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Review

Digital Twins for Intelligent Green Buildings

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Abstract: At present, the integration of green building, the intelligent building industry and high-quality development are facing a series of new opportunities and challenges. This review aims to analyze the digital development of smart green buildings to make it easier to create contiguous ecological development areas in green ecological cities. It sorts out the main contents of Intelligent Green Buildings (IGB) and summarizes the application and role of Digital Twins (DTs) in intelligent buildings. Firstly, the basic connotations and development direction of IGB are deeply discussed, and the current realization and applications of IGB are analyzed. Then, the advantages of DTs are further investigated in the context of IGB for DT smart cities. Finally, the development trends and challenges of IGB are analyzed. After a review and research, it is found that the realization and application of IGB have been implemented, but the application of DTs remains not quite integrated into the design of IGB. Therefore, a forward-looking design is required when designing the IGBs, such as prioritizing sustainable development, people's livelihoods and green structures. At the same time, an IGB can only show its significance after the basic process of building the application layer is performed correctly. Therefore, this review contributes to the proper integration of IGB and urban development strategies, which are crucial to encouraging the long-term development of cities, thus providing a theoretical basis and practical experience for promoting the development of smart cities.

Keywords: intelligent green building; Digital Twins; smart city; information interaction; real-time visualization

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1. Introduction

Intelligent Green Building (IGB) has progressed from environmental idealism to a business case with strong industry growth and long-term business opportunities over the last two decades [1]. IGB projects are gaining popularity among architects, engineers and owners. Climate, environment, resources, economy and culture should all be considered when deciding where to build, and its index system includes categories such as safety and durability, health and comfort, convenient life, resource conservation and livable environment [2–4]. Green building encompasses many aspects of living, such as temperature, sunlight, light source, voice control and air, all of which require scientific and technological support. Green buildings, as opposed to conventional buildings, should incorporate green concepts into all aspects of construction, including design, research and development, building materials, sales, construction, operation and maintenance, and they should form a closed-loop construction industry chain [5,6]. To build such a green industrial system and reduce carbon emissions, scientific and technological innovation must be combined and infiltrated into all links; therefore, digital and energy innovation can be combined and infiltrated into all links. Promoting energy-saving building transformations, carrying out urban heating system transformations, vigorously developing green building materials and promoting building industrialization are key elements for the construction industry to achieve carbon neutrality [7–9].

At present, the integration of green construction and the intelligent building industry, as well as high-quality development, are confronted with a slew of new opportunities and challenges. More and more new things are emerging, such as new infrastructure, new driving forces, new industries and new models, which bring more market space to the construction industry and put forward higher requirements for strengthening and playing a larger role in the construction industry [10,11]. Intelligent building energy saving is a new science that is part of the green energy-saving building branch, and the original professional division of labor is different. Many professional areas, such as architecture, construction, heating and ventilation, are included in smart architecture, which is formed by the intersection and combination of many professional disciplines [12–14]. The analysis and evaluation of intelligent buildings should follow the green building energy-saving principle. Various management systems of intelligent buildings are systematically designed based on the building energy-saving design, from optimization to the control of technical measures. Driven by the environment and energy conservation, intelligent buildings use buildings as platforms and actively promote the progression of building platforms to green environmental protection and ecological balance [15]. The connotations and technical means of intelligent building are constantly expanding in these fields. At present, the construction industry's unavoidable progression trend includes green concepts and intelligent means. As a result, intelligent building planning and design must be based on green concepts and related methods, and intelligent technologies should also be used for supervision and control in green buildings [16,17]. Relevant standards have been established, and intelligent technology is required for green building, thus providing strong support for green building performance improvement.

In IGB, computerization and digitization have a significant impact on how physical/engineering assets are managed throughout their life cycles. In the operation and maintenance stage, the realization of a comfortable living environment and intelligent building management is a complex issue that not only necessitates comprehensive information, such as historical operation, maintenance records, facility performance and accurate location, but it also involves multiple stakeholders. During the operation and maintenance phase, the asset management process must maintain integrity, effectiveness and interoperability. To maintain dynamic information, support activities and create a comfortable environment, an effective and intelligent asset management system is required. To improve operations management, various tools are used, including a computerized maintenance management system, a computer-aided facilities management system, a building automation system and an integrated workplace management system. However, facility management professionals continue to expend significant effort and time extracting the various operations and maintenance (O and M) data they require [18–20]. As a result, there is still a lack of an integrated system to manage information distributed across multiple databases and to support the various activities in the operation and maintenance phases. Digital Twins (DTs) are widely promoted as a digital model that both represents assets dynamically and mimics real-world behavior [21,22]. DTs are data-driven, which necessitates a well-defined and well-organized system architecture to oversee its concrete implementation, constantly identify gaps with the real world and provide a path for future trends.

To summarize, DTs have become an important component of new infrastructure, and the wave of new infrastructure also encourages the emergence of DT cities. The physical world's infrastructure is transformed into an intelligent form in the core series of data elements, and the digital world forms a new form with DTs as traction. Green buildings have become the mainstay of realizing this vision, with the goal of "dual carbon" and the gradual advancement of smart cities. Therefore, exploring the intelligent and digital development of IGBs is of great practical significance to the progress of social, economic and environmental intelligence. In the field of green building, invisible innovation creates a new ecosphere within the DTs of architecture. The key contents of IGB are sorted out, and the application and value of DTs in intelligent buildings are summarized, providing a theoretical foundation and practical experience for promoting smart city progression. The overall structure of this review is as follows:

- Section 1 introduces the development status and trend of the core word involved, green building, and mentions the advantages of the combination of DTs and IGB.
- Section 2 conducts a specific overview and analysis of the intelligent application, realization and trend of IGB.
- Section 3 discusses development research on the integration of IGB and DTs.
- Section 4 summarizes and studies the subsequent development advantages and challenges of IGB, making their advantages and problems more prominent.
- Section 5 is the conclusion. It summarizes this review, highlights the results of this research and further understands the deficiencies and follow-up prospects.

2. Intelligent Development of Green Building

The core of green building advocates for energy saving and low carbon emissions throughout the building's life cycle, as well as human-centered and harmonious coexistence with nature. Green building development and construction is not only an important way to save energy and reduce emissions in cities, but it is also an unavoidable choice for implementing sustainable development. The carbon dioxide emission reduction effect of green buildings with different logo types and stars, on the other hand, varies. Green building has grown rapidly over the last decade, and the number of projects with green building evaluation marks has also increased dramatically. However, it should not be overlooked that there are still issues such as unbalanced regional development, insufficient technical requirement implementation and an imperfect market promotion mechanism in the process of green building development. The key is to encourage the development of green and ecological urban areas, to create contiguous green building development areas and to encourage the large-scale progression of high-level green buildings.

