EVALUATION MODELS AND DRIVING MECHANISM OF GREEN BUILDING DEVELOPMENT: A SPATIAL PERSPECTIVE

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Evaluation Models and Driving Mechanism of Green Building Development: A Spatial Perspective

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CERTIFICATE OF ORIGINALITY

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ABSTRACT

The increasing carbon emissions lead to severe climate issues of global warming, which has aroused public concerns in recent decades. The construction industry is one of the main contributors to carbon emissions. It is essential to apply sustainable innovations in the construction industry to tackle the climate challenge. As an innovative initiative to mitigate global warming, green buildings (GBs) perform well in energy-saving and carbon reduction, and they also provide a more comfortable living environment, which benefits residents' physical and mental health. Green building development (GBD) is on the agenda in many countries to alleviate climate change and reduce environmental pollution. In mainland China, along with the rapid increase of GBD, regional divergences of GBD are noticed and need to be assessed quantitatively. Meanwhile, the impact of geographical elements on critical success factors (CSFs) of GBD needs to be explored.

This study aims to develop comprehensive evaluation models to measure GBD and further explore CSFs and the driving mechanism of GBD. To achieve the aim, this study has five research objectives: (1) To establish a GBD evaluation model from a macroeconomic perspective, and to investigate spatial patterns of GBD in mainland China; (2) to propose a GBD efficiency assessment model, and to explore spatial patterns of GBD efficiency in mainland China; (3) to develop a model for investigating

the spatial correlations of GBD between different regions, and to explore the structure of the spatial correlation network in mainland China; (4) to identify CSFs of GBD, and to quantitatively analyze and compare the global CSFs and Chinese CSFs; (5) to clarify the driving mechanism of GBD, and to develop strategies for GBD improvement based on the research results. These objectives were achieved through different research methods, including systematic review, catastrophe progression model, data envelopment analysis, social network analysis, meta-analysis and questionnaire survey.

First, this study developed evaluation models to examine GBD, GBD efficiency and spatial correlations of GBD. The empirical analysis was conducted through the provincial data from 2008 to 2020 in mainland China. The results demonstrate that these evaluation models are effective. GBD in mainland China shows a three-step pattern in geography. The southeastern coastal regions were better than the inland regions, followed by the western regions. GBD efficiency was not stable, and the distribution patterns of GBD efficiency were not similar to GBD except for Guangdong and Shanghai, which indicates that most of the regions ranked high in GBD did not perform well in energy saving and carbon reduction. The spatial correlations of GBD in mainland China were insufficient. Two core regions and multiple centers eventually emerged in the GBD correlation network.

Moreover, this study identified CSFs of GBD through a systematic review, then

analyzed global CSFs and Chinese CSFs through meta-analysis and questionnaire survey, respectively. Furthermore, CSFs of GBD in different regions were compared quantitatively. The results demonstrate that different regions have different preferences for CSFs of GBD. CSFs in the government and management categories rank high around the world. Chinese practitioners believe financial CSFs are the most effective factors in GBD. Besides, the northwest region in mainland China tends to improve GBD through research and innovations, while the northeast region chooses the culture, education and knowledge.

In addition, the driving mechanism of GBD was explored based on the CSF analysis and stakeholder analysis. There are three bases in the mechanism: finance, labor and technology. Besides, the GB market and GB industry complement each other in GBD. The strategies for GBD improvement in mainland China are proposed, including improving the GB standard system, coordinating GBD and GBD efficiency, strengthening spatial correlations of GBD and solving the financial dilemma of GBD.

This research contributes to the GB knowledge body by presenting the investigation into GBD evaluations from a macro perspective and the driving mechanism incorporating CSFs of GBD. The findings would enable researchers, policymakers and practitioners to develop effective policies and make strategies to enhance the widespread implementation of GBs. Although the empirical analysis was conducted in

mainland China, the findings would be helpful to other countries worldwide, especially developing countries.

Keywords: Green building development; Evaluation model; Driving mechanism; Critical success factors; Spatial perspective; Mainland China

LIST OF RESEARCH PUBLICATIONS

Journal articles (Published):

[1] **Chen, L.***, Chan, A. P. C., Owusu, E. K., Darko, A., & Gao, X. (2022). Critical success factors for green building promotion: A systematic review and meta-analysis. *Building and Environment*, 207, 108452.

[2] **Chen, L.**, Chan, A. P. C., Darko, A.*, & Gao, X. (2022). Spatial-temporal investigation of green building promotion efficiency: The case of China. *Journal of Cleaner Production*, 362, 132299.

[3] **Chen, L.**, Gao, X., Hua, C.*, Gong, S., & Yue, A. (2021). Evolutionary process of promoting green building technologies adoption in China: A perspective of government. *Journal of Cleaner Production*, 279, 123607.

[4] **Chen, L.,** Gao, X., Gong, S.*, & Li, Z.* (2020). Regionalization of Green Building Development in China: A Comprehensive Evaluation Model Based on the Catastrophe Progression Method. *Sustainability*, 12(15), 5988.

[5] Pi, Z., Gao, X., **Chen, L.***, & Liu, J. (2019). The new path to improve construction safety performance in China: An evolutionary game theoretic approach. *International Journal of Environmental Research and Public Health*, 16(13), 2443.

[6] Gong, S., Gao, X., Li, Z.*, & **Chen, L.** (2021). Developing a dynamic supervision mechanism to improve construction safety investment supervision efficiency in China: Theoretical simulation of evolutionary game process. *International Journal*

of Environmental Research and Public Health, 18(7), 3594.

[7] Hua, C., Liu, C.*, Chen, J., Yang, C., & **Chen, L.** (2022). Promoting construction and demolition waste recycling by using incentive policies in China. *Environmental Science and Pollution Research,* 1-16.

[8] Yue, A., Mao, C.*, **Chen, L.**, Liu, Z., Zhang, C., & Li, Z. (2022). Detecting changes in perceptions towards smart city on Chinese social media: A text mining and sentiment analysis. *Buildings*, 12(8), 1182.

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[10] Su, W., **Chen, L.** & Gao, X*. (2022). Emergency decision-making: a literature review and future directions. *Sustainability*, 14(17), 10925.

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[12] Hua, C., **Chen, L.***, Liu C., & Yang C. (2023). The effect of incentive policies on the diffusion of construction and demolition waste recycling: A complex network

game model. *Waste Management & Research*, Manuscript ID: WMR-22-0829.

Conference papers:

[13] **Chen, L.***, Chan, A. P. C., Yang, Q., Darko, A., & Gao, X. (2022). Forecasting green building growth in different regions of China. *CIB World Building Congress 2022*, 27-30 June, Melbourne, Australia.

[14] Owusu, E. K., Chan, A. P. C., **Chen, L.**, & Amoah, P. (2022). Digitization, digitalization, and digital transformation (3Ds): explicating the disparities and applications of the 3Ds in the construction industry. *Construction Research Congress 2022*, 9-12 March, Virginia, USA.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 INTRODUCTION[1]

1.1 Research Background

Climate change, especially global warming, has become a challenging task that needs the joint efforts of all countries (Shi et al., 2017). The report from the Intergovernmental Panel on Climate Change (IPCC) reveals that the temperature around the world will increase 1.1-6.4 °C by 2100 (IPCC, 2007), leading to more extreme weather and natural disasters (IPCC, 2014). Building construction consumes numerous natural and human resources and emits vast greenhouse gas, the main contributor to global warming (Zuo et al., 2017). Besides, buildings consume much energy and emit greenhouse gas in the operation stage and the process of building renovation, refurbishment and retrofitting (Sharma et al., 2011). The disposal of buildings also consumes energy and generates solid waste, leading to a high landfill cost. Globally, buildings account for the largest share of energy consumption (35%) and carbon emissions (38%), the main drivers of

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[1] This chapter is largely based upon:

Chen, L., Chan, A. P. C., Owusu, E. K., Darko, A., & Gao, X. (2022). Critical success factors for green building promotion: A systematic review and meta-analysis. *Building and Environment*, *207*, 108452.

Chen, L., Chan, A. P. C., Darko, A., & Gao, X. (2022). Spatial-temporal investigation of green building promotion efficiency: The case of China. *Journal of Cleaner Production*, *362*, 132299.

Chen, L., Gao, X., Hua, C., Gong, S., & Yue, A. (2021). Evolutionary process of promoting green building technologies adoption in China: A perspective of government. *Journal of Cleaner Production*, *279*, 123607.

Chen, L., Gao, X., Gong, S., & Li, Z. (2020). Regionalization of Green Building Development in China: A Comprehensive Evaluation Model Based on the Catastrophe Progression Method. *Sustainability*, *12*(15), 5988.

climate change. Reducing buildings' energy consumption and carbon emissions is highly significant for environmental protection and people's living quality. Sustainable attempts in the construction industry have aroused public attention worldwide.

The World Commission on Environment and Development (WCED) first proposed sustainable development and defined it as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1988). According to the definition, three aspects of sustainability were deemed important: environmental sustainability, economic sustainability and social sustainability. Various innovative initiatives have been applied in the construction industry concerning the imperative trends of sustainable development. Green building (GB) is one such initiative applied in the construction industry.

1.1.1 Origin of Green Building

The origin of GBs could be dated back to a century or more ago (Li et al., 2014). The passive system (e.g., roof fan and underground air-cooling box) used in the early 19th century was a part of GB requirements to adjust the indoor temperature. In the 1960s, Paolo Soleri proposed a new concept of "Ecological Building," which could be considered the origin of the GB concept (Soleri, 1970). The book entitled "Design with Nature," written by Ian Lennox McHarg, was published in 1969, which marked the birth of the "ecological building" (Soleri, 1970). The energy crisis in the 1970s promoted energy-saving innovations in buildings, such as solar and geothermal energy. The Heads of State and Chiefs of Government gathered at the United Nations Conference on Environment and Development (UNCED) in 1992. It is a milestone event because Agenda 21 and the Rio Declaration on Environment and Development proposed at the conference are the first documents to connect the environment with economic and social development. They provided fundamental principles to guide governments in formulating policies that consider the environmental implications of socio-economic development. All the events laid the groundwork for the current GB prevalence.

Many researchers and institutions have defined GB, but no widely accepted definition exists. Robichaud and Anantatmula (2011) highlighted four pillars of GBs, including *minimizing* environmental impacts, *enhancing* the wellbeing and productivity of the whole communities, *receiving* economic returns and *applying* life-cycle approaches. Although GB definitions vary in different countries, these definitions have some elements in common: environment friendly, life-cycle management, economic sustainability, and energy-saving.

GBs gradually substitute conventional buildings (Hwang et al., 2017a). Previous empirical studies have shown that carbon reduction is not the only merit of GBs. GBs emphasize achieving sustainable goals, including protecting the environment and saving energy, land, water and materials (Wang et al., 2019d). GBs saved 50% of water and generated less solid waste than conventional buildings. Therefore, GB promotion has been on the agenda in many countries (Zhang, 2015).

1.1.2 Global Green Building Development

GB rating system provides a guideline and evaluation standards for GBs, including green characteristics and innovations (Zhang et al., 2019c). Based on the GB rating system, the green performance of GBs is examined, and GBs that get through the evaluation would be certified GB labels, making them more competitive in the building market (Li et al., 2020b; Todd et al., 2013). In 1990, Building Research Establishment Environmental Assessment Method (BREEAM), the first rating system in the world, was proposed in the United Kingdom (UK) (Illankoon et al., 2017; Shan & Hwang, 2018). After that, many countries developed their own GB standards considering different climates, social cultures, and geographical features (Doan et al., 2017). More than 600 GB rating systems exist around the world, such as the Leadership in Energy and Environmental Design (LEED) in the United States, Building Environmental Performance Assessment Criteria (BEPAC) in Canada, Green Mark in Singapore, Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) in Japan, Green Star in Australia, Green Rating for Integrated Habitat Assessment (GRIHA) in India, Evaluation Standard for Green Building (ESGB) in China and BEAM Plus in Hong Kong (Zhang et al., 2019a). Some of them were issued by non-profit institutions (e.g., BREEAM, LEED and Green Star). Some of them were issued by governments (e.g., ESGB and CASBEE) (Doan et al., 2017; Zhang et al., 2019c). Among these standards, LEED is the most widely used in the world (Awadh, 2017).

Research on GBs has appeared in at least 44% of countries (Wuni et al., 2019). After decades of development, strategies, policies, and regulations have been developed to promote GBs, and some countries have made outstanding achievements (Wang et al., 2019a). According to a report from the World Bank Group, the investment in GBs is estimated at 24.7 trillion dollars by 2030 (Likhacheva Sokolowski et al., 2019). A project entitled “Small but Mighty” housing initiative was launched in Nigeria to alleviate the housing pressures with modular green housing (Atanda & Olukoya, 2019). However, there are still obstacles to green building development (GBD) around the world, such as the low quality of GBs, difficulties in GB delivery and green renovation of existing buildings (Chen et al., 2020; Liu et al., 2020; Ma et al., 2020; Olanipekun et al., 2017).

1.1.3 Green Building Development in China

Ancient China already had some simple and sustainable thoughts, but the GB concept was clarified after the 1990s, along with the international GB construction tide (Xiao & Qiao, 2009; Zuo et al., 2017). With the trend of global green initiatives, the Ministry of Housing and Urban-Rural Development (MOHURD) in China proposed to develop energy-efficient housing and public buildings in 2005 (MOHURD, 2005). Afterward, the first version of ESGB (GB standard in China) was issued in 2006 (MOHURD, 2006). According to ESGB (2006 version), design labels and operation labels would be certified for buildings that meet the GB criteria. There are three levels to certify GBs in China: one-star, two-star, and three-star.

The ESGB was revised several times. The latest version was published in 2019 (MOHURD, 2019). Significant changes in this version include: (1) The structure of ESGB was rebuilt, and GBs are accessed from six aspects; (2) The basic GB label is newly proposed to award those buildings that meet all the basic requirements; (3) The design label and operation label were canceled to push the stakeholders to switch their attention to greening the operation phase of buildings.

To improve GB standards' applicability, various GB projects are considered in the GB rating system. For instance, Green Star in Australia has four rating tools: Communities, Buildings and Design & As Built, Interiors, and Performance. ESGB is suitable for the green performance evaluation of civil buildings. Except for ESGB, China has released other standards, such as Evaluation Standard for Green Office Building (GB/T 50908-2013), Evaluation Standard for Green Industrial Buildings (GB/T 50878-2013), Assessment Standard for Green Campus (GB/T 51356-2019).

Research showed that buildings with GB labels only account for a small proportion (Zhang et al., 2018a). In order to improve GBD, the central government in China has formulated various policies and regulations, including the *Notice on Issuing the Measures for the Management of Green Building Labels* (MOHURD, 2007), the *Code for Green Design of Civil Buildings* (MOHURD, 2010a). So far, a relatively comprehensive promotion system with clear objectives, supportive policies, and standards has been developed in mainland China. The cumulative GB area in China has reached 6.645 billion square meters by the end of 2020 (Global Times, 2021).

Recently, the Chinese government has launched a series of initiatives to accelerate the speed of GBD and build a prosperous future for GBs. *Green Building Action Plan*, published in 2020, was jointly initiated by seven central government departments (MOHURD, 2020a). It proposed eight main tasks and organization requirements, including fully implementing the green design in the following years. It also set a goal for the proportion of GB area in new urban buildings to reach 70% in 2022. Many local governments responded to the action plan immediately. They supplemented the action plan with more details, developed multi-dimensional local policies, and implemented them in their administrative scope. Some policies are shown in **Table 1.1**.

Table 1.1 Local GB policies in recent years.

Date	Region	Policy	Key points
March 2021	Hunan	*Green Building Development Regulations in Hunan Province (Draft)*	Government should incorporate GB technology research, application and promotion into the industry development, and promote GBs to industrialization, digitalization and intelligence.
November 2020	Liaoning	*Green Building Action Plan in Liaoning Province*	The GBs will account for 70% of new buildings in Liaoning Province by 2022. The existing buildings are encouraged to renovate based on GB standards.
September 2020	Heilongjiang	*Implementation Plan of Green Building Action*	The GB design area in new buildings will reach more than 70% by 2022. The capital city in Heilongjiang will strive to reach 90%.
October 2020	Chongqing	*Implementation Plan of Green Building Action in Chongqing*	The GB area in new buildings will reach 70% by 2022. GB materials are encouraged to use.
September 2020	Shanxi	*Implementation Plan of Green Building Action in Shanxi Province*	The GB area in new buildings will reach 70% by 2022, and the buildings with GB labels will reach 20%.

Furthermore, a new trend emerged in the GB area: green finance is applied to raise GB investments. Accordingly, a new regulation in China stipulates that green finance can support the cost of GB projects and GB materials, alleviating the financial pressure on GBs (National Development and Reform Commission, 2021). Meanwhile, green loans and bonds are increasing, driven by policy incentives. Besides traditional fiscal approaches (e.g., green loans and bonds), many financial institutions have begun exploring innovative financial products and services to release GBD with adequate investments.

Meanwhile, GBs are prevalent in Hong Kong, Macau and Taiwan. To implement the ESGB in Hong Kong and Macau, some provisions have been modified, supplemented or replaced to formulate the Hong Kong and Macau version of ESGB. According to China Green Building and Energy Saving (Macau) Association (China GBC Macau), the student activity center at the University of Macau (shown in **Figure 1.1**) is the first GB certified by ESGB (Macau version). Meanwhile, it is the first GB with three stars in Macau, the highest level of GBs (China GBC Macau, 2014). MGM Macau, as shown in **Figure 1.2**, is another typical building with GB design and operation labels, the first in Macau and Greater Bay Area (China GBC Macau, 2021).

Figure 1.1 Student activity centre at the University of Macau.
Note: This figure is extracted from the University of Macau's WeChat public account (University of Macau, 2022)

Figure 1.2 MGM Macau.
Note: This figure is extracted from a piece of news in the NetEase (Global Travel News, 2021)

Although ESGB has the Hong Kong version, BEAM Plus is more widely used in Hong Kong. BEAM Plus is established by Hong Kong Green Building Council (HKGBC), including BEAM Plus New Buildings, Existing Buildings, Interiors and Neighbourhood. Building-related activities consume 90% of the electricity and generate 60% of carbon emissions in Hong Kong, so GBs play a crucial role in achieving a sustainable built environment (HKGBC, 2022b). GB projects in Hong Kong and the growth rate are shown in **Figure 1.3**. As of March 2022, 1982 GB projects applied BEAM Plus in Hong Kong (HKGBC, 2022a).

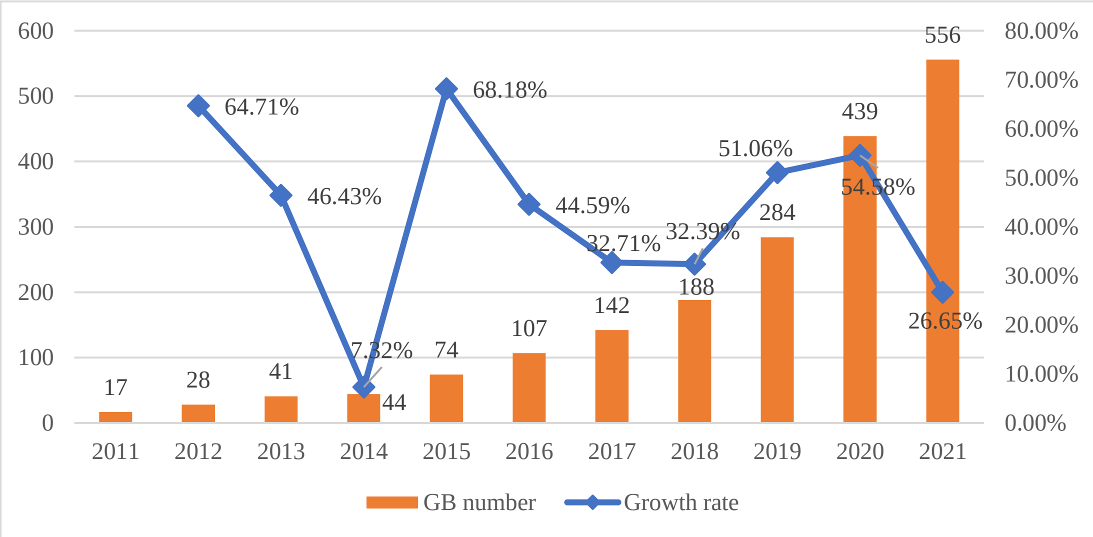

Figure 1.3 Green building projects and the growth rate in Hong Kong.
Note: The data were collected from the HKGBC website (HKGBC, 2022a).

Taiwan launched the GB certification scheme in 1999, which assessed GBs from the ecological, energy-saving, waste-reduction and healthy aspects, so it was called Ecology, Energy saving, Waste reduction and Health (EEWH). EEWH comprises five levels of GB labels (eligible, bronze, silver, gold and diamond). After accomplishing planning and design, buildings could apply for the candidate GB certificate. After completing the building construction and site examination, the GB label could be issued (Kuo et al., 2016). The statistics from the Ministry of the Interior (MOIDS) in Taiwan show that 10,296 GB labels were issued by the end of December 2021. It is estimated that GBs in Taiwan save 2.351 billion kWh of electricity and 114.9 million tons of water annually, and reduce 1.3257 million tons of CO_2 emissions annually. Besides, GBs have increased significantly in recent years, as shown in **Figure 1.4**. For example, GBs in 2021 reached 1,041, with a growth rate of 22.76% (MOIDS, 2022).

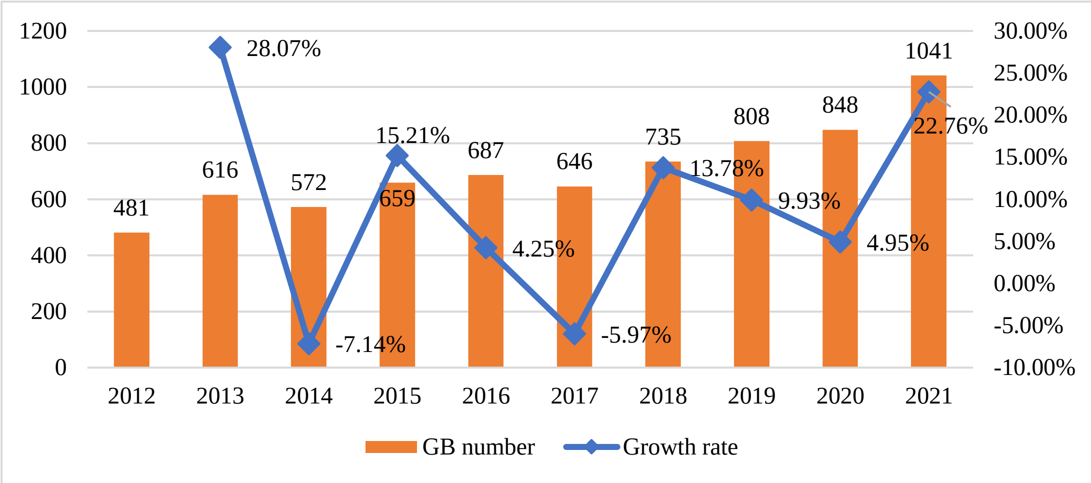

Figure 1.4 Certified green building numbers and the growth rate in Taiwan. Note: The data were collected from the MOIDS website (MOIDS, 2022).

1.1.4 Why Focus on mainland China?

Developing countries are facing similar dilemmas, such as rapid urbanization, social inequity, and environmental pollution (Du Plessis, 2007). It is estimated that 85% of the population lives in developing countries (Klugman, 2011), revealing that the impacts of developing countries are tremendous. Global sustainability cannot realize with the efforts of developing countries. As one of the largest developing countries, China has the largest population in the world (more than 1.4 billion) and the third-largest territory, covering an area of approximately 9.6 million square kilometers. China is the world’s second-largest economy and one of the major economies with the fastest economic growth. The growth rate of Gross Domestic Product (GDP) keeps ranking first among the top 20 countries in economic outputs. Due to the large territorial area and the rapid urbanization trend, the GB market is growing fast in mainland China, with increasing investments and a rapid construction pace. This study focused on and collected data from China because China is one of the developing countries that perform well in GBD.

