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How Can Smart Buildings Enabled by IoT Technology Accelerate Sustainable Green City Development: Case Studies in China

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Abstract: The purpose of this paper is to explore the role of Internet of Things (IoT) enabled smart buildings in accelerating sustainable green city development, especially in light of the stated targets by the Chinese government of achieving carbon peaking and carbon neutrality, which are known as dual carbon goals. This paper uses CiteSpace to make a comparative analysis of domestic and foreign literature, and finds that relatively speaking, the application of IoT in China is still in the design and construction stage of buildings, and the later operation management lacks consideration. At the same time, the individual smartness of architecture has not yet been connected to a smart ecosystem. Therefore, this paper further selects three project cases of the Beijing Winter Olympic Games project, Haier Smart Home and Xiongan New Area, corresponding to three scenarios of event venues, residences and entire communities, and puts forward suggestions on the promotion of sustainable urban development by IoT driven smart buildings.

Keywords: smart buildings; IoT; sustainability; CiteSpace; China; urban city development; carbon

1. Introduction

Nowadays, the global urbanization process is developing rapidly, the urban population is increasing, and the urban infrastructure is facing great pressure. The construction sector traditionally satisfies urban demands, but it also leads to significant energy consumption and environmental degradation. It is reported that this industry is responsible for over 40% of the world's energy consumption and contributes to 37% of worldwide emissions of greenhouse gases (United Nations Environment Programme, 2022; Chen et al., 2021). How to achieve sustainable development in the process of urbanization has become a global concern.

The development of smart city concepts represents a progressive strategy to tackle environmental and sustainability issues. At the forefront of this revolution are smart buildings, a fundamental pillar in the development of green and sustainable urban environments. Enabled by the technology of Internet of Things (IoT), smart buildings are likely to be integrated seamlessly into the fabric of smart cities, contributing significantly to the efficiency, comfort, and ecological footprint of urban landscapes (Allam & Dhunny, 2019).

China, with its ambitious environmental targets and burgeoning urban development, presents a unique landscape for the execution and scaling of IoT-enabled smart buildings. Chinese government's commitment to achieving carbon peaking and carbon neutrality—collectively referred to as the dual carbon goals—demands innovative strategies and technologies that can propel the nation towards a more sustainable future. This commitment aligns with the global endeavor to mitigate climate change and foster sustainability, just as the United Nations (UN) sustainable development goals outlined (Xu, Chen, et al., 2024).

This paper will be based on the concept of smart buildings, where IoT technology is applied in order to achieve a climate-neutral and sustainable economy. In Section 2, we will have a review of the state of the global smart building industry and present the existing literature and cases on the application of the IoT in smart buildings for sustainability. Section 3 and Section 4 will throw light on the current hot spots and evolution of IoT-enabled smart buildings in China through a comparative analysis using CiteSpace and a review of policies. Section 5 will thereafter focus on three distinct case studies in China: the Beijing Winter Olympic

Games project, Haier Smart Home, and the Xiongan New Area. Each case represents a unique scenario—large-scale event venues, residential living, and entire community development, respectively—showcasing the multifaceted role of IoT in enhancing urban sustainability. In Section 6, we will summarize and propose actionable recommendations for leveraging IoT-driven smart buildings to foster sustainable urban development.

2. Literature Review

The advancement of innovative technologies like the Internet, artificial intelligence, big data, blockchain, etc., has made smart construction an increasingly critical element in driving the sustainable evolution of urban areas (Jia et al., 2019). Smart buildings are connected through sensor devices and networks to achieve intelligent interaction between the building and the environment, helping to intelligently manage and optimize the environment in and around buildings. Unlike the "intelligent buildings" often mentioned in the past, intelligence is only a part of the composition of smart buildings. While "intelligent" emphasizes the use of ICT in buildings, "smart" also considers the needs of people and communities (Buckman et al., 2014). A smart building involves many factors such as the behavior of the building and its users, as well as all the surrounding buildings and all the people, objects, and external environments that may be associated with it. Therefore, smart building is a product of the integration and development of people, buildings, environment, and smart technology (Criado & Gil-Garcia, 2019). The future smart building is not a single building, but a building cluster, or even a building ecology (P. Yu, Hu, et al., 2023; P. Yu, Liu, et al., 2022).

IoT is essential to "smartening" buildings since managing intricate networks of interconnected functional entities from many architectural features is one of its concerns (Stojkoska & Trivodaliev, 2017). It is an "interconnection of sensing and actuating devices providing the ability to share information across platforms through a unified framework, developing a common operating picture for the building. actuating devices providing the ability to share information across platforms through a unified framework, developing a common operating picture for enabling innovative applications. (Yang et al., 2013; Gubbi et al., 2013)" Incorporating IoT technology into every facet of buildings' design, construction, and operation not only effectively reduces the carbon footprint of buildings, but, in the long run, also makes it more favorable for the economy to grow in a more sustainable and environmentally friendly manner (Kwok et al., 2024a, 2024b).

Currently, there are three primary ways that IoT technology is being applied in the building sector. The first aspect is the smart management of building construction, including building structure monitoring, construction quality monitoring and abnormal handling of the construction process (Lu et al., 2020). For example, Niu et al. (2016) make better decisions in construction by empowering construction resources to interact with the surrounding environment. The second aspect is the interconnectivity of devices within the building, which includes realizing smart energy saving and smart security in buildings, detecting environmental parameters, and providing smart building management and services (Yu et al., 2021). For example, Viswanath et al. (2016) used IoT to build a system of energetic management that adjusts the buildings' demand in response to a more balanced load control; Lulla et al. (2021) connected security devices inside and outside the building through IoT to realize the linkage and smart management of video surveillance, access control management, alarm system, etc., and to improve the safety of the building. The third aspect is the application of IoT in smart homes. Smart homes can greatly enhance residential comfort and green lifestyles because all home appliances are automatically connected (Choi et al., 2021; P. Yu, Lu, et al., 2022). For example, OpenHAB, an open-source IoT-based smart home software platform, optimizes services and energy use by monitoring the number and activities of occupants (Yang et al., 2018; Parocha & Macabebe, 2019).

Consider looking at the Sustainable Development Goals (SDGs) to gain a knowledge of sustainability. UN put forth these objectives in 2015 as a worldwide call to action to end poverty, safeguard the environment, and guarantee prosperity and peace for all people by the year 2030. In the framework of "peak carbon and carbon neutral" goals and policies, this paper focuses on the green growth of Chinese buildings and cities, particularly the beneficial contribution of smart buildings to the enhancement of urban sustainability. Thus, SDG7, Affordable and Clean Energy, SDG11, Sustainable Cities and Communities, SDG12, Responsible Consumption and Production, and SDG 13, Climate Action will be the main topics of this paper (see Figure 1).