2.1. Content and Adoption of Green Building

2.1.1. Content and Development of Green Building

Green building has become a hot topic all over the world as a representative of building energy conservation. Green building exploration and research on a global scale began in the 1960s. Paolo Solerui, an Italian–American architect, was the first to propose the new concept of arcology [23]. Thermal comfort is prioritized, passive design is prioritized and renewable energy is maximized, resulting in lower energy consumption. In 1991, Brenda and Robert Weil proposed the definition of green building for the first time. In contrast to Paul Solerui's arcology, Brenda Weir and Robert Weir's green building concept takes climate, environment and energy into overall consideration in the architectural design [24–26]. Green building evaluation is a revolution and enlightenment movement in the field of architecture, and its significance extends far beyond energy saving. It is innovative and organically integrated from multiple perspectives, resulting in a building that is in harmony with nature, that maximizes resource and energy use and that creates a healthy, comfortable and beautiful living space. Its revolutionary impact on architecture is examined from the perspectives of technology, society and the economy. The sustainability dimensions of green buildings are shown in Figure 1.

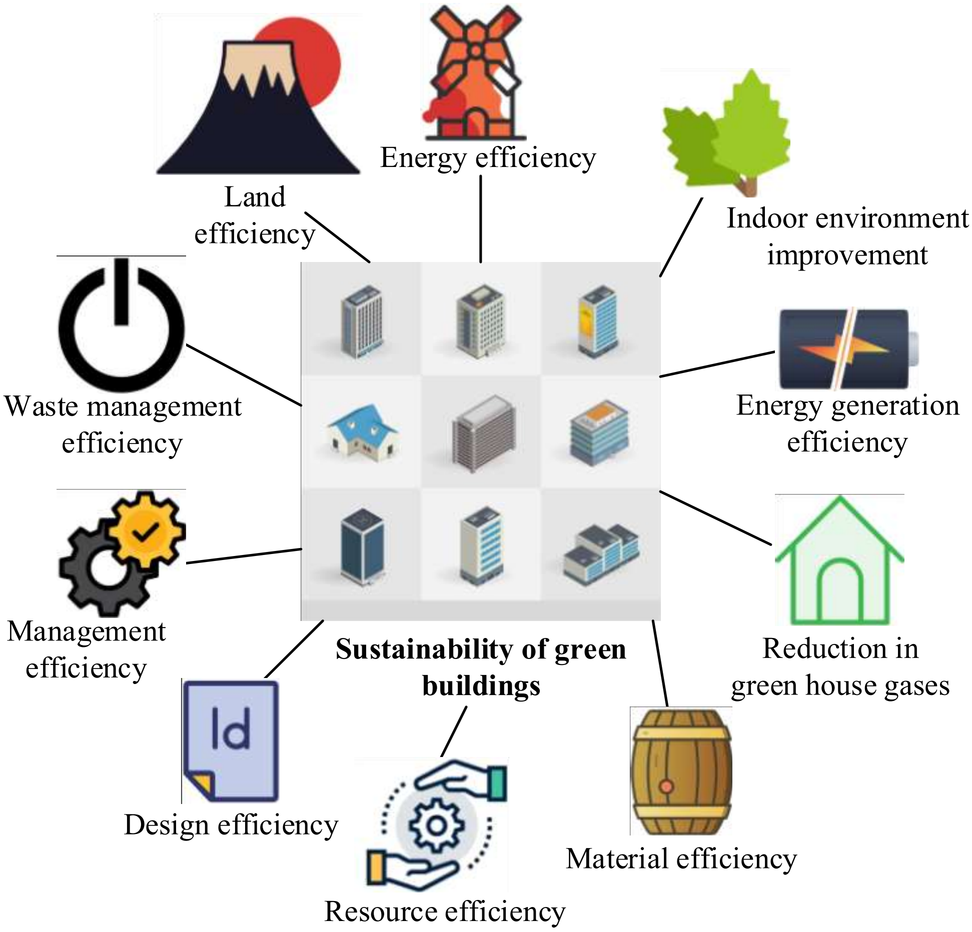

Figure 1. Sustainability dimensions of green buildings (Source: the authors).

As shown in Figure 1, the sustainability dimensions of IGB are mainly reflected in energy efficiency, land efficiency, indoor environment improvement, waste management efficiency, power generation efficiency, management efficiency, the sustainability of green buildings, greenhouse gas reduction, design efficiency, material efficiency and resource efficiency. Early green building research was primarily focused on single technical issues, and technical means were isolated and one-sided, with no organic body. The consciousness of integrated design and economic research is far from divorced from economic analysis, and it is only the cognitive stage attached to strategy research [27]. However, the early results of single technology research have laid a solid foundation for the multidimensional progression and system integration of contemporary green building. The advancement and deepening of green building strategies are carried out in various fields such as materials, equipment and morphology. With the advancement of technology, the integration of technology and other design elements has begun to shift from simple superposition in the past, focusing more on the design of the envelope itself, to an organic combination of technology and the overall system of the building, gradually becoming a green building system [28–30].

When an IGB is designed, the architect's task is not only to add visual pleasure to artifacts. To build sustainable architecture that adheres to social progress, the visual design process must be based on environmental regeneration and human health. There are many studies on the sustainable design of IGB. According to Plageras et al. (2018) [31], it is critical to ensure that buildings are green and sustainable in order to build a green and sustainable city. Green building refers to the application of green technologies throughout a building's life cycle, i.e., reducing waste through the use of sustainable building materials and recycling them from construction to operation to demolition. In addition to sustainable materials, energy consumption control and CO_2 reduction are important factors for green buildings [32–34]. If properly implemented, energy-efficient windows, heat and cold regulators, insulation systems, ventilation systems, efficient pumps, smart meters and smart management systems can reduce energy consumption by 50%. Greening requires the efficient design of energy systems. Natural light can be used efficiently to reduce electricity costs while also improving people's health and productivity. Green buildings, according to Su et al. (2021) [35], can use low-energy appliances and energy-saving lighting. Passive solar design is used to heat, cool and light homes without the use of electricity or mechanical devices. The design elements of a passive solar building are depicted in Figure 2.

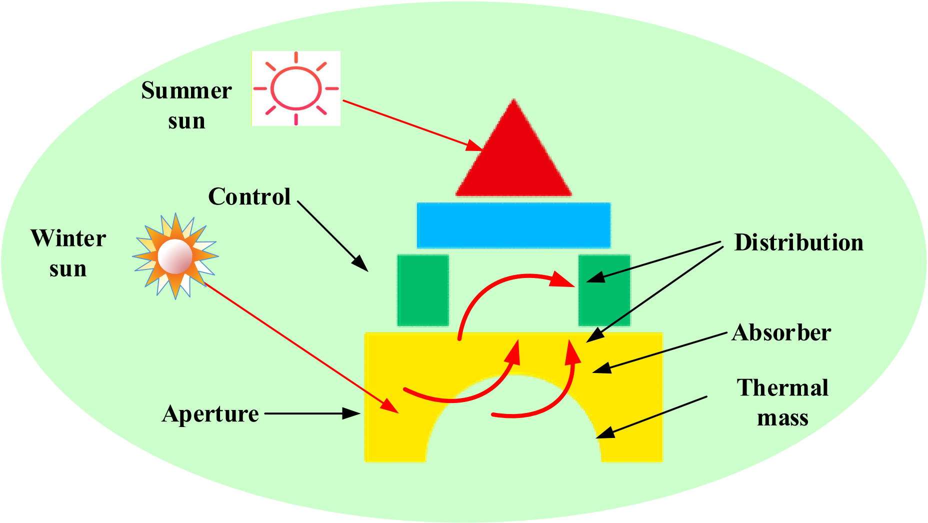

Figure 2. Design elements of passive solar buildings (Source: the authors).