In addition, because of the large territory, there are five climate zones in China: tropical monsoon zone, subtropical monsoon zone, temperate continental zone, mountain plateau zone, and temperate monsoon zone (Zhao et al., 2022). GB design needs to change with the climate. Besides, there are 31 provinces in mainland China. The local GB policies and situations are different, which provides a good sample for investigating GBD from a spatial perspective. Although this study was conducted in China, the findings would be helpful to other countries around the world. The lessons from GBD in China could reference other developing countries and regions.

1.2 Problem Statement

GBs spread fast in mainland China. As Section 1.1.3 has mentioned, the cumulative GB area in China has reached 6.645 billion square meters by the end of 2020 (Global Times, 2021). However, GBD in China has great potential to be explored. Improving the knowledge of GBD patterns is significant to policy-makers and practitioners. It helps governments make effective policies to promote GBs and provides references to practitioners in wise market decisions. Previous research assessed GBD situations mainly using certified GBs, which can be improved by considering more elements related to GBD, including finance, technologies and other variables. Besides, the efficiency of GB activities and spatial correlations have received little attention from previous studies. Therefore, the first research question is *how to evaluate GBD comprehensively*. It will provide a clear overview of GBD situations in mainland China. Moreover, geographical factors (e.g., climate, topography and soil type) impact GB designs, construction and operation, but limited research on the spatial patterns of GBD. Therefore, the second question is *what the spatial patterns of GBD are*. These patterns benefit center region identification, contributing to narrowing down the regional divergences of GBD and making full use of the strength of spillover effects. After exploring GBD evaluation and spatial patterns, a further research question has been raised to investigate why regional divergences generate. Therefore, the third question is *what the critical success factors (CSFs) and the driving mechanism of GBD are.* Answering this question is a crucial step for in-depth GBD research. Also, it builds a bridge between research and practice, facilitating effective approaches to improve GBD in mainland China.

The spatial perspective has two different meanings in this research. First, it refers to the space definition in geography. Second, it means three sub-dimensions of GBD. The first dimension is the GBD state, establishing evaluation models to measure GBD in quantity. The second dimension is the GBD efficiency, establishing evaluation models to measure GB activities in quality. The third dimension is to examine spatial correlations of GBD. The aim of examining spatial correlations of GBD is to promote the quantity and quality of GBD by strengthening the spatial correlations between regions. Besides, the spatial perspective also investigates the essential factors contributing to GBD in different regions.

This first question "*How to evaluate GBD comprehensively*" contains three sub-questions. The first one is "How to evaluate GBD in quantity?" GB number is a direct indicator, but GBD requires many resources from the economic perspective, such as investments, labor, technologies and policies. The second one is "How to evaluate GBD efficiency?" GBD efficiency reflects the quality of GB activities. A previous study has demonstrated that economic growth could be realized through a quantity and a quality channel (Koetter & Wedow, 2010). In 2017, the 19th National Congress of the Communist Party of China proposed high-quality development. The meaning of "quality" in economics is embodied in production efficiency or scale efficiency, which could be understood as "good quality with affordable price or fair price" in production (Bei, 2018). The connotation of the high-quality development of the economy is the transformation from speed and scale type to quality and benefit type (Liu et al., 2021). GBD efficiency assessment helps to minimize resource inputs and maximize the economic and environmental benefits of GBD. The last one is "How to examine the spatial correlations of GBD?" Strengthening the spatial correlations of GBD aims to enhance the geographical spillover effects of GBD and improve the GBD in quantity and efficiency.

For the second question “What are the spatial patterns of GBD?”, as an innovative initiative, GB has positive economic externalities and spillover effects on economic geography. Exploring the spatial patterns of GBD helps to eliminate the regional gaps of GBD and improve regional coordination, leading to better practice in the future.

The third question is “What are the CSFs and the driving mechanism of GBD?” GBD is affected by many factors. CSF analysis aims to catch the most significant part of GBD. Moreover, there are interactions among CSFs, which formulate a complex system and drive GBD. Therefore, exploring the driving mechanism based on CSFs helps systematically promote GBD.

1.3 Research Aims and Objectives

This research aims to develop GBD evaluation models from three aspects and further explore CSFs and the driving mechanism of GBD. The GBD data in mainland China from 2008 to 2020 are applied for empirical analysis to verify the evaluation models. The CSFs of GBD in different regions are investigated quantitatively to explore the driving mechanism of GBD. To achieve the aim, five research objectives are established as follows.

1. To establish a GBD evaluation model from a macroeconomic perspective, and to investigate spatial patterns of GBD in mainland China;
2. To propose a GBD efficiency assessment model, and to explore spatial patterns of GBD efficiency in mainland China;
3. To develop a model for investigating the spatial correlations of GBD between different regions, and to explore the structure of the spatial correlation network in mainland China;
4. To identify CSFs of GBD, and to quantitatively analyze and compare the global CSFs and Chinese CSFs;
5. To clarify the driving mechanism of GBD, and to develop strategies for GBD improvement based on the research results.

The relationship between research objectives is shown in **Figure 1.5**. Objectives 1, 2 and 3 aim to develop three different models to evaluate GBD, GBD efficiency and the spatial correlations of GBD, respectively. Objective 1 aims to examine GBD in quantity, while Objective 2 aims to assess resource efficiency in GBD. Objective 3 explores how to improve GBD and GBD efficiency by strengthening spatial correlations, which is based on Objectives 1 and 2. Then, Objective 4 aims to investigate the CSFs of GBD in different regions, probing the reasons for GBD patterns. Objective 5 explores the driving mechanism of GBD based on CSF analysis and proposes strategies to improve GBD in mainland China.

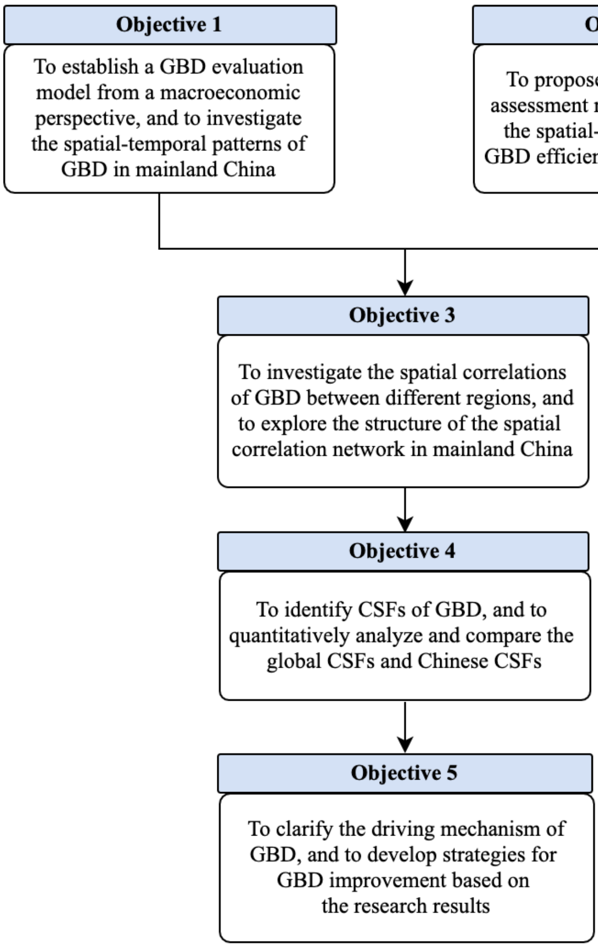

Figure 1.5 Research objectives

1.4 Research Methodology in Brief

This section briefly introduces the overall research flowchart and methods, including data collection and analysis. The research flowchart is shown in **Figure 1.6**, including research phases, objectives, methods, outputs and the corresponding chapters. Five phases are proposed to achieve the research aims and objectives.

Phase 1 is initial research. The initial literature review and informal discussion were conducted in this phase to establish research aims, objectives and methodology.

Phase 2 is the primary research that includes two chapters and achieves Objectives 1 and 2. In Objective 1, an evaluation model was established to *assess GBD* through three steps: indicator selection, attribute reduction and model establishment. The research methods include K-means clustering, rough set theory and optimized catastrophe progression models. The K-means clustering aims to convert continuous data to discrete data for the following calculation. The rough set theory aims to reduce the redundant indicators, and the catastrophe progression model was optimized with the entropy method to quantitatively identify the indicators' importance. In Objective 2, another evaluation model was established to *examine the efficiency of GBD* by the data envelopment analysis (DEA) model that combined Super-Slacks-Based Measure (Super-SBM) with window analysis. The research process contains three steps: selecting input and output indicators, calculating the static efficiency and calculating the dynamic efficiency. In addition, the empirical analysis based on the Chinese context was conducted to investigate the spatial patterns of GBD and its efficiency.

Phase 3 is the further research that achieves research objective 3. The gravity model *examined the spatial correlations of GBD*, and the correlation networks of GBD were constructed. Social network analysis (SNA) was applied to analyze the network, including network structure analysis, centrality analysis, and block model analysis. Similar to Phase 2, an empirical research was conducted in mainland China.

Phase 4 achieves research objectives 4 and 5 to identify and compare CSFs of GBD locally and globally. The CSFs of GBD were identified through a systematic literature review. The global CSFs and CSFs in mainland China were examined and ranked quantitatively through the meta-analysis and questionnaire survey, respectively. Then CSFs in different regions were compared. The driving mechanism of GBD was explored based on the CSF analysis, and the strategies for GBD improvement were proposed on the basis of previous results.

Phase 5 is the closing phase. Research conclusions were presented, and research contributions, limitations and recommendations were summarized.

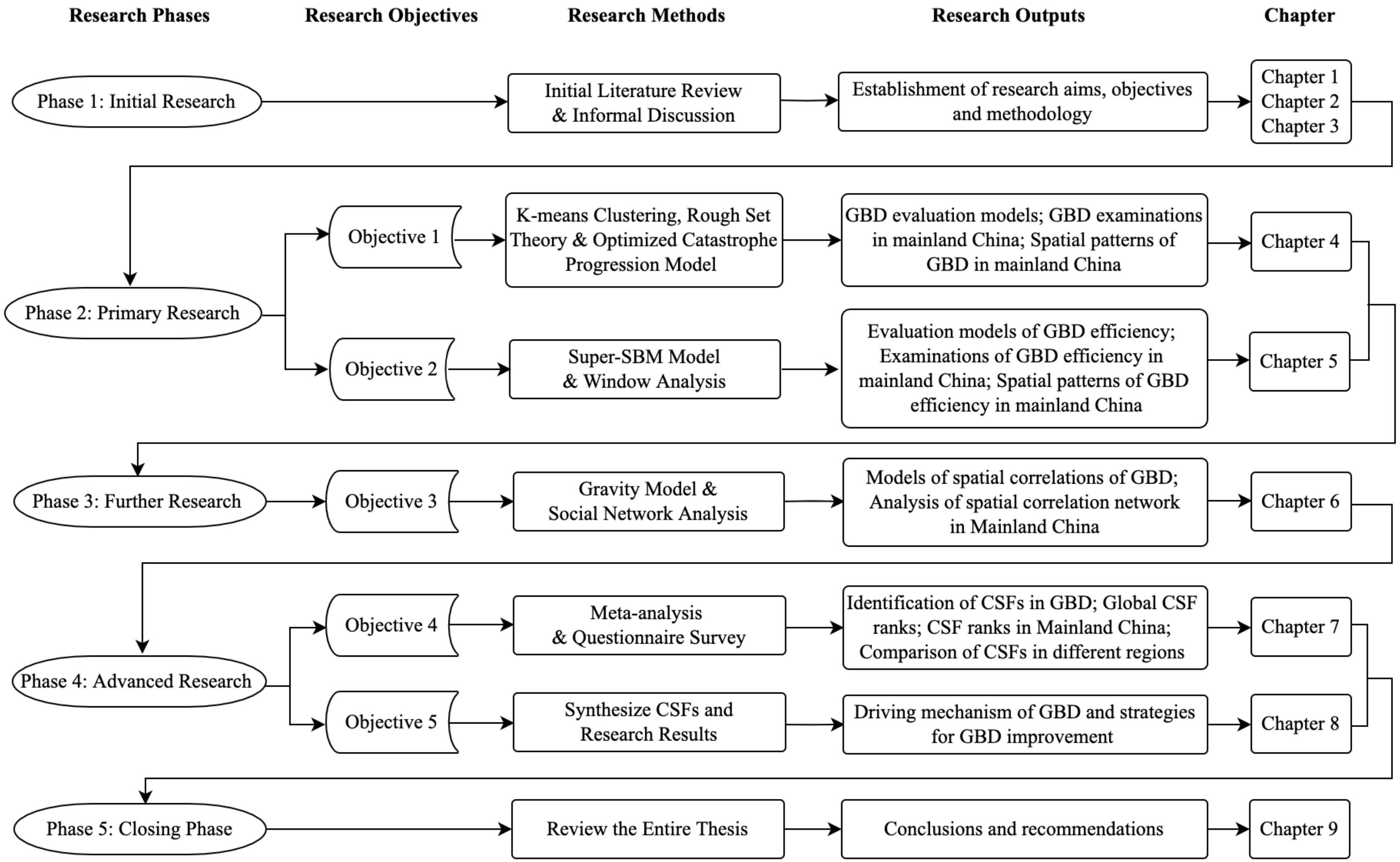

Figure 1.6 Flowchart of the entire study.

1.5 Research Significance

Although a number of studies have been devoted to GB research, few studies concentrate on GBD from a spatial perspective. The spatial perspective in this study aims to link GBD with geographical location, probing GBD from regional development and correlations. As regional divergence exists in a country with a vast territory, spatial analysis is valuable for narrowing the regional divergence and coordinating regional development. This research shed light on a thorough overview of regional GBD, evaluating it comprehensively and exploring the driving mechanism of GBD. This research contributes to the knowledge body of GB research and provides valuable references to the practitioners. The research significance of this study contains three aspects:

- Theoretically, this research extends the GB research by proposing evaluation models to examine GBD, GBD efficiency and the spatial correlations of GBD. This research also conducts the spatial investigation of GBD in the Chinese context. The CSFs in different regions are first compared in this research.
- Regarding research methods, the catastrophe progression model is optimized by the entropy method so that the importance of indicators can be assessed objectively. The Super-SBM model is combined with the window analysis to calculate the dynamic efficiency of GBD, and applying SNA to conduct spatial correlation analysis is innovative for GB research. In addition, meta-analysis is applied to analyze CSFs quantitatively with a large sample size, which is rare in previous

studies.

- This study has provided an overview of GBD in mainland China. The evaluation models help identify the low-GBD regions and central regions in the correlations of GBD, provide valuable references to policymakers and help them develop suitable and effective policies to promote the widespread implementation of GBs. In addition, this research benefits practitioners in exploring the market potentials in different regions and making strategies to improve their competitiveness by seizing the great chance of taking the lead in GBD.

1.6 Structure of Thesis

This thesis includes ten chapters. A brief introduction to each chapter is presented in the following. Chapter 1 is the introduction. This chapter introduces the background of this research, clarifies the research problems and outlines the research aims, objectives and methodology. The research significance and the structure of the thesis are demonstrated. Chapter 2 is the literature review. This chapter discusses GB definitions, summarizes the research paradigm and provides a comprehensive literature review on GBD. The research gap is identified based on the literature review in this chapter. Chapter 3 is the research methodology. This chapter presents the research methodology and introduces the research methods involved in this research, including the data collection and analysis techniques. Chapter 4, Chapter 5 and Chapter 6 establish evaluation models to examine the GBD, GBD efficiency and spatial correlations of

GBD, respectively. The spatial patterns of GBD, GBD efficiency and GBD correlations in mainland China are investigated based on the evaluation models. Chapter 7 identifies CSFs of GBD from previous studies. Then the global CSFs and Chinese CSFs are prioritized through the meta-analysis and questionnaire survey, respectively. Comparisons are made to analyze CSFs in different regions. Chapter 8 develops the driving mechanism of GBD based on stakeholder analysis and CSF analysis, mainly considering the relationship between CSFs. According to previous results, strategies are proposed to improve GBD in mainland China. Chapter 10 demonstrates research conclusions and summarizes the contributions and limitations of this study. The recommendations for future research are provided in the end.

1.7 Chapter Summary

This chapter provided a comprehensive introduction to the thesis. The research background described the essential information for this study, followed by research problems that this study worked on. The research aims, objectives and methodology were introduced to describe the holistic research framework. The research significance was demonstrated, and the structure of the thesis was reported.

CHAPTER 2 LITERATURE REVIEW[2]

2.1 Introduction

As a hot topic in the construction industry, GBs have aroused heated discussions in the academic community. There are extensive studies on GBs from different perspectives. This chapter summarized GB concepts and comprehensively reviewed GBD from four aspects. Previous studies related GBs were collected and analyzed. Then the common research themes and methodology in the GBD field were identified. This chapter critically analyzed previous studies and reported the identified research gaps, which will be addressed in the following chapters.

2.2 Green Building Concepts

Several innovative terms that have similar meanings were proposed to achieve sustainable development in buildings, such as "Sustainable Building," "Green Building," "Low-energy

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[2] This chapter is largely based upon:

Chen, L., Chan, A. P. C., Owusu, E. K., Darko, A., & Gao, X. (2022). Critical success factors for green building promotion: A systematic review and meta-analysis. *Building and Environment*, *207*, 108452.

Chen, L., Chan, A. P. C., Darko, A., & Gao, X. (2022). Spatial-temporal investigation of green building promotion efficiency: The case of China. *Journal of Cleaner Production*, *362*, 132299.

Chen, L., Gao, X., Hua, C., Gong, S., & Yue, A. (2021). Evolutionary process of promoting green building technologies adoption in China: A perspective of government. *Journal of Cleaner Production*, *279*, 123607.

Chen, L., Gao, X., Gong, S., & Li, Z. (2020). Regionalization of Green Building Development in China: A Comprehensive Evaluation Model Based on the Catastrophe Progression Method. *Sustainability*, *12*(15), 5988.

Building" and "Net-zero Energy Building." Among these terms, "Ecological Building" is a new architectural design concept emphasizing the interaction between architecture and ecology. "Sustainable Building" and "Green Building" are interchangeable concepts in many studies (Darko et al., 2019; Zhao et al., 2019b). At first, the GB definition emphasizes the "green" aspects of buildings, which means that environmental protection is the dominant element in GBs. However, the definition has evolved. The triple bottom lines of sustainability and life-cycle management are incorporated in GB definition, including economic development, social progress and environmental protection (Al Alwan & Saleh, 2020; IotaComm, 2020). Therefore, "Green Building" and "Sustainable Building" have similar concepts, resulting in interchangeable situations in the research. "Low-energy Buildings" and "Net-zero Energy Buildings" pay more attention to the energy-saving attributes of buildings, making efforts to reduce CO_2 emissions (Deng et al., 2014). Some studies considered "Zero Energy Building" a type of high-performance GBs (Brown & Vergragt, 2008). GBs have strict and mature assessment processes in many countries, which provides convincing statistics for the research. Therefore, this study chooses "green building (GB)" for consistency.

Many researchers and institutions have defined GB, but no universally accepted definition exists. The definitions of GB represent the sustainable requirements in local buildings, which means that the definitions vary in different countries:

- World Green Building Council (WorldGBC). A GB is a building that, in its design, construction and operation, reduces or eliminates negative impacts and creates positive impacts on our climate and natural environment (WorldGBC, 2021).

- Environmental Protection Agency in the United States (USEPA). A GB is a practice of creating structures and using environmentally responsible and resource-efficient processes throughout a building's life cycle, from siting to design, construction, operation, maintenance, renovation, and deconstruction (USEPA, 2016).
- Green Building Council in the United States (USGBC). The planning, design, construction, and operations of buildings with several central, foremost considerations: energy use, water use, indoor environmental quality, material section and the building's effects on its site (Kriss, 2014).
- Green Building Council Australia. GB incorporates principles of sustainable development, meeting the needs of the present without compromising the future (Green Building Council Australia, 2022).
- Inter-Ministerial Committee on Sustainable Development (IMCSD) in Singapore. GB is energy and water efficient, with a high-quality and healthy indoor environment, integrated with green spaces and constructed from eco-friendly materials (Building and Construction Authority, 2022).
- Ministry of Housing and Urban-Rural Development (MOHURD) in China. A GB is a high-quality building that can save resources, protect the environment and reduce pollution to provide people with a healthy, applicable and efficient space and maximally realize harmonious coexistence with nature during its whole life cycle (MOHURD, 2020b).
- Hong Kong Green Building Council (HKGBC). GB is a practice of reducing the environmental impact of buildings and enhancing the health and wellbeing of building occupants through four aspects (HKGBC, 2022b): Life-cycle planning that focuses on both

the environment and people; Optimized efficiency in resource consumption and adoption of renewable energy and eco-friendly materials; Waste reduction and pollution prevention; High indoor environmental quality and indoor air quality.

These definitions have some elements in common: environmentally friendly, life-cycle management, economic sustainability, and energy efficiency.

2.3 Review of Green Building Development

Although many countries developed clear GB concepts and had a good understanding of sustainable development, obstacles still exist in the GB practice, which hinders GBD and sustainable progress in the construction industry. Several systematic and bibliometric reviews have been published in the GB research field, which visualized research trends and provided research paradigms from different perspectives to provide an overview of the existing body of knowledge.

Zuo and Zhao (2014) identified three common research streams: GB definition, the cost and benefits of GB construction, and the measures of achieving GBs. Besides the common elements, such as GB certifications and energy performance of GBs, GB project delivery and advanced GB technologies were systematically reviewed by Darko and Chan (2016). A bibliometric review of GB research from 2000 to 2016 was conducted by Zhao et al. (2019a). The global GB research trends and patterns were revealed and visualized (Darko et al., 2019). Results showed that previous studies paid more attention to the environmental performance of GBs.

Other themes, like the social and economic aspects of GBD, were noticeably neglected. Ahmad et al. (2019) proposed three tiers by reviewing GB area studies. It is believed that GBD research is a part of GB research, and six research paradigms supported the GBD research: GB project delivery, GB barriers and drivers, critical success factors (CSFs), GB risks and benefits. Besides, Zhang et al. (2019c) provided a GBD overview in many countries, including the backgrounds and current statuses, and summarized the influencing factors. Zhang et al. (2018b) summarized GBD in China from four aspects: GB policies, academic research, standards and technologies. Huo and Yu (2017) reviewed GB studies in ten international journals and classified the studies into five aspects: GB management, the benefits and barriers of GBD, GB performance, stakeholders and strategies.

After reviewing previous studies, it was found that some studies mentioned GBD (Ahmad et al., 2019; Huo & Yu, 2017; Zhang et al., 2018b), but few studies clearly defined GBD. Researchers tended to incorporate various aspects related GBs into the field of GBD, such as GB performance, GB policies and GB rating systems. This study defines GBD as all the achievements reached in the GB field to promote GB activities, improve GB performance and enhance GB implementations.

This study aims to probe GBD from a macroeconomic perspective to advance the GBD understanding and practice. Macroeconomics considers an economy's overall or aggregate performance, for example, the total output of goods and services (Barro, 1997). A stable macroeconomic framework is a prerequisite for sustainable economic growth (Fischer, 1993).

The macroeconomic perspective in this research means considering all the economic elements of GB activities together, aiming to achieve stable and sustainable GBD in mainland China. Therefore, the research streams related to the project level (e.g., project delivery, life-cycle assessment and building performance) are not incorporated into the paradigms. Based on previous reviews, this study proposed a new research paradigm under the GBD topic, shown in **Figure 2.1**.

