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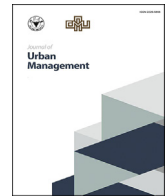
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Research Article

Recognition of digital twin city from the perspective of complex system theory: Lessons from Chinese practice

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ABSTRACT

Urban system theory seeks to comprehensively capture the complexity of cities. Digital twin cities are “digital mirror images” or symbionts of physical cities, and thus, they form a complex adaptive system. Unlike the reductionist practice of urban informatization and digitalization, digital twins are expected to enable human beings to enjoy the complex beauty of the city for the first time, capable to perceive more information of city and deal with more complex urban problems. Some practical misunderstandings have emerged, however, as a result of simple technical stacking, which is not able to solve urban problems from the root of the problem; has biased thinking about digital twin cities, which treats them as technical tools; and has slowed development of digital twin innovative applications. To solve these problems, we need to draw on basic urban theory. On the basis of complex system theory, in this study, we comprehensively analyzed the characteristics and mechanisms of digital twin cities and constructed a system framework for digital twin cities. We further elucidated the digital twin city and deconstructed it from the perspective of system theory into four subsystems: the planning system, infrastructure system, industrial system, and public service facility system. We then analyzed the subsystem rules and changes in the digital twin city, as well as the principles and development trends that conform to the self-organization and self-adaptive laws of the city.

1. Introduction

The idea of the digital twin was born in the field of aerospace and industrial manufacturing, where it has been used to simulate and control complex systems (Shafto et al., 2012; Digital, 2017; Bolton et al., 2018). A city is a human-made complex adaptive system, which has become an important field for digital twin application. The concept of digital twin cities was pioneered in the second half of 2017 during the planning and construction of the Xiong'an New Area, which involved the innovative planning for this concept as well as its basic structure and implementation mechanisms. Since then, the relevant research on digital twin cities has increased rapidly. A large number of studies have assessed the practice and technology of digital twin cities (Zhou & Liu, 2018; Ham & Kim, 2020; Lehner & Dorffner, 2020; Xue et al., 2020), but an understanding of digital twin cities from the perspective of the urban system is lacking (Shahat et al., 2021). The direction of digital twin cities in practice is unclear, the goal is missing, and numerous problems exist, including repeated construction and low platform utilization.

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Therefore, it is particularly important to return to the noumenon of the city and recognize the city as a complex system and to reassess city development under information technology from a broad perspective. In this study, we built a digital twin city development framework based on system theory and analyzed the transformation of the whole city and its constituent subsystems under the development of informatization to determine the original intention of digital twin city construction and create a guide from concept to practice and implementation.

The remainder of this paper is structured as follows. Section 1 introduces the literature related to urban system theory and digital twin cities. The literature has introduced the evolution of urban system theory and thinking about digital twin city development, and situates the digital twin city as a stage of the urban development process. Section 2 introduces the practical experience and development difficulties of digital twin cities in China, including, in detail, the construction objectives, paths, and current measures of digital twin cities in Xiong'an, Beijing Subcenter, Guangzhou, Nanjing, and Shenzhen. Sections 3 and 4 construct the system theory framework for the digital twin city to adapt to the complexity of the city as well as deeply analyze the characteristics and development trends of the four digital twin city subsystems.

2. Urban system theory and the development of digital twin cities

Human philosophy has shaped our understanding of cities and has determined urban development and planning modes. Ancient Chinese and Western philosophers gradually developed the thought of a simple holism in the process of systematic reflection on the relationship between man and nature. In Chapter 42 of Laozi's *Tao Te Ching*, he observed, “The Dao produced one; one produced two; two produced three; three produced all things. All things leave behind them the obscurity (out of which they have come), and go forward to embrace the brightness (into which they have emerged), while they are harmonized by the breath of vacancy” (Feng, 2019). Aristotle, an ancient Greek philosopher, put forward the famous diagnosis that “the whole is greater than the sum of its parts” (Humphrey, 2007). The founder of general systems theory, Ludwig von Bertalanffy, affirmed this famous saying when expounding his integrity principle (Wu, 1992). Philosophers not only developed the idea of the harmonious coexistence between humans and nature, but also applied it in practice. For example, the urban plan for XianYang, the capital city of the Qin Dynasty, mirrors a star map, a practice called “modeling the principle of Heaven and Earth,” which serves as an example of the harmonious development of humans and nature.

Reductionism also has had a profound impact on modern urban research and practice. Le Corbusier's urban planning philosophy pursued mechanical beauty and rationality. His plan for the city of Chandigarh is the most direct embodiment of this philosophy. As represented by the Charter of Athens, reductionism emphasizes the planning and management of cities through simple functional classification. This concept is based on the idea of a mechanical urban system that ignores the fundamental characteristics of the city as a living body and that naturally cannot be fully grasped in the characteristics and development that govern cities. Urban practice guided by reductionism has resulted in a series of problems, including community isolation, vitality decline, and traffic congestion.