As demonstrated in Figure 2, as part of the building's green design, windows and skylights are arranged with elements such as sunshades, panels and heat absorbers to capture and distribute natural heat and light. Passive solar heating works by capturing the heat of the sun and storing it for use when the sun is not shining on the building.

Architectural design should account for space utilization as well. According to Bano and Sehgal (2018) [36], an open-plan raised floor system and a reduction in building height are two effective ways to use space that can help make the building greener. Furthermore, the open spaces aid in good air circulation and light transmission, resolving heating and lighting issues and reducing the building's reliance on air conditioning and lighting. According to Nguyen et al. (2017) [37], green building can improve building efficiency while also reducing the negative environmental impact of the construction industry through recycling. Green buildings, as an architectural innovation, face numerous challenges in entering the market, which is occupied by traditional buildings. The first is saving for the building, which refers to total savings over the entire life cycle. Saving materials, water, electricity and gas are common concerns; however, saving land and capital should also be considered. According to Cecchini et al. (2019) [38], land conservation is the most important thing in a city. Only with land can roads, parking, landscaping and squares be built to make the city more comfortable and livable. Saving money is also essential. A virtuous business model can only be created by spending less money, serving more people and creating more value. According to Fan and Xia (2018) [39], efficiency and saving are complementary, and one of the fundamental goals of green building is to maintain high efficiency over a long term. Efficiency must lead to economic growth. For example, if existing energy-saving lamps for indoor lighting are replaced with LEDs, the same lighting can have much lower power and high electricity efficiency, thus saving a lot of electricity. At the moment, the efficiency of green buildings is challenged by two issues. First, most efficient systems and equipment have higher initial investment costs and are more technically complex than existing conventional practices, making them difficult to promote and accept during construction. Second, building system efficiency necessitates a high level of maintenance management. Most buildings' maintenance and management levels are currently low, and the efficiency of many systems and equipment is difficult to demonstrate.

As a result, the above studies suggest that achieving high efficiency is difficult and necessitates breakthroughs in scientific and technological innovation [40–42]. The establishment of a green building evaluation system is an unavoidable result of green building's gradual improvement and systematization. It integrates green building organically, allowing green building, information, computers and many other disciplines to coexist on a unified platform [43–46]. The evolution of a comprehensive evaluation system provides designers, planners, engineers and managers with an easier and more regulated green building evaluation tool and design guide than ever before.

2.1.2. Concrete Adoption of Green Building

At present, some IGBs have been launched, such as solar buildings in Chicago, many solar-panel-powered buildings near Tower Bridge in London and solar homes in Harvard, Massachusetts, as follows:

There is a magnificent eco-building in Chicago. There are no brick walls or panels, but plants were planted to divide each room where the walls should be. This type of wall is known as a green wall, and this type of building is known as a plant building. According to Chandrika et al. (2019) [47], the tracking device on the facade of a solar building has multiple circular solar collectors. Throughout the day, it can rotate in the direction of the sun, increasing the power generated by the solar panels attached to the tracking device by 40%. Even the wind pressure experienced by solar panels can be converted into clean energy. Building integration design refers to solar houses in which semiconductor solar cells, which convert solar energy into electricity, are embedded directly in walls and roofs rather than having bulky equipment mounted on roofs to collect solar energy [48,49]. T.R. Hamzah and Yeang Sdn Bhd, internationally renowned ecological architects, designed the Singapore Ecological Design in the Tropics (EDITT) building. Its design, which won a tropical eco-architecture competition, is located in Singapore at the intersection of Waterloo and Middle Roads. The EDITT is an eco-building that meets the client's needs for retail space, exhibition space, an auditorium and a variety of other environmentally friendly features. The plant-covered skyscraper can increase biodiversity, restoring the local ecosystem and increasing greenery. The ratio of green space to living space is one-to-one. One of the most important aspects of organic design is observing plant habits in surrounding buildings to ensure that the chosen plants coexist harmoniously with the building and do not compete with native plants. The green space stretches from the street entrance to the roof, combining with the 26-story EDITT tower to create a one-of-a-kind ground-level landscape. The activity of the street shops and the surrounding pedestrians enhances this extension from a flat space to a vertical space. With respect to the environment and energy savings, it has an 855-square-meter solar panel area that can provide 39.7 percent of the building's energy. Second, it has biogas production equipment, which produces gas and fertilizer through bacterial action and is used for lighting and plant fertilization. Third, its building materials are largely recycled, and each floor has a resource recovery system, making it the building with the highest level of environmental protection and greening [50–52].

There are numerous new designs in the vicinity of the famous Tower Bridge. The most recent is the vertical farm, which uses two tall towers to capture solar energy to power Tower Bridge. Plants grown in the tower are available for sale at London Bridge

Market. The Dubai Tower is not entirely powered by solar energy, which is only a theoretical goal. According to Kumar et al. (2020) [53], the vertical farm is unique because the bottom is covered with solar panels, and the tower is flat and angled to reduce sunlight penetration below. The tower houses people, whereas the underground houses cinemas, restaurants and shops. Three massive 225-kilowatt wind turbines generate massive amounts of energy in the design. Furthermore, the south-facing facade is covered with 4000 photovoltaic panels, which effectively absorb the desert's endless sunlight.

Jenson-DeLeeuw is a gorgeous 2200-square-foot home in Harvard, Massachusetts. Renewable energy is generated to power electric vehicles and to meet the energy needs of homes. It is built on a gently sloping site to maximize solar energy for its solar panels and interior spaces. It produces 21,000 kilowatt-hours of electricity per year. Extra energy is saved in two 16 kWh batteries. The solar panel and battery power three branches, which provide heating and cooling as required. The battery system, which is monitored on a daily basis, can store energy for use at night and in inclement weather. The house generates 23% more energy than it requires. This provides owners with a large amount of reserve energy at a low cost.