Figure 1. 17 Sustainable Development Goals by UN.
Source: https://www.undp.org/sustainable-development-goals

3. Bibliometric Analysis

3.1. Research Methodology and Data Processing

Bibliometrics employs mathematical and statistical methods to conduct a quantitative examination of literature, scrutinizing its structure, evolution, and interrelationships. This approach equips researchers with a systematic methodology for evaluating the scholarly progression and future trajectory in specific academic domains (Liu et al., 2021). CiteSpace, which was crafted by Dr. Chao-Mei Chen, is the chosen analysis tool for this paper. This potent scientometric software discerns nascent trends, pivotal articles, and clusters of frequently co-cited research by examining the interconnectedness of keywords and referenced works (Chen, 2016; Chen & Leydesdorff, 2014).

This paper presents a comparative visualization and analysis of data from China and international literature related to the field of smart buildings. The data source of English literature is taken from the Web of Science (WoS) core collection database, and the search is set to "article"; the data source of Chinese literature is taken from journals in China Knowledge Network (CNKI) database, and the advanced screening is done by using "Beida Core", "CSSCI", "CSCD", etc. as the literature source, and the time span is set to 2012 to 2022. In order to closely relate to the research content of the article, this paper adopts three groups of subject terms, namely "smart building & smart city", "smart building & IoT", and "smart building & carbon emission", making the comparison results more comprehensive. With the aim of improving the literature data’s quality and accuracy, the exported statistics are de-weighted.

3.2. Analysis of Research Hotspots in Chinese and Foreign Literature

In scholarly works, keywords serve as concise encapsulations and high-level synopses of the research subject matter, capturing the essence and core themes of the documents (Chen & Ma, 2023). For this analysis, CiteSpace was utilized to perform a co-occurrence examination of keywords. The software configuration entailed a yearly time slice, the selection of "keyword" as the node type and the implementation of a g-index threshold (K=25). To improve network graph clarity, the resulting networks were refined through the application of Pathfinder and Pruning techniques.

To evaluate the structural integrity and clarity of clusters in a keyword clustering network, CiteSpace offers two distinctive metrics: the clustering module value (Q-value) and the mean silhouette score (S-value). Networks are deemed well-ordered when the Q-value falls between 0.3 and 1.0, while an S-value exceeding 0.7 indicates effective clustering (Chen et al., 2023).

3.2.1. Co-occurrence and clustering of "Smart Building" & "Smart City"

Table 1. High-frequency keywords in the co-occurrence analysis of "Smart Building" & "Smart City" based on WoS and CNKI databases.

Serial Number	WoS Keywords	Frequency (Centrality)	CNKI Keywords	Frequency (Centrality)
1	smart city	343 (0.37)	smart city	148 (0.96)
2	internet	63 (0.05)	smart building	60 (0.45)
3	big data	51 (0.07)	intelligent building	28 (0.15)
4	management	41 (0.20)	IoT	26 (0.16)
5	framework	38 (0.11)	architectural design	22 (0.21)
6	model	35 (0.09)	AI	17 (0.08)
7	challenges	26 (0.07)	cloud computing	13 (0.06)
8	design	25 (0.05)	appliance	12(0.05)
9	system	24 (0.06)	big data	10 (0.01)
10	innovation	23 (0.03)	smart community	9 (0.05)

Table 1 summarizes the top 10 most frequent keywords in WoS and CNKI databases. In addition to the search terms "smart city" and "smart building", "design" is a common high-frequency keyword at home and abroad, indicating that the design of buildings is the focus of attention in this field. Whether it is the high-frequency term "internet" in WoS or, "IoT", "AI", "cloud computing" in CNKI, as well as "big data" appears in both, all indicate that smart technology is the basic prerequisite for realizing architectural and urban smartness. In addition to focusing on information technology, international researchers are also concerned about the overall framework, management and innovation model of smart cities, which may be because international research is already deepening into smart buildings and smart city integration.

The main clusters formed by the collection of WoS core articles from 2012 to 2022, shown in Figure 2, include #0 "design," #1 "service-dominant logic," #2 "ICT," #3 "difference-in-differences," #4 "facility data infrastructure," #5 "equality," #6 "meta-heuristics algorithms," #7 "digital twin," #8 "data mining," #9 "digital divide," #11 "data-driven smart cities," #12 "green city". It indicates the increasing concentration of international scholars on the design and service model of smart buildings and smart cities. The effective clusters formed by CNKI's core journals in Figure 3 are #1 "internet of things," #2 "bim," #5 "informatization," #6 "urban architecture," #7" intellectualization," #9 "applications," #10 "intelligent buildings," and # 11 "building energy". It shows that Chinese scholars pay more attention to the technology application and degree of informatization of smart architectures and smart city.

Smart buildings are the foundation for cities to become "smart". The synergy between smart buildings and the overall smart city concept is pivotal for enhancing energy efficiency and advancing sustainable urban growth. Therefore, smart buildings need to be crafted with particular objectives in mind, aligning their design and functionality within a specific framework to support their role in smart city infrastructure (Apanavičienė & Shahrabani, 2023). The incorporation of smart buildings into the smart city matrix necessitates weaving them into the larger tapestry of urban systems. Leveraging information and communication technology (ICT), extensive data analytics, and a diverse array of IoT-connected devices and innovations, these buildings are structured to offer personalized and adaptable environments for inhabitants. They progressively expand their services to the community level, contributing to the formation of intelligent neighborhoods that enrich the broader urban living standard (Froufe et al., 2020; Mohanty et al., 2016; Al-Rimawi & Nadler, 2023). However, the current trajectory in the maturation of smart buildings and urban ecosystems faces challenges due to the existing fragmentation in smart technology application and the hurdles in achieving a cohesive network of sensors across building structures and infrastructures (Gyrard & Serrano, 2015).

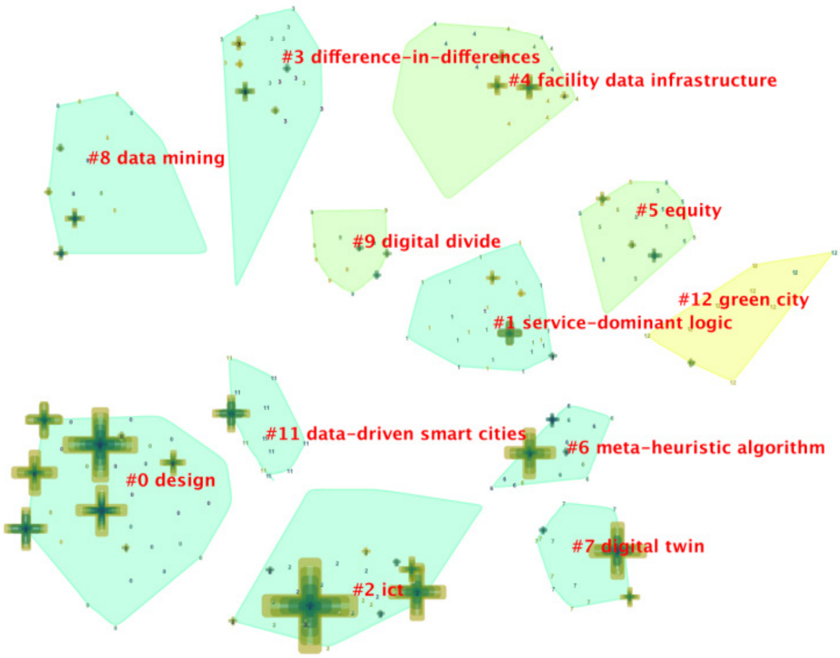

Figure 2. Knowledge map for keyword co-occurrence network analysis based on WoS database for "Smart Building" & "Smart City".
Note: Q=0.6084, S=0.8029