In European and North American countries, where large-scale urbanization started earlier in the industrial age, academics have been able to pay attention to the problem that modern urban planning theory based on mechanical reductionism is ineffective in dealing with urban complexity and uncertainty. As a result, they have realized the significance of adapting to urban adaptability and complexity to achieve sustainable development (Holland, 2000; Jacobs, 1961; West, 2018). Researchers have sought to understand cities from a systematic perspective: For example, Jane Jacobs defined cities as “Organized Complexity, the most complex and vigorous life” in *The Death and Life of Great American Cities* (Jacobs, 1961). The study of complex adaptive systems (CAS) based on the development of modern natural science was introduced by the Santa Fe School in the United States. Since the 1980s, the Santa Fe School has applied CAS theory to urban research (Holland, 2000). Geoffrey West noted that “a city is the combination of two kinds of ‘flows,’ one is the flow of energy and resources to maintain and promote its own infrastructure and resident development, and the other is the flow of information in a social network connecting all the public” (West, 2018). Michael Batty posited that cities are unpredictable in nature and can be created; he explored laws that are common to all cities from the perspective of factor flow and the network as the basis for creating future cities, and his flow and network model focuses on the process of creation, not the creation itself (Batty, 2019). In China, Qian Xuesen first promoted the study of urban development from the perspective of system science and proposed the establishment of urbanism as the theoretical basis of urban planning (Qian, 1985). Many scholars have also tried to understand cities from the perspective of complex systems (Qiu, 2009; Wu, 2001; Zhou, 2009). Increasingly, researchers have emphasized the changes in the understanding of urban systems brought about by information and computer technologies. Across multiple studies, Wu Zhiqiang proposed a rational, sustainable method for urban planning that promotes the new generation of smart technology in providing technical support for the instrumental rationality of urban planning, and explored innovative practices such as the urban intelligent model (i.e., the city information model [CIM]) and artificial intelligence deduction of urban land layout (Wu et al., 2021; Wu & Gan, 2018). Drawing on complexity theory, Zhang Tingwei studied and discussed the introduction of artificial intelligence into urban planning to make up for the defects of

Table 1
Urban theory and development model.

Support Theory	City Cognition	City Development Mode	Planning Method
Ancient simple holism	Cities follow natural rules, and the whole is greater than the part	Expanding from the center	Modeling the principle of Heaven and Earth
Mechanical reductionism	Cities are organisms composed of different functions	Collage city, linear city, urban organism	Functional classification
Complex adaptive system	A city is a complex system, which has many characteristics, such as self-evolution and emergence	Digital city, smart city, digital twin city	Internet of Things, 5G, network analysis, intelligent simulation, city information platform

traditional planning modes (Zhang, 2017).

The systematic characteristics of the city have gradually been recognized. The digital twin city has all the characteristics of an urban complex system corresponding to the physical urban system. Its essence is the agglomeration of people, and its complexity can be drawn from that of the people in the city. The response and adaptation process of digital twin cities to external environmental changes is that of the people to external environmental changes. Digital twin cities are intuitively expressed as the physical city and its “digital mirror” (or cyber city) grow together, evolve together, and interact in real-time with each other, thus reflecting various characteristics of complex adaptive systems. Digital twin cities are able to engage with urban information in real time utilizing new technical means, such as the Internet of Things, network analysis, and intelligent simulation. Thus, it has become easier to perceive human information, connect data from various urban areas, form an interactive mechanism between the physical city and the cyber city, and address urban complexity (Table 1).

3. Practical experience and confusion of digital twin cities in China

China has pursued the most research, exploration, and practice cases of digital twin cities. The Xiong'an New Area was the first to introduce the concept of digital twin cities into urban construction cases, which was then carried out in demonstrations and promotions nationwide (Zhou & Liu, 2018). The digital China initiative and smart society have been elevated to a national strategy, and China is witnessing the rapid construction of new infrastructure, such as the Internet of Things, 5G, and artificial intelligence, which have formed the basis for the construction of the digital twin city. China therefore serves as a typical case study of the digital twin city for analysis.

3.1. Practical experience

3.1.1. Native digital twin city practice: Xiong'an new area

In 2018, the administration of the Xiong'an New Area stated that “from the beginning of planning and construction, we should adhere to the synchronous planning and construction of digital cities and real cities, and build the keynote of digital twin cities and smart cities” (The People's Government of Hebei Province, 2018). This is by far the most complete application of CAS theory in urban practice (Zhou & Liu, 2018). As a native digital twin city, Xiong'an New Area has symbiotic characteristics, synergistic advantages, and system integrity that other cities do not have. This is reflected in four aspects, including (1) the digital infrastructure construction (i.e., acquisition and transmission of Geographic Information Science-based global spatiotemporal big data, high-precision urban survey data, complete regional economic, and social and humanistic big data); (2) the simultaneous construction of a management platform (using building information model [BIM] or a CIM to realize digital construction before physical construction); (3) a twinned data standard system (city data dictionary and unified management standard system); and (4) city-level intelligent collaboration and operation capabilities (Fig. 1).

3.1.2. Other pilot digital twin cities

The systematic innovation of Xiong'an New Area has inspired the construction of digital twin cities and led to many pilot projects. In November 2018, China's Ministry of Housing and Urban-Rural Development announced a pilot CIM platform construction in the Beijing Municipal Administrative Center, Guangzhou, Nanjing, Xiamen, Xiong'an New Area (Dang et al., 2022), and elsewhere in combination with the reform of the inspection and approval system for engineering construction projects, which forms an important supporting platform for digital transformation. The focus of each pilot city differs. The Beijing Municipal Administrative Center is set to expand based on the original BIM platform and to gradually form a city-level CIM platform (Chen & Lee et al., 2021); Guangzhou began with the inspection and approval of engineering construction projects to prepare to establish a city-level CIM platform standard system and a