2.2. *The Intelligence of Green Building*

Smart ecological cities represent an opportunity for the intelligent building industry, as competition in the intelligent building industry is fierce right now. A smart ecological city represents an opportunity for the intelligent building industry's future advancement. Many scholars have applied artificial intelligence technology to the research of green building. According to Eze et al. (2021) [54], many green construction technologies, such as solar power generation and water source heat pumps, are required under green evaluation standards. In addition, because these contents are indeed unbearable for small buildings with respect to construction and operation costs, the realization of key technology value for energy conservation and environmental protection must be specialized. Green building is limited and restricted. To achieve sustainable development, it must be viewed through the lens of an ecological city. Green building should be prioritized above the city, and green ecological cities are an unavoidable trend of green building. Singh et al. (2020) [55] define a smart city as having "information communication infrastructure, information application basic system, intelligent building, and smart industry." In addition to these, a smart city operation guarantee system is required, and these smart cities cannot be sustainable without these mechanisms and institutions. The concept of intelligent buildings advances the goal of green building by reducing hazards. Building management is made more sustainable and cost effective by combining intelligent building technology and analytics with advanced digital services. According to Almeida et al. (2020) [56], the most advanced IGB primarily employs sensors for the automatic control of lighting, air quality and climate, as well as intelligent instruments and energy management systems, allowing intelligent buildings to achieve intelligent energy control. Finally, efficient energy distribution between buildings is realized, transforming the entire city into a sustainable and energy-saving city. According to Yu and Zhang (2021) [57], the principle of reduce, reuse, and recycle (3Rs) refers to actively participating in the design, construction and operation of intelligent buildings; therefore, they are more likely to be green. Intelligent buildings necessitate more computing power because they contain many complex heterogeneous subsystems. Intelligent buildings can increase their computing power by incorporating technologies such as cloud computing, fog computing, etc.

Based on the above studies, it can be found that the emergence of the Internet of Things (IoT) not only reduces our burden of life, but it also facilitates the construction of intelligent buildings. In the field of the IoT, the use of IoT devices, such as smart phones and various sensors, improves the experience of intelligent buildings while also increasing power consumption and costs, such as electronic product radiation and growing carbon footprints [58–60]. As a result, intelligent buildings must be more environmentally green, which is why IGB exists. IGB aims to protect the environment by implementing energy efficiency and intelligent design, as well as to provide an ideal climate environment that can adapt to the various activities and demands of users. Intelligent green building design has now become a critical component in preserving natural sustainability and protecting non-renewable resources.

The rapid development of information and communication technology and the Internet of Things in IGB require the mass production of related supporting equipment, which consumes a lot of resources, especially electricity, thereby increasing the carbon footprint. To ensure environmental sustainability, reduce our carbon footprint and combat global warming, we must pay close attention to reducing electricity consumption, greenhouse gas emissions and e-waste. Many scholars have applied intelligent technology in IGBs. According to Jin et al. (2021) [61], intelligent buildings provide maximum comfort and achieve smooth coordination between existing heterogeneous systems, allowing for easy control, coordination and management. Intelligent buildings can be green by utilizing environmentally friendly building materials, deploying alternative energy sources, optimizing energy use and lowering greenhouse gas emissions. An IGB is linked to the complex external environment because the weather has a large impact on the activity of such buildings. According to Prada et al. (2020) [62], energy consumption is a critical factor in greening, and the intellectualization of buildings should ensure the optimization of energy consumption in order to reduce greenhouse gas emissions. IGBs can be used as nodes for renewable energy generation centers, distributing excess energy generated by microgrids and smart grids.

In summary, when intelligent technology is applied to the sustainable development of green construction, intelligent buildings employ sensors, actuators and microchips to create a network of intelligent and adaptive software that provides occupants with a responsive environment that makes life easier and smoother [63,64]. Many sensors deployed on different devices in different subsystems generate massive amounts of data, which are sensed by cloud computing platforms, and expert solutions are provided via machine learning. Figure 3 depicts the architecture of an IGB's heating, ventilation and cooling systems.

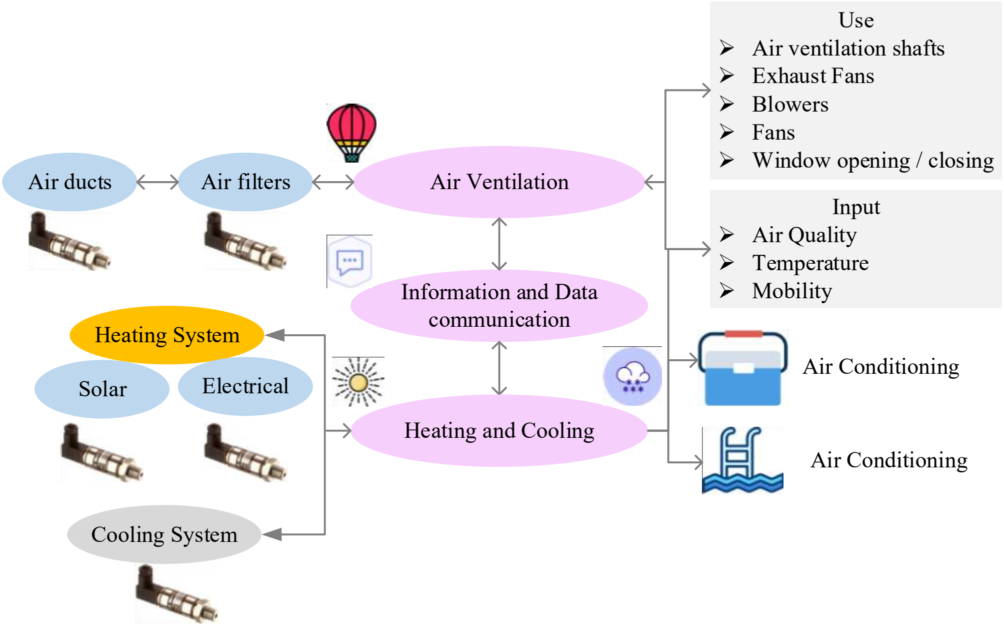

Figure 3. Architecture of heating, ventilation and cooling systems for intelligent green buildings (Source: the authors).

As shown in Figure 3, in an IGB system, the smart grid is an important part of it, which obtains electricity from various sources and distributes it within the building as needed. Smart grids draw power from a variety of sources, including conventional power lines, by utilizing natural resources such as wind and solar power. Smart grids are in charge of balancing electricity from various sources, such as wind turbines and solar panels. The smart grid exchanges data with the cloud service primarily based on input parameters such as temperature, air quality, mobility and brightness captured by sensors installed in and around the building. The final decision on which device to run the fans, air conditioners, lights, elevators and other equipment is made based on the input data. Yu et al. (2020) [65] proposed that communication technology and the Internet of Things (IoT) are the two pillars of intelligent building. Intelligent standards are achieved by connecting sensors and control systems to lighting, electricity meters, water meters, pumps, heating, fire alarms, refrigeration equipment, elevators, access control systems and shading systems. According to Global Market Research Consulting, the global intelligent building market is expected to grow from 5.37 billion USD to 24.73 billion USD by 2021. According to Panteli et al. (2020) [66], the environmental benefits of intelligent buildings include the conservation of natural resources, reductions in waste generated by buildings and the preservation of ecosystems. Greenhouse gas emissions are the most significant pollutant emitted during building construction and operation, and the primary source is the combustion of fossil fuels and coal. As a result, when compared to non-green buildings, smart patterns in green buildings reduce electricity consumption by 30%. The use of IGB has greatly reduced the negative effects of global warming. Smarter use of green building components can increase worker productivity, and green building materials can also improve people's health.