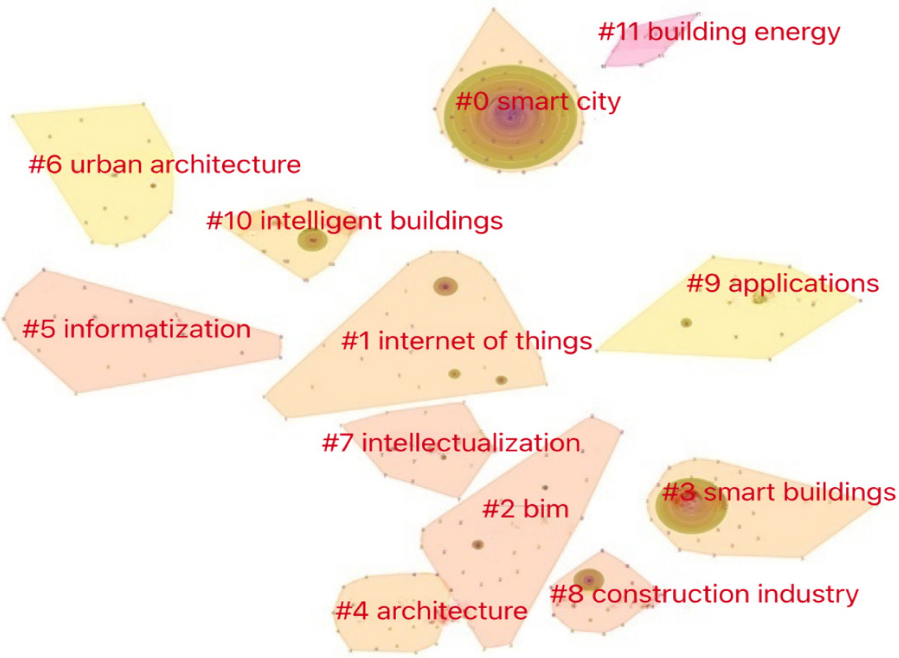

Figure 3. Knowledge map of keyword co-occurrence network analysis based on CNKI database for "Smart Building" & "Smart City".
Note: Q=0.726, S=0.9144

3.2.2. Co-occurrence and clustering of "Smart Building" & "IoT"

Table 2. High-frequency keywords in the co-occurrence analysis of "Smart Building" & "IoT" based on WoS and CNKI databases.

Serial Number	WoS Keywords	Frequency (Centrality)	CNKI Keywords	Frequency (Centrality)
1	IoT	255 (0.16)	IoT	77 (0.47)
2	internet	169 (0.10)	smart building	74 (0.42)
3	smart buildings	92 (0.13)	smart city	38 (0.29)
4	management	87 (0.10)	cloud computing	27 (0.33)
5	big data	36 (0.11)	AI	23 (0.06)
6	model	35 (0.15)	smart site	20 (0.06)
7	system	35 (0.10)	big data	17 (0.13)
8	framework	33 (0.02)	appliance	16 (0.10)
9	network	30 (0.03)	architectural design	14 (0.07)
10	energy efficiency	28 (0.16)	intellectualize	9 (0.04)

According to Table 2, it is found that in addition to the subject terms "IoT" and "smart building", "big data" is still the main keyword in domestic and international research, reflecting the importance of data processing and analyzing in this field. The difference is that international research focuses more on the management and modeling of smart buildings and IoT, while Chinese research focuses more on the application of IoT in smart buildings' design and construction (Xu, Lin, et al., 2024).

Effective clusters formed by WoS core articles from 2012 to 2022, shown in Figure 4, include #0 "5g," #1 "waste management," #2 "indoor air-temperature forecasting," #4 "virtualization," #6 "library renovation," #7 "algorithm design," #9 "hvac," #11 "intelligent smart energy management system," #12 "privacy," #13 "bim". where #1 "waste management," #2 "indoor air-temperature prediction," #6 "library renovation," #9 "hvac," #11 "intelligent smart energy management system," are the specific application objects and applicable scenarios of IoT in smart buildings. Figure 5 effective clusters formed by the core journals of CNKI are: #0 "intelligentization," #3 "cloud computing," #4 "big data," #5 "bim," #8" internet," #10 "smart site," #12 "upgrading and transformation," #14 "network layer." This clustering result reflects that China’s research on smart building and IoT focuses on the development of information technology and the application of IoT in building construction. The comparison reveals that the clustering results of international studies are more segmented and cover more relevant and specific applications, while the clustering results of China are relatively fewer and the topics are broader, indicating that China's research on IoT and smart buildings needs to be further deepened, especially in the mid- and late-stage of building operation and management.

The lifecycle of a building typically encompasses several key phases: design, construction, operation, maintenance, and ultimately demolition (O’Sullivan et al., 2004; Moreno et al., 2014). IoT technology can enhance the energy efficiency, security, and comfort of smart buildings throughout their entire lifecycle by harnessing data gathering, analytics, and advanced control mechanisms. The utilization of IoT within smart buildings has been delineated in the preceding introductory section. "BIM" (Building Information Modeling) is an innovative digital platform that facilitates the creation, administration, and rendering of construction projects. In recent periods, the construction domain has seen a fusion of intelligent technologies with BIM, leading to their deployment across various construction segments (Shin & Cha, 2023).