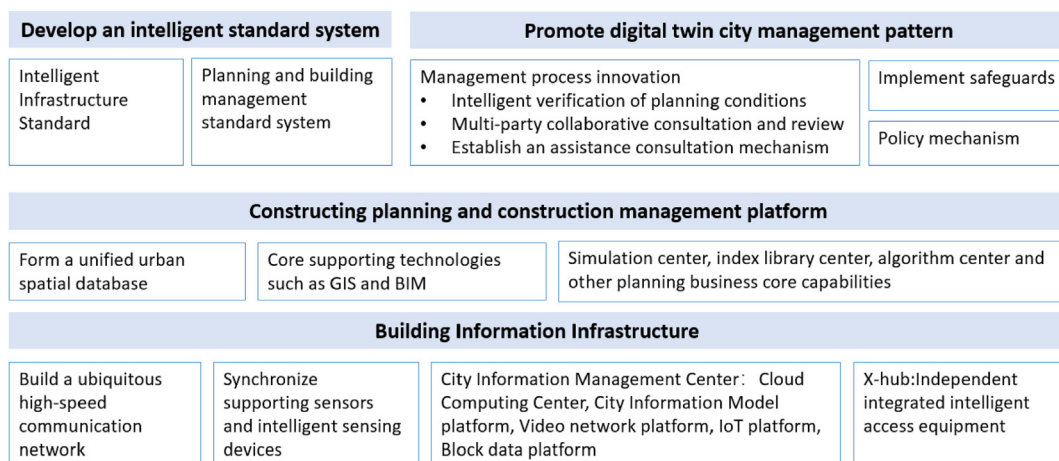


Fig. 1. Main construction content of Xiong'an Digital Twin City.

three-dimensional (3D) status model to form a “3D base map” to shift inspections from humans to machines (Guangzhou Municipal Housing & Urban-Rural Development Bureau, 2022). Nanjing has emphasized the construction of data and platform management standards (Wu, 2020), while Shenzhen has started with data backplane and visualization, established a complete 3D data backplane, and connected data to support various services (Yuan, 2020). Details for each of these pilots are given in Table 2.

3.1.3. Experience

Digital twin cities have attracted significant attention from all parties globally, and The Chinese government included the concept of digital twins in “Outline of the 14th Five-Year Plan”. The preliminary practice of digital twin cities is in full swing. Although there is no unified construction mode, some consensus has been reached on the topic, including a unified standard system, new systematic infrastructure, data standards, and new management service models. Because the Physical city construction is earlier and more complete than the digital city, it is difficult to imagine that the original digital twin city can grow along with the physical city. The pilot cities are subjected to existing digital twin city achievements and carrying out digital twin updates in their distinct fields.

The construction of digital twin cities is a step-by-step process. The construction of digital twin cities in Xiong'an New Area has distinct conditions. It is a rare case in China that has started from a new area and has attempted to simultaneously build and grow a physical city and a digital city. The construction of the Xiong'an City Computing (Supercomputing Cloud) Center, Xiong'an City Information Model, driverless roads, smart logistics, and smart light poles all have been built in an orderly manner. Although the data of different systems have not been completely connected, the application of digital twins in those aspects represents the first step of the digital twin city construction. Xiong'an Digital Twin City has not been built because of the lack of a stable overall planning department in the implementation process, and the existing infrastructure support and technology application are immature. For example, new infrastructure, such as blockchain platform for privacy protection and data sharing, has not been fully established. However, cognition is the premise of all practices. With the strengthening of the understanding of the importance and necessity of the construction of the digital twin city, as well as improvements in the administrative mechanism and new infrastructure, the Xiong'an's digital twin city will be built gradually.

3.2. Confusion in practice

Although it is widely recognized that digital twin cities are an important direction for future urban development, practical experience is also needed. Apart from the difficulties in data and model construction (Tao & Qi, 2019), the current digital twin practice has remained focused primarily on the construction of a 3D visualization of the city and a single administrative business line, including the application of planning management, such as intelligent planning approval, rather than penetrating the urban economy, culture, society, and other aspects of intelligent design. This approach reveals that people's understanding of digital twin cities remains biased. The construction of digital twin cities is more often discussed from a technical perspective than in terms of the urban system or the diversified needs of the people living in cities. In practice, this issue is reflected in the following three problems.

3.2.1. Simple technical stacking cannot solve the root of urban problems

In recent years, the smart city framework of many cities has superimposed the application of digital twin technology, without an

Table 2

Key points and characteristics of each pilot city.

City Name	Goals	Construction Path
Beijing Municipal Administrative Center	<ol style="list-style-type: none"> 1. Create a foundation platform that includes city data 2. Ensure full-cycle integrated design and construction 	The design scope is gradually expanded based on BIM, and the whole process integration for electronic approval and construction application is established to gradually expand to the urban scope and build the urban CIM platform.
Guangzhou	<ol style="list-style-type: none"> 1. Create one CIM basic database and a CIM basic platform 2. Create one smart city-integrated operation center 3. Create two auxiliary systems based on examination and approval system reform, 4. Create one unified business management platform 	The focus is on accelerating the construction of the CIM platform standard system. City-level standard system and three-dimensional model is constructed, and by focusing on the examination and approval of engineering construction projects, a three-dimensional digital auxiliary examination and approval system is constructed.
Nanjing	Ensure one-click decision-making, single netcom governance, and one-end service sharing	The focus is on standard construction. BIM and CIM standard systems for urban engineering construction projects are constructed and compilation to BIM standards and CIM standards is begun.
Shenzhen	Centered on the four business links of planning preparation, implementation management, decision support, and public participation, provide digital support for users in different roles throughout the whole process	This path starts from the space model. The construction of a visual urban spatial digital platform was started in May 2018; it perfected the basic data for “land, building, room, property, human,” taking spatial location as a link, integrating three-dimensional spatial data (including BIM and tilt photography), pursuing capabilities (e.g., high-precision location service, dynamic monitoring of natural resources, and geographic information, spatial analysis, and optimization), and providing the only spatial infrastructure for the construction of Shenzhen's digital government and smart city.