2.3. Realization and Adoption of Intelligent Green Building

The field of intelligent buildings has been paying increasing attention to green development, and the coordination of buildings and their surroundings is fully considered during the construction process. Energy-efficient and environmentally green buildings have become an unavoidable trend in building development [67–69]. There are many intelligent green buildings all over the world right now. The Siemens Crystal Tower in London is 6300 square meters in size. It can save 50% of its electricity and reduce CO_2 emissions by 65%, making it a model of high energy efficiency. The Crystal Tower's heating and cooling needs are met by renewable energy. The roof also includes a photovoltaic model for green electricity generation and a rainwater collection model for recycling rainwater.

It is necessary to collect information in various fields such as the environment and buildings during the IGB construction process in order to create favorable conditions for the control and management of green buildings. According to Bibri et al. (2020) [70], building control is diverse, and solar energy can be used to provide light and heat while consuming little energy. Environmental ecology, energy, resources, buildings, security and communication networks are all part of building management. Green goals must be achieved through integrated management on a unified platform. The eco-house, which is located in the city of Tokuoka, has become a model of eco-friendly housing in the area and is one of 20 eco-house projects funded by the Ministry of Environment. Moisture and heat can be diffused through the skylight in such a space, making it an air conditioner. The exterior wall is finished with fire-resistant stucco. Moisture and heat are captured by interior walls. As a result, the eco-house can draw heat from the sun in the winter and cool outdoor air at night in the summer to reduce indoor temperatures. The eco-house incorporates a solar power system that utilizes direct solar heat. The flow of hot air is controlled by circulation fans. Underfloor heating in the void spaces creates a comfortable interior environment with high operational efficiency.

According to Zhang et al. (2020) [71], IGB integrates green configuration, natural ventilation, natural lighting, a low energy consumption envelope, new energy utilization, green building materials and smart control through scientific overall design. It has the characteristics of efficient resource utilization and circulation, energy-saving measures and a healthy environment. The Phipps Sustainable Landscape Center in Pittsburgh, USA, systematically demonstrates advanced technologies in landscape design, energy efficiency, indoor environmental quality and material conservation. All waste and storm water on the site can be effectively treated within its own boundaries as a result of green infrastructure. When designing the appearance and structure of the center, the designers used natural lighting whenever possible to reduce power consumption. The building′s interior is outfitted with a geothermal system that can be adjusted to an appropriate room temperature based on temperature changes in the four seasons. It not only improves people′s indoor comfort, but it also significantly reduces energy consumption caused by indoor heating and cooling.

An analysis of the current situation of IGB construction by the above-mentioned relevant scholars reveals that greening requires the establishment of environmental, energy, resource, ecology, security and other monitoring and management systems. The achievement of these objectives is inextricably linked to the category of intelligent building. The implementation of intelligent building systems and the realization of greening are inseparable and not mutually exclusive. The Bullitt Center in Seattle, billed as the greenest office building, employs biomimetic, or bionic, concepts to create an organic structure that runs on sunlight and rain. The structure is topped with 575 solar panels, which generate 232,000 kilowatt-hours of electricity per year. When the sun shines in the summer, excess power is used to feed power plants and is recycled when it rains. Only the bottom two floors of the six-story building are made of cement to reduce carbon emissions. The remainder of the structure is mostly made of wood. Aside from solar energy, the IGB can also be composted on-site.

3. Intelligent Green Building in a Digital Twin Smart City

A smart city based on DTs is a complex system that balances economic, social and environmental progress. In this system, technology and nature are fully integrated, allowing humans to maximize their creativity and productivity while also promoting urban civilization and the coordinated sustainable progression of natural and artificial environments. Green building conserves resources, protects the environment, and reduces pollution while also providing healthy, applicable, and efficient space and harmoniously coexisting with nature throughout the building′s entire life cycle. IGB is not only a general architectural trend for the future, but it is also one of the defining characteristics of a smart city. Cities can become greener and improve the quality of life of their residents while lowering costs with the right technology. As a result, IGB has become the cornerstone of smart city construction.

3.1. Digital Twins in Smart Cities

3.1.1. Digital Twin 3D Modeling and Real-Time Visualization

Grieves first formally proposed DTs in 2011 to address NASA aircraft design, operation and monitoring. Many scholars have conducted research on the 3D modeling of DT technology. Sepasgozar et al. (2021) [72] proposed using real-time data acquisition and analysis technology to build a DT system and investigated the feasibility of realizing a production system with virtual and real fusion via DTs. Strong visual technology and real-time 3D technology are required to support the DT space. Real 3D, DTs, smart cities and other concepts have radically altered the architecture industry. Yang et al. (2021) [73] stated that true 3D is built by transporting structural and semantic geographical entities that support human–machine compatible understanding and real-time perception of the IoT on 3D geographical scenes. The digital elevation model, digital surface model, digital orthophoto, real orthophoto, oblique 3D model and laser point cloud are all examples of geographic scenes. Geographic entities are composed of basic geographic entities as well as component 3D models. A basic geographical entity consists of the ground object entity and the geographical unit, both of which can be expressed in two-dimensional and three-dimensional forms.

Therefore, a 3D model includes structural building parts, interior building parts, road facility parts and underground space parts. Other entities include specialized entities created by other industries. Real-time sensing data of natural resources, urban IoT sensing data and online Internet capture data are all examples of IoT sensing data. Natural resource real-time sensing data include real-time videos and images obtained through natural resource management services, as well as real-time information from automatic monitoring equipment. Data from urban IoT perception sources include surveillance videos, real-time images, such as for vehicle navigation, and mobile base stations. Online data are captured via the internet, including geographic location and text tables. The supporting environment consists of data acquisition and processing, database building management and an application service system, as well as the hardware and software infrastructure that supports the system’s operation. The acquisition processing system acquires, processes and fuses spatial data volume and IoT sensing data. The data integration database construction and database management systems are referred to as database construction management systems. An application service system is a service system that is focused on applications. The term “hardware and software infrastructure” refers to networks that are autonomous and controllable, as well as security, storage and computing display devices.