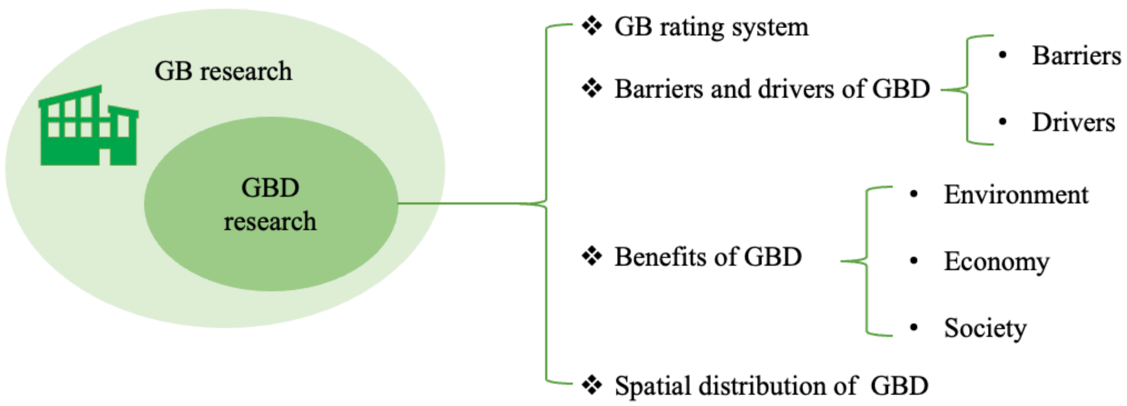

Figure 2.1 Research paradigms in the GBD field.

2.3.1 Green Building Rating System

The GB rating system is the assessment tool for GBs, providing the benchmark for GBs. The attributes of GBs are defined, and detailed provisions are provided. Only those buildings that meet requirements and get through the assessment could be certified with GB labels, and the public could recognize their green performance. World Green Building Council (WorldGBC) is an international organization that aims to accelerate GB practice worldwide, leading the world to achieve the Paris Agreement and the United Nations Global Goals for Sustainable

Development. Green Building Councils in many countries are members of WorldGBC, and they administer most of the GB rating systems. In addition, WorldGBC published the Quality Assurance Guide for Green Building Rating Tools in 2015 to serve as a guideline, helping operators establish robust and transparent GB standards. Statistics showed that the certified GB space through members of WorldGBC had reached 1.04 billion square meters by 2016.

Extensive studies were conducted to establish new GB rating systems or to improve the existing GB rating systems. Some studies made comparisons and discussed items in different GB rating systems. Some studies proposed improvement strategies and revised the items of the GB rating system by analyzing the pros and cons.

2.3.1.1 Green Building Rating System in Various Countries

It is estimated that almost 600 GB rating systems exist worldwide (Doan et al., 2017). Various countries apply GB rating systems to guide the design, operation and management of GBs. This study summarized GB rating systems in 37 countries (**Table A1** in Appendix A). Ten of them are shown in **Table 2.1**.

Table 2.1 GB rating systems in ten countries.

NO.	Continent	Countries	GB Standard
1	Europe	Germany	Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB)
2	Europe	United Kingdom	BREEAM
3	Europe	Netherlands	BREEAM-NL, DGBC Woonmerk, GRESB

Table 2.1 GB rating systems in ten countries (Continued).

NO.	Continent	Countries	GB Standard
4	North America	United States	LEED, Green Globes, ILFI Zero Energy and Zero Carbon
5	North America	Canada	BREEAM Canada, LEED Canada
6	Oceania	Australia	Green Star, National Australian Built Environment Rating System (NABERS)
7	South America	Brasil	Alta Qualidade Ambiental (AQUA), LEED Brasil, GBC Brasil CASA
8	Africa	South Africa	Green Star SA, Excellence in Design for Greater Efficiencies (EDGE)
9	Asia	Japan	Comprehensive Assessment System for Building Environmental Efficiency (CASBEE)
10	Asia	China	Evaluation Standard of Green Building (ESGB)

It is noticed that many countries have more than one GB rating system, and they apply multiple GB assessment tools at the same time. Different assessment approaches focus on different aspects and are applied in different circumstances. Developers make a choice based on the market requirement. In addition, some international GB standards are popular in many countries (Illankoon et al., 2019). For example, BREEAM was popular in Europe, and LEED has become the most popular GB standard worldwide. Many countries first introduce the international GB rating system to the local market, accelerating the development of local rating systems. The local version was customized to meet the requirements of local buildings. For instance, BREEAM was adopted in Canada in 1996. USGBC set up a sister organization in Canada, Canada Green Building Council (CaGBC). CaGBC launched the Canadian version of LEED to adapt to local circumstances, substituting BREEAM and becoming the mainstream of GB activities in Canada.

Although it is easy to share the experience of developing GB rating systems across countries, the specific evaluation criteria are usually applicable in a specific context. Countries with close locations share similar climates and social cultures, increasing the applicability of GB evaluation systems. Therefore, neighboring countries usually use the same international GB evaluation system. European areas tend to adopt BREEAM, while North America and South America tend to adopt LEED. In Australia and New Zealand, Green Star and NABERS are the mainstream. In addition, Green Star has a place in Africa. However, the situation is different in Asia. Many Asian countries prefer to apply their own local GB rating systems.

Over the past 30 years, GB rating systems have rapid development. They have changed from emerging tools to basic tools when evaluating the green performance of buildings. The history of some critical GB rating systems has shown in **Figure 2.2**.

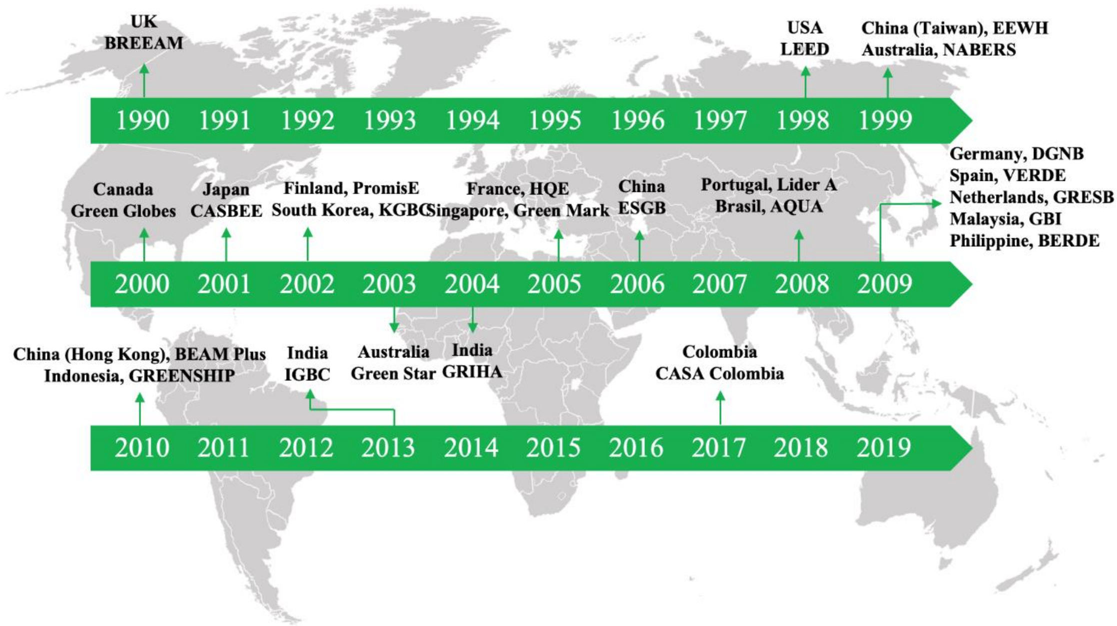

Figure 2.2 History of GB rating systems.
Note: The figure was revised from the study of Zhang et al. (2019c)

GB rating system emerged in 1990. It is acknowledged that BREEAM in the UK was the first GB assessment tool worldwide. The development of GB rating systems was in its infancy from 1990 to 1997. Then, rapid growth appeared from 1998 to 2010, which aligns with the studies of Shan and Hwang (2018), revealing a surge that occurred in the 2000s. New rating systems were established almost every year. 2009 is a special year because five countries (Germany, Spain, Netherlands, Malaysia and the Philippines) established GB rating systems in the same year, which seems a burst. After 2011, the status of GB rating systems became steady. The rating systems' provisions are increasingly mature after several rounds of revision. New concepts and higher performance of buildings have aroused much attention, such as the standards for net-zero energy buildings. Furthermore, green attributes in larger areas and infrastructures have become a new focus. For example, BEEM Plus Neighbourhood in Hong Kong was established to contribute to a border framework, which laid the ground for urban sustainability.

2.3.1.2 Comparison of Green Building Rating Systems

Since various GB rating systems were developed worldwide, extensive studies compared GB rating systems. As shown in **Figure 2.3**, Li et al. (2017) reviewed the studies on GB standard comparison and summarized four research paradigms: general comparison, category comparison, criterion comparison and indicator comparison. Meanwhile, other research sorted the studies with a concise classification. Two groups were proposed: general comparison and comparison of specific aspects (Zhang et al., 2019a).

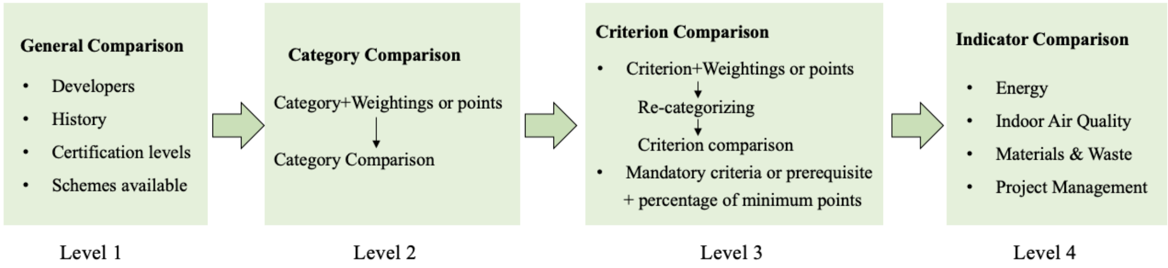

Figure 2.3 Four types of studies on GB rating system comparison.
Note: The figure was revised from the study of Li et al. (2017).

Regarding comparing different GB rating systems, research showed that 70% of previous studies compared the differences among mature international GB rating schemes (e.g., BREEAM, LEED, CASBEE) (Doan et al., 2017). For example, Roderick et al. (2009) compared LEED, BREEAM and Green Star in the energy performance assessment approach. Doan et al. (2017) compared LEED, BREEAM, CASBEE and Green Star NZ and found that indoor environment quality, energy, and material are the primary concerns for all rating systems. Two Asian GB rating systems were compared, and research shows that the formula scoring method and direct scoring method have the highest level of maturity and the lowest levels, respectively (Zhang et al., 2019b). Moreover, some studies compared GB rating systems in different continents. For example, the study conducted by Varma and Palaniappan (2019) compared ten GB rating schemes prevalent in North America, Europe and Asia, aiming to explore the next generation of the GB rating system in India. What is interesting in the findings is that few similarities were discovered after evaluating the credit structure of GB rating systems. It is reasonable because GB rating systems are not the global standard. Although they share the same vision of sustainable development, the evaluation must adapt to the local context, including the design, construction, materials and technologies.

As for the GB standards in China, Geng et al. (2012) first presented the standard and compared it with the GB rating system in other countries. Zou (2019) compared two GB rating systems applied in China. Results showed that business and industrial buildings with foreign investment in metropolitans tend to assess buildings' green performance through LEED. Shao et al. (2018) established a hybrid Multiple Criteria Decision Making model to improve the GB rating system in China.

Although GB rating systems were developed with the hope and aspiration to upgrade the construction industry, evidence shows that their influence on the market is limited (Ade & Rehm, 2020). Buildings with green certifications account for a small proportion of all the new and existing buildings. Furthermore, buildings' green performance is usually assessed after the building is in operation. The green label cannot benefit the developers because developers have transferred the building to the homeowners, tenants or building occupants in the operation stage. The green performance assessment may harm developers' reputations as the building performance may not be as good as claimed. More strategies should be taken to accelerate GB practice.

2.3.2 Benefits of Green Building Development

The benefit is the advantage that something provides or brings a positive effect (Oxford, 2022). This section discusses the benefits of GBD from three aspects: environment, society and economy, the triple goals of sustainable development. Research demonstrated that the environmental aspects have the highest priority in the GB performance evaluation, followed by the social aspects (Varma & Palaniappan, 2019). The economic attribute is considered less important than the environmental and social aspects in the evaluation, but it is the most important element in the GB market, largely influencing stakeholders' behaviors on GB adoption. The preference of decision-makers is different for an individual GB. If they focus on buildings' environmental and social effects, they consider attributes such as occupants' health, climatic conditions and indoor air quality. If they aim to maximize buildings' green performance with limited investments, they pay more attention to the attributes such as operation and maintenance costs (Vyas et al., 2019).

2.3.2.1 Environmental Benefits

Our planet and environment benefit from sustainable activities (e.g., using renewable energy and sustainable construction materials). Research shows that GBs in the LEED Existing Building Operations and Maintenance datasets have reduced carbon footprint by consuming 50% water and generating 48% construction solid waste less than conventional buildings (Eisenstein et al., 2017).

Since the most critical criterion in GB performance is energy saving (Shan & Hwang, 2018), various studies have examined the energy consumption in GBs. GBs' energy-saving effects are apparent. Wang et al. (2019c) examined the energy efficiency in 11 Chinese green industrial buildings (cigarette manufacturers) in 2015. Results show that GBs saved 9441.7 tce energy consumption and reduced 24548.3 tons of CO_2 emission. Similar research was conducted on LEED GBs. Harvard's Co-Benefits of the Built Environment Calculator was applied to examine pollutant emissions of certified GBs in six countries (the United States, Brazil, Germany, Turkey, China, and India). Results show that GBs certified with LEED reduced energy costs by 7.5 billion dollars and prevented much air pollution from entering the atmosphere (33MT of CO_2, 51 kt of SO_2, 38 kt of NO_x, and 10 kt of $PM_{2.5}$) (MacNaughton et al., 2018). Pan et al. (2008) simulated the energy consumption of two office buildings in Shanghai and compared the energy-saving cost in operation phases between GB design and non-GB design, revealing a sizeable energy-saving potential in LEED-certified buildings.

The green vegetation system contributes to the sustainable attributes of buildings. It has become prevalent because of multiple environmental benefits, such as improving air quality, mitigating the heat island effect and increasing biodiversity in urban areas. Besides, the system helps reduce stormwater runoff and noise pollution (Feng & Hewage, 2014). Green walls and green roofs are two common practices in GBs, which belong to the green vegetation system. Green facades and living walls are two types of green walls. Green facades need climbing plants or hanging shrubs to cover the surface. In contrast, green roofs support the plants with more sophisticated structures (e.g., pre-vegetated panels, vertical modules and planted blankets). A green roof is a building roof covered with a layer of vegetation. According to planting conditions, green roofs are classified into intensive green roofs, semi-intensive green roofs and extensive green roofs.

Otherwise, GBs have advantages in building materials, waste management and water consumption. In modern society, people spend 80% of their time in buildings. Building materials affect occupants' health. GB materials are ecological, recycled and high-performance building materials with low embodied energy and pollution, reducing environmental burdens. To resolve the incompatible problem of multiple GB material criteria, a hybrid multi-criteria decision-making method was proposed to analyze the criteria (Khoshnava et al., 2018). Recyclability is a critical attribute of GB materials. As the circular economy calls for, construction and demolition waste can be recycled and turned into renewable products in GBs (Yin et al., 2019). Research shows that the effects of green product labels, taxes, and technical standards on the construction and demolition waste recycling industry are evident, but green product labels and technical standards are less implemented in practice (Li et al., 2020a). Water efficiency in GBs is a primary concern for those regions facing freshwater shortages. After looking through the GB program and strategies for improving water efficiency in Taiwan, Cheng (2003) proposed a water conservation index with a quantitative method and conducted a case study with a building in Taipei.

2.3.2.2 Economic Benefits

Despite the potential for environmental benefits, the sustainable design and materials in GBs lead to higher initial construction costs than conventional buildings. The cost premium for three-star GBs in India is around 2%-5%, while the cost premium for five-star GBs is as high as 5%-17% (Vyas & Jha, 2018). The price of green-labeled housing in China is 6.9% higher than non-green housing. Besides, official GB labels provide more effective criteria in the market than the green behaviors developers adopt (Zhang et al., 2017a). Uğur and Leblebici (2018) examined the construction cost of a gold building and a platinum building under the LEED system in Turkey. The construction cost increments are 7.43% and 9.43%, respectively. Meanwhile, the annual energy costs in GBs are highly reduced, e.g., 31% saving for a gold building and 40% saving for a platinum building. In the past twenty years, the built environment in schools has followed GB design. Sustainable buildings on campus generate a healthier environment for students, such as carefully maintained ventilation, adequate natural light, and appropriate acoustic conditions. A study in Israel shows that the construction cost increment is 8.9%, but the operation costs in green schools are reduced by 24% (Meron & Meir, 2017).

Whether the cost savings can cover the construction cost premium in the operation stage of GBs has aroused a heated discussion. Under ideal circumstances, the economic benefits of GBs in the whole life cycle will largely exceed the initial cost premium. Many studies quantified GB economic benefits to verify this assumption. Research conducted in office buildings shows that the economic returns of GBs are substantial, and the energy efficiency contributes to GBs' premium in rents and asset values (Eichholtz et al., 2013). A life cycle cost analysis of non-residential GBs in Singapore shows that annual averages of construction cost and operation cost are S$ 91.85/m^2 and S$ 130.18/m^2 (S$ is Singapore dollar). The one-level increase of the GB standard would increase the life cycle cost and operation cost by S$ 47.81/m^2 and S$ 25.37/m^2, respectively, but it cannot impact the operation cost (Li et al., 2020c). Another research shows that the life cycle cost of GBs in India is positive, indicating that GB cost savings exceed the cost premium. The payback periods of three-star GBs and five-star GBs are 2.04-7.56 years and 2.37-9.14 years, respectively (Vyas & Jha, 2018). Evidence shows that GB construction increases employee productivity, saving labor costs for GBs. Other benefits include improvements in human well-being and savings from energy and operation costs (Ries et al., 2006).

However, not all the stakeholders are willing to pay the premium. Research shows that consumers with GB knowledge tend to pay for GBs because GBs provide a better living environment and benefit their health. In contrast, architects hold a neutral attitude toward GBs. Meanwhile, developers familiar with GBs have a higher possibility of choosing non-GBs. Architects and developers cannot receive multiple benefits of GBs in the operation stage. The higher initial construction costs and limited benefits brought by GBs hinder developers' willingness (Ofek & Portnov, 2020). As for the benefits to stakeholders, developers benefit from the higher sales prices or property value by providing competitive products (GBs) in the market. Purchasers and owners benefit from the rental premiums while building occupants benefit from an improved living environment, such as better indoor air quality and lower operating costs (Ade & Rehm, 2020).

2.3.2.3 Social Benefits

Social sustainability cannot be ignored as one of the three pillars of sustainable development. Although many studies acknowledge that the social benefits of GBs play a pivotal role in GB promotion, few studies have focused on and conducted thorough research on this topic. In this study, the social benefits of GBs are defined as the benefits that the green attributes of buildings bring to stakeholders, the public and society, enhancing human wellbeing.

For example, green facilities in industrial buildings improve the working environment with better daylight, air quality and thermal comfort, increasing employee satisfaction (Ries et al., 2006). A similar conclusion was drawn in another research. There is a tendency for employees in GBs to have higher job satisfaction. The effect may be direct or indirect. For instance, GBs offer employees a comfortable indoor environment, which can soothe and stabilize the employees' emotions and improve working efficiency. It is worth noting that not all the GB attributes improve occupants' satisfaction (Newsham et al., 2018). Evidence from GBs in Australia shows that only the parameters related to building design and facility management can improve occupants' satisfaction (Khoshbakht et al., 2018).

2.3.3 Factors Influencing Green Building Development

Drivers are critical elements that significantly impact or make something successful (Darko et al., 2017b). Barriers often mean problems or obstacles that prevent somebody from doing something or make it unsuccessful (Hwang et al., 2017b). For GBD, drivers are the factors promoting GB projects or GB construction; barriers are factors hindering GB practice (Ahmad et al., 2019). Generally, the drivers and barriers are the critical factors related to GBD, so some studies integrate them and name them "critical success factors." Many studies identified GB drivers and barriers from previous studies and interviews. Some studies further examine the drivers and barriers with a quantitative approach. These studies are usually applicable to specific contexts. Meanwhile, the typical research method is the questionnaire survey. Based on the drivers and barriers, effective strategies were proposed to facilitate GBD.

2.3.3.1 Drivers of Green Building Development

GBD drivers are the positive actions or persuasions that promote GB practices (Darko et al., 2017b). Many studies have identified GBD drivers with different priorities. The drivers of GB practice include the benefits of GBs, which have been mentioned in Section 2.3.2. Furthermore, drivers include the actions/decisions/behaviors from internal or external stakeholders that motivate green implementations in the construction industry. Darko et al. (2017b) conducted a comprehensive literature review of drivers for GBs. There were 64 drivers identified from previous empirical studies, and drivers were classified into five main categories: external drivers, corporate-level drivers, property-level drivers, project-level drivers and individual-level drivers. Research showed that green premium could not explain the growth of green commercial buildings independently, but it was a potential driver in the UK and the USA (Oyedokun, 2017). Moreover, GBD needs support from external environments, such as the economy, new technologies, and policy incentives (De Santoli et al., 2017; Liu et al., 2020).

Table 2.2 shows several representative studies that identified GB drivers. Three studies addressed that indoor environment improvement is a critical GBD driver, which enhances the working and living atmosphere as well as occupant comfort. The environmental improvements (e.g., indoor environment, resource protection, water management) and cost savings in the operating phase (e.g., energy costs) belong to the environmental and economic benefits of GBs, respectively.

Table 2.2 GB drivers

Drivers	Reference
Indoor environment improvement	(Liu et al., 2012; Ahn et al., 2013; Doan et al., 2021)
Government incentives and regulations	(Liu et al., 2012; Serpell et al., 2013)
Environmental and resource protection	(Ahn et al., 2013; Doan et al., 2021)
Waste reduction and waste management	(Doan et al., 2021; (Ahn et al., 2013)
Company awareness	(Serpell et al., 2013; Doan et al., 2021)
Operation cost reduction	(Serpell et al., 2013; Windapo, 2014)
Client demand	(Liu et al., 2012; Serpell et al., 2013)
Gain social reputation through sustainable development efforts	(Liu et al., 2012)

Governments in various countries get involved in the GB practice. Previous studies identified the government as a critical external stakeholder who guides and regulates GB markets. The incentives from the government can be classified into financial incentives (e.g., tax reduction, bonus and rebates) and non-financial incentives (e.g., regulations and laws) (Zou, 2019). Four financial incentives are available for GBs in Canada: tax, loans, grants, and rebates (Rana et al., 2021). Among them, rebates are the most widely used measures available for all provinces. He et al. (2021) examined the effect of government subsidies and simulated the scenarios under four subsidy strategies. Moreover, GB regulations and policies have proven effective (Zhang et al., 2018a). The mandatory regulations and legislation toward energy efficiency and carbon emission motivate stakeholders to adopt GBs. The pressures push stakeholders to rethink green innovations and consider more sustainable activities in the market. Formulating clear norms and standards is the first stage of GB promotion. Besides, compulsory policies should be implemented based on regional conditions (Kuo et al., 2016).

2.3.3.2 Barriers to Green Building Development

In some studies, the term barrier was substituted by obstacle and challenge (Darko & Chan, 2017). GBD barriers are the factors or elements that hinder the GB practice and the wide implementation of GBs. Darko and Chan (2017) identified 61 barriers to GB adoption from previous studies and reported 37 barriers mentioned in at least two articles. The review shows that many studies identified the same GB barriers. High initial costs and the lack of information, incentives, demand and GB code hinder stakeholders from adopting GBs. Potential obstacles to GBD included a lack of environmental awareness and policies and an immature market (Wu et al., 2019). Furthermore, the influence of these obstacles could be examined by the partial least squares structural equation model (PLS-SEM). **Table 2.3** shows several representative studies that identified GB barriers. If the study has prioritized the drivers, the top 5 drivers were selected and presented in the table.