understanding of the means of this wisdom. Digital twin pilot projects continue to focus on the addition of demand modules for digital management platforms that are proposed by various government business units. These projects highlight the application of BIM to the management of planning and construction. Although this work has expanded the application of real-time urban perception data, it is essentially a continuation of existing management rules. Many so-called urban brains remain in essence an “urban cerebellum”—that is, at a theoretical level, they fail to recognize that the digital twin city is a brand-new urban development model based on systems thinking. As a result, the smart city framework cannot adapt to the complexity of the city.

Algorithms and models in specific applications cannot continue to focus on optimizing the efficiency of execution for existing city rules, but instead, they must improve the city's intelligence and adaptive feedback capabilities. This is the only way to solve the confusion behind the notion that the digital twin city is a technological upgrade of a smart city or that digital twin cities are simply building CIM.

3.2.2. Digital twin cities are limited to technical tools

In some pilot projects, digital twin cities are regarded as plug-in tools to assist with administrative actions, rather than a brand-new urban development method. With the help of new tools, everything in the city can be accurately perceived and witnessed, making it easier to control the city according to an established plan to obtain specific results through digital technology. Trying to control complexity and emergence, instead of optimizing governance by perceiving changes in all things, has led to biased views: the significance of digital twin cities for urban governance mainly lies in the optimization of the planning and construction management processes for physical cities; a new city, which is more suitable for the task of building from scratch, has no obvious effect on existing cities.

3.2.3. Development of innovative digital twin application is slow

Existing pilot projects, such as Xiong'an, Guangzhou, and Nanjing, have been led by the government, and most projects have been led by planning and construction management departments instead of by urban citizens. The dominant features of strong administrative departments are as follows: a government focused on management processes and management tools development; digital modeling of urban physical space and existing rules, such as using 3D visualization to display the physical city; and using programs to quickly execute the established rules instead of doing so by hand, while paying less attention to the connection and interaction process between urban agents. The results of digital twin city projects primarily are explicit, institutional rules and rigid indicators. Consideration of the diversity of objectives in multiagent participation and situations of uncertainty has been insufficient. The disadvantages of this method are obvious, including the following: relatively little consideration has been given to the whole urban system to promote the deep-seated transformation of governance concepts and methods; the output results primarily have been explicit policies and rigid indicators; insufficient consideration has been given to the diversity of objectives based on multiagent participation and uncertainty situations; the development of technological innovation environment has been slow; and industrial driving ability has been insufficient.

4. Theoretical framework of digital twin cities based on urban system theory

4.1. CAS theory and characteristics and mechanism of digital twin cities

According to CAS theory, the transformation, evolution, and development of any system is the collective result of the awareness of the agents to the external environment, and the adaptability of agents leads to the complexity of the system. (Shi et al., 2021). Complex adaptive system theory provides a theoretical tool for a comprehensive understanding and deconstruction of complex systems, and many studies have been conducted in the field of urban planning (Chen et al., 2021; Lv et al., 2021; Shi et al., 2021; Huang et al., 2022). Shi et al. (2021) successfully explained the mechanisms and characteristics of a complex urban system using complex system theory. Based on John Holland's theory of complex adaptive systems, in this study, we adopted the core concept of complex systems—that is, “agent” and seven features around the “agent.” Specifically, we used aggregation, nonlinearity, flow, diversity, tagging, internal models, and building blocks to analyze the characteristics and mechanism of the city as a complex system. Among these features, aggregation, nonlinearity, flow, and diversity are the four basic characteristics of CAS; tagging, internal model, and building blocks are the three basic mechanisms of CAS system. From the perspective of the development trend and operation principle of the digital twin cities, and combined with the seven basic characteristics of CAS, we determined and analyzed the complexity of the digital twin city.

Digital twin cities produce new agents, including various physical equipment and facilities supporting the interaction between virtual and real city; government and enterprise organizations, such as urban government platforms; and big data trading platform organizations, which manage and operate the massive data generated by digital twin cities. Digital twins correspond to urban physical entities in digital space to achieve comprehensive simulations, including CIM and BIM. These new agents make the urban system more complex. The interaction between the subjects is more diverse, the aggregation level is larger, and the interaction is more nonlinear. These new subjects also have developed new urban characteristics and mechanisms. Digital twin cities have new characteristics, agents can break the restrictions of physical space and time, including their identities and other aspects, and can achieve more open, flexible, large-scale, higher frequency, and more real-time aggregation. As a result, they can form “urban function modules” with diverse functions, such as supercomputing center and blockchain. Digital twin cities also have broken the linear pattern of “urban planning–construction–operation–problem discovery–problem solving” and have formed a nonlinear development sequence. With the acceleration of information flow, development efficiency has presented nonlinearly and system risk also has increased nonlinearly. The optimization of real logistics has been achieved through 5G, Internet of Things, artificial intelligence, and other information technologies, and has generated information flow between agents, thus forming a complex connection network within and between cities and becoming valuable digital assets with the accumulation and precipitation of data. Digital technologies have created a “hyper-connected

world” (Krishnan, 2017) and a “participatory culture” (Jenkins et al., 2015), which has been combined with traditional urban culture to discover and refine urban wisdom, has highlighted the characteristics of cities, and has become more people oriented. At the same time, digital twins produce new operating mechanisms. Data generated by all agents and element flows have provided basic format standards. Solid components are created with a unique identity authentication, which corresponds to one or more tags. Digital twin cities are a new urban form that has made some implicit internal models “dominant,” thus using algorithms and models to forecast and verify urban operation. Digital twin cities have added a special category to the building blocks of the urban system and have added a new dimension to the building blocks or an ability to unpack the building blocks. Through these digital models, cross-category “virtual encapsulation” can be created between the building blocks of different functions and different service scenarios, which makes it easier to study the internal models of urban operation.