Similarly, the real-time visualization feature of DT technology has attracted the attention of many scholars. According to Perc and Topolek (2020) [74], when using scanners to collect data, multi-directional and multi-site data should be collected. As a result, point cloud data from multiple sites distributed in different local coordinate systems are generated independently. The most effective method for data splicing for point cloud data obtained from different sites is object-based registration. Shi et al. (2020) [75] proposed that, in the registration process, target fitting modelling for the target in the two adjacent stations should be performed first, the coordinates of the center point should be solved and target pairs should be formed after the target numbering is completed. The target pair is used to solve all the conversion parameters needed for adjacent site registration, and the point cloud data registration of two adjacent sites is completed by rotation, translation and scaling. In Revit, the elevation function is used to slice point cloud data into layers, and the specific shape and height of each physical object in the model are determined to build the corresponding model. According to Wang et al. (2021) [76], real-time visualization technology for DTs is essentially a real-time connection formed between the multidimensional data of the physical world and the virtual Digital Twin, in order to realize dynamic mapping between the two. Since the dynamic behavior of various models and physical entities in the virtual scene is consistent, users can master all physical world trends in real-time in the DT system. The parameters of various devices are collected by sensors with the help of the IoT, and the data are stored in real-time in the corresponding database. According to Jiang et al. (2021) [77], DTs emphasize simulation, modelling, analysis and auxiliary decision making, focusing on the reproduction, analysis and decision making of physical world objects in the data world, whereas visualization is the true reproduction and decision support of the physical world. A business decision model is established through data visualization based on its own massive data information, which can evaluate the development status of current transactions and can diagnose problems in the past. Furthermore, it can forecast future trends, providing managers with a comprehensive and accurate decision-making basis.

In summary, in the visualization-related research of DT technology, non-contact high-speed laser measurement is used in 3D laser scanning to obtain geometric data and image data of terrain or complex objects [78,79]. Post-processing software is used to process and analyze the collected point cloud and image data in order to convert them into 3D space coordinates in the absolute coordinate system or to create 3D visual models of irregular scenes with complex structures. As the data source of a spatial database, point clouds can also output a variety of different data formats to meet the needs of various applications.

3.1.2. Adoption of Digital Twins in Smart Cities

DTs are currently used in eleven major fields, including environmental protection, urban management, oil and gas, aerospace, electric power, automobile, health care, railway transportation, manufacturing, construction and shipping [80–82]. A city-level DT system based on visualized data can accurately reproduce the management elements of a wide range of cities in various fields after fully integrating the city's information resources in various fields, and it can achieve multi-dimensional visualization analysis of data indicators in business fields. According to Fan et al. (2020) [83], visual decision systems can effectively combine artificial intelligence model algorithms such as face recognition, human feature recognition and vehicle recognition. The main functions of a DT city are shown in Figure 4.

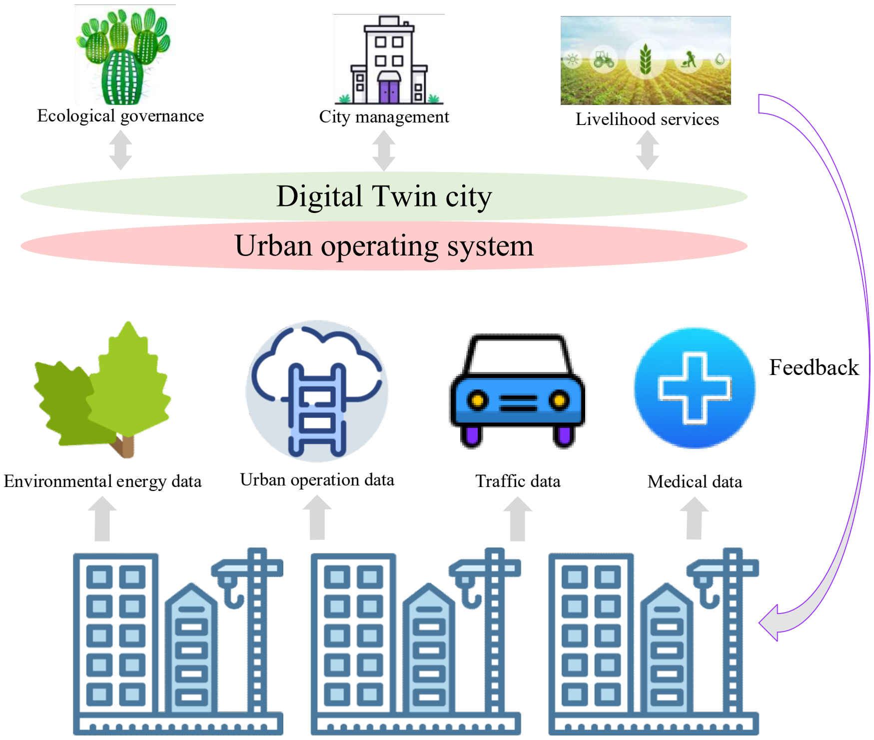

Figure 4. The main function of a DT city (Source: the authors).

As shown in Figure 4, in urban DTs, the information resources in various fields of the city and the results of artificial intelligence are visually analyzed to provide intelligent analysis support for users and better urban operation applications for city managers. Intelligent construction DTs serve as a link between the digital and physical worlds. Connected sensors and IoT devices collect real-time data about physical objects. These data are then combined with context and are processed before being used to comprehend, analyze, operate and optimize processes within an intelligent building. Nguyen et al. (2022) [84] proposed that the evolution of DT cities began with the 3D type in the 1.0 stage, progressing to the perceptive type in the 2.0 stage and then to the foresight type in the 3.0 stage. With respect to the model, data and calculations, the 1.0 stage 3D model is a spatial static model + statistical data + off-line calculation. The 2.0 stage perception type is a spatial static model + sensing data + perceptual calculation. The 3.0 stage predictive type is a spatial dynamic model + social data + in-loop computing. Shirowzhan et al. (2020) [85] stated that, with the development and rise of DT cities, urban information models, real 3D city models, urban simulations and other related concepts and technologies have rapidly developed. Second, the development of DT cities demonstrates collaborative momentum. The pace of urban interdisciplinary simulation and cloud simulation is quickening, and standard specifications and application scenarios will become DT cities' driving wheels. DT cities are virtual mapping objects and intelligent controllers of future physical cities, forming a complex, giant system of virtual and real correspondence, mutual mapping and collaborative interaction. With respect to construction focus, the core is the urban information model based on multi-source data fusion. The premise is the intelligent facilities and perception system, and the guarantee is the intelligent private network supporting the efficient operation of DT cities.

3.2. Integration of Smart Cities and Intelligent Green Building

Energy consumption, particularly in large cities, is expected to skyrocket by 2050, according to projections. As a result, smart cities are critical for maintaining a balance between supply and demand. Digital transformation promotes urban governance reform and can achieve energy conservation and emission reductions throughout the industrial chain as well as life scenes from production to consumption, which is consistent with the goal of carbon-neutral development. Although science and technology are redefining cities, when urban construction is optimized through science and technology, the negative externalities of science and technology should be addressed. Digitalization should be regarded as a significant breakthrough in order to realize the green transformation of an entire city. Many scholars in related fields have studied it.