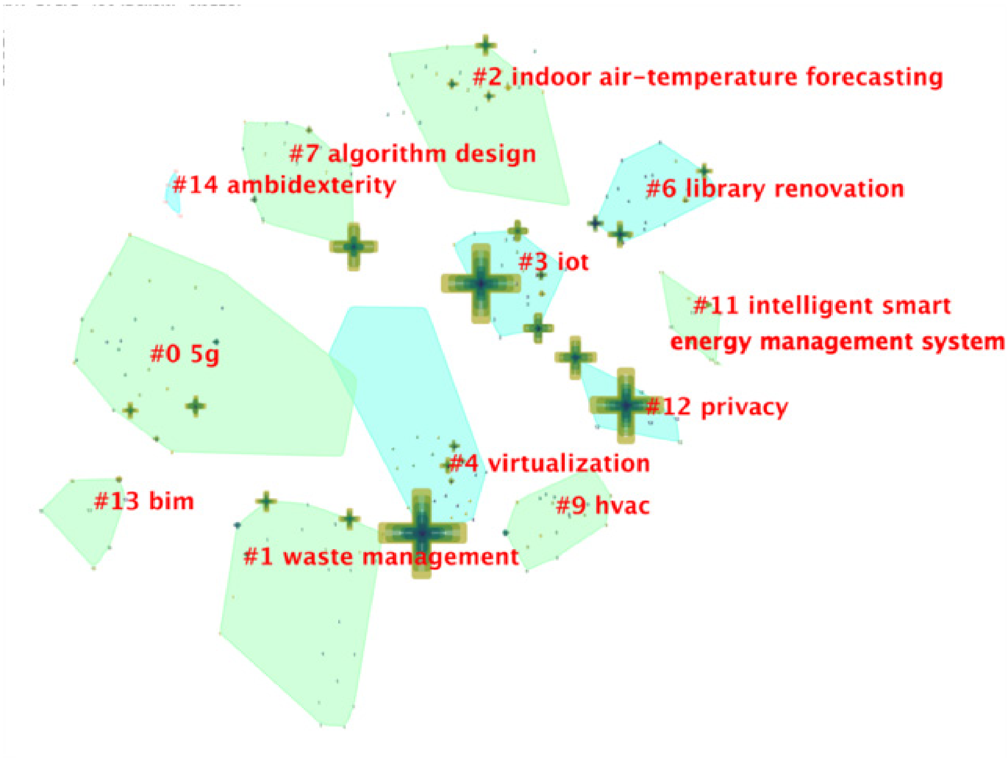

Figure 4. Knowledge map for keyword co-occurrence network analysis based on WoS database for "Smart Building" & "IoT".
Note: Q=0.5742, S=0.7828

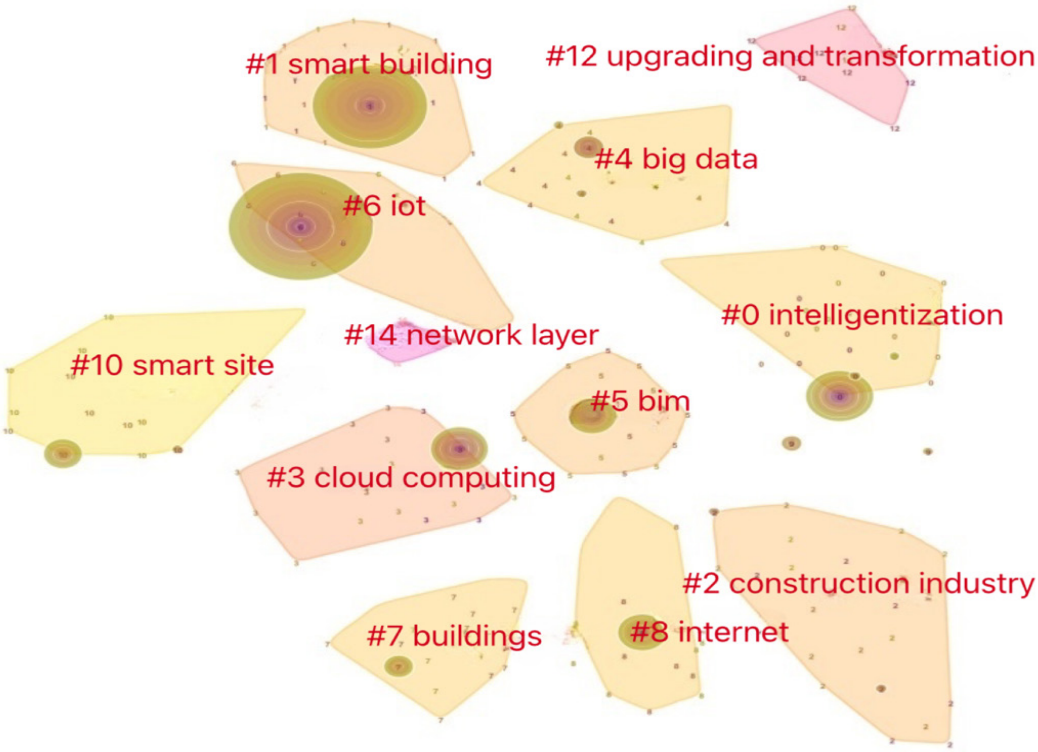

Figure 5. Knowledge map of keyword co-occurrence network analysis based on CNKI database for "Smart Building" & "IoT".
Note: Q=0.7023, S=0.8691

3.2.3. Co-occurrence and clustering of "Smart building" & "Carbon Emission"

Table 3. High-frequency keywords in the co-occurrence analysis of "Smart Building" & "Carbon Emission" based on WoS and CNKI databases.

Serial Number	WoS Keywords	Frequency (Centrality)	CNKI Keywords	Frequency (Centrality)
1	system	44 (0.06)	smart building	47 (0.58)
2	performance	36 (0.24)	green building	23 (0.30)
3	energy	31 (0.16)	smart city	15 (0.18)
4	design	29 (0.09)	green construction	11 (0.33)
5	model	29 (0.06)	AI	8 (0.04)
6	optimization	27 (0.16)	expositions	8 (0.06)
7	energy efficiency	26 (0.15)	carbon neutral	7 (0.04)
8	greenhouse gas emission	26 (0.07)	IoT	6 (0.07)
9	management	26 (0.12)	intellectualize	6 (0.09)
10	climate change	25 (0.12)	cloud computing	5 (0.08)

Looking at the high-frequency keywords comparison in Table 3, the outcome indicates there are obvious differences between Chinese and foreign scholars' research on the topics of "smart building" and "carbon emission". WoS keywords are mainly studied from the perspective of technology, performance and energy, emphasizing the optimization and management of smart buildings in energy efficiency and environmental impact. CNKI mainly focuses on the overall concept, development trend, technology application and smart urbanization of smart buildings, emphasizing the role of smart buildings in urban development and intelligence.

The main clusters formed by WoS core articles from 2012 to 2022, shown in Figure 6, include #0 "heuristic algorithms," #1" predictive rule-based control," #2 "thermal," #3 "climate-smart agriculture," #4 "district cooling," #5 "climate change mitigation," #6 "tvoc," #8 "scenario analysis," #9 "emissions," #10 "hydration" #11 "global warming potential". As highlighted earlier, the energy utilization of buildings constitutes a significant fraction of the worldwide energy demand. The escalating issue of climate change and global warming has underscored the importance of incorporating energy efficiency into the design parameters of smart buildings (Wurtz & Delinchant, 2017). The #0 "heuristic algorithm" and #1 "predictive rule-based control" are important algorithms and control methods for smart buildings in terms of carbon emissions, which can help buildings realize more efficient energy use and reduce carbon emissions. #2 "thermal," #3 "climate-smart agriculture," and #4 "district cooling" are specific applications for improving energy efficiency. #6 "tvoc," #9 "emissions," and #10 "hydration" relate to the study of smart buildings in terms of indoor environmental quality. Smart buildings enhance the standards of indoor habitats by regulating elements like pollutant levels and moisture. This ensures a more agreeable and salubrious living space for occupants (Floris et al., 2021).

