbu City in Saudi Arabia as an example, the paper analyzes the application and challenges of high-frequency data strategic analysis in practice.

The paper points out that urban analysis plays a vital role in guiding long-term urban policy formulation. To achieve this goal, the following recommendations are made: first, establish a comprehensive data collection and management system to ensure the breadth, accuracy, and depth of data; second, cultivate and attract high-end talent in data analysis to enhance the city's ability to interpret and analyze data; and finally, regulate the management and usage processes of data to establish a clear data governance framework for the reasonable, safe, and efficient use of data.

Through the case analysis of Yanbu's smart city construction, this paper reveals the problems in data collection, analysis, and usage and proposes corresponding solutions. These strategies are not only applicable to Yanbu City but also to similar issues encountered by other cities in smart city construction. In general, this paper emphasizes the potential of big data in urban policy formulation and points out the challenges that need to be overcome to realize this potential. By constructing an urban analysis framework based on complex adaptive system theory, cities can better understand and respond to the dynamics and complexity of cities, thereby achieving the goal of sustainable development. Ultimately, through effective urban analysis and data utilization, a more livable, efficient, and intelligent urban environment can be created for city residents.

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