4.2. Composition of digital twin cities

The root of these problems is the lack of a systematic and comprehensive understanding of digital twin cities. Digital technology has endowed the city with the genes of a new era and has formed new social rules. Information and communication technology (ICT) has expanded the scope and frequency of interpersonal communication and has deepened both interactions and restraint between people. ICT has made everyone a producer, disseminator, and consumer of information; has increased the connection and complexity of the city; and has changed the underlying principle of the urban system. It is thus necessary to reassess this new form of urban city—the digital twin city.

Digital twin cities follow the basic law of the formation and evolution of the urban system. Individual and group evolution is achieved through the continuous material and energy exchange with the external world. With the rapid development of digital technology, the opportunity, ability, and intensity of interactions between people and the environment have been greatly improved. People, enterprises, and other agents have adjusted behavior to adapt to an environment in which interactions have taken on stronger nonlinear characteristics; these microcosmic changes have led to changes at the macrocosmic level. Digital technologies not only accelerate the evolution of cities but also provide the ability to break through the limitations of human intellectual capacity in fully understanding cities and their complexity, which establishes an important foundation for building digital twin cities. The study of the theoretical and technical framework of artificial societies started in the 1990s with the development of complex system theory, artificial intelligence, and other technologies (Epstein & Axtell, 1996). Such research sought to study the vitality, development power, and related phenomena of society itself and looked to produce a global macro law for society using a local micro model of individual behavior. The core methods of digital twin cities included agent-based modeling, simulation, and analysis (Wang & Lansing, 2004), which have provided technical support for the theoretical and practical exploration of digital twin cities.

To understand the city from the perspective of system theory, we regard the city as an organic organism similar to human life, and we unpack the urban system with reference to the classification of the human body system. This unpacking follows four principles: self-consistency of subsystems, equivalence of module levels of subsystems, consistency of continued unpacking of subsystems, and the same meaning of basic agents of subsystems. After many attempts and analysis, this research has unpacked the complex urban system into four additional intuitive subsystems: planning subsystem, infrastructure subsystem, industrial subsystem, and public service facility subsystem. These subsystems better reflect the overall picture of the urban system (Liu & Hou, 2012). Planning subsystems represent the intelligent ability of urban life and guide the collection of goals, paths, measures, and tools for urban economic and social development. In this study, these subsystems can be understood as a strategic, comprehensive, and systematic comprehensive solution for the city. The infrastructure subsystem represents the elastic capacity supporting a city, including urban infrastructure, ecosystem, and other basic elements supporting urban development. The industrial subsystem creates the ability for renewal and the innovative power of city. It conforms to the pursuit of human development and interests and thus becomes an important power of the city. In turn, it places increasing demands on the infrastructure subsystem, which determine the height (ceiling) of urban development. The public service

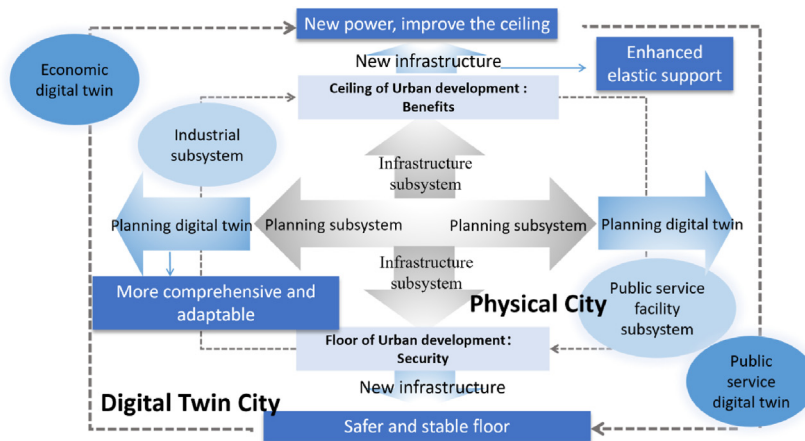


Fig. 2. Structural relationship of a digital twin city's four subsystems.

facility subsystem is the basic guarantee for human living in a city, and it ensures the safety and stability of urban life. This subsystem also experiences a stress reaction to the “growing pains” of the process of urban development. It is the bottom line (floor) of urban development.

In this research, we analyzed how the urban system responds and forms the corresponding digital twins with digital technologies against the backdrop of the information revolution, thus constructing a system theory framework for digital twin cities. As discussed, the development of the digital twin cities has formed a new urban development and operating mode, leading to the evolution of the four urban subsystems, which are illustrated in Fig. 2.