The effective clusters formed by CNKI core journals in Figure 7 are #0 "green building," #2 "abb," #3 "low carbon," #5 "social intelligence," #6 "v2b," #7 "intelligent operation and maintenance," #8 "residential housing". In the context of the Chinese government's goal of "peak carbon and carbon neutrality", how to realize building #3 "low carbon" is an urgent problem, especially the building #7 "operation and maintenance" link (Yang et al., 2023). This requires not only the support of innovative technologies, but also focuses on the interaction between the building and its inhabitants and the application of #5 "social intelligence". One of the innovative solutions is #6 "v2b" (Vehicle-to-Building), which enables electric vehicles to be connected to the building's energy system, realizing a two-way flow of energy (Lo et al., 2023; Xu, Wang, et al., 2024). As for "green building", which appears in both CNKI keywords and clusters, it is also a concept based on building sustainability. Both smart buildings and green buildings focus on low energy consumption and resource saving, and the expansion of green buildings cannot be separated from the technical support of smart buildings, which also promotes the improvement of green building efficiency. Therefore, the combination of smart building and green building will become the future development trend (Jadhav, 2016).

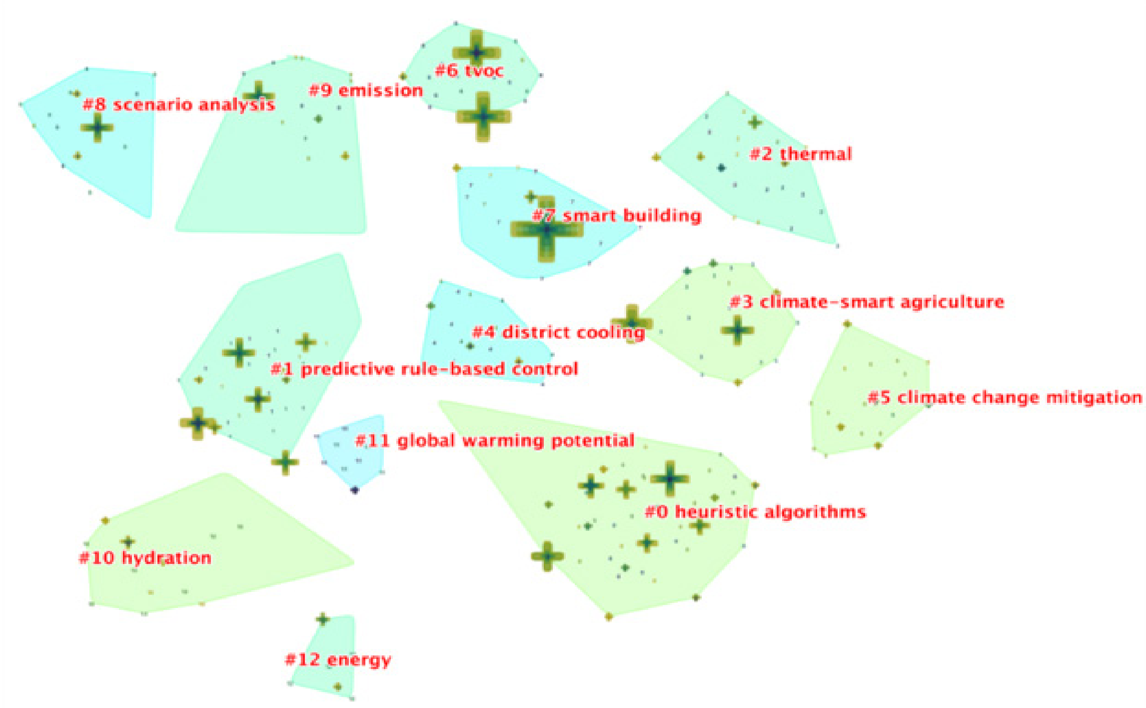

Figure 6. Knowledge map for keyword co-occurrence network analysis based on WoS database for "Smart Building" & "Carbon Emission".
Note: Q=0.5731, S=0.7807

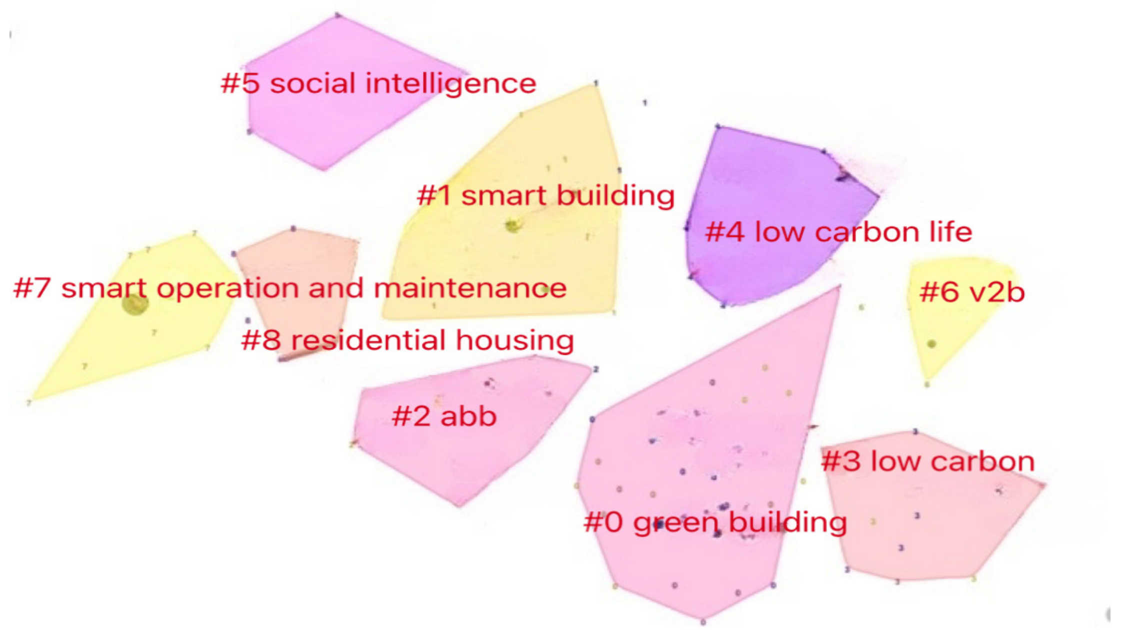

Figure 7. Knowledge map of keyword co-occurrence network analysis based on CNKI database for "Smart Building" & "Carbon Emission".
Note: Q=0.7465, S=08447

4. Major Policy Discussion

From the above analysis, it can be seen that China and the world both recognize the significance of integrating IoT, big data, and other smart tech in buildings. They understand that developing smart buildings and cities requires comprehensive solutions, and the breadth and depth of their research are expanding. However, we also note that the application of IoT and other technologies to smart buildings in China is not yet mature compared to that in foreign countries, and how to realize green and low-carbon buildings and even cities in the process of urbanization remains to be explored. Therefore, the following article will further study the policy guidance of the Chinese government, typical project cases, and the challenges and prospects of smart building development.