As mentioned in Section 2.3.2.2, the high initial cost of GBs is a significant barrier to stakeholders, including purchase costs of GB technologies (e.g., ground-source heat pumps and solar heating appliances), higher labor costs and higher design fees. As for the lack of incentives, it mainly refers to the lack of incentives from external stakeholders. Governments can promote GB implementation through multiple policies and regulations. The clients/occupants/tenants also influence the GBD. If clients show no interest in the green innovations of buildings, they will continue choosing conventional buildings. If the occupants and tenants have no awareness of sustainable technologies, they will not pay the bill. Considering the balance between supply and demand, expanding GB demand will stimulate the supply and attract more investments in GB construction. Therefore, raising public awareness is significant to GBD.

Table 2.3 GB barriers.

Barrier	Reference
High costs of GB practices	(Ahn et al., 2013; Bond, 2011; Doan et al., 2021; Hwang & Tan, 2012; Serpell et al., 2013; Wong et al., 2021)
Long payback periods	(Ahn et al., 2013; Bond, 2011)
Lack of communication between stakeholders	(Hwang & Tan, 2012; Serpell et al., 2013)
Low market demand	(Hwang & Tan, 2012; Wong et al., 2021)
Lack of incentives	(Serpell et al., 2013; Doan et al., 2021)
Lack of GB knowledge and understanding	(Ahn et al., 2013; Doan et al., 2021; Wong et al., 2021)

Social media provides a platform for the public to express their opinions, share information and communicate with friends. Billions of people around the world are users of social media. Social media has many benefits, such as connecting with family, friends and colleagues. Moreover, knowledge spreads fast on social media platforms. Twitter is one of the most popular social media platforms for spreading GB knowledge. Palmer and Udawatta (2019) examined the public awareness of GBs with Twitter data. The Twitter text analysis and influential user identification showed that some GB stakeholders reach a substantial audience on Twitter, which helps the audience deepen their understanding of GB construction. Before the public trusts and applies new technologies, they need to get familiar with the new object and learn about it first. Researchers can capture the sentimental preference during the process. Liu and Hu (2019) detected the public attention and sentiment on GBs by analyzing posts and users on Sina Weibo, China's most popular social media platform. Results show that public awareness of GBs in China has enhanced significantly in recent years, but it still has the potential to improve. There is an interesting finding that the obstacle of the GB market has no relationship with the technical and economic elements. It comes from the social and psychological aspects.

2.3.4 Spatial Distribution of Green Building Development

Construction products are different from manufacturing products. Most manufacturing products come from mass production. Modern mass production requires standardized design in a constant flow. On the contrary, construction products are generally customized by clients and have permanent locations. Construction resources are transportable and flow from one region to another. As innovative construction products, GBs have the same characteristic. GBs also show diversity in different regions because of the divergence of climate, culture, economy, policies and technologies, which means that GBD may have different patterns in different regions.

The regional problem has attracted much attention. Cidell (2009) investigated regional GBD in the United States from GB distribution and professional distribution. Results show that the clustering patterns of GBs and professionals differed. Coastal regions are the cradle of GBs. GB activities concentrated on the Pacific Northwest and political centers (e.g., Baltimore-

Washington and Denver), while the clustering patterns of GB professionals match the population concentrations. GB construction needs the support of professionals. Education and training contribute to cultivating skilled construction workers and management staff. Another study explored the spatial patterns of GBs in the United States and found that buildings certified with LEED and Energy Star emerged in metropolitans and sub-metropolitans first, then spread to other regions (Zou et al., 2017). Evidence showed that heterogeneous patterns of GB activities exist in metropolitan regions. Smith (2015a) compared the spatial distribution patterns of LEED-India projects and the patterns of GRIHA projects, finding that most GB projects cluster in the Greater Mumbai metropolitan region, followed by Tamil Nadu.

Some studies explored the spatial correlations of GBs. The spatial fraction logit model was applied to analyze the commercial GBs in New York, Arizona, Colorado and Florida (Qiu et al., 2015). Results showed a strong spatial correlation in the diffusion of commercial GBs. Besides, the geographical proximity effect positively impacts the collaboration networks in GB projects, contributing to GB development (Qiang et al., 2021).

According to previous studies, a consensus has been reached that the regional GBD is uneven. The uneven and complex geography of 810 GB projects in India supports this conclusion (Smith, 2015a). GBs in China have been developed for decades, but the regional distribution patterns are uneven and imbalanced (Zou et al., 2017).

2.4 Gaps in Knowledge

Literature review shows that previous studies have discussed GBD improvement from many perspectives. Some GB research is specific to a country or a region because GBD is affected by various external variables, such as climate, culture, policies and economy. Every region or country has unique building conditions. Although many countries have reached a consensus on the core meaning of GBs, variances exist in the detailed requirements of GBs in practice. Many GB studies investigated GBD patterns in developed countries, such as the United States, Australia, and Finland. GBD research in the third world is less than the research in developed countries. China is a typical developing country with a vast territory and a mass population. Although some studies have explored sustainable initiatives in the context of China, regional problems still need a thorough examination to facilitate GBD across the country.

Concerning the spatial research on GBD, previous studies mainly investigated GB projects by exploring the geographical distribution and clustering patterns, lacking the analysis of the development level and spatial patterns of the GB industry from a macro perspective. As for spatial analysis, a map provides much information. Spatial analysis is more than mapping the locations. It helps researchers find patterns, assess trends, or make decisions, as wll as describe the characteristics of places and the relationships between them, which help us better understand GB activities and human behaviors. Meanwhile, spatial analysis provides more valuable information for decision-makers. With respect to the macro perspective, GBD requires many variables, such as investment, public awareness, technologies, supporting policies and guidelines. Previous studies rarely started from a macro standpoint. A macro perspective means analyzing how economic activities are performing with big-picture concepts, such as the number of products, total values, and the number of experienced workers, which provides a long-term view of strategies at the national level. This study aims to adopt a macro perspective to propose effective strategies and guidelines for policy-making to accelerate the future GBD.

Moreover, the questionnaire survey is the dominant research method. Only a few studies have investigated GBD from the spatial and temporal dimensions. However, such studies mainly focused on the spatial distribution of GBs, which did not consider other elements of GBD nor the GBD efficiency and spatial correlations. GBs are innovative initiatives owning economic attributes. Resource inputs are the prerequisites for GB construction, including investments, labor and technologies. GB efficiency is to investigate the ratio of resource inputs and outputs in GBs.

Overall, regarding GBD evaluation and its spatial patterns, the published studies have only focused on the spatial distribution of GBs and explored geographical clustering patterns. Such studies considered one single indicator (GBs), which is insufficient. Other critical indicators required for GBD, such as investments, technologies and labor, were neglected. A few studies have analyzed the regional development level of the GB industry from a macro perspective, but the indicator system needs to be improved. Besides, they only analyzed the scale of GBD, while the efficiency and spatial correlations of GBD need more attention.

Other studies have measured the efficiency of GB promotion, but the CO_2 emission was not incorporated in the efficiency assessment, which means a critical element was omitted. In addition, the static efficiency cannot be compared in different years. Another research gap is that the spatial correlations of GBD have not been measured and discussed. In terms of the driving mechanism of GBD, some studies have analyzed GBD factors and built models to investigate the interactions of factors. However, it lacks studies exploring GBD factors from a spatial perspective. Comparisons are needed to examine CSFs of GBD in different regions. Based on the analysis, the driving mechanism of GBD could be established.

Therefore, the existing studies on GBD from a spatial perspective are not systematic. It needs thorough research and discussion on the GBD evaluation and the driving mechanism. In order to deepen the GBD research, this study established models to evaluate GBD from three aspects: GBD, GBD efficiency and GBD spatial correlations. This study then constructs a GBD driving mechanism based on the CSFs of GBD.

2.5 Chapter Summary

This chapter provided a comprehensive literature review on GBD and identified the research gaps in this field. First, GB definitions were discussed. Second, the GBD research paradigm was proposed, and previous GBD studies were classified into four categories: GB rating system, GB benefits, GBD factors and GBD spatial distributions. This chapter reviewed previous studies critically and reported the identified research gaps, providing a solid foundation for the following chapters.

CHAPTER 3 RESEARCH METHODOLOGY[3]

3.1 Introduction

This chapter provides an overview of the research methodology applied in this study. It presents how researchers systematically design a study, guarantee valid and reliable results, and fulfill its aims and objectives. Although there is a brief introduction to the research methodology in the first chapter, this chapter aims to describe the research design and methods in more detail.

All the research methods applied in this study and the corresponding research objectives are shown in **Table 3.1**. The data collection methods include statistical data collection, literature review and questionnaire survey. The data analysis methods include the rough set theory, catastrophe progression model, DEA, gravity model, SNA, meta-analysis, Cronbach's Alpha technique and the mean score ranking technique.

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[3] This chapter is largely based upon:

Chen, L., Chan, A. P. C., Owusu, E. K., Darko, A., & Gao, X. (2022). Critical success factors for green building promotion: A systematic review and meta-analysis. *Building and Environment*, *207*, 108452.

Chen, L., Chan, A. P., Darko, A., & Gao, X. (2022). Spatial-temporal investigation of green building promotion efficiency: The case of China. *Journal of Cleaner Production*, *362*, 132299.

Chen, L., Gao, X., Gong, S., & Li, Z. (2020). Regionalization of Green Building Development in China: A Comprehensive Evaluation Model Based on the Catastrophe Progression Method. *Sustainability*, *12*(15), 5988.

Table 3.1 Research objectives and research methods.

Research objectives		Objective 1	Objective 2	Objective 3	Objective 4	Objective 5
A. Data collection methods	A1. Statistical data collection	√	√	√		
	A2. Literature review				√	√
	A3. Questionnaire survey				√	
B. Data analysis methods	B1. Rough set theory	√				
	B2. Catastrophe progression model	√				
	B3. DEA		√			
	B4. Gravity Model			√		
	B5. SNA			√		
	B6. Meta-analysis				√	
	B7. Cronbach's Alpha Technique				√	
	B8. Mean score ranking technique				√	

3.2 Research Design

The research methodology and the flowchart of the entire study have been introduced briefly in Chapter 1. This section aims to address the research frameworks of each part of the study.

3.2.1 Evaluation Model Design

The research design of Chapter 4 is shown in **Figure 3.1**. There are four phases and four objectives in this research. The first phase is indicator selection. Based on a series of selection criteria, the indicators were selected from research articles, government policies, and industry reports (Shen et al., 2018). These documents showed the cognitions of GBD from researchers, governments, and industry practitioners, three critical stakeholders in GBD. The draft of the indicator framework was established after a three-round selection. The first round aims to select indicators from research articles through an extensive literature review. The second round aims to select complementary indicators from the policy documents and industry reports. The third round was a theoretical analysis. The reasons for choosing each indicator were discussed among the research team. A draft indicator framework was received in this phase. The indicators in the evaluation model were classified into four categories: certification, economy, policy, and technology.

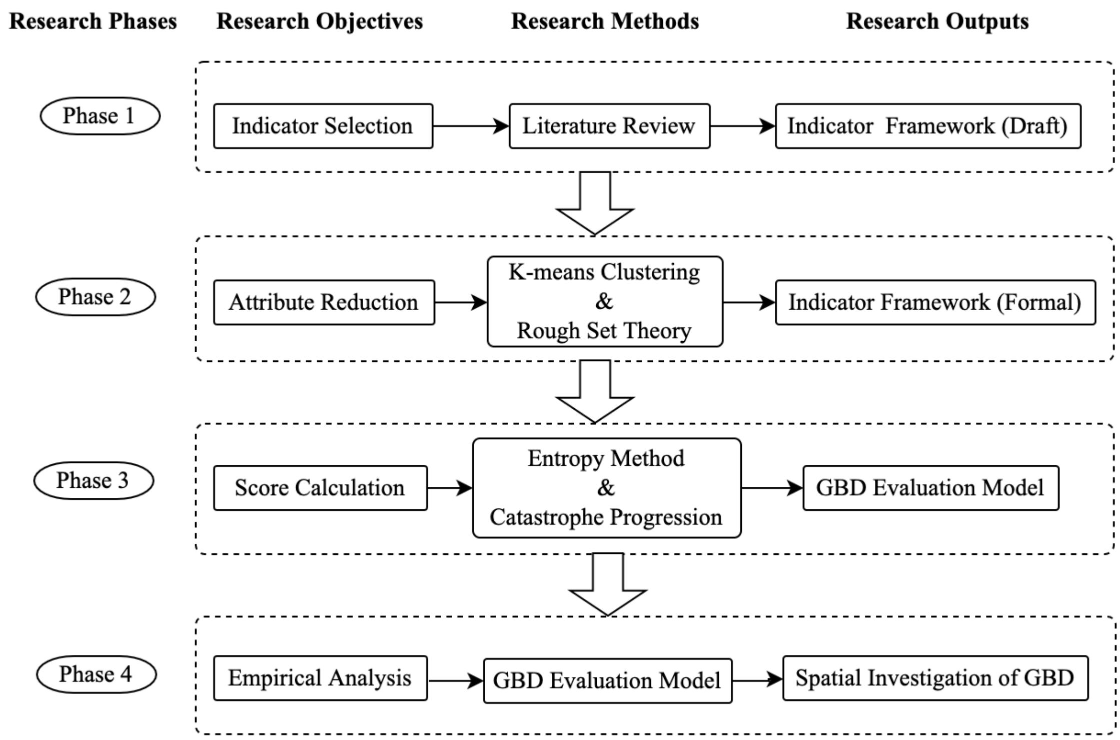

Figure 3.1 Research flowchart of GBD evaluation.

The second phase was attribute reduction. The indicators that were selected in the framework may incorporate redundant information. This phase was designed to check whether the selected indicators had redundant attributes and to ensure the evaluation framework was concise. The rough set theory and K-means clustering were applied in this phase. Before rough set theory was applied, the continuous data needed to convert into discrete data. K-means clustering was chosen to complete this conversion. Then rough set theory was applied to delete the excess information without harming the needed parts (Zhang et al., 2017b). After that, a formal framework was achieved.

The third phase was score calculation. Various approaches could be utilized in the evaluation, e.g., principal components analysis (Mao et al., 2017), fuzzy analytic hierarchical process (Kuo et al., 2017), techniques for order preference by similarity to the ideal solution (Streimikiene et al., 2020) and artificial neural network (Ma et al., 2019). These methods have different advantages in the calculation, leading to slightly different results. Choosing the evaluation method followed two criteria: (1) objective, which means reducing the subjective opinions from researchers as much as possible; (2) comprehensive, which means incorporating information as much as possible. Therefore, this study chose the optimized catastrophe progression method to evaluate.

The last phase was the empirical analysis conducted in mainland China. All thirty-one provinces were incorporated into the analysis. Hong Kong, Macao and Taiwan were not included because they have different GB standards from mainland China, which cannot be compared under the same criterion.

3.2.2 Efficiency Assessment Design

The research flowchart of efficiency assessment is shown in **Figure 3.2**. There were four main steps in this research. The first step was indicator selection. The input and output indicators presented the resource input and the product output in GBD were selected. Afterward, the resource efficiency of a specific year in GB practice was examined through the Super-SBM model. The efficiency in this stage is static. Therefore, the window analysis was conducted to change the static efficiency to the dynamic efficiency, making the efficiency of different years comparable. Because the energy data was unavailable in Tibet, the empirical analysis only included thirty provinces in mainland China.

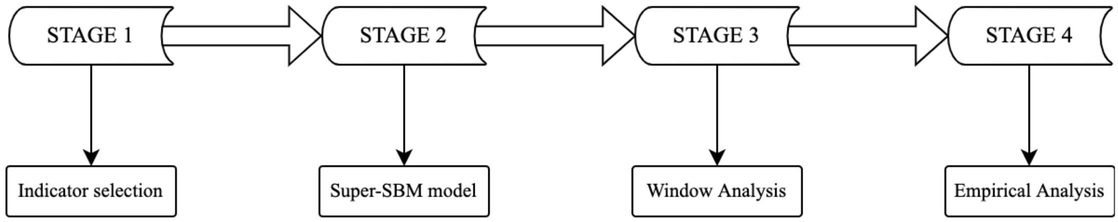

Figure 3.2 Research flowchart of efficiency assessment.

3.2.3 Research Design for Spatial Correlation Analysis

The research flowchart of spatial correlation analysis is shown in **Figure 3.3**. A weight matrix was built through a gravity model, and a spatial correlation network was constructed. Then, the social network analysis was conducted to analyze the spatial correlations of GBD, including the structure analysis, centrality analysis and block model analysis. The correlations between 30 provinces in mainland China were analyzed. Tibet was excluded because of lacking data.

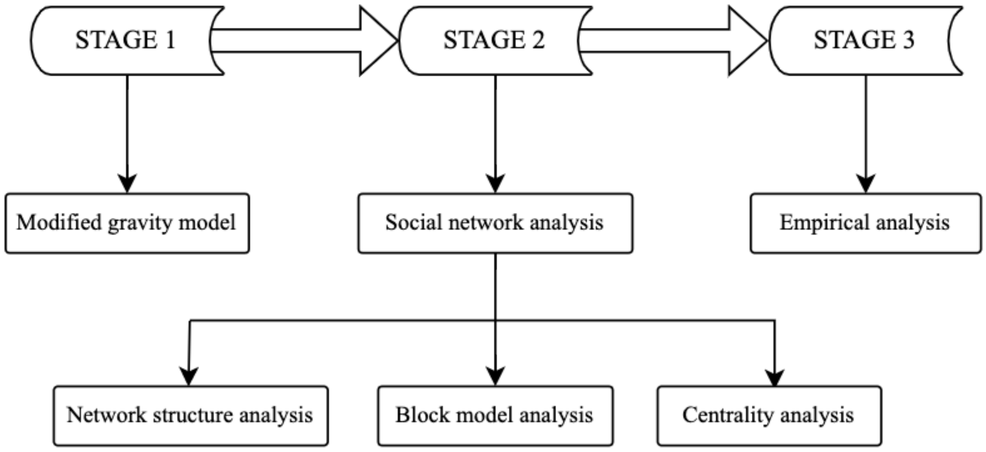

Figure 3.3 Research flowchart of spatial correlation analysis.

3.2.4 Research Design for Critical Success Factor Analysis

The research flowchart of CSF analysis is shown in **Figure 3.4**. The PRISMA framework was adopted in this part. Developed by Liberati in 2009, PRISMA guidelines provide an evidence-based approach to analyzing previous studies (Liberati et al., 2009). Systematic review and meta-analysis are two inseparable parts of the PRISMA framework. When conducting a literature review, the systematic review is the primary option for many researchers because it has a systematic process (Grant & Booth, 2009). The rules of systematic review guarantee that all the relevant literature was collected comprehensively, but most systematic reviews analyze previous studies with a narrative commentary. The quantitative analysis is lacking. The defect could be made up by meta-analysis. A meta-analysis is a quantitative approach to analyzing previous studies. It integrates independent empirical studies and conducts comprehensive synthesis (Nicolson et al., 2018; O'Grady et al., 2021), so it is called "analysis of analyses" (Hunter & Schmidt, 2004). According to statistical principles, meta-analysis regards previous empirical studies as samples, relying on the data extracted from previous studies, so the included studies must be comprehensive, which could be ensured by systematic review (Borenstein et al., 2009). Therefore, this part adopted a systematic review to identify the CSFs and further analyze the factors with meta-analysis.

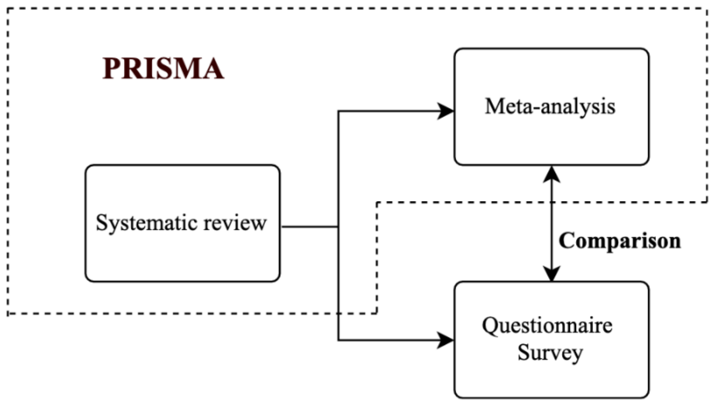

Figure 3.4 Research flowchart of CSF analysis.

As the figure shows, a systematic review was conducted to identify CSFs from previous studies. Afterward, the meta-analysis and questionnaire survey were conducted independently based on the factors identified by the systematic review. Meta-analysis has a large sample because it contains the results of many empirical studies conducted in various countries, so the meta-analysis was considered to have a global sample. In contrast, the questionnaire survey was conducted in mainland China. In the end, a further investigation was performed by comparing the results of the meta-analysis and the questionnaire survey to probe the divergence of CSFs between mainland China and other regions or countries around the world. Meanwhile, the results from different regions in China were compared.

3.3 Data Collection Methods

3.3.1 Statistical Data Collection

As empirical studies were applied to verify the evaluation models, statistical data in mainland China were collected from different websites and other channels. Hong Kong, Macao and Taiwan were not included because the GB standards are different between mainland China and these regions. The first Chinese GB certification was issued in 2008 (Chen et al., 2020), so the research period was chosen from 2008 to 2020. All the data sources are listed in **Table 3.2**.

Most of the data were collected from the National Bureau of Statistics (NBS) website. It is necessary to address the data sources of the number of certified GBs. From 2008 to 2015, the number of certified GBs was collected from the Chinese Green Building Evaluation Label Website. From 2016 to 2020, most data were collected from government websites in different regions, but some data was lacking because not every province released GB information. Therefore, three mathematical methods were adopted to ensure the accuracy of the data: (1) if the data was missing in the middle years, it was replaced by the average of the previous year and the following year; (2) if the data is missing at the end of the sequence, the GM(1,1) model was applied to predict the data; (3) if the data were missing at the end of the sequence, but it was not applicable to use the GM(1,1) model, the Long Short-Term Memory (LSTM) model was adopted as a supplementary method. The GM(1,1) model shows high accuracy in prediction with a few samples (Wang et al., 2018b), which is the main reason for applying it in this study. As a critical method in deep learning, the LSTM model can capture the long-term relationship in time-series data as the memory blocks in the network could access and store information for a long time, which becomes a primary option for time-series prediction.

Table 3.2 Data sources in this research.

Code	Data item	Data source
1	Number of certified GBs	a. Chinese Green Building Evaluation Label Website[1] b. Local government websites c. Mathematical models
2	Output value in the building construction	NBS Website[2]
3	Building construction area	NBS Website[2]
4	Number of construction enterprises	NBS Website[2]
5	Number of staff and workers in construction enterprises	NBS Website[2]
6	Total assets of construction enterprises	NBS Website[2]
7	Business revenue of construction enterprises	NBS Website[2]
8	Total profits of construction enterprises	NBS Website[2]
9	Paid-up capitals of construction enterprises	NBS Website[2]
10	Total value of signed contracts	NBS Website[2]
11	Number of local policies	PKULAW Website[3]
12	Net value of machinery and equipment owned	NBS Website[2]
13	Power of machines per worker	NBS Website[2]
14	Number of GB innovation awards	MOHURD website[4]
15	Number of GB patents	National Intellectual Property Administration Website[5]
16	Revised investment in fixed assets	NBS Website[2]
17	Amount of energy consumption	China Energy Statistical Yearbook[6]
18	Amount of CO_2 emission	China Energy Statistical Yearbook[6]
19	Population	NBS Website[2]
20	Distance	Google Maps Website[7]
21	GDP	NBS Website[2]
22	GDP per capita	NBS Website[2]

Note: [1]http://www.cngb.org.cn/index.action?sid=402888b44f81b20f014f81dd5b21000c;
[2]https://data.stats.gov.cn/english/easyquery.htm?cn=E0103;
[3]https://www.pkulaw.com/law?isFromV5=1;
[4]https://www.mohurd.gov.cn/gongkai/fdzdgknr/tzgg/202101/20210125_248933.html;
[5]http://pss-system.cnipa.gov.cn/sipopublicsearch/portal/uiIndex.shtml;
[6]https://navi.cnki.net/knavi/yearbooks/YCXME/detail;
[7]https://www.google.com/maps

The number of local policies was collected from the PKULAW Website, searching with the keyword of "green building." The search results were selected manually. Because the Green Building Innovation Awards are released every two years, the average values were used each year. Similar to policies, the number of GB patents was searched in the database of the National Intellectual Property Administration Website by the keyword and selected manually.