Yigitcanlar et al. (2021) [86] believed that the coordinated development direction of digitalization and greening is an unavoidable trend in the process of building smart cities incorporating green buildings. They constructed a basic data acquisition system from the standpoint of building hardware facilities, such as an urban smart governance platform. To fully exploit its green and low-carbon utility, it is necessary to broaden more collection approaches and collection directions based on specific needs in the construction process, as well as to solve the problem of having or not having data. After data are obtained, it is important to consider how to ensure data quality; therefore, the data can be conducive to the smooth operation of urban smart management. In the calculation and sharing link, it may be worth investigating the use of deep learning algorithms to monitor the carbon emissions of city buildings. Furthermore, comprehensive analyses of urban carbon emissions, carbon footprint tracking, learning and simulation are required to optimize carbon emission activities. Green and low-carbon technologies are now integrated into all aspects of economic development. As a result, when the infrastructure is strengthened, more emphasis should be placed on opening up the follow-up application endpoint. According to Lian (2021) [87], in order to achieve green and low-carbon development, it is necessary to begin with a waste-free city. The organic combination of intelligent construction and the recycling of wastewater, waste gas, waste things and waste heat can significantly promote energy savings and carbon reductions in society. There is also a lot of digitization and green exploration in transportation, buildings and other energy consumption "big consumers" from the perspective of urban application scenarios. With respect to transportation, the use of alternative fuel vehicles is an important step toward reducing pollution from mobile sources. The construction of some intelligent charging piles that can collect data can not only meet the needs of car owners, but it can also assist operators in analyzing charging pile site selection, designing charging prices and optimizing operation, all of which can play a role in the layout of the urban power grid system. Mahmoud et al. (2021) [88] believed that the IGB itself could use a variety of sensors to achieve real-time monitoring of the building environment and energy consumption, as well as to improve building users' sense of acquisition and participation via terminal visualization devices. While meeting people's health and comfort needs, it can better guide the formation of green behavior habits, which is very beneficial for promoting sustainable urban management and human behavior management. First, building simulation technology is used to optimize the design; therefore, the building's energy saving rate can reach the standard of nearly zero energy consumption. Second, photovoltaic building integration technology is widely used, and air source heat pumps and fresh air heat recovery are installed to increase renewable energy proportions and to achieve energy cascade utilization. Furthermore, the installation of a smart energy and environmental management platform provides the owners with an intuitive and accurate energy consumption and environmental situation. Furthermore, intelligent equipment fault diagnosis service is available for property management systems, which can improve management efficiency while lowering operation and maintenance costs.

In summary, the above studies suggest that the fundamental requirement of IGB is to reduce the load on the environment while also providing a safe, healthy and comfortable living space. It is environmentally friendly and achieves the harmonious coexistence and long-term progression of humans, architecture and the environment [89,90]. Its concept is in-line with the needs of smart city construction. In a vast expanse, smart cities cannot exist on their own. As a result, the advancement of green buildings must be linked to the advancement of smart city construction. Sustainable development and people's livelihoods should be prioritized in the evolution of smart cities, and green building should be prioritized as well. In recent times, urban buildings have been continuing to evolve in a large-scale direction. If there is no intelligent building automatic control system for unified energy consumption management, the waste of water, electricity and other materials and human resources is unavoidable, and user satisfaction cannot be guaranteed. As a result, the intelligent building automatic control system should be the energy-saving building system of choice. Many building automation brands have also incorporated the product and technical concept of minimizing building energy consumption and facilitating personnel management into their development. Furthermore, they help management to realize distributed monitoring and the intelligent application of a building's central air conditioning system, water supply and drainage system, air supply and exhaust system and intelligent lighting system. In this day and age of IoT and cloud computing, businesses are actively pursuing technological transformation and innovation in order to provide users with a more intelligent and environmentally green experience.

Moreover, 715 million tons of carbon dioxide annually can be saved globally by capturing and managing energy consumption and improving building efficiency. With the rapid progression of the economy, the growth of economic construction will inevitably lead to a rigid increase in building demand, putting resources, energy and environmental protection under greater strain in the future. Strengthening green building design and implementing current IoT energy management tools for urban construction through green environmental protection and low carbon emission reduction are consistent with the national green low-carbon energy saving and consumption reduction guiding ideology. In addition, it can reduce resource consumption, maximize resource utilization and improve a city's economic and social benefits.

4. Development Advantages and Challenges of Intelligent Green Building

4.1. Development Advantage and Adoption Value of Intelligent Green Building

Firstly, green advancement of the building industry is critical in leading and promoting the continuous innovation of building technology. Long et al. (2021) [91] believed that, in today's rapid progression of the construction industry, the construction industry needs to accelerate development speed in order to realize energy conservation, environmental protection and greening, and to provide a healthy production and living environment for humans. IGB has a significant annual impact on building energy efficiency and CO_2 emission reduction, and these positive effects are expected to grow in the near future. Using photovoltaic systems can supplement consumers' energy needs while reducing their reliance on fossil fuels, thereby reducing global warming. The advancement of photovoltaic materials encourages the integration of photovoltaics and architecture, and photovoltaic building components can be manufactured to construct photoelectric buildings. The integration of a photoelectric building and an energy-saving building causes the building to increase energy based on energy savings and, as a result, to increase production capacity. According to Shafique et al. (2020) [92], photovoltaic systems can save resources, improve energy efficiency, reduce pollution and play a significant role in alleviating energy shortages in society.

Secondly, IGB integrates BIM, GIS, the IoT and cloud computing. As data centers become more important in new infrastructure, and as carbon emissions become a critical test, determining how to generate greater marginal benefits from ever-larger data centers is a critical issue. According to Azizi et al. (2020) [93], the IoT of buildings can be defined as a network of embedded software, sensors, electronic devices and connected buildings that can collect and exchange building data. The rapid deployment of data acquisition equipment and the automated control of traditional buildings is transforming the facilities management industry, and utilizing these data can provide practical assistance in improving management efficiency. The next step for IGB is to transition to zero-energy buildings. A zero-energy building significantly reduces energy demand by improving energy efficiency and ensuring energy demand balance through the use of renewable technologies. Solar photovoltaics has been widely used in the field of architecture to meet this requirement. Figure 5 depicts a schematic diagram of a zero-energy building's calculation boundary.