As the world's population superpower, China has experienced rapid economic growth since its economic reforms and opening-up policies, which has accelerated urbanization. Projections suggest that by 2050, 80% of the nation's population will be urban (United Nations, 2019). This trend indicates that China's traditional growth model, which depends on factors such as land and a large population, is becoming unsustainable (Qian et al., 2021). In response, China initiated smart city trials in 2012, guided by a directive from the Ministry of Housing & Urban-Rural Development, which identified the first set of 90 smart city pilots. The "National New Urbanization Plan" for 2014 to 2020 later integrated smart city development into the country's strategic agenda. By 2013, the number of pilot cities had expanded to 193 and further to 290 by 2014 (Wang & Deng, 2022; Wu, 2022). To support these initiatives, the government provided financial aid and various policy supports. For instance, pilot cities had preferential access to substantial, long-term loans with low interest from the China Development Bank, allocating as much as 100 billion yuan (approximately 127 billion U.S. dollars) for the next decade to aid these projects (Debnath et al., 2014). The Ministry of Housing & Urban-Rural Development conducts evaluations of the pilot cities at intervals of three to five years, with each city's pilot phase lasting between three and five years (Song et al., 2021).

The swift progress of smart city initiatives in China has led to a higher requirement of new infrastructures like IoT (Guo et al., 2016). In 2015, the development of IoT was integrated into broader government programs, including the "Made in China 2025" plan issued by the State Council. "Made in China 2025" calls for accelerated research and promotion of IoT technologies and proposes applications such as smart manufacturing and smart homes. Government financial support for IoT continues to appear in IoT planning documents, like the Ministry of Industry & Information Technology 's 2017 release of the IoT Development Plan (2016-2020), which calls for the establishment of IoT-related venture capital funds as part of stimulating IoT innovation and strengthening the link between financial capital and the IoT industry (P. Yu, Xu, et al., 2024a, 2024b). Increased venture capital support for the development of the IoT industry is encouraged (GSMA Connected Living Program, 2015).

With the intensive introduction of major policies on smart cities and manufacturing, as well as robust technology support such as IoT, China's construction industry is moving into the fast lane and ushering in a golden period of development. The smart building market is projected to expand with a CAGR growth of over 18.5% from 2021 to 2026, and the Asia-Pacific region, particularly China, is leading the charge (Mordor Intelligence, 2021). The "14th Five-Year Plan" outlines objectives for the smart growth of the construction industry, emphasizing the advancement of IoT applications and the smart conversion of municipal utilities, buildings, etc.; and implementing the digital management of urban buildings, public spaces, etc., "one map" and the unified management of the urban operation of one network; In the fields of smart community and smart home, a good digital ecology is created to provide data support for intelligent management of buildings. It can be seen that the government is actively guiding the organic integration and synergistic development of smart buildings and urban planning (Zhao et al., 2021).

Along with the 2020 carbon peak and carbon neutral "double carbon" target officially proposed, the construction industry's low-carbon emission reduction measures have also been followed up one after another. According to an important research result of the Ministry of Housing & Construction, "Study on the Implementation Path of Carbon Peak and Carbon Neutrality in Construction", under the scenario of total volume control, the total CO2 emission of China's buildings will reach its peak in 2030 (Yao et al., 2023). In 2022, the Ministry of Housing & Construction issued the General Code for Energy Efficiency and Renewable Energy Use in buildings, making the calculation of a building's carbon footprint a compulsory requirement for the first time. Carbon emission reduction will be carried out in the whole lifecycle of the building.

Table 4. Policy evolution of smart buildings/smart cities/IoT-carbon neutrality/Smart-Tech-green in China.

Time	Policy	Authority	Implications
2006.2	Outline of the National Medium- and Long-term Plan for Scientific & Technological Development (2006-2020)	State Council (PRC)	For the first time, the importance of developing IoT was raised.
2011.3	Outline of the 12th 5-Year Plan for National Economic and Social Development	State Council (PRC)	For the first time, guidelines for building smart cities were introduced.
2012.11	Interim Measures for the Management of National-Smart City Pilots	Ministry of Housing & Urban-Rural Development	China's 1st batch of smart city pilot cities ordered.
2014.3	National New Urbanisation Plan (2014-2020)	State Council (PRC)	For the first time, the construction of smart cities was included in the framework of the national new urbanization plan.
2015.5	Made in China 2025	State Council (PRC)	Highlight intelligence also greening as key directions for the construction industry's growth, stressing the use of energy-saving and intelligent building technologies, and encouraging technological innovation, transformation, and upgrading in the building industry.
2016.3	Government Working Report	State Council (PRC)	Accelerating the "cross-border integration, integrated innovation and large-scale development" of IoT provides policy support for researchers and scholars to apply IoT technology to the construction field.
2017.2	Opinions on the Promotion of the Continuous and Sound Development of Construction Industry	State Council (PRC)	It is pointed out that in new buildings and existing buildings renovation should promote the popularization of smart use and perfect the intelligent system O&M mechanism to modernise the construction industry.
2017.12	3-Year Action Plan to Propel the Next-Generation Artificial Intelligence Industry (2018-2020)	Ministry of Industry & Information Technology	It is the deepening of the implementation of "Made in China 2025", which makes it clear that IoT and other technologies are fully utilized to enrich the smart home products and smart building applications.

2019.4	New Urbanisation Priorities for 2019	PRC National Development & Reform Commission	Explicitly suggest to enhance the evaluation of new smart city construction by refining the evaluation index system for the smart cities' construction and development.
2020.11	Recommendations on the preparation of the 14th 5-year plan for National Economic and Social progress and the Vision for 2035	State Council (PRC)	For a start, the "dual-carbon" objective was put forward in the form of a document, emphasizing the consolidation of IoT sensing devices and communication systems into the unified plan and building of public infrastructures, and the promotion of IoT usage and the smartness transformation in buildings.
2021.10	Opinions on Advancing Urban and Rural Construction Green Development	General Office of the Communist Party of China Central Committee, State Council	Improving the green development of urban and rural construction in the three dimensions of "planning, construction and management".
2022.4	General Specification for Building Energy Efficiency and Renewable Energy Utilisation	Ministry of Housing & Urban-Rural Development	The first mandatory carbon emissions target for the construction industry.
2022.6	Circular on the Peak Carbon Implementation Scheme for the Urban and Rural Construction Sector	Ministry of Housing & Urban-Rural Development, PRC National Development & Reform Commission	Propose building green low-carbon cities, creating green low-carbon counties & villages, and peaking carbon emissions from urban and rural construction by 2030.
2022.10	Announcement of Pilot Cities for Smart Construction	Ministry of Housing & Urban-Rural Development	Beijing and 24 other cities are listed as pilot cities for smart construction for three years.