Some data need to be further processed based on the raw data. The revised investment in fixed assets was calculated by excluding four unrelated industries: (1) agriculture, forestry, animal husbandry and fishery; (2) mining; (3) production and supply of electricity, heat, gas; and (4) transport, storage and post. Similar to the revised investment in fixed assets, the amount of energy consumption only included three statistical items: (1) construction; (2) wholesale and retail trades, hotels and catering services; and (3) residential. Item (2) and item (3) were chosen because the energy consumption in the operation stage was considered. The choice was supported by studies that proved the operation stage of buildings consumes much energy and emits greenhouse gas (Sharma et al., 2011). All the energy (e.g., raw coal, gasoline and natural gas) were converted into standard coals based on previous studies (Chen et al., 2019; Lin & Liu, 2015). The distance between provinces was measured by the shortest road transportation distance between the capital cities of two provinces. The distance data were collected from Google Maps.

3.3.2 Literature Review

A literature review was adopted to identify the indicators in the evaluation models, and a systematic review was applied to identify the CSFs of GBD from previous studies and collect the data for the meta-analysis. The section mainly concentrates on the process of systematic literature review on CSFs. The first step is to search studies on the CSFs of GBD comprehensively. The second step is to select the studies base on the selection criteria. The third step is to identify the CSFs of GBD from the selected studies.

3.3.2.1 Search Strategies

Web of Science (WoS) and Scopus are databases containing numerous academic resources (Falagas et al., 2008). They have high reputations around the world, so many researchers apply the search engines WoS and Scopus to track the latest academic literature (Peters et al., 2020; Zhu & Liu, 2020). Moreover, another merit of WoS and Scopus is that they have a clear list compared to other databases, especially Google Scholar (Levine-Clark & Gil, 2009). Therefore, WoS and Scopus were applied to search the relevant literature in this study.

This study used two search strategies: keyword search and snowballing search. Keywords contained "critical success factor," "green building" and "sustainable building." "Sustainable building" is a substitution for "green building" (Darko & Chan, 2016). The comprehensive searching strings with Boolean operators include: (green building OR sustainable building) AND (critical success factor). It is not enough to search literature with keywords because other studies may refer to CSFs, such as the barriers and drivers of GBD (Rogers et al., 2020). Therefore, snowballing search, including backward snowballing and forward snowballing, was applied to avoid omitting information. Backward snowballing is to select relevant literature from the selected studies' reference lists. Forward snowballing is to select relevant literature from articles that have cited the selected studies.

3.3.2.2 Literature Selection

The inclusion and exclusion criteria were set up to select the studies. There were two inclusion criteria. The first is to include studies related to GBD factors. The second is to include empirical studies that report the mean, standard deviation (SD), and sample size. There were three exclusion criteria. The first is to exclude non-English articles. The second is to exclude duplicate articles. The third is to exclude the articles without full text. No restrictions were set in literature selection, e.g., publication year and article type.

Literature was selected in May 2021. **Figure 3.5**, revised based on the new PRISMA statement (Page et al., 2021), shows the flowchart of the literature selection. There were 426 studies after searching the keywords. **Figure 3.5** shows that only nine studies that met the inclusion criteria were left in the keyword search. After the snowballing search, thirteen studies were identified and included in the literature database. Therefore, there were twenty-two studies included in the meta-analysis. Among these studies, three were conducted by the same research team and had the same sample size. Two were excluded from the literature database to avoid duplicate samples in the meta-analysis. Therefore, there were twenty studies in the literature database. These quantitative studies adopted the five-point Likert scale to examine factors' importance, making the data comparison easier.

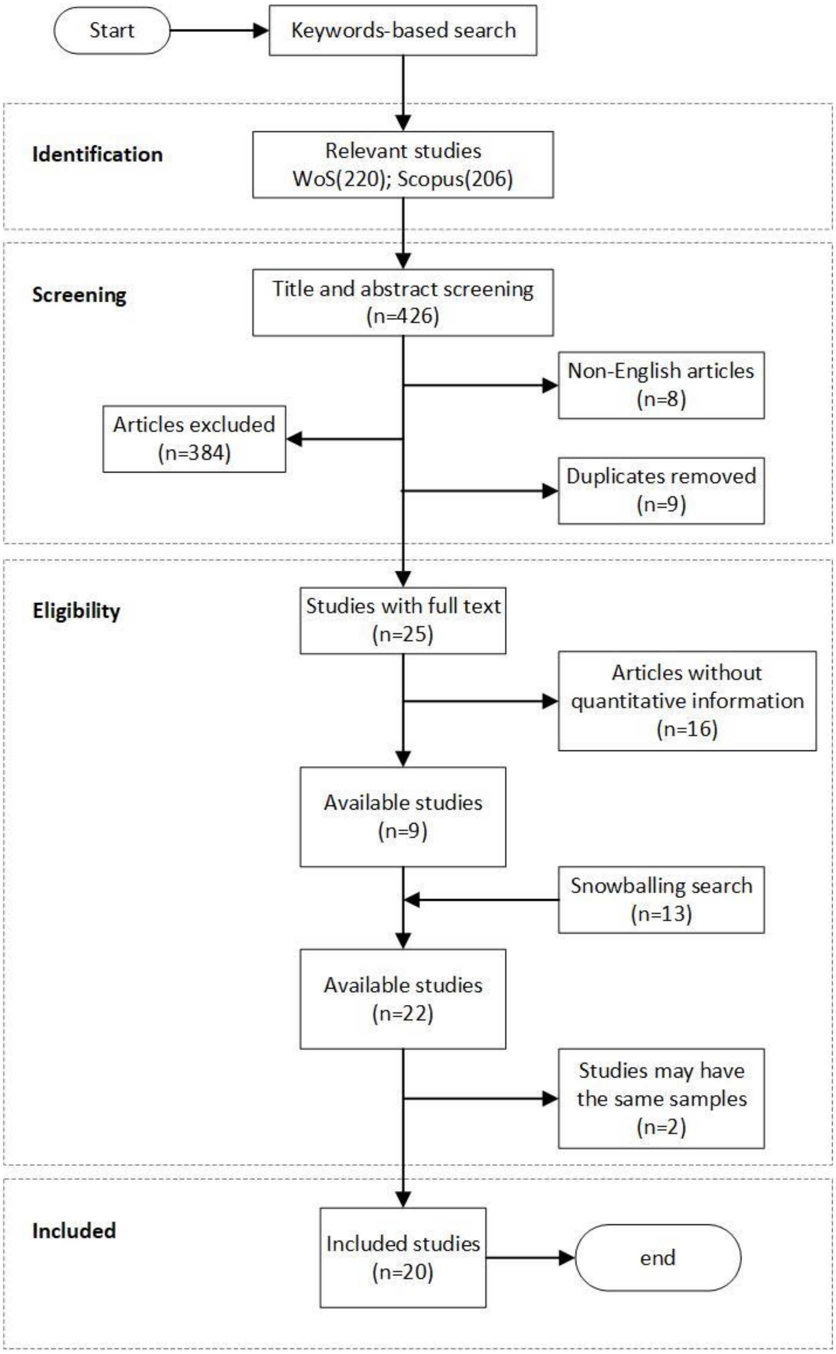

Figure 3.5 Flowchart of literature selection.

3.3.2.3 CSF Identification

The next step is to conduct a context analysis of the selected literature to identify the CSFs of GBD. The CSFs were picked out from previous studies and coded independently if CSFs appeared in two or more studies. During the coding process, each sample can only be used once. If multiple independent samples exist in a study, the CSFs in each sample can be coded independently. In addition to identifying and coding the CSFs, it needs to collect data from the screened literature to conduct the following meta-analysis, including the mean and standard deviation of CSFs and the sample size.

3.3.3 Questionnaire Survey

A questionnaire survey is a sample-based research method for collecting data effectively (Shan et al., 2020), a prevalent research method in the GB area (Chan et al., 2009; Hwang et al., 2015; Teng et al., 2019). The questionnaire survey shows the advantages of objectivity and quantitative. It can objectively reflect the respondents' cognition of certain questions and analyze the responses quantitatively (Brace, 2018). Meanwhile, most questionnaires are anonymous, protecting the respondents' privacy and allowing them to express themselves without limitation. Besides, the cost of questionnaires is low, so researchers prefer to choose this method. Sometimes, the cognitive bias of the respondents reduces the objectivity of the questionnaire results, but the bias could be eliminated by selecting the sample population scientifically and designing the questionnaire reasonably. The questionnaires in this research aim to investigate respondents' perceptions of CSFs in GBD, thus further providing a quantitative description of the entire sample.

The Likert scale, proposed by psychologist Rensis Likert, is the most widely used form in questionnaires (Likert, 1932). It assumes that respondents' agreement toward a statement can be quantified and that respondents' attitudes are a continuous function from strongly agree to disagree strongly, so the Likert scale can examine the degree of respondents' agreement with a statement (Danquah et al., 2017). The Likert scale breaks the binary pattern of respondents' attitudes (yes or no), allowing respondents to have different degrees of opinions. Therefore, the Likert scale can collect quantitative data for the following analysis. There are different types of the Likert scale, such as the five-point Likert scale and the seven-point Likert scale. The five-point Likert scale is the most widely used in the GB research field (Liu et al., 2019; Nguyen et al., 2017; Ahn et al., 2013), so the main part of the questionnaire adopts it.

The questionnaire in this research consists of three parts. The first part introduces the research purpose and the research content of the project. The second part collects the respondents' background information, such as their roles in GB projects and working experience. The third part collects respondents' opinions on the CSFs of GBD. The questionnaire is shown in Appendix B.

The questionnaires were distributed through the internet. The respondents are practitioners and researchers working in construction, consulting, design, real estate, and academic institutions. The mandatory requirement of respondents is that they must have the working experience of GBs. If it is not satisfied, this questionnaire is invalid. Meanwhile, the respondents are from all provinces in mainland China except Tibet. The main reason is that Tibet has a small number of practitioners with GB working experience. It is a difficult task to find practitioners in Tibet. A total of 348 questionnaires were returned to this survey. After checking manually, there were

224 valid questionnaires and 124 invalid questionnaires, with an effective response rate of 64.37%. Therefore, the sample size of the questionnaire survey is 224.

3.4 Data Analysis Methods

3.4.1 Rough Set Theory

The Rough Set Theory, proposed by the Polish mathematician Pawlak in 1982, is derived from the basic research on the logical properties of information systems (Pawlak, 1982). It has been an essential theoretical basis for data mining or knowledge discovery in relational databases (Kusiak, 2001). Rough set theory and fuzzy mathematics theory are new fields of uncertainty mathematics (Liang et al., 2002). Their rapid development provides the basis for "soft computing," promoting the progress of neural networks, machine learning and evolutionary computing.

Rough set theory is an effective mathematical tool for discovering patterns from the data. It can identify the data’s dependencies and eliminate redundant data, so it is often used in feature selection, feature extraction and data reduction (Shi et al., 2016). Since there may be overlapping information between indicators, the rough set theory was applied to remove redundant attributes in the indicator system and retain information as much as possible (Zhang et al., 2017b). There are three steps when reducing the attributes with the rough set theory: data standardization, K-means clustering and attribute reduction.

3.4.1.1 Data Normalization

Indicators have different dimensions and magnitudes, so the raw data were normalized to reduce the difference (Jia et al., 2018). Effective comparison between indicators could be achieved after data normalization (Jia et al., 2018). Data normalization obeyed **Equation 3.1**.

$$r_{ij} = \frac{x_{ij} - Min_j\{x_{ij}\}}{Max_j\{x_{ij}\} - Min_j\{x_{ij}\}} \tag{3.1}$$

where x_{ij} is the value of the region i for the indicator j (i = 1,2,3,…,m; j = 1,2,3,…,n); r_{ij} is the normalized value of x_{ij}; $Max_j\{x_{ij}\}$ and $Min_j\{x_{ij}\}$ are the maximum original value and the minimum original value among the regions for a specific indicator j, respectively.

3.4.1.2 K-Means Clustering

The data cannot be directly utilized in the attribute reduction because most data are continuous. The rough set theory needs discrete data. To achieve the transformation, K-means clustering was applied in this step. K-means clustering is a clustering algorithm that divides the sample set. It first divides the sample into K categories, then distributes the samples into each category, and makes sure that the distance between each sample and the center of the category to which the sample belongs is the smallest. Each sample can only belong to one category in the K-means clustering.

The process of K-means clustering can be summarized as follows: (1) Determine the initial k, distribute the samples into k categories and find out the center of each category; (2) Calculate the distance between each sample and the center of each category, then find out the shortest distance and classify them into the category; (3) Find the center of new categories, and then compare the result with (2); (4) if the classification result is the same as the previous one, the classification will be ended. If it is different, the classification will repeat (2). This part of the data analysis was implemented through Python programming.

3.4.1.3 Attribute Reduction

The domain U is a non-empty finite set of the objects discussed, and $K = (U, R)$ is a knowledge base, where R and U have an equivalence relation. If P is a non-empty set and $P \subseteq R$, $\cap P$ means an indistinguishable relationship for P, so it can be presented as $ind(P)$. $U/ind(R)$ is the set of equivalent classes comprising all $ind(R)$. r is assumed as a cluster of equivalence relation, and $r \in R$. If $ind(R) = ind(R - \{r\})$, the conclusion could be drawn that r is unnecessary for R (Zhang et al., 2017b). Therefore, r can be deleted from the indicators, and the attribute reduction process could end. If $ind(R) \neq ind(R - \{r\})$, r is a significant factor that cannot be removed.

3.4.2 Catastrophe progression models

The catastrophe theory can quantitatively explain that quantitative changes cause qualitative changes in the system. According to the catastrophe theory, the points in the system can form an equilibrium surface. However, the dynamic system will mutate when the control variables meet some requirements. The catastrophe theory believes that the state variables of the system and the control variables in the external environment determine the changes in the system. The catastrophe progression model is a comprehensive evaluation method developed on the basis of catastrophe theory and fuzzy mathematics theory. It is applied to study catastrophe phenomena with discontinuous changes in natural science and social science. The catastrophe progression models have seven types. Among them, four types are commonly used, as shown in **Table 3.3**. The assumption was proposed that the state variable is *x*, and the potential function of *x* is *f* . *a*, *b*, *c*, and *d* means the control variables of the state variable *x* (the importance of *a*, *b*, *c*, and *d* decreases in turn).

Table 3.3 Common catastrophe models and their potential functions.

Category	Dimension of Control Variables	Potential Function	Normalization Formula
Folded model	1	$f(x) = x^3 + ax$	$x_a = \sqrt{a}$
Cusp model	2	$f(x) = x^4 + x^2 + bx$	$x_a = \sqrt{a}; x_b = \sqrt[3]{b}$
Swallowtail model	3	$f(x) = x^5 + ax^3 + bx^2 + cx$	$x_a = \sqrt{a}; x_b = \sqrt[3]{b};\ x_c = \sqrt[4]{c}$
Butterfly model	4	$f(x) = x^6 + ax^4 + bx^3 + cx^2 + dx$	$x_a = \sqrt{a}; x_b = \sqrt[3]{b};\ x_c = \sqrt[4]{c};\ x_d = \sqrt[5]{d}$

An evaluation model based on the catastrophe progression method was established through four steps: normalizing the data, establishing the evaluation framework, examining the importance of indicators, and calculating the results. Among them, data normalization has the same process as Section 4.2.2.1. When establishing the evaluation framework, the catastrophe progression method has a number limit of the control variables, so the control variables would be classified into different categories if the variables are more than four, leading to multiple layers in the framework. The evaluation framework in this research followed the number limit when it was established.

The effects of different control variables on state variables are different, so it needs to examine the importance of indicators first. Some studies extracted the importance from previous research (Wang et al., 2019b), while others examined the importance through experts' experience (Zhang et al., 2017b). However, subjective opinions may highly affect the results of these methods. The entropy method was adopted in the catastrophe models because it can process the weight of indicators with a subjective attitude (Jia et al., 2018; Shen et al., 2018). The entropy values of indicators, denoted as w_j (j = 1,2,3,…,m), can be obtained through **Equations (3.2–3.4).**

$$y_{ij} = \frac{r_{ij}}{\sum_{i=1}^{m} r_{ij}} \tag{3.2}$$

$$e_j = -\frac{1}{\ln m}\sum_{i=1}^{m} y_{ij} \ln y_{ij} \tag{3.3}$$

$$w_j = \frac{1 - e_j}{n - \sum_{j=1}^{n} e_j} \tag{3.4}$$

where r_{ij} is the normalized value of the region i for the indicator j (i = 1,2,3,…,m; j = 1,2,3,…,n); m is the number of sample regions; w_j is the entropy value of indicator j; if y_{ij}=0, y_{ij} lny_{ij} is also equal to 0 in **Equation 3.3**.

The calculation principles are different when there is more than one control variable. Except for the indicators in the top layer and the bottom layer, indicators of the evaluation framework could be state variables and control variables in the models of different layers. The calculation principles are shown as follows. This study found that all indicators are related, so the evaluation model applied the complementary principle.

- Complementary principle: If there are high correlations between the control variables, the calculation follows the complementary principle. The state variable is the average of the control variables, e.g., $x = (x_a + x_b + x_c + x_d)/4$ in the butterfly model.
- Non-complementary principle: If control variables have no obvious correlations, the calculation follows the non-complementary principle. The state variable is the minimum of control variables, e.g., $x = min(x_a, x_b, x_c, x_d)$ in the butterfly model.

3.4.3 Data Envelopment Analysis

The efficiency measurement theory aims to evaluate the quantitative relationship between the resource input and the product output. Stochastic frontier analysis (SFA) and DEA have been commonly applied in efficiency measurement (Sun et al., 2019). SFA is a parametric method, while DEA is a nonparametric method (Sun et al., 2019). They have different calculation thoughts in efficiency measurement. Compared to SFA, DEA does not need specific assumptions and functions, avoiding the impact of subjective factors (Daraio & Simar, 2007). A benchmark frontier, named "efficient frontier," would be estimated in DEA, and the distance from the unit to the benchmark frontier is calculated as the efficiency of decision-making units (DMUs) (Daraio & Simar, 2007). Mathematical programming provides the theoretical basis for DEA. Therefore, DEA is suitable for situations involving many variables and relations (i.e., inputs and outputs) when evaluating the performance of DMUs (Cooper et al., 2011). This characteristic makes solving complex problems in social and management research areas easier. Due to these advantages, DEA was chosen to assess GBD efficiency in this research, including the Super-SBM model and the window analysis.

3.4.3.1 Super-SBM Model

Traditional DEA models, such as the Charnes-Cooper-Rhodes (CCR) model and the Banker-Charnes-Cooper (BCC) model (Banker et al., 1984), have not considered the slack variables. Thus, they could not deal with the inefficiency problems. In an attempt to define inefficiency based on slacks, SBM was first proposed by Tone (2001). As a DEA method, SBM effectively assesses the efficiency of DMUs with undesirable outputs. The unit of variables in input and output items would not affect the result in an SBM model. For instance, the efficiency result remains the same regardless of whether the distance unit is kilometers or miles.

It is assumed that there are n DMUs with the input matrix $X = (x_{ij}) \in R^{m\times n}$ $(X > 0)$ and output matrix $Y = (y_{ij}) \in R^{s\times n}$ $(X > 0)$. P is defined as the production possibility set, and $P = \{(x, y) | x \geq X\lambda, y \leq Y\lambda, \lambda \geq 0\}$ (λ is a non-negative vector in R^n). A DMU $(x_{0,}\ y_0)$ can be described as $x_0 = X\lambda + s^-$ and $y_0 = Y\lambda - s^+$ with $\lambda \geq 0$, $s^- \geq 0$ and $s^+ \geq 0$. The vectors $s^- \in R^m$ and $s^+ \in R^s$ indicate the input excess and output shortfall of this expression. They could be considered slacks. ρ is defined as the value of efficiency. Therefore, a fractional program can be formulated to construct an SBM model as **Equation 3.5**.

$$
\begin{aligned}
&\text{Min} \quad \rho = \frac{1-\frac{1}{m}\sum_{i=1}^{m} s^-/x_{i0}}{1-\frac{1}{s}\sum_{r=1}^{s} s^+/y_{i0}} \\
&\text{Subject to } \ x_0 = X\lambda + s^-, . \\
&\qquad\qquad\quad y_0 = Y\lambda - s^+,
\end{aligned}
\tag{3.5}
$$

$$\lambda \geq 0, s^- \geq 0, s^+ \geq 0$$

The efficiency of DMUs ranges from 0 to 1 in DEA models. However, there may be more than one DMUs whose efficiency is 1 in a model, making it impossible to further distinguish their efficiencies. Therefore, the concept of "super-efficiency" was proposed by Andersen and Petersen (1993) to improve traditional DEA models. The DMUs whose efficiency is 1 in traditional models may be more than 1 in the super-efficiency model, making the result more accurate. Tone (2002) proposed a new model by combining the SBM model and the super-efficiency model, which could define inefficiency based on slacks and evaluate the efficiency of DMUs in the efficient frontier.

In this research, in a Super-SBM model, $P\backslash(x_0, y_0)$ was defined as a production possibility set that excludes (x_0, y_0), and $P\backslash(x_0, y_0) = \{(\bar{x}, \bar{y}) | \bar{x} \geq \sum_{j=1,\neq 0}^{n} \lambda_j x_j, \bar{y} \leq \sum_{j=1,\neq 0}^{n} \lambda_j y_j, \bar{y} \geq 0, \lambda \geq 0\}$. Furthermore, a subset $\bar{P}\backslash(x_0, y_0)$ of $P\backslash(x_0, y_0)$ was defined as $\bar{P}\backslash(x_0, y_0) = P\backslash(x_0, y_0) \cap \{\bar{x} \geq x_0, \bar{y} \leq y_0\}$. Moreover, δ was defined as the super-efficiency of (x_0, y_0). Therefore, a fractional program was formulated to construct a Super-SBM model as **Equation 3.6**:

$$\text{Min} \quad \delta = \frac{\frac{1}{m}\sum_{i=1}^{m} \bar{x}_i / x_{i0}}{\frac{1}{s}\sum_{r=1}^{s} \bar{y}_r / y_{r0}}$$

$$\text{Subject to} \quad \bar{x} \geq \sum_{j=1,\neq 0}^{n} \lambda_j x_j, \tag{3.6}$$

$$\bar{y} \leq \sum_{j=1,\neq 0}^{n} \lambda_j y_j,$$

$$\bar{x} \geq x_0, 0 \leq \bar{y} \leq y_0, \lambda \geq 0.$$

To solve the programming problem and evaluate the efficiency, **Equation 3.6** can be transformed into a linear programming problem, as **Equation 3.7** shows.

$$\begin{aligned}
\text{Min} \quad & \tau = \frac{1}{m}\sum_{i=1}^{m} x^{*}/x_{i0} \\
\text{Subject to} \quad & \frac{1}{s}\sum_{r=1}^{s} y_r^{*}/y_{r0} = 1, \\
& x^{*} \geq \sum_{j=1,\neq 0}^{n} \varsigma_j x_j, \\
& y^{*} \leq \sum_{j=1,\neq 0}^{n} \varsigma_j y_j, \\
& x^{*} \geq t x_0, 0 \leq y^{*} \leq t y_0, \varsigma_j \geq 0, t \geq 0.
\end{aligned} \tag{3.7}$$

3.4.3.2 Window Analysis

Efficiency results in Super-SBM models are relative values because they originate from the distance between DMUs and the efficient frontier. Due to this characteristic, efficiency results cannot reveal the efficiency trend because the efficiency frontier differs in every period (Wu et al., 2020). To overcome this shortage, results are usually further processed with window analysis or the Malmquist productivity index in previous research (Park et al., 2018b; Tohidi et al., 2012). However, research shows that the Malmquist productivity index may not reflect technological progress characteristics (Oh & Heshmati, 2010). Window analysis is chosen in this study.