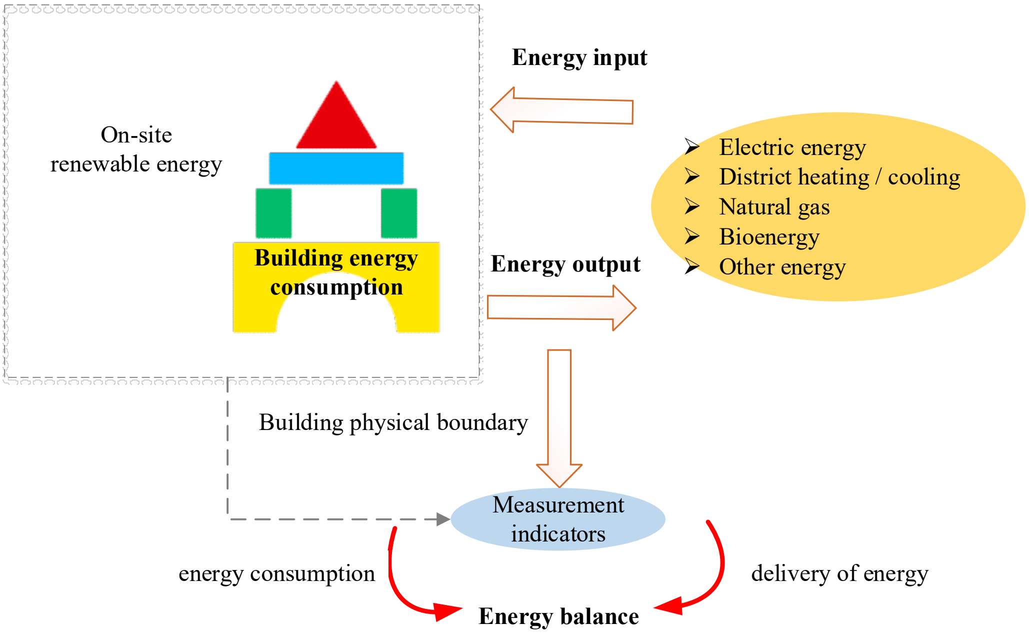

Figure 5. Schematic diagram of calculation boundary of zero-energy building.

As demonstrated in Figure 5, a zero-energy system is primarily powered by renewable energy and can operate independently of the power grid. According to Taherahmadi et al. (2021) [94], zero-energy green buildings not only save energy but also reduce greenhouse gas emissions. Solar, wind, biofuels and other renewable energy sources are primarily used in zero-energy building designs to meet the building's electricity and air conditioning needs. Wind turbines, solar hot-water collectors and geothermal energy are examples of in situ renewable energy generation technologies. There are currently four indexes for measuring a zero-energy building: end-use energy, primary energy, energy cost and energy carbon emissions [95–98]. The evaluation results of the four indicators listed above show significant differences. Given the intelligent building evaluation index factors, an attempt is made to build a simple IGB evaluation system under green building evaluation, thereby enriching the new green building evaluation standard and promoting the evaluation and progression of IGB. In addition, modern buildings are becoming more people-oriented, shifting away from the previous concepts of engineering, architecture or technology as the center. This has prompted architects, developers, and others to place a greater emphasis on providing more adaptable spaces while also increasing their emphasis on occupant comfort.

4.2. Challenges and Opportunities of Intelligent Green Building

First, given the current trend of vigorously promoting energy conservation, emission reduction and green building, it is no surprise that all industries are striving for carbon neutrality. It is natural for the construction industry to exert control over the entire construction process in order to achieve energy conservation and emission reductions, which is why green construction is aggressively promoted. Intelligent buildings have obvious benefits with respect to resource conservation, energy conservation and emission reductions. Intelligent construction is what makes environmental protection and low costs a reality. Green buildings, according to the IGB, necessitate more elaborate designs than ever before. Fine refers to high quality. If a design is not perfect, the installation is more difficult to perfect. Refinement necessitates increased effort on the part of the design unit. A large number of professionals are involved in the design of a building. Refinement includes not only the design of each major but also the overall matching and coordination of the design team [99,100]. As a result, the requirement of integrated design is advanced, posing a greater challenge to the current production and organizational modes of each design institute.

Second, green buildings necessitate higher standards and more stringent oversight. The existing standard code is the qualified line for construction, and strictly adhering to the standard code ensures only the pass line for construction. If the link between design and construction is broken, it is not a qualified product, let alone a green building. Currently, the overall quality of the building, from design to construction, is gradually deteriorating. Raising the standard requirements will increase the difficulty of design even further. The current market environment does not support the design initiative to raise standards or go above and beyond standard specifications. It is not only a cost issue but also a significant challenge for architectural design. It takes bravery to create a design that deviates from the norm. It also necessitates effort and social acceptance.

Third, green building necessitates forward-thinking design. From design to construction, the average project takes three to five years, and larger projects can take even longer. If advanced products are used in the design, the technology may not be mature, and the price may be higher. There should be considerations regarding what technology to use and what conditions to set aside for future technology. At the moment, most design institutes do not place a premium on these issues. In the event of a public health emergency, such as COVID-19, for example, the entire central air-conditioning system must be upgraded. Green building necessitates that the technology and products used in the building are appropriately advanced beyond the current level, leaving space and conditions for future improvement, which necessitates a superb design level and superb research and innovation abilities, both of which are beyond the capabilities of most design units [101].

To summarize, IGB is a globally recognized architectural development direction. With the advancement of social economy, today′s society is becoming more aware of the concept of sustainable development, which should focus not only on immediate benefits but also on long-term benefits. IGB emphasizes not only design and construction but also operation and maintenance during the construction process. Simultaneously, the design quality, construction quality, material equipment, operation and maintenance level of the building are important factors and preconditions influencing the building′s operation performance. The advancement of IGB necessitates a comprehensive improvement in the quality of the building′s foundation. IGB′s significance can only be demonstrated by doing the fundamental work of building application levels well.

5. Conclusions

The rapid advancement and cross-fusion of key enabling technologies such as digital design, virtual simulation and the industrial IoT have resulted in DTs undergoing a boom. Physical and digital models can be linked into a visual environment to visualize sensor data with the help of DTs. Three-dimensional visualization of the product′s operation, assembly, disassembly and maintenance processes may also be performed in order to facilitate product training and maintenance. Industries such as public safety, traditional retail, transportation and communal life are being reinvented as new smart cities emerge. Artificial intelligence, cloud computing, big data, 5G and the Internet of Things are all evolving, and several black technology projects in the domains of security, business, transportation and community have developed. Buildings are more complicated than ever before, and complex systems and subsystems must communicate with one another. DTs make it easier to manage these complicated spaces and all of the work that the company conducts with them, and they all work together to bring the building to life from conception to completion.

To achieve green urban development, environmental, energy, resources, ecology, safety and other monitoring and management systems must be established as DTs mature. As a result, the realization of greening and the introduction of intelligent building intelligent systems are inextricably linked. The development, essence and assessment indexes of IGB, a new industry, are all thoroughly described. The specific use of DTs in the field of intelligent buildings is examined in conjunction with the present frontier DTs. Furthermore, the opportunities and obstacles faced by IGB in the development process are summarized, along with the current social background and technological status quo, in the hope of providing a reference for supporting the sustainable growth of cities. IGB′s technical important elements and development trends are extensively summarized. IGB, on the other hand, needs to improve its intelligent control system for its interior environment. We will undertake study on this subject and perform an in-depth analysis of relevant technologies for creating IGB in future research.

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