4.3. System framework for the digital twin city

In digital twin cities, it is first necessary to model the spatial and temporal state of urban material space and the existing rules, and then make a holographic record of the factor flow generated in the interaction between urban agents and between urban agents and the material environment. Based on the latest technical developments (6G, IoT, AI etc.), these massive historical and real-time data have shown an orderly flow and organic integration. By combining artificial and human intelligence, we can further verify the influence of various social factors, including laws and regulations, ethics, social networks, agent values, and value orientations on large and small decisions in urban development, while also identifying the external and internal panorama of urban activities. These data are processed, analyzed, and visualized in specific applications, and the specific decision-making impact in multiple scenarios and dimensions is simulated and evaluated. These multiscene simulations need to conform to urban self-organization and self-adaptation, give feedback and guidance to material space, fully perceive the complex behavior of urban agents, accurately determine the related elements and influencing factors, and suggest appropriate interventions for key elements. Public behavior in the digital twin city can neither be ignored nor considered irrelevant. Following all these principles, the digital twin city can run as a comprehensive system. The framework is shown in Fig. 3.

Like most complex artificial life, the operation and development of cities cannot be completely recorded and reproduced in the long term, and the characteristics of nonlinear development also mean that the future of cities cannot be accurately predicted. It may even be impossible to experiment with its research objects, let alone repeat experiments. The digital gene pool and knowledge base for cities, however, will become increasingly abundant. The significance of building a digital twin city lies in the fact that both the public and private sectors can overcome the limitations of cognitive scope and grasp the whole picture of urban operations more easily than before. Although the ability of various adaptive agents to cope with environmental changes has improved, digital twin cities also virtually improve the fairness and transparency of a city's overall economic and social operation. The voices of all parties can be heard and respected, and the intensity and overall complexity of development can be further improved. These developments, in turn, significantly improve the city's overall vitality and ability to cope with risks.

5. Deconstruction of the digital twin city subsystems

System theory can be used to unpack urban systems into more intuitive subsystems (Liu & Hou, 2012). In this study, we deconstructed the urban system using complex adaptive system theory, further compared the differences between digital twin cities and previous cities from the subsystem level, and analyzed the internal operation law of digital twin cities. These results may be useful for practitioners.

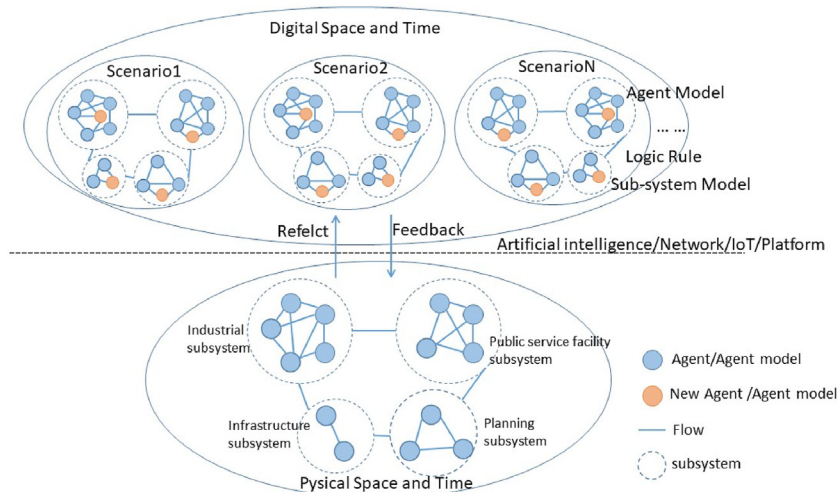


Fig. 3. Digital twin city framework based on system theory.

5.1. Planning subsystem

As a city planning system, urban design and planning is a collection of goals, paths, measures, and tools to guide urban economic and social development. Top-level design can be understood as the positioning of the city in a larger system, such as within urban agglomerations, major economic regions, countries, and even the whole world, thus having a stronger impact on urban planning and coping decisions. This effort includes strategic, overall, and systematic comprehensive judgment. Planning can be understood as a tool to address the correlation between urban function and space. Top-level design and planning compilation can be deconstructed into three interrelated processes of wisdom provision, integration, and practice, which also correspond to the three agents of wisdom provider, integrator, and practitioner. Under the guidance of the governance concept of respecting the law of urban self-organization, the mechanism for these three processes and the agglomeration characteristics of these three agents can undergo fundamental changes.

The forecast ability and accumulated wisdom of digital twin cities will be comprehensively improved. Wisdom providers have become more comprehensive and the ideas provided are more complete. The agent of intelligent integration has developed stronger technical methods in the planning process, and the integration and optimization of intelligence has become more efficient. The adaptability of management decision-making to various emergencies has improved, as has the flexibility of urban operation. The enthusiasm of executive agents has been stimulated, and various innovations have emerged in succession. As a result, valuable innovations will be discovered and will develop and grow in an appropriate environment, thus providing positive feedback to urban intelligence and enabling smart integrated agents to continuously optimize and adjust urban top-level design and system rules. All kinds of scattered social agents can reflect the diversity of cities and better understand the relationship between their local areas and overall urban operation. The digital twin thus provides an effective channel for these agents to contribute intelligence.

A variety of scattered social agents can reflect the diversity of the city and better understand the relationship between the local and overall operation of the city. Digital twins provide an effective channel for these agents to contribute wisdom, organically integrate ideas into the traditional pyramid of an intelligence collection system, play a role in horizontal and vertical coordination, and optimize the internal structure of the pyramid. As a result, the traditional pyramid opportunity integration model becomes flat. The process of wisdom provision and integration can thus clarify the complexity of cities, and wisdom can emerge in the bottom-up agglomeration of agents and disciplines. In the process of wisdom integration and practice, the qualitative role of key decision makers on intelligence integration and practice has not disappeared, but it can prevent the results from being influenced by personal positions, experiences, values.