Aiming to provide a dynamic evaluation of efficiency, Klopp proposed window analysis in 1985 to evaluate the performance of army recruiting units (Charnes et al., 1984). Window analysis is widely utilized in various research fields, such as the coastal ferry industry (Park et al., 2018b), environmental assessments (Sueyoshi et al., 2013), urban infrastructure carrying capacity (Wang et al., 2020), and environmental efficiency (Song et al., 2016). Window analysis has two strengths. First, it could combine DMUs in different datasets, solving the problem of insufficient DMUs. Second, it helps to compare all the efficiency results in any time series and show the efficiency trend, which is the main reason for choosing window analysis in this study.

Window analysis utilizes moving averages to reveal the efficiency trends in DMUs. It is assumed that the number of DMUs in one period is n, and the number of periods is k. Each DMU in a specific time is regarded as an independent record. After the window length (p) was chosen, DMUs in adjacent periods were collected to calculate the efficiency performance in a DEA model. According to the concept of moving averages, the number of window (w) can be obtained from the formula: $w = k - p + 1$. It is feasible to calculate the average efficiency in every period. After that, the trends or behaviors in the long period could be determined. The window length selection should consider its impact on efficiency results' reliability and stability (Wu et al., 2020). Based on the study of Park et al. (2018b) and Wang et al. (2020), the window length was set as 3. An example of a window analysis table is shown in **Table 3.4** to help readers better understand the process.

Table 3.4 An example of window analysis table.

Windows	Periods: 1	2	3	…	…	…	k-3	k-2	k-1	k
1	Window length									
2										
3										
…										
…										
w										
Average efficiency										

3.4.4 Gravity Model

According to Newton's law of universal gravitation, gravity exists in every two particles. The force is proportional to the mass of objects and inversely proportional to the distance between two objects (Watanabe et al., 2021). The gravity model originates from Newton's law, and it considers the region as a point in geography and investigates the social and economic relationship between regions.

The gravity model was first proposed to explore internal migration flows (Bakens et al., 2018). For example, Karemera et al. (2000) applied a gravity model to analyze the migration flow relationship between Canada and the United States with 1540 observations from 1976 to 1986. Park et al. (2018a) studied the migration flows under marriage patterns through a gravity model. The application of the gravity model has been extended to other research fields, such as traffic flow and international economic trade. The gravity model can present the relationship between trade and resource elements, so it has been an important method in international trade research and regional trade research over the past 50 years (Baier & Standaert, 2020). For example, de la Mata and Llano (2013) examined the relationship between interregional services trade and migration flows through a gravity model.

The gravity model provides a method for establishing spatial correlations in economic geography, which is widely used to describe and predict social behaviors in social science research (Crymble et al., 2018). For example, Han et al. (2018) explored the evolution path of the urban system in China through a gravity model including socioeconomic variables. Liu et al. (2018) applied an improved gravity model and an SNA model to explore the network structure of urban agglomeration. In addition, many studies adopted gravity models to investigate carbon emissions. Wang et al. (2018a) used a revised gravity model to establish the carbon emission network between provinces and applied SNA to analyze the network. Similarly, the method combined with gravity models with SNA has also been applied to analyze the spatial correlation of low-carbon innovations (Yang & Liu, 2020b).

The gravity model has significant advantages in establishing the spatial correlation network (Ma et al., 2019; Wang et al., 2018a), so this study adopts it to examine the spatial correlation of GBD and establish the spatial correlation matrix. The gravity model is constructed as shown in **Equation 3.8**.

$$x_{ij} = \frac{E_i}{E_i + E_j} \times \frac{\sqrt{P_i E_i G_i} \times \sqrt{P_j E_j G_j}}{(\frac{D_{ij}}{g_i - g_j})^2} \tag{3.8}$$

Where i and j represent Region i and Region j; x_{ij} is the correlation of GBD between Region i and Region j, E is the GB number, P is the number of population, G is the regional GDP, D is the distance between two regions and g is the per capita GDP. We assume that the number of regions is k, then $i = 1,2,\cdots,k$ and $j = 1,2,\cdots,k$.

A correlation matrix C could be obtained from the gravity model, shown in **Equation 3.9**.

$$C = \begin{pmatrix} x_{11} & \cdots & x_{1k} \\ \vdots & \ddots & \vdots \\ x_{k1} & \cdots & x_{kk} \end{pmatrix} \quad (3.9)$$

Where C is the correlation matrix; x_{ij} is the correlation of GBD between Region i and Region j.

As the outcome of the modified gravity model, the correlation matrix is symmetric. Previous studies further processed the matrix (He et al., 2020). The average of correlations in the region was considered as a threshold. The values higher than the average was recorded as 1, while the lower values were recorded as 0. This approach changed the matrix into a directed 0-1 matrix. Afterward, further network analysis, such as network structure and centrality analysis, was conducted based on the revised matrix. The process is shown in **Equation 3.10**.

$$x'_{ij} = \begin{cases} 1, when\ x_{ij} \geq Average \\ 0, when\ x_{ij} \leq Average \end{cases} \quad (3.10)$$

Therefore, the new spatial correlation matrix is shown in **Equation 3.11**.

$$C' = \begin{pmatrix} x'_{11} & \cdots & x_{1k} \\ \vdots & \ddots & \vdots \\ x_{k1} & \cdots & x_{kk} \end{pmatrix} \quad (3.11)$$

3.4.5 Social Network Analysis

Social Network Analysis (SNA), a quantitative network analysis method based on graph theory, is applied to investigate complex social phenomena by constructing networks. The social phenomenon and social structures are quantitatively analyzed through network science (Zheng et al., 2016). Actors can be regarded as nodes, and the correlations between actors can be regarded as edges in SNA (Yang & Liu, 2020a). Actors not only refer to specific individuals but also refer to groups and institutions. The research objects of SNA include the actor behaviors, the correlations between actors and the network structure (Yang & Zou, 2014). Although social network analysis has been widely used in various research fields (Choi et al., 2021; McClean et al., 2021), its application in spatial analysis remains further explored (Ma et al., 2020).

After establishing the spatial correlation matrix of GBD by the gravity model, the spatial network was developed by Ucinet 6, an SNA software. The network, degree centrality and block modeling were analyzed to identify the characteristics of the overall network structure, network centrality, and clusters of regions.

3.4.5.1 Network Analysis

The network scale includes the number of actors and the correlations of actors. A larger network means more complex network structures. The density, efficiency, hierarchy and connectedness of the network are applied to analyze the network structure. The network density is the ratio of the actual number of edges to the maximum number of edges in the network, which ranges from 0 to 1. It represents the completeness of the correlations and the closeness between nodes in the network. Meanwhile, the large network density means the interactions between actors are more significant. The network density calculation follows **Equation 3.12** in directed networks (Yang & Liu, 2020b).

$$D = \frac{L}{N \times (N-1)} \tag{3.12}$$

Where D represents network density, L is the number of ties in the network, N is the number of nodes. $N \times (N-1)$ is the maximum number of ties, and it happens when there is an edge between every two nodes.

The connectedness reflects the robustness of the network. If all nodes in the network are connected, then the connectedness of the network is high. The calculation equation of connectedness is shown in **Equation 3.13**.

$$C = 1 - \frac{V}{N \times (N-1) \times 2} \tag{3.13}$$

Where C is the connectedness of the network, V is the nodes that have correlations with other nodes.

The network hierarchy measures the hierarchical status existing in the network. In this research, the high network hierarchy means integrating regions with high GBD and low GBD is difficult. The calculation equation of the network hierarchy is shown in **Equation 3.14**.

$$GH = 1 - \frac{R}{Max(R)} \tag{3.14}$$

Where *GH* is the network hierarchy, *R* is the number of symmetrical reachable nodes in the network, *Max(R)* is the maximum number of possible symmetrical reachable nodes.

The network efficiency reflects redundant correlations in the network. The low network efficiency means many correlations in the network, and the network is more cohesive. The calculation equation of network efficiency is shown in **Equation 3.15**.

$$GE = 1 - \frac{K}{Max(K)} \tag{3.15}$$

Where *GE* is the network efficiency, *K* is the number of redundant edges, and *Max(K)* is the maximum possible number of redundant edges.

3.4.5.2 Network Centrality

The centrality analysis concentrates on the nodes in the network, measuring the status and function of nodes. Nodes at the center of the network have a stronger influence on the network, while the central nodes influence nodes at the edges. The network centrality includes degree centrality, closeness centrality and betweenness centrality.

The degree centrality measures the direct correlations of the nodes. For a directed network, degree centrality contains out-degree and in-degree, as shown in **Equation 3.16**.

$$C_{deg}(v) = \frac{d_v}{|N| - 1} \tag{3.16}$$

Where d_v is the number of nodes that connect with the node *v*; *N* is the sets of all nodes in the network; $|N|$ is the number of all nodes in the network.

The closeness centrality measures the sum of the paths from this node to other nodes. The small closeness centrality means that the path between the node and other nodes is short, indicating that this node can connect to other nodes quickly. The equation for calculating closeness centrality is shown in **Equation 3.17**.

$$C_{close}(v) = \frac{|R(v)|}{|N| - 1} \frac{1}{\sum_{u \in R(v)} d(u, v)} \tag{3.17}$$

Where $|R(v)|$ is the set of reachable nodes from the node *v*; $d(u, v)$ is the shortest distance of the node *u* and the node *v*.

The betweenness centrality examines the number of shortest paths through the node. The high betweenness centrality means more shortest paths through the node, indicating that the node acts as the bridge of connections between many nodes. Without this node, the connectivity of the network is reduced significantly. The equation for calculating the betweenness centrality is shown in **Equation 3.18**.

$$C_{btw}(v) = \sum_{s,t \in N} \frac{\sigma_{s,t}(v)}{\sigma_{s,t}} \tag{3.18}$$

Where $\sigma_{s,t}$ is the number of shortest paths between the node *s* and the node *t*; $\sigma_{s,t}(v)$ is the number of shortest paths between the node *s* and the node *t* and getting through the node *v*.

3.4.5.3 Block Modeling

Block Modeling is a clustering method in SNA. It simplifies the complicated network by classifying regions into several blocks according to similar actors' behaviors, which is easier for researchers to identify the fundamental characteristics of a complex network (Glueckler & Doreian, 2016). The aim of block modeling in this study is to probe spillover impacts of GBD efficiency further and investigate its evolution. The spillover effect means that economic activities in one region can influence surrounding regions and generate spatial externalities (Zhou et al., 2019). Similar features in the same block were concluded, and the difference was compared between different blocks. Block modeling was conducted through the CONCOR module in the Ucinet 6. Regions with no GBs were deleted from the original data before the block model analysis was conducted.

In line with previous research (He et al., 2020; Yang & Liu, 2020a), this research classified regions into four blocks, namely "main spillover," "primary beneficial," "bidirectional spillover" and "agent." The main spillover block means the provinces in this block send more spillover relationships to other provinces. There are fewer relationships between provinces within this block, and they rarely receive relationships from other provinces. The primary beneficial block means that the provinces in this block have more internal and fewer external relationships and fewer spillover effects on other sectors. The agent block means that the provinces in this block play the role of the bridge. They receive the relationship from other provinces and send out relationships to other provinces, but there are few internal relationships in the block. The bidirectional spillover block has strong spillover relationships with other blocks, and there are spillover relationships between members within the block, but they rarely receive relationships from other blocks. The judging criterion of blocks refers to the study of

Wasserman and Faust (1994), as shown in **Table 3.5**. In the table, g_k means the number of provinces in the block, and g means the number of all provinces.

Table 3.5 Judging criterion of blocks.

Ratio of internal relationships	Ratio of received relationships	
	≈ 0	> 0
$\geq (g_k - 1)/(g - 1)$	Bidirectional spillover	Primary beneficial
$< (g_k - 1)/(g - 1)$	Main spillover	Agent

3.4.6 Meta-analysis

Meta-analysis was first applied in medical research to analyze clinical trial results (Sebri, 2015). Afterward, it was applied in other research fields (Feng et al., 2020; Minunno et al., 2021; Peters et al., 2020). The systematic review ensures that the selected literature is comprehensive, combined with the meta-analysis (Araujo et al., 2020; Bhandari et al., 2015; Pomponi et al., 2016). The results of meta-analysis may get closer to the true effect size because it synthesizes the results from previous studies, and the sample size is larger than the individual quantitative studies (Sun et al., 2018; Van der Kroon et al., 2013). The data applied in the meta-analysis were collected by a systematic literature review. The fixed-effect model or the random-effects model was chosen to analyze the data (Nicolson et al., 2018).

Two statistical models could be chosen for meta-analysis: the fixed-effect model and the random-effects model (Borenstein et al., 2009). Their application scopes are different because they are based on different assumptions. Researchers can build the fixed-effect model when they believe only one true effect size exists. The external conditions should be consistent, so the requirements of the fixed-effect model are strict, which is difficult in social science. Experiments in the laboratory are more suitable. On the contrary, the random-effects model permits different true effect sizes in previous studies, which is closer to this research. Therefore, this study applied random-effects models to conduct the meta-analysis. The software Comprehensive Meta Analysis 3.3 (CMA 3.3) was applied for meta-analysis. Before calculating the mean effect size, the weight of included studies was calculated by **Equation 3.19**.

$$W_i^* = \frac{1}{V_{Y_i} + T^2} \tag{3.19}$$

Where W_i^* represents the weight assigned to study *i*; V_{Y_i} represents the within-study variance for study *i*; T represents the between-studies variance.

The calculation process for mean effect size is shown in **Equation 3.20**, and the calculation process for variance in the random-effects model is shown in **Equation 3.21**. Each factor coded from previous studies must get through the calculation.

$$M^* = \frac{\sum_{i=1}^{k} W_i^* Y_i}{\sum_{i=1}^{k} W_i^*} \tag{3.20}$$

Where M^* represents the weighted mean; Y_i represents the observed effect for study *i*.

$$V_m^* = \frac{1}{\sum_{i=1}^{k} W_i^*} \tag{3.21}$$

Where V_m^* represents the variance of the summary effect.

If there is only one true effect size, there is no heterogeneity problem in the meta-analysis, which is an ideal situation (Borenstein et al., 2009). In the random-effects model, heterogeneity comes from two parts. The first is the real heterogeneity, indicating that previous studies have different true effect sizes. The second part is the within-study error. I^2 is the ratio of excess dispersion to total dispersion, which is utilized to detect heterogeneity (Borenstein et al., 2009). 25% and 75% are two dividing lines. If I^2 is less than 25%, the heterogeneity is low, and If I^2 is more than 75%, the heterogeneity is high (Higgins et al., 2019).

The studies with high effect sizes are more likely to be published and included in the meta-analysis, leading to publication bias (Borenstein et al., 2009). The funnel plot could display the publication bias. Meanwhile, some methods could determine publication bias quantitatively, e.g., Fail-safe N, Orwin's Fail-safe N, and Duval and Tweedie's Trim and Fill. Duval and Tweedie's Trim and Fill can adjust the effect size if there is a publication bias, so it was chosen in this research.

3.4.7 Cronbach's Alpha Technique

The Cronbach's alpha technique, one of the most prevalent methods in the questionnaire survey, was proposed by Lee Cronbach in 1951. It is normally applied to examine the reliability of scales, which shows internal consistency. it checks whether the Likert scale surveys with multiple questions are reliable. The range of Cronbach's alpha is from 0 to 1. A high Cronbach's alpha means the high reliability of scales. Generally, the value of Cronbach's alpha should be more than 0.7 in empirical studies. In this research, Cronbach's alpha technique was applied to show the reliability of the questionnaire survey, and it was calculated by SPSS.

3.4.8 Mean Score Ranking Technique

The mean score ranking technique is a typical data analysis technique in the questionnaire survey, which has been widely adopted in GB research (Darko et al., 2017c). It is applied to determine the mean scores of factors and rank the factors. In this study, the mean score ranking technique was used to prioritize the CSFs of GBD. The equation of mean score ranking is shown in **Equation 3.22**. The CSFs of GBD are in descending order of importance according to respondents' opinions. If more than one factor has the same mean score, the standard deviation will determine the ranks. Factors with a smaller standard deviation rank higher.

$$B_i = \frac{\sum_1^n \alpha_{ij}}{n} \tag{3.22}$$

Where n is the number of respondents in the questionnaire survey; α_{ij} is the importance of factor i rated by respondents j; B_i is the mean score of the importance of factor i.

3.5 Chapter Summary

This chapter summarized the research methodology of this study. First, the research design framework was developed to show the process of this study. Second, the data collection methods were clarified, including the statistical data collection, literature review, and questionnaire survey. Then, the data analysis methods were demonstrated, including the rough set theory, catastrophe progression models, DEA models, SNA models, Cronbach's alpha method and mean score ranking technique in the questionnaire survey.

CHAPTER 4 GREEN BUILDING DEVELOPMENT EVALUATION MODEL[4]

4.1 Introduction

GB promotion is critical to sustainable urban construction (Smith, 2015b). More buildings have been awarded GB labels in recent years. The growth in the GB number is considered a direct indicator of GBD, and some studies have used GB distribution to demonstrate regional GBD and its evolution. In the United States, GBs first emerged in the coastal regions, then appeared in other regions (Cidell, 2009). Buildings certified LEED label and Energy star concentrated on the metropolitans and sub-metropolitans (Kaza et al., 2013). Smith (2015a) investigated the spatial distribution of LEED-India and GRIHA projects and compared the difference. The GB distribution in China was uneven, and the situation of GBD was not optimistic (Zhang et al., 2018a; Zuo et al., 2017). Most previous studies take the GB number as the only indicator of GBD. However, GBD is influenced by various elements, e.g., labor, investments, technologies and government policies (Kaza et al., 2013). More indicators need to be incorporated to give an overview of GBD, and a more comprehensive evaluation system needs to be constructed to measure GBD in different regions.

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[4] This chapter is largely based upon:
Chen, L., Gao, X., Gong, S., & Li, Z. (2020). Regionalization of Green Building Development in China: A Comprehensive Evaluation Model Based on the Catastrophe Progression Method. *Sustainability*, *12*(15), 5988.

This chapter aims to propose a comprehensive evaluation model to examine GBD and investigate GBD from a spatial perspective. This chapter applies a hybrid approach that combines rough set theory with the catastrophe progression method to achieve the goal. Moreover, empirical analysis is conducted to verify the model, and the data of 31 provinces in China from 2008 to 2020 are adopted. The overall trend and spatial patterns of GBD in China are demonstrated based on empirical results.

4.2 Evaluation Framework of Green Building Development

Fifteen GBD indicators in China were chosen from research articles, government policies and industry reports. These indicators were divided into four categories: certification, economy, policy and technology. The initial GBD evaluation framework was established, as shown in **Table 4.1**. Considering the number limitation of control variables in the catastrophe progression model, the number of indicators in each category was controlled within four when constructing the GBD evaluation framework.

4.2.1 Certification Indicators

According to ESGB, if the building met GB criteria, it could be certified with GB labels. The GB spatial distribution could reflect the region GBD directly (Zhang et al., 2019c), so the number of local certified GBs was chosen in this category. However, if the research only concentrates on certified GBs, it will lose important information and a holistic overview of GBD. GB is a construction initiative highly impacted by the economy and society. At the same time, technology development is critical to GBs, and GBD is a complex system. Although certification is often considered the symptom of local GBD, the evaluation framework attempts to involve other indicators in compliance with the completeness principle, a critical selection criterion for establishing a comprehensive indicator framework. Therefore, more indicators related to the other three categories (economy, policy, and technology) were chosen in this research.

Table 4.1 GBD evaluation framework.

Category	Subcategory	Indicator Layer
Certification (A_1)	Certification (B_1)	Number of certified GBs (C_1)
Economy (A_2)	Industry (B_2)	Output value of building construction (C_2)
		Building construction area (C_3)
	Enterprise (B_3)	Number of construction enterprises (C_4)
		Number of staff and workers in construction enterprises (C_5)
		Total assets of construction enterprises (C_6)
	Finance (B_4)	Business revenue of construction enterprises (C_7)
		Total profits of construction enterprises (C_8)
		Paid-up capitals of construction enterprises (C_9)
		Total value of signed contracts (C_{10})
Policy (A_3)	Policy (B_5)	Number of local policies (C_{11})
Technology (A_4)	Technology (B_6)	Net value of machinery and equipment owned (C_{12})
		Power of machines per worker (C_{13})
		Number of GB innovation awards (C_{14})
		Number of GB patents (C_{15})

4.2.2 Economy Indicators

Previous research presented that strong relations existed between the economy and GBD (Zuo et al., 2017). If the local economy develops well, more investments could be put into GB construction. Although some regions have a small number of GBs, the potential for GB construction is huge because of the financial support. Nine candidate indicators were chosen and classified into the industry, enterprise, and productivity indicators.

There are two indicators in the industry category: the output value of building construction and the building construction area. Previous studies usually utilized Gross domestic product (GDP) to measure economic development. For example, through regression analysis, Prum and Kobayashi (2014) found a positive relationship between GDP and buildings with GB labels. Zuo et al. (2017) selected the economy-related variables to build the model and proved that the economic variables could represent GBD to some extent. GDP and GBD have strong relations, but GDP includes all the products of manufacturing, agriculture, and services. As a kind of building product, GB accounts for a small proportion of GDP. Therefore, a targeted indicator (the output value of building construction) in the construction industry was selected to present GBD.

There are three indicators in the enterprise category. The construction enterprise plays a significant role in GBD. They are responsible for GB construction. The number of construction enterprises, the number of staff and workers in the enterprises and the total assets of construction enterprise were chosen to examine the scale of the enterprises. There are four indicators in the finance category. The business revenue of construction enterprises, total profits of construction enterprises, paid-up capital of construction enterprises and the total value of signed contracts were chosen to show enterprises' financial status.

4.2.3 Policy Indicators

Governments play a significant role in GBD (Darko & Chan, 2016b). Governments get involved in the GB practice by making policies (Zuo & Zhao, 2014). Policies could be classified into positive incentives and mandatory policies based on the effects (Zhang et al., 2019c; Zuo & Zhao, 2014). Positive incentives contain subsidies, density bonuses, floor area ratio bonuses, and tax reductions. Mandatory policies include penalties and compensations. Previous studies showed that government policies helped promote GBs and enhanced GBD effectively (Prum & Kobayashi, 2014). In Taiwan, mandatory policies for public buildings and incentive policies for private buildings are the most effective (Kuo et al., 2017). Meanwhile, the Green Building Action Programme in mainland China is an effective national policy, stipulating GBD and urges local governments to release technical standards and financial policies (MOHURD, 2020a). The central government usually provides guidelines for GBD promotion principles and goals, and local governments formulate detailed policies to regulate GB construction activities (Darko et al., 2017b). The effect of policies is difficult to examine, so this research simplified it with the number of local policies.