Source: Central Government website https://www.gov.cn

5. Case Study

The research method of case study is based on in-depth investigation of the phenomenon and situation of individual cases, which is a comprehensive research method for specific problems (Yin, 2014). In the following research process, we will discuss about typical cases of the application of IoT to smart buildings in China and give suggestions on how IoT-enabled smart buildings help accelerate and navigate the shift towards a more environmentally friendly and sustainable development.

5.1. Winter Olympics Games Program

The Beijing 2022 Olympic and Paralympic Winter Games adhere to "green hosting" idea, utilizing low-carbon technologies and existing venues and facilities to the fullest extent (Shi et al., 2023). Simultaneously, those newly constructed low-carbon venues, all adhering to green building criteria, includes four ice venues which use new CO2 refrigerants, and the completion of more than 50,000 m^2 hyper-low energy pilot projects. All venues utilize low-carbon energy, and 100% green electricity is used for conventional energy during the games to achieve carbon neutrality (Liu et al., 2023).

Take Bird's Nest as example. Through the in-depth application of the AIoT smart building operating system, the Bird's Nest has become the world's first 5G+AI+IoT large-scale cultural and sports venue. AIoT is based on artificial intelligence (AI) and IoT, intelligent computing like big data and blockchain as support, semiconductor as intelligent algorithm carrier, network communication and information security technologies as implementation guarantees, and 5G and other networking technologies as catalyst. In this way, AI can be empowered in IoT and finally realize the smart upgrade of IoT and buildings.

In terms of energy optimization and intelligent control, the Bird's Nest built a set of distributed low-carbon smart energy network for the venue by transforming energy-consuming equipment and installing IoT sensing and control nodes. The large screen of the command center can present the energy use of different zones, different time periods and different energy types in real time, so as to ensure energy utilization for major activities, and realize the smart management of energy consumption and carbon emission in operation. Through smart control of energy optimization, energy consumption is expected to be reduced by 20%-30% compared with before the transformation. With regard to smart control of health environment, Bird's Nest built a multi-dimensional health environment system covering quality of air, thermal and light comfort. Through the deployment of more than 450 sets of environmental intelligent sensors, more than 2800 sets of intelligent control terminals, including automatic pathogen elimination, air purification, air conditioning, fresh air, lighting, etc., the venue environment comprehensive perception, intelligent risk identification and comprehensive management of environmental problems are realized.

According to the Beijing Olympic and Paralympic Winter Games Economic Legacy Report (2022), the smart building integrated system will serve the use of the Beijing Winter Olympics during and after the games, and become a demonstration project of Beijing's digital twin city in public buildings and residential communities. The Winter Olympics project will effectively solve the industry's pain point problem of emphasizing construction over operation, explored a new model of smart building design, construction and sustainable operation in the post-Olympic era, and provided a demonstration case of "smart transformation and upgrading" for sustainable operation.

5.2. Haier Smart Home

At present, China's traditional household appliances, mobile phones, digital, household goods and other industries have already been in a state of demand saturation, and the growth is weak. The emergence of smart home will undoubtedly bring new development opportunities to the above industries, especially the current domestic smart industry of the whole house is still in its infancy, the market penetration is still relatively low, and consumers generally do not know enough about it. According to CSHIA, the number of domestic smart home units in 2019 is about 200,000 to 400,000 units, and in 2020 will continue to grow substantially on this basis, about 300,000 to 500,000 units, but it still only accounts for 1% of new developments. Compared with the fierce competition in traditional household appliances, mobile phones, digital, household products and other industries, Smart home market especially the whole house intelligent field can be said to be a piece of blue ocean market to be developed.

One of the gravest concerns the current industry faced is the absence of system-level scene linkage and spatial interaction between smart home products, and the ecological interoperability and product incompatibility between various manufacturers (Zeng et al., 2020). In 2020, domestic smart home enterprises have exceeded 242,000, but the vast majority of them are smart single product enterprises whose main business is smart appliances, smart lock, smart video and audio. The data in Figure 8. confirm this problem. It can be seen that there are many smart home products on the market, but it is difficult for enterprises to integrate smart solutions of the whole house, and it is difficult to achieve connectivity and function integration in a true sense.

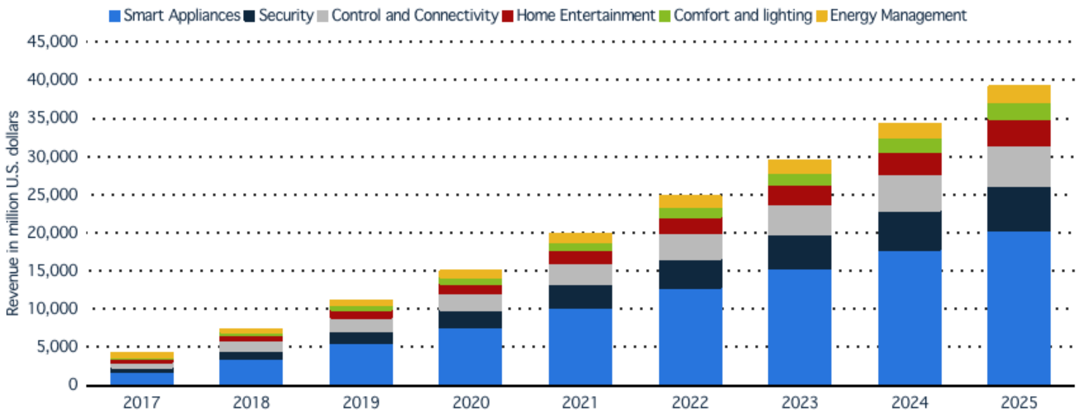

Figure 8. China Smart Home Revenue Forecast by Segment, 2017 - 2025 (Unit: USD Million).
Source: Statista

Haier Smart Home UhomeOS 3.0 is the latest upgraded version of Haier smart home ecosystem, based on IoT, cloud computing, big data, AI and other technologies, through user behavior analysis, data analysis, data modeling and other ways to achieve the goal of intelligence, connectivity, collaboration and openness, becoming the first enterprise in the industry to enter the decision-making intelligence. Different from the common hardware ecology and platform ecology which mainly focus on connected products in the industry, UhomeOS 3.0 is a complete and open smart home ecosystem. Through the interconnection between Haier itself and several manufacturers, it connects nearly 10,000 high-quality resource parties in various fields such as clothing, food and decoration, and builds the largest smart home scene ecology in the industry, which realizes equipment interconnection, data sharing and ecological collaboration.