In the era of digital twin cities, information flow in the process of providing, integrating, and practicing wisdom can be recorded holographically, which will greatly enhance the openness and transparency of related work, greatly reduce the inadvertent omission or unfair treatment of group recommendations, and significantly increase the difficulty and cost of individual subversive influence. The urban intelligence model has been gradually constructed in learning and iteration and can assist government agencies and research institutions in analyzing the impact of decision-making. In the meantime, it also can support smart deduction, which are becoming increasingly complex and close to reality, and compare multiple solutions in-depth. In addition, it can consider the demands of all parties involved in planning, thus solving the problems associated with high cost and irreversibility of trial and error in traditional wisdom practice. In practice, each strategy corresponds to a set of actual scenes and a set of digital models in the urban system. Intelligent feedback and evaluation of the implementation effect not only can realize rigid control of and early warnings about bottom-line indicators, but also can propose the dynamic optimization of suggestions for development indicators. This process can truly reflect rigidity where rigid control is needed, thus allowing decision makers to avoid the pressure of potential risks in cases in which flexibility is needed. These demands will be predictable to a certain extent based on the perception of the real state of various subjects, which provides further support for the dynamic optimization of top-level design and planning. Such design will no longer be seriously divorced from reality in the implementation process, which will make it possible to avoid being overturned completely at every turn, so as to realize an accurate blueprint.

5.2. Infrastructure subsystem

In the *Urban Hidden Order*, urban infrastructure is a supporting system related to the rise and fall of cities (Liu, 2017), but in current cities, this development is often passive. It is with some difficulty that the relatively fixed urban carrying capacity can satisfy the infinite expansion of desire for development under the irrational needs of urban growth. In this game between development desire and carrying capacity, infrastructure often becomes the scapegoat for mistakes. Digital twin cities make it possible to consider urban support systems that include not only traditional physical infrastructure subsystems, but also digital infrastructure subsystems that support the real-time interaction between physical infrastructure and urban adaptive agents to optimize their running state, which constitutes a new urban support facility system.

Digital twin cities can realize the effective coordination of supply and demand of infrastructure systems, including whole and local, internal and external, construction and operation. In this process, subsystems, such as water, electricity, roads, gas, communication, and ecology, as well as various regions of the city, cannot be separated. Instead, it is necessary to perceive and integrate the information flow completely to form a historical database for the operation of the urban support system. It is also necessary to realize the efficient interaction between the urban support system and other urban subsystems and realize the complementarity of human wisdom in artificial intelligence based on understanding to gradually enrich the urban knowledge base. Thus, the city's ability to predict, control, and respond to the potential risks created by development will be enhanced. In addition, the disorder or even the collapse of the urban system caused by the local abnormality of a subsystem in the supporting system will be avoided to the greatest extent possible and at a controllable cost. For example, after traffic paralysis caused by local congestion or operation shutdown caused by insufficient income,

cities usually need to incur multiple costs to make temporary remedies. The support system is thus expected to upgrade from a simple passive response to a systemic strategy to realize dynamic perception, active early warning, and flexible response to emergencies, thus improving operational efficiency and economy.

The construction of digital twin cities also creates new supply of and demands for infrastructure. New infrastructure, such as urban supercomputing centers, urban optical networks, CIM platforms, and blockchain, make urban support systems more intelligent and flexible. In this study, we briefly analyzed two new infrastructure subsystems, CIMs and blockchain in the Xiong'an New Area, and further expanded on the operation principle of digital twin cities. CIM is the digital mirror image of a physical city. It is also a complete complex adaptive system that plays a supporting role in information interaction between urban agents and between urban agents and the physical environment. Future cities can perceive and record the integrity of the adaptive behavior of urban agents based on the CIM, and all of the information flows related to urban physical existence need to be supported by the CIM. At the same time, the CIM is not a simple storage and splicing of all kinds of BIM and non-BIM data. The digital image of these real agents form a new type of urban adaptive agent in a digital form. These agents also interact in real time and emerge layer by layer, which is the principle behind urban decision-making suggestions and multisenario previews. CIM can be explained as a *city information model*, which also includes the meanings of a *city intelligent model* and *city intelligent management* (Billen, 2000; Zingariello, 2021; Wu al., 2021). As a new type of infrastructure, CIM not only provides services for government agents but also provides support for various urban adaptive agents. All urban agents will participate in CIM to realize system self-maintenance and self-optimization.

Blockchain technology guarantees order for digital twin cities. The Xiong'an blockchain infrastructure and CIM were built before the large-scale construction of the physical city and were applied to the first project: the Millennium Xiulin (the Forest of Xiong'an). The relevant attributes of enterprises and internal employees, performance process, and key information about the interaction between agents were uploaded and certified using blockchain to anchor the flow of capital and information. The real and transparent environment supported by blockchain also enabled credit transfer among agents at all levels of the supply chain. The information for the entire process for each tree—from seedling and transportation to planting and maintenance—was recorded, and the correspondence between the physical tree and digital tree was realized. Because of the transparency of the records of the whole process, all kinds of agents spontaneously performed their duties in good faith without increasing the investment in traditional supervision, and the phenomenon of bad money driving out the good was greatly reduced. This was a direct manifestation of the transformation of urban governance concepts.