4.2.4 Technology Indicators

GB technologies provide benchmarks for GBs (Ahmad et al., 2019), but the importance has been underestimated (Zhang et al., 2019c). The technologies aim to improve the GB performance in five aspects, including protecting the environment and saving energy, materials, water, and land. The Green Building Innovation Award is a national award for GB projects, enterprises and individuals who contribute significantly to GB research or practice (MOHURD, 2010b). The award reflects the innovation and technology level of GBs in the regions, so it was selected as an indicator. Research showed that green patents were increasing.

New technologies are applied to tackle environmental pollution, and the effects are obvious (Kesidou & Wu, 2020), so GB patents were selected for the indicators. Moreover, machines and equipment utilized in the construction could represent the technology level in GB construction, so the net value of machinery and equipment owned and the Power of machines per worker were selected.

4.3 Research Results

4.3.1 Attribute Reduction Results

After checking the indicator framework, results show that only the evaluation framework in 2008 had overlapping information. In the finance category, $S = (U, A)$ was assumed, where $U = \{1,2,3, \cdots, 30,31\}, A = \{C_7, C_8, C_9, C_{10}, \}$. Then, **Equation 4.1** can be shown. Therefore, C_7 was deleted in 2008. Besides, there was no GB patent in 2008, so C_{14} was also deleted.

$$U/ind(A) = U/ind(A - \{C_7\}) \tag{4.1}$$

4.3.2 Evaluation Results

4.3.2.1 Results of Indicator weights

Indicator weights, shown in **Table 4.2**, were calculated through the entropy method. In the catastrophe progression method, the state variable's weight is the sum of all the control variables' weights. The table shows that most indicators' weights have no obvious changes in these years. Certified GB (C_1), GB innovation awards (C_{14}) and GB patents (C_{15}) are the most significant indicators, and they have direct relations with GB construction. It makes sure the scientificity of GBD evaluation models. The business revenue of construction enterprises (C_7) and the number of GB innovation awards (C_{14}) were unavailable in 2008. Their weights were mainly carried by the number of certified GBs (C_1) and the number of local policies (C_{11}). The weight of GB policies was decreasing. It means that although GB policies were essential in the initial phase of GBD, they were gradually weakened as the supporting environment was improved.

Table 4.2 Weight of indicators.

Indicator	2008	2011	2014	2017	2020
C1	0.166	0.087	0.068	0.092	0.097
C2	0.053	0.050	0.065	0.073	0.062
C3	0.056	0.030	0.074	0.082	0.073
C4	0.034	0.036	0.044	0.042	0.041
C5	0.047	0.056	0.078	0.072	0.072
C6	0.040	0.042	0.050	0.051	0.048
C7	-	0.038	0.050	0.055	0.054
C8	0.048	0.047	0.060	0.071	0.075
C9	0.034	0.040	0.045	0.050	0.043
C10	0.040	0.040	0.051	0.054	0.052
C11	0.133	0.086	0.051	0.040	0.034
C12	0.034	0.037	0.057	0.056	0.071
C13	0.042	0.030	0.036	0.031	0.055
C14	-	0.219	0.125	0.142	0.104
C15	0.273	0.163	0.147	0.090	0.120

Note: (1) C_7 were deleted in 2008 because of the attribute reduction;
(2) C_{14} was deleted in 2008 because there was no patent in 2008.

4.3.2.2 Results of green building development level

The GBD evaluation model adopted the complementary principle because of the strong correlation between the indicators. The GBD evaluation scores in 31 Chinese provinces and their rankings are shown in **Table 4.3**. As the table shows, GBD in most provinces changed slightly in these years. The provinces with high ranks in GBD are Beijing, Hebei, Shanghai, Jiangsu, Zhejiang, Hubei and Guangdong. The provinces with low ranks in GBD are Jilin, Hainan, Yunnan, Tibet, Qinghai and Ningxia. Heilongjiang, Guizhou and Gansu have a clear downward trend, while Anhui, Jiangxi, Shandong and Shaanxi have a clear upward trend in GBD.

Table 4.3 Evaluation results of green building development level.

Region	2008		2011		2014		2017		2020	
	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
Beijing	0.572	6	0.551	6	0.746	2	0.735	4	0.697	5
Tianjin	0.461	9	0.442	9	0.723	5	0.685	9	0.642	15
Hebei	0.466	8	0.445	8	0.730	4	0.703	6	0.687	8
Shanxi	0.280	19	0.262	19	0.646	13	0.621	20	0.601	19
Inner Mongolia	0.258	27	0.244	27	0.627	17	0.593	21	0.555	26
Liaoning	0.357	12	0.337	12	0.484	29	0.583	22	0.585	20
Jilin	0.263	24	0.248	25	0.575	25	0.577	24	0.557	25
Heilongjiang	0.662	5	0.645	5	0.602	19	0.573	26	0.571	21
Shanghai	0.710	3	0.689	2	0.702	10	0.693	8	0.688	7
Jiangsu	0.557	7	0.526	7	0.799	1	0.824	1	0.821	1
Zhejiang	0.754	1	0.724	1	0.714	6	0.747	3	0.723	3
Anhui	0.277	20	0.258	21	0.658	12	0.685	10	0.650	13
Fujian	0.273	22	0.254	22	0.602	18	0.633	16	0.642	14
Jiangxi	0.253	28	0.240	28	0.588	23	0.652	15	0.664	11
Shandong	0.313	13	0.287	14	0.711	8	0.726	5	0.706	4
Henan	0.303	15	0.280	15	0.644	14	0.656	14	0.623	16
Hubei	0.689	4	0.666	4	0.711	7	0.698	7	0.690	6
Hunan	0.287	17	0.266	17	0.639	15	0.676	12	0.659	12
Guangdong	0.712	2	0.687	3	0.732	3	0.753	2	0.746	2
Guangxi	0.259	26	0.244	26	0.600	21	0.625	19	0.601	18
Hainan	0.191	31	0.195	31	0.482	30	0.536	30	0.506	29
Chongqing	0.440	10	0.423	10	0.703	9	0.663	13	0.665	10

Table 4.3 Evaluation results of green building development level (Continued).

Region	2008		2011		2014		2017		2020	
	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
Sichuan	0.290	16	0.268	16	0.635	16	0.628	18	0.603	17
Guizhou	0.405	11	0.398	11	0.601	20	0.631	17	0.568	22
Yunnan	0.264	23	0.248	24	0.593	22	0.576	25	0.551	27
Tibet	0.227	30	0.221	30	0.154	31	0.179	31	0.196	31
Shaanxi	0.282	18	0.263	18	0.676	11	0.682	11	0.674	9
Gansu	0.306	14	0.290	13	0.556	28	0.569	27	0.558	24
Qinghai	0.239	29	0.231	29	0.570	26	0.578	23	0.564	23
Ningxia	0.263	25	0.250	23	0.569	27	0.540	29	0.513	28
Xinjiang	0.274	21	0.258	20	0.577	24	0.566	28	0.503	30

4.4 Discussion

4.4.1 Overall Trend of Green Building Development

A box plot is a statistical diagram showing the dispersion of data, which can reflect data distribution characteristics and compare data characteristics among multiple groups. To show the overall GBD trend, a box plot was drawn based on the results, as shown in **Figure 4.1**. In this figure, the top lines show the maximum GBD, while the bottom lines show the minimum GBD. The bottom and top edges of the box show 25% and 75% percentiles, respectively. The middle lines of the box show the average GBD. Besides, this figure shows the outliers, which are the points outside the box.

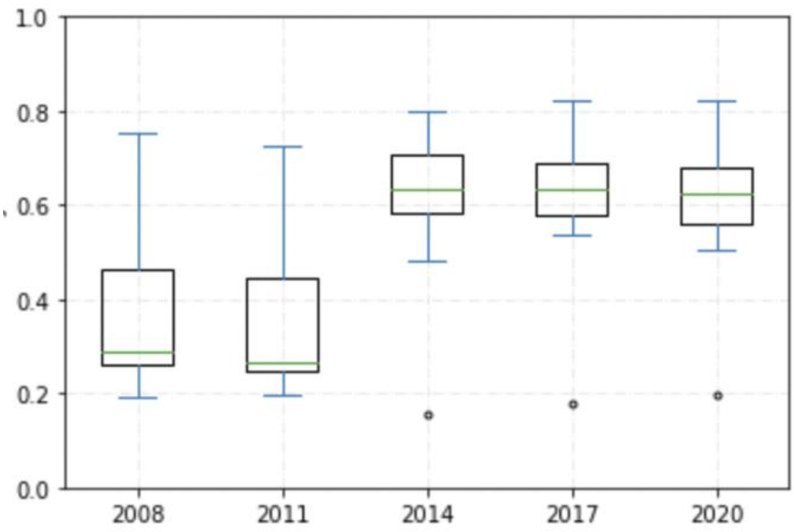

Figure 4.1 The overall trend of GBD in China.

As shown in the figure, the upward trend of GBD in China is obvious, and there was a significant increase from 2011 to 2014. The average value of GBD in China declined slightly and then increased significantly. Besides, it remained steady after 2014. The slight variation of the upper limits of GBD revealed that the regions with high GBD kept a steady growth trend. Notably, the lower limit of GBD has increased significantly, in line with the average growth trend. It means the GBD promotion effect was significant in the regions with low GBD. The huge differences between the upper and lower limits of the box plot from 2008 to 2011 reveal that GBD varied significantly from region to region. Moreover, the lower position of the average line in the box plot indicates that GBD in most regions kept low positions, which was not satisfactory to GB practice. However, the distance between the upper and lower limits of GBD has shortened significantly since 2014, indicating that the GBD gap in different regions has narrowed significantly. As the figure shows, there was an outlier from 2014 to 2020. Combining the evaluation results, it is found that this outlier is Tibet, the bottom region in GBD. According to official statistics released by Tibet, the GB area in Tibet only accounted for 35%

of the new building area by the end of 2019, far from the national target of 70% by 2022. The Tibetan government has begun to take positive actions to promote GBD in recent years. For example, the Tibetan government released the draft of *the GB Management Scheme*, *the Implementation Rules for the Green Building Evaluation and Labelling*, and *the Implementation Plan for GB Action* in 2021. GBD in Tibet has taken an important step forward.

4.4.2 Spatial Patterns and Evolutionary Trends of Green Building Development

The maps were drawn by Python to present the spatial distribution of GBD in mainland China vividly, as shown in **Figures 4.2-4.6**. K-means clustering was conducted with the evaluation results to demonstrate the distribution patterns of GBD. Taking the K-means clustering results into account, provinces in China were classified into five categories: (1) The highest GBD regions with scores greater than 0.701; (2) High GBD regions with scores between 0.601 and 0.700; (3) Moderate GBD regions with scores between 0.501 and 0.600; (4) Low GBD regions with scores between 0.201 and 0.500; (5) The lowest GBD regions with scores less than 0.2000. Colors were used to identify the GBD performance in the figures. The darker the color, the better the performance of GBD. The colors of Hong Kong, Macau and Taiwan are grey because the GBD assessment did not include these regions.

As shown in **Figure 4.2** and **Figure 4.3**, there were four critical regions for GBD promotion from 2008 to 2011: (1) Shanghai and Zhejiang on the eastern coast; (2) Guangdong on the southern coast; (3) Hubei on the center; (4) Heilongjiang in the northeast of China. The spatial heterogeneity of GBD was relatively high in this period because most provinces stayed in the lowest GBD regions. The spatial structure of GBD should exhibit an olive-shaped structure under ideal circumstances. It means a small number of provinces are located in high GBD regions and low GBD regions, while most provinces are located in moderate GBD regions. However, GBs in China appeared in 2008, so most provinces lacked GB standards and codes in the initial stage of GBD. The high heterogeneity is acceptable in this period. Overall, the spatial patterns of GBD in 2008 and 2011 changed slightly, as GBD in Guangdong declined slightly, from the highest GBD region in 2008 to the high GBD region in 2011.

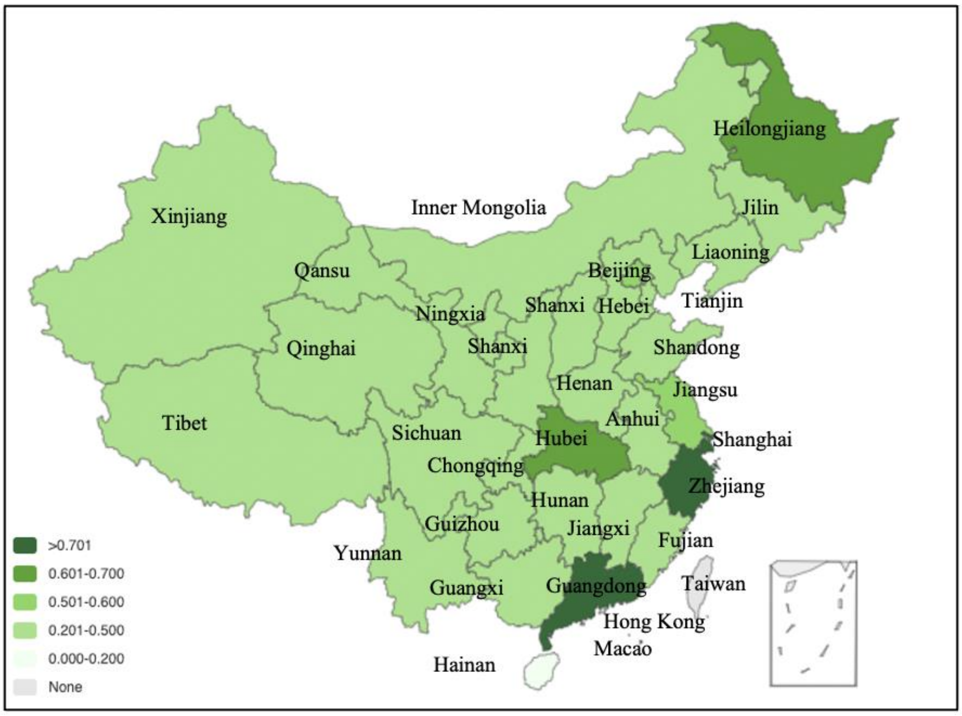

Figure 4.2 Spatial patterns of GBD in 2008.

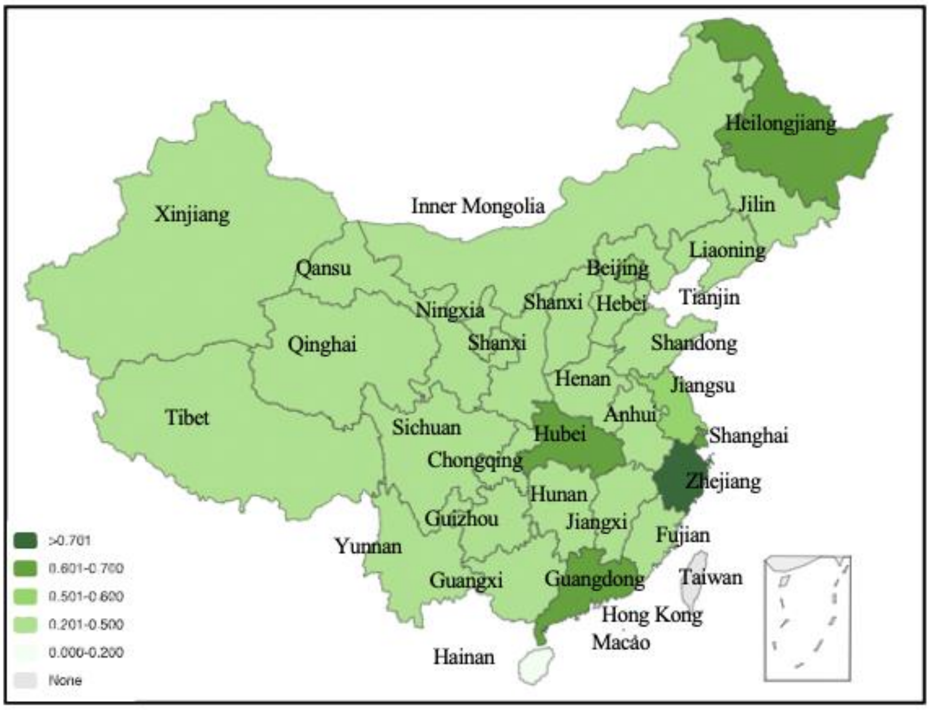

Figure 4.3 Spatial patterns of GBD in 2011.

As shown in **Figure 4.4**, the spatial pattern of GBD in 2014 has been integrated again, and the spatial structure of GBD has rapidly evolved from "point" to "line". 2014 is the best year for GBD in China. Most provinces have achieved great performance in GBD, but the western regions and some other regions have the potential to improve. The spillover effects needed to be strengthened because some regions adjacent to high GBD regions did not show great performance in GBD, such as Jiangxi and Guangxi.

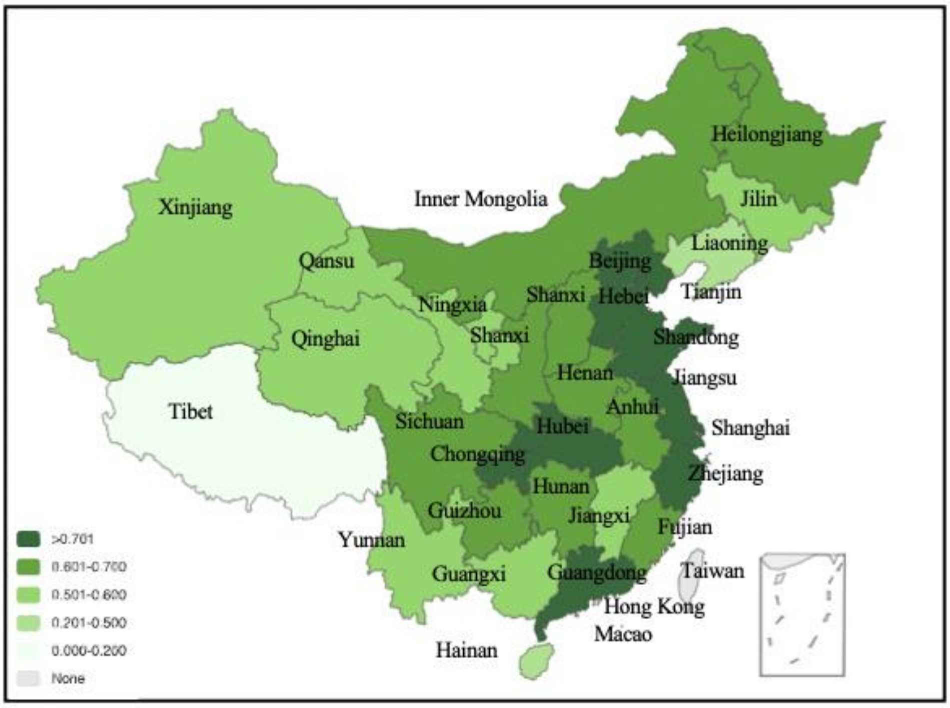

Figure 4.4 Spatial patterns of GBD in 2014.

As shown in **Figure 4.5** and **Figure 4.6**, the spatial pattern of GBD has tended to be stable since 2014. Compared to GBD in 2014, GBD in 2017 and 2020 continued declining, but the decline range was limited. The integration of GBD spatial patterns has been significantly improved in these years. The green performance of Heilongjiang, Inner Mongolia, Hubei and Tianjin showed significant degradation in 2017. The GBD advantage in Hubei gradually disappeared, so it failed to support other provinces in the central region. The degradation of Heilongjiang and Inner Mongolia has weakened the green performance in Northeast China. GBD in Hebei and Guizhou degraded in 2020, so the green performance in Southwest China has been further weakened, and the regional integration advantage in North China has disappeared.

Figure 4.5 Spatial patterns of GBD in 2017.

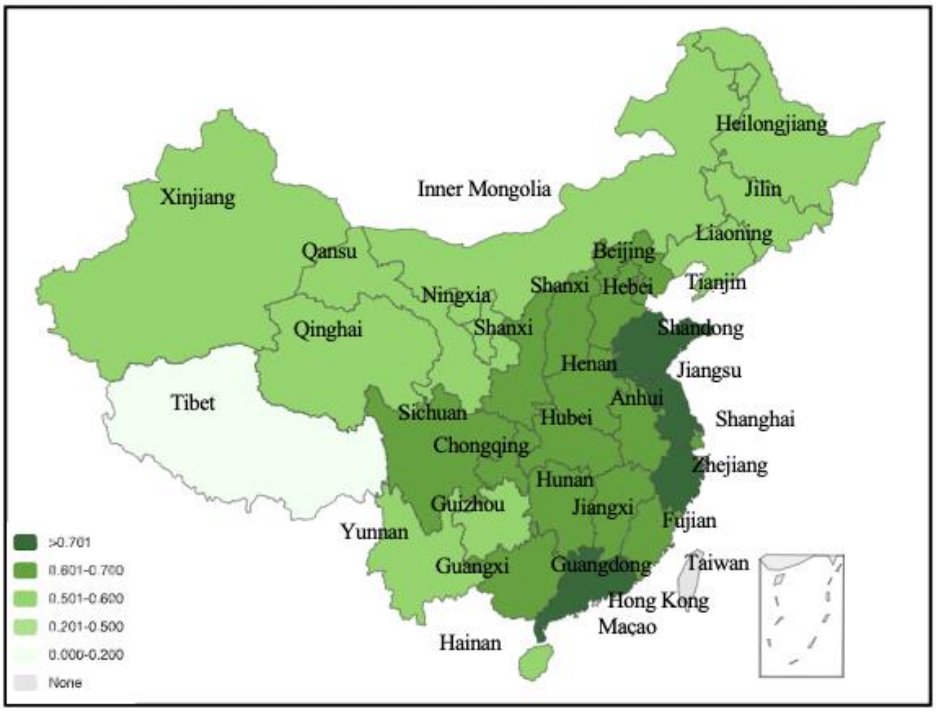

Figure 4.6 Spatial patterns of GBD in 2020.

To sum up, the spatial patterns of GBD demonstrated that GBD in the southeastern coastal areas is better than that in the inland areas, and the inland areas are better than the western areas. The highly developed regions in GBD concentrated on three areas: the Beijing-Tianjin-Hebei area, Yangtze River Delta and Pearl River Delta, leading GBD across the country. Eastern and central areas in China had more population and better economic development than other areas, providing strong support for GBD. As for inland regions, Hubei had better performance in GBD due to its economic advantages, but the advantages faded away. Tibet was always the bottom province in GBD.

In the initial phase of GBD, Shanghai had obvious advantages in GB construction. As a critical metropolis in China, Shanghai is an economic center, attracting numerous foreign investments. Many buildings invested by foreign capitals applied for LEED certifications before ESGB was released in 2006. In line with international standards, these activities accelerated the promotion of local GBs. Although Beijing did not rank at the top in the early years, the official data show that it had more high-quality GBs than other regions.

4.5 Chapter Summary

This chapter proposed a comprehensive GBD evaluation model and conducted an empirical analysis through the GBD data from 2008 to 2020 in China to verify the model and investigate spatial patterns of GBD in China. The results showed that the evaluation model performed well in the GBD examination. The GBD on the southeast coast was better than in other areas, and the synergistic advantages of the Beijing-Tianjin-Hebei, Yangtze River Delta and Pearl River Delta regions were obvious. The evolutionary trends of the GBD spatial pattern present an inverted “U” shape. The critical regions evolved from “point” to “line”, then some regions showed a slight degradation.

CHAPTER 5 EFFICIENCY ASSESSMENT OF GREEN BUILDING DEVELOPMENT[5]

5.1 Introduction

It is acknowledged that achieving sustainability includes sustainable development in the environment, economy and society. As a sustainable and innovative building initiative, GB is born with ecological and economic attributes. Ecological attributes of GBs exhibit the advantages of environmental protection. For example, GBs are committed to saving energy and reducing carbon emissions. Research shows that LEED-certified buildings can save US$7.5 billion in energy costs and reduce carbon dioxide emissions by 33 metric tonnes (MacNaughton et al., 2018). The economic attributes of GBs come from the commodity nature of building products. The construction industry is a pillar industry in some countries, and building construction is an important economic activity for society. Some studies have shown that GBs have a high potential for economic returns, and their ecological attributes help to increase GB rents and asset value premiums (Eichholtz et al., 2013).