For example, UhomeOS 3.0 supports diversified manufacturers of the main manufacturers of ecological cooperation, covering all kinds of equipment of the future household appliances, such as the speed preheating of intelligent oven, intelligent range hood negative ion adsorption, intelligent air conditioning one key air purification and so on, through the data, analysis, control to achieve equipment management and controlled in user habits of the release of services.

5.3. Xiongan New Area

The establishment of Xiongan New Area in Hebei Province was issued by the CPC Central Committee and The State Council on April 1, 2017. As a national plan for the millennium, Xiongan New Area is a new smart city. Xiongan New Area Smart IoT integrated transportation management platform takes building information model (BIM) as the carrier, uses IoT platform equipped with SiREID Engine, integrates the scattered equipment parameters and operation data of multi-brands and multi-systems into the daily operation and maintenance management functions of buildings and parks, and realizes the "strong combination" of BIM and IoT technology (P. Yu, Zhao, & Hanes, 2023; P. Yu, Zhao, & Sampat, 2023).

With the development of city perception system or IoT, the capture, calculation and sharing of real-time data have become a reality in combination with 5G, air-heaven integrated network, edge computing and blockchain, etc. The traditional BIM model construction mode has changed, especially with the introduction of AI, which enables the model to learn from real-time data. A new model is generated after continuous adjustment. The model of GIS+BIM+IoT has been widely discussed, in which data is organized and models are constructed in a loosely coupled way from the perspective of business scenarios, which has become one of the hot topics, such as the discussion between data center and model center. CIM mode formed on this basis is regarded as the initial state of digital twin cities, supporting the operation of smart cities in the future.

Xiongan BIM platform project firmly focuses on the space core, adopts digital technology to record the real-time growth and evolution law of Xiongan, and explores the construction of digital twin cities. It includes 6 stages: status quo, general regulation, control regulation, design (initial expansion depth), construction and completion. After completion, this BIM information model will be disassembled according to the operation requirements and return to the current space, and combined with IoT to realize the monitoring, early warning and evaluation of the city. The platform uses XDB open data format to realize the organic integration of multi-source data such as "big scene 3DGIS data + small scene BIM data + micro IoT data", so that digital municipal, civil buildings, roads and bridges, landscaping, and even urban furniture can operate on this platform, which will be connected with the ground and underground, indoor and outdoor spatial data. Planning, construction, and spatial data such as IOT water meters are integrated and communicated with each other to record the constant changes of spatial resources and assist urban decision-making and governance.

Therefore, Xiongan BIM management platform, as a platform integrating a variety of smart building technologies, can realize the whole-life cycle management and data-based operation of urban buildings, and explore the replicable and effective roads of transition from "individual smart" to "regional smart" and eventually to "urban smart".

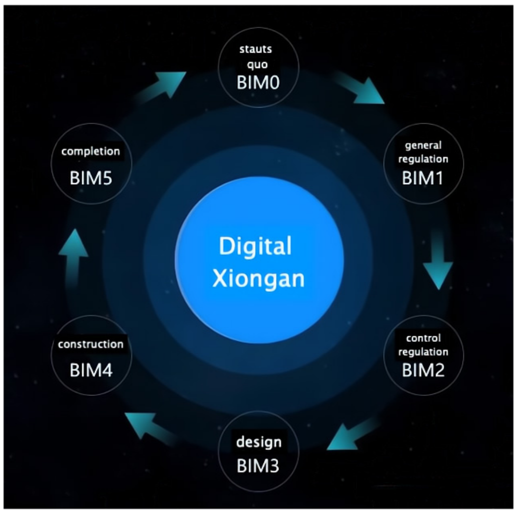

Figure 9. Six stages of BIM information model.

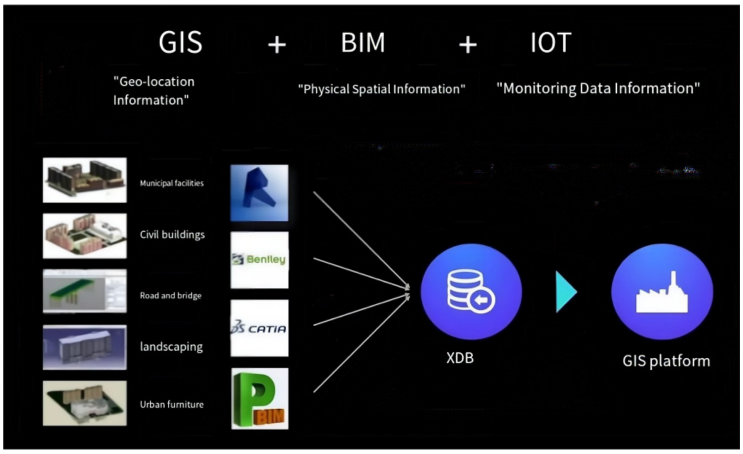

Figure 10. BIM management platform operating mechanism.
Source: DOI:10.16670/j.cnki.cn11-5823/tu.2023.01.01.

6. Conclusion

The exploration into the role of IoT-enabled smart buildings as a catalyst for sustainable green city development in China has provided valuable insights into the current landscape and future potential of this technology. Through the comparative analysis facilitated by CiteSpace, thispaper has identified that while China has made strides in incorporating IoT in the design and construction stages of building development, there remains a significant opportunity for growth in the operational management phase and in combining architectures into a broader smart ecosystem. The case studies of the Beijing Winter Olympic Games project, Haier Smart Home, and Xiongan New Area have illustrated the diverse applications of IoT technology in buildings, ranging from event venues and residences to entire community developments. These examples have shown that when IoT is effectively implemented, it can lead to enhanced operational efficiency, reduced environmental impact, and enhanced life quality for dwellers. However, they also highlight the necessity for strategic planning, sustained investment, and cross-sector collaboration to fully achieve the benefits of smart buildings for sustainable urban development.

This paper ends with a plea to policymakers, urban planners, and industry leaders to make the incorporation of IoT technology into building operations a priority, and to strive for interconnected smart ecosystems. This includes encouraging innovation, public-private partnerships, and investing in necessary infrastructure for widespread IoT adoption. It is also suggested that future research and development address the critical challenges of scalability, interoperability, and security. Additionally, there should be a focused effort to educate and involve all stakeholders, including end-users, to ensure that the shift to smart buildings is inclusive and beneficial to all.

By embracing the recommendations outlined in this paper, China can advance towards its dual carbon goals and set a benchmark for sustainable urban development that can be emulated by cities globally. Integrating IoT-enabled smart buildings into the urban fabric is not just a technological upgrade but a necessary evolution towards a more resilient, sustainable, and human-centric future.

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