5.3. Industrial subsystem

Industry is the power system of the city, and innovation is the fundamental source of industrial power. The agents of urban industry include people with industrial action ability, related organizations and institutions, and artificial objects participating in industrial activities. The agents of the industrial system can be divided into three categories: dynamic, participatory, and external. The occupation and identity of a specific individual or organization may be diverse. In the industrial subsystem, the aggregation of agents eventually forms two big blocks: essential and additional industries. We did not analyze the dynamic system of cities in detail, but briefly described the typical performance of digital twin cities to promote innovation and urban industrial development from the perspective of agents, agent agglomeration, and factor flow.

Improvements in the data flow mechanism in digital twin cities have greatly improved the scale and integration of data resources, which have provided convenience for active dynamic agents, such as technology entrepreneurs, business incubators, and venture capital funds to accurately perceive market fluctuations and carry out industrial development and wealth creation activities. Holographic perception, virtual-real mapping, and smart simulation also provide a basis for the optimization of management processes and technical solutions within the enterprise and improve work efficiency and creativity among participating agents. As an important external subject, the government plays a decisive role in optimizing the overall innovation environment of society. Digital twin cities enable the government to coordinate existing experience, the current situation, and future trends; get feedback from all aspects in real time; make appropriate encouraging industrial policies; reduce negative intervention; and promote the market to play a decisive role in factor allocation.

5.4. Public service facility subsystem

The public service system is a balanced urban system. Because the tensions between survival and development and security and interests always exist, there is a dynamic change in which one goes down and the other goes up. Public service is an important force needed to balance these ups and downs. Unlike the private service, public service is for all people and includes public use and benefit. It is a regulating force that can smooth fluctuations and maintain balance to avoid social collapse and maintain the continuous operation of the current system. Supply, execution, demand, and supervision are the four adaptive agents of the urban balance system. The two characteristics of the public service facility subsystem are being indispensable and being excessive.

In digital twin cities, through real-time information aggregation and big data analysis of agents and factor flows, the specific public service demand agents can be accurately determined. The degree of information asymmetry among the four types of agents will be greatly reduced, and public service providers can provide more diversified services and achieve the large-scale production of personalized public services while fully respecting the private information of agents. Through immediate feedback and behavior data, demand and supervision can be realized, and public service systems can be optimized. Connection makes social individuals more equal and generates trust. Through these interconnection of everyone and everything, the relationship between subject and object (i.e., administrators and citizens) can be improved, and everyone can share resources, information, and opportunities. Different types of actors will

be in an equal position, thus achieving decentralization and flattening the levels of government. Better allocation of public resources can be achieved based on symmetry of information and substantial reduction of transaction costs. The value of intelligence lies in ensuring resource allocation approaches information symmetry to the greatest extent possible, making transaction costs approach zero, and allowing wider and fuller public services even with limited budgets. The key to the intelligence of public services is not to pursue the correct implementation policies in advance, but rather to support the policy learning and adapting to changes in the environment to meet the differentiated needs of different individuals, at different times, in different places. The digital twin city has greatly improved public service resources, and employment has become more flexible and diverse. The high-cost model of “rearing troops for a thousand days and using troops for a while” will be replaced by the normal mode of “all soldiers respond at any time.” Cities can thus respond more effectively to emergencies and the abilities of individual citizens will be effectively brought into play. Personal values will be more respected.

In the planning stage, Xiong'an New Area proposed building an urban smart bus, which would be responsive to the needs of users. Based on the digital twin city architecture, the customized bus was introduced to meet the needs of citizens for high-quality bus travel according to real-time and diverse demands, which included automatically forming bus lines and arranging suitable vehicles. A comfortable station community was generated, and the specific routes were automatically generated based on demand corresponding to the station and vehicle. While optimizing services, smart buses can also reduce wasted resources and avoid the provision of excess public services. Market-oriented suppliers can participate in the operation and maintenance of the urban public transport system and are subject to unified standards as well as to fair and transparent supervision.

6. Conclusion

The opportunity to build future cities from scratch is scarce in urban development, but it is still possible to apply the digital twin concept to small-scale complex systems, such as enterprises and parks, before expanding to the whole city and even urban agglomerations. The quantity of digital twin practices has provided a broad space for theoretical, technological, and management application innovation.

Problems emerge when expanding urban territory, and to solve them, we need to reflect on basic urban theory, analyze digital twin cities from the perspective of urban system theory, and guide the healthy development of these cities, instead of being bound by technology. According to the practice of developing digital twin cities in China, some consensus has been reached. Supported by new infrastructure, such as the 5G base station, high-speed railway, urban rail transit, new energy vehicle charging stations, big data centers, and artificial intelligence, we have established a complete 3D database, unified data standards, and new management services for application in urban society, economy, culture, and many other fields, with a focus on planning and urban governance scenes. While expanding the urban territory, digital twin cities inevitably have encountered three problems: (1) technology stacking cannot fundamentally solve urban problems, and cognitive limitations (2) lead to the treatment of digital twin cities as management tools and (3) slow development of innovation and application of digital twin cities. These problems are due to a lack of understanding of digital twin cities from the perspective of the whole city. Thus, we need to realign the concept of digital twin cities based on system theory.

This current study looked at digital twins from the complex system perspective, building a systematic framework for digital twin cities and deconstructing the digital twin city into four subsystems for planning, infrastructure, industry, and public service facilities. We analyzed the rule changes of these four subsystems against the backdrop of the information age to gain a comprehensive and in-depth understanding of digital twin cities. The construction of digital twin cities should be separated from the technologies employed and considered from the perspective of the city's overall development trend.

Declaration of competing interest

The authors declare that there are no conflict of interests, we do not have any possible conflicts of interest.

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