According to the Oxford English Dictionary, “efficiency” is a special term in Economics, often related to “economic efficiency” and “technical efficiency” (Oxford English, 2021). In the

[5] This chapter is largely based upon:
Chen, L., Chan, A. P., Darko, A., & Gao, X. (2022). Spatial-temporal investigation of green building promotion efficiency: The case of China. *Journal of Cleaner Production*, *362*, 132299.

dictionary of economic terms, the term efficiency is defined as "the condition that exists when there is no way that resources can be reallocated to increase the production of one good without decreasing the production of another (Raupp & Raupp, 2018)." In essence, GBs are innovative initiatives owning economic attributes. Resource inputs are the prerequisites for GB construction and operation, including investments, labor and technologies. Efficiency analysis is an important topic in economic research (Chien & Hu, 2007). In contemporary economic theory, efficiency analysis refers to investigating the relationship between the positive and negative effects of any economic activities (Wolff, 2002). Efficiency in economics aims to consume as few resources as possible to produce more products to ensure product quality. Besides, the term efficiency could be utilized in the social and economic analysis from both the micro and macro perspectives.

GB efficiency attracted much attention in academia. However, most of the studies concentrated on the efficiency of a specific attribute of buildings, aiming to enhance building performance, especially energy efficiency, water efficiency, and financial efficiency. For instance, the bionic green architecture, inspired by the natural environment, was proposed as a new design concept to increase GB energy efficiency. The typical bionic green architecture utilizes the natural ventilation system in termite mounds, suspension cable in cobwebs, and thin-shell structure in eggshells (Yuan et al., 2017). A design strategy model was established for energy efficiency improvement in the green campus (Liu & Ren, 2020). Besides, a sustainable framework for green residential buildings was proposed, taking energy efficiency into consideration to achieve integrated sustainability (Cai et al., 2013). Ohueri et al. (2018) developed a framework that integrated technologies, policies, and strategies for occupants to increase energy efficiency in the practice of green office buildings. In addition, some studies considered the building occupancy and space efficiency in the indicator systems for GB energy efficiency assessment (Darko & Chan, 2018; Kavousian & Rajagopal, 2014).

Concerning the water efficiency in GBs, Cheng et al. (2016) developed a water usage baseline to assess the efficiency in all kinds of buildings. Green BIM was applied to water efficiency assessment to automatically generate reports and documents needed for GB certification (Khoshdelnezamiha et al., 2020). For financial efficiency, research showed that the financial returns of GBs were substantial (Eichholtz et al., 2013). The attributes related to thermal and energy efficiency made contributions to GB premiums. These studies mainly focused on a specific attribute to assess GB efficiency. However, they did not investigate the economic attributes of GBs from a macro perspective, especially the resource efficiency in the process of GB promotion.

This chapter aims to propose an evaluation model to examine the relationship between resource inputs and product outputs in the GBD process from a macro perspective. The quality of GB economic activities can be described through the model, and the efficiency of resource allocation in GBD can be investigated. Furthermore, the spatial pattern and evolutionary trends of GBD efficiency can be revealed. This chapter adopted DEA as the main research method and combined the Super-SBM model with Window Analysis to examine GBD efficiency quantitatively. This chapter contributes to the GB body of knowledge by presenting an innovative investigation into the efficiency issues in GBD. The findings would enable researchers, policymakers, and practitioners to develop suitable and efficient policies and strategies to promote the widespread implementation of GBs.

5.2 Input and Output Indicators

The first step in conducting DEA is to scientifically select input and output indicators (Nahangi et al., 2019). It is essential for the assessment because the indicator selection process improves the result accuracy (Chen et al., 2021b). Each region is regarded as a DMU in the efficiency assessment process, with resource inputs and product outputs. As shown in **Figure 5.1**, this research proposed an indicator framework for assessing GBD efficiency. Six aspects, including investment, labor, equipment, energy, innovation and policy, are considered input variables in the efficiency assessment. The output variables contain desirable output and undesirable output. The desirable output is certified GBs, and the undesirable output is CO_2 emissions during GB construction and operation.

Investment, labor and equipment are the basic elements in building construction. Previous studies often considered investment, labor and energy as the input variables in the efficiency assessment (Chen et al., 2021b; Sun et al., 2019). Research showed that foreign investment greatly enhanced domestic GBs in most developing countries (Devine & McCollum, 2019). This conclusion is in line with GBD history in mainland China. At the initial stage of GBD, buildings with foreign investments have better performance in energy-saving. Some buildings actively applied for LEED certifications, which promoted the formulation of GB standards in

China. Therefore, how to attract more investments in GBs through various policies is a critical question when government promotes GBs in developing countries (Darko & Chan, 2017).

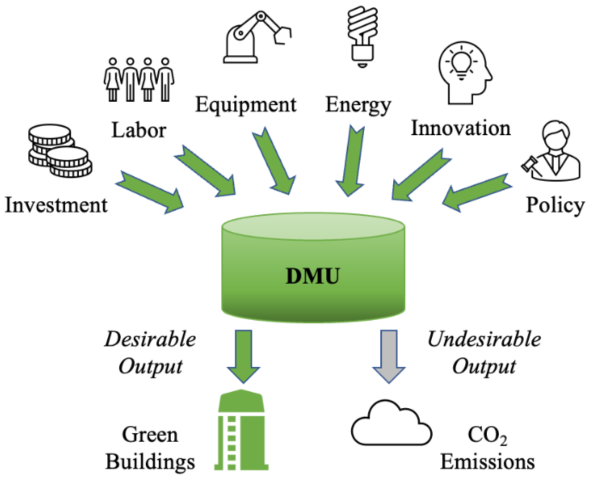

Figure 5.1 An indicator framework for efficiency assessment.

As for labor and equipment, they directly relate to GB construction productivity, which also reveals one facet of efficiency. The construction industry has the labor-intensive characteristic for many years. Although automation in construction is a hot topic (Chen et al., 2018), the mechanization level in building construction remains relatively low compared with manufacturing (Hwang et al., 2020). Powered equipment represents the mechanization level to some extent (Lamsal, 2012). Therefore, labor and equipment are inputs representing the complementary resources in GB construction.

Evidence shows that applying GB technologies contributes to the better achievement of sustainable goals of GBs (Darko et al., 2017a). Innovation is a critical driver of technologies, and patents reflect the innovation level in a region. In line with the primary goal for GBs, reducing energy consumption is essential in the whole life cycle of buildings. To realize high GB efficiency, stakeholders should fully use the energy. Besides, the effectiveness of policies has been examined and verified by previous studies (Chen et al., 2021a; Olubunmi et al., 2016), so innovation, energy and policy are incorporated into the inputs.

The output indicators contain desirable output and undesirable output. The GB number is the most obvious indicator to reveal the level of GBD (Chen et al., 2020), so it was chosen as the desirable output indicator. Similar to previous studies (Sun et al., 2019), CO_2 emission, which fuels the notorious challenge of climate change, was reasonably chosen as an undesirable output. The indicators of GBD efficiency assessment are shown in **Table 5.1**.

Table 5.1 The indicators of GBD efficiency assessment.

Category	Subcategory	Indicator
Input variable	Investment	Revised investment in fixed assets
Input variable	Labor	Number of staff and workers in construction enterprises
Input variable	Equipment	Net value of machinery and equipment
Input variable	Energy	Amount of energy consumption in building construction and operation
Input variable	Innovation	Number of GB patents
Input variable	Policy	Number of GB policies
Output variable	GBs	GB number
Output variable	CO_2 emission	Amount of CO_2 emission in building construction and operation

5.3 Research Results

The resource efficiency of GBs in mainland China from 2008 to 2020 was calculated through super-SBM models and window analysis. Strict desirable output orientation was followed during the calculation, which means that if a region had no GBs in a particular year, it was excluded from the dataset. The results are shown in **Table 5.2**. As can be seen from the table, GBD efficiency in the same region fluctuated in these years, and the changing trend was not clear. The efficiency values and the ranks in some regions had drastic changes with sharp increases and declines. Four regions ranked in the top 10 of GBD efficiency: Shanghai, Guangdong, Hainan and Qinghai. Shanghai and Guangdong had different reasons for ranking high in GBD efficiency compared with Hainan and Qinghai. The economy in Shanghai and Guangdong is better than that of other provinces, so they have more investments and technologies to support GB construction. However, Qinghai and Hainan do not have an advantage in the economy. Their excellent efficiency performance originates from the low CO_2 emissions. In the following section, the results will be analyzed in depth from the overall GBD efficiency trend and the spatial patterns of GBD.

Table 5.2 GBD efficiency results.

Region	2008		2011		2014		2017		2020	
	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
Beijing	0.475	2	0.997	6	0.733	15	0.470	18	0.751	13
Tianjin	—	—	1.635	2	0.967	11	0.323	22	0.484	17
Hebei	—	—	0.472	12	0.885	13	0.122	29	0.188	26
Shanxi	—	—	—	—	0.563	18	0.394	19	0.401	19
Inner Mongolia	—	—	0.187	19	0.246	27	0.227	25	0.538	15
Liaoning	—	—	0.147	21	0.836	14	1.000	5	0.905	12
Jilin	—	—	0.419	14	0.378	23	0.883	7	1.529	1
Heilongjiang	—	—	0.238	17	0.177	29	0.060	30	0.156	29
Shanghai	0.753	1	1.563	3	1.302	5	0.798	8	1.076	3
Jiangsu	0.439	3	2.040	1	1.010	10	0.961	6	0.726	14
Zhejiang	0.094	6	0.426	13	0.342	24	0.278	24	0.977	10
Anhui	—	—	0.093	24	0.321	25	0.538	12	0.238	23
Fujian	—	—	0.887	7	0.389	22	0.208	27	0.223	24
Jiangxi	—	—	0.344	15	1.369	4	0.359	20	1.253	2
Shandong	—	—	0.146	22	1.423	3	0.523	13	0.185	27
Henan	—	—	0.069	25	0.589	17	0.777	9	0.399	20

Table 5.2 GBD efficiency results (Continued).

Region	2008		2011		2014		2017		2020	
	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
Hubei	0.151	5	0.172	20	0.484	20	0.303	23	0.210	25
Hunan	—	—	0.645	10	0.486	19	0.346	21	0.294	21
Guangdong	0.357	4	1.310	4	1.073	8	1.746	2	1.073	4
Guangxi	—	—	0.333	16	2.643	1	0.629	11	0.533	16
Hainan	—	—	1.000	5	1.585	2	1.424	3	1.000	6
Chongqing	—	—	0.124	23	0.297	26	0.217	26	0.172	28
Sichuan	—	—	0.818	8	0.240	28	0.152	28	0.098	30
Guizhou	—	—	—	—	0.424	21	1.947	1	0.242	22
Yunnan	—	—	0.200	18	0.903	12	0.521	14	1.006	5
Shaanxi	—	—	0.504	11	1.289	6	0.644	10	0.935	11
Gansu	—	—	—	—	1.036	9	0.499	16	0.453	18
Qinghai	—	—	—	—	1.201	7	1.033	4	1.000	7
Ningxia	—	—	0.749	9	0.663	16	0.520	15	1.000	8
Xinjiang	—	—	—	—	0.147	30	0.486	17	1.000	9

Note: "—" means no GB this year in this province.

5.4 Discussion

5.4.1 Overall Trend of Green Building Development Efficiency

A box plot was drawn to demonstrate the overall trend of GBD efficiency, as shown in **Figure 5.2**. The average GBD efficiency (the middle line in the box) first shows an obvious upward trend (from 2008 to 2014), then declines significantly and fluctuates in the following years. The highest GBD efficiency values are more than one except it in 2008, revealing that more than one province is in the efficient frontier. The Super-SBM model can further determine the DMUs in the efficient frontier, proving the effectiveness of the Super-SBM model.

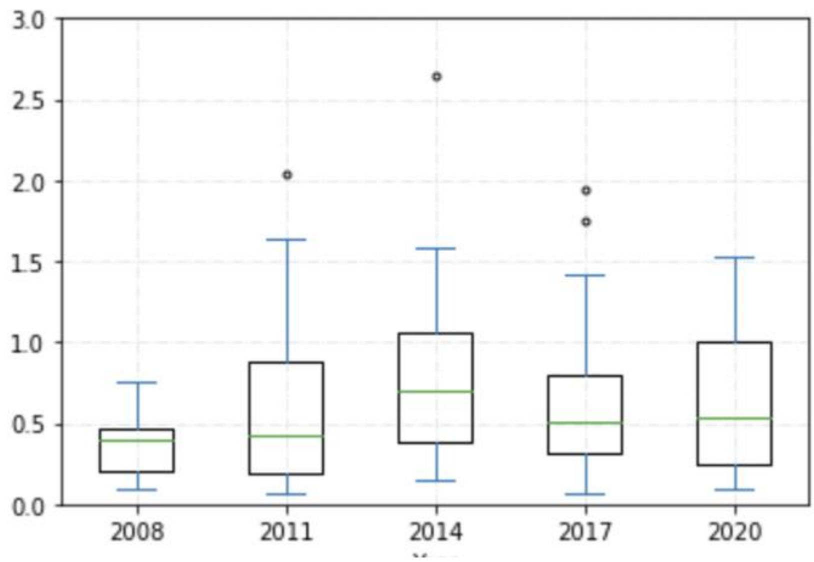

Figure 5.2 Box plot of GBD efficiency.

The minimum efficiency keeps steady over the years, but the maximum efficiency fluctuates significantly. This figure shows that a huge gap exists between the minimum efficiency and the maximum efficiency, and the largest gap appeared in 2011, indicating the uneven status in the spatial distribution of GBD efficiency. Outliers appeared in 2011, 2014 and 2017. In the box plot, outliers are examined based on quartiles and interquartile distances. Outliers in this study mean the values outside the normal range of the data set. Outliers are all higher than the upper limit of the box in this figure. It reveals that the GBD efficiency in some provinces far exceeds that of the rest, another reflection of the huge efficiency gap.

China formulated the *Evaluation Standard of Green Building* in 2006, which defines GBs and provides the benchmark for GBs, and the first local GB certification was issued in 2008. Since then, GBs have spread fast across the country. Under governments' guidance and great support, many provinces have made significant progress in GB practice, including the GB design, construction and operation. Compared to conventional buildings, GBs perform better in building design, materials, construction methods, and heating and ventilation equipment, leading to construction cost premiums and low investment returns. Besides, China was exploring new approaches to the management and organization modes of GB activities. That is the reason why GBD efficiency was low in the initial stage. Along with the deepening recognition of GBs, GB practice has achieved significant improvements since 2014.

Although GBD has made several impressive achievements, some problems still exist. First, GBs tend to apply design labels than operation labels. It means many buildings have a green design, but their energy-saving effects have not been examined in the operation stage. Reducing energy consumption is a critical task for GBs, which needs to be fulfilled in the operation stage. It is not enough for buildings only with GB design. Second, some buildings acquired GB certification by providing fake materials. The cheating behaviors disturb the GB market. Third, GB technologies are not sufficient in practice. On the one hand, the application of GB technologies is not extensive, e.g., self-thermal insulation walls, energy-efficient windows and doors, efficient lighting and ventilation technologies. On the other hand, the application of information technology is not extensive, e.g., the BIM technology and artificial intelligence approach in the GB field. Besides, the application of new construction technologies is not extensive, e.g., the internet of things and construction robotics. These barriers hindered GB promotion in China, resulting in low GBD efficiency.

Therefore, after GBs were adopted in many provinces, the government and practitioners switched their attention from improving the GBD to increasing the quality of GB activities. First, the design label of GBs was canceled in the latest version of ESGB released in 2019. The new standard regulates that buildings can apply for GB certification after construction. If buildings only have the construction design, the pre-evaluation can be carried out. This provision shifts certifying GB labels from the design stage to the operation stage, eliminating the possibility of “fake GBs.” So far, many provinces have taken action and canceled the evaluation work of GB design labels. Second, the high quality of GB functions helps promote GB efficiency. Previous versions of ESGB pay more attention to the green attributes of buildings, but the new standard has improved by emphasizing occupants’ health and comfort, focusing on occupants’ feelings and satisfaction. In addition, sustainable materials are the future trend. The standard of GB material has been released to guide the market.

5.4.2 Spatial Patterns and Evolutionary Trends of Green Building Development Efficiency

According to the results, the spatial patterns of GB efficiency in China are shown in **Figures 5.3-5.7**. Combined with the K-means clustering results, the provinces in China were classified into four categories: (1) Low-efficiency regions with scores less than 0.300; (2) Moderate-efficiency regions with scores between 0.301 and 0.550; (3) High-efficiency regions with scores between 0.551 and 1; (4) Super-efficiency regions with scores higher than 1. Colors were used to identify the GBD efficiency in the figures. The darker the color, the better the performance of GBD. The efficiency evaluation followed the strict output orientation, so the provinces with no GBs were deleted in the assessment, showing blank in the figures. The colors of Hong Kong, Macau and Taiwan are grey because their data are unavailable.

2008 is the first year of certifying GBs. Only six provinces had GBs this year: Beijing, Jiangsu, Zhejiang, Shanghai, Hubei and Guangdong. The total number of GBs was ten. The other provinces had no GBs, so many regions are blank in **Figure 5.3**. The provinces concentrate on the low-efficiency and moderate-efficiency regions. Super-efficiency regions did not exist.

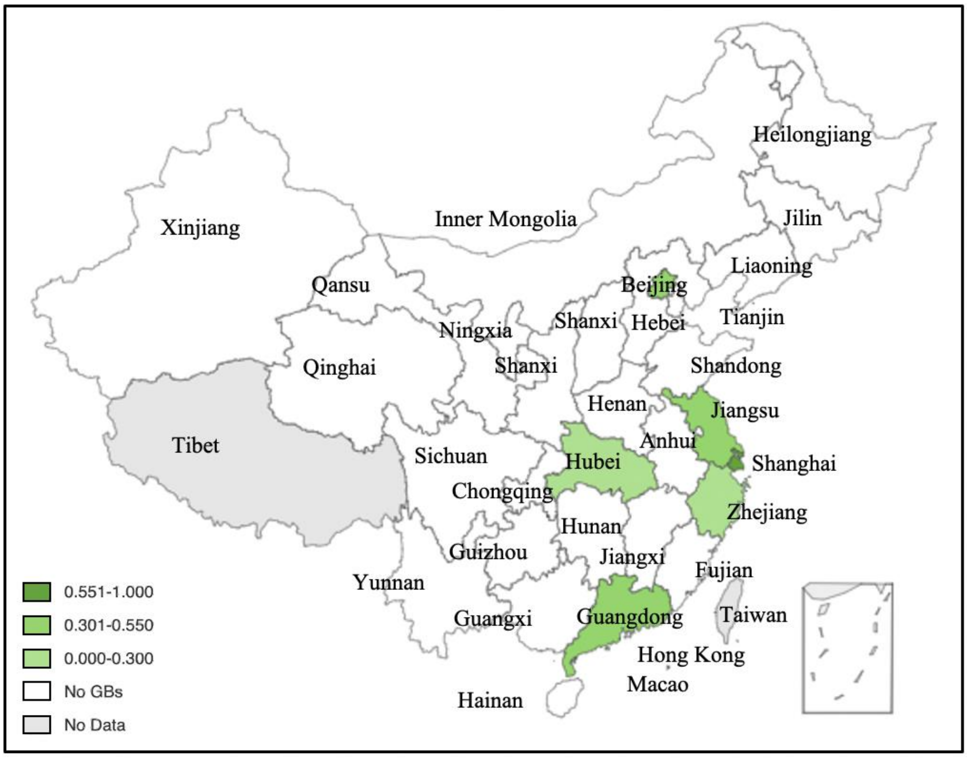

Figure 5.3 Spatial patterns of GBD efficiency in 2008.

More and more provinces have been involved in GB construction since 2008. Compared to **Figure 5.3** and **Figure 5.4**, GB spread fast across the countries. Among 30 provinces, 25 provinces had GBs in 2011. Super-efficiency regions were concentrated in the Beijing-Tianjin-Hebei Area, Yangtze River Delta Area, and Pearl River Delta Area, located in the coastal areas and have strong relations with the local economy. In addition, these regions also performed well at GBD, which was mentioned in Chapter 4. Except for the three core areas, GBD efficiency in Ningxia, Sichuan, Hunan and Fujian showed more advantages than in other regions, but their GBD was not as well as their GBD efficiency. Their advantages in GBD efficiency originated from the low CO_2 emissions. The spatial structure of the GBD efficiency in this period showed three core regions and multiple centers, and GBD efficiency was gradually decoupled from local GB Status.

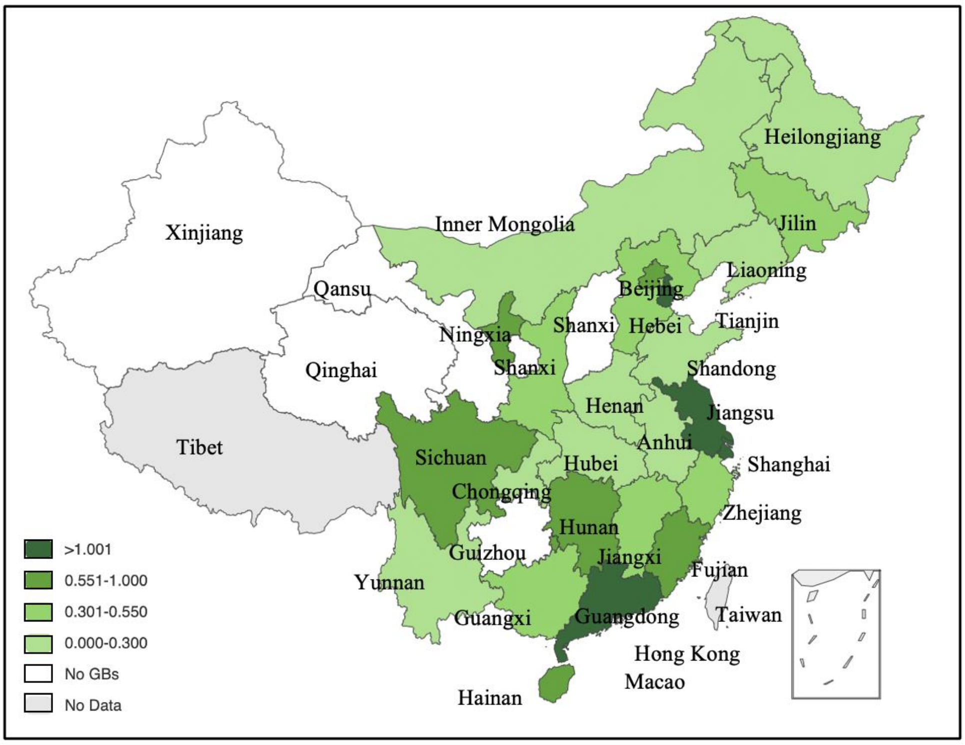

Figure 5.4 Spatial patterns of GBD efficiency in 2011.

All the regions had GBs in 2014, as shown in **Figure 5.5**. Although there were still three core regions and multiple centers, the spatial distribution of GBD efficiency had significant changes. First, super-efficiency regions obviously increased in this period, accounting for a third of the total provinces. Second, the areas of the core regions changed and increased. The advantages of the Beijing-Tianjin-Hebei Area have disappeared. The north-western inland region, led by Qinghai, Gansu and Shaanxi, became the new core area of GBD efficiency. The original Yangtze River Delta Area has spread to Shandong. The original Pearl River Delta Area has spread to Jiangxi, Guangxi and Hainan. A conclusion could be drawn from the figure that the spatial correlations of GBD efficiency have strengthened because high-efficiency regions emerged closely. Only some provinces performed well both in GBD and GBD efficiency, such as Shanghai, Jiangsu and Guangdong. Most provinces had different ranks in GBD and GBD efficiency, revealing the decoupling trend with the local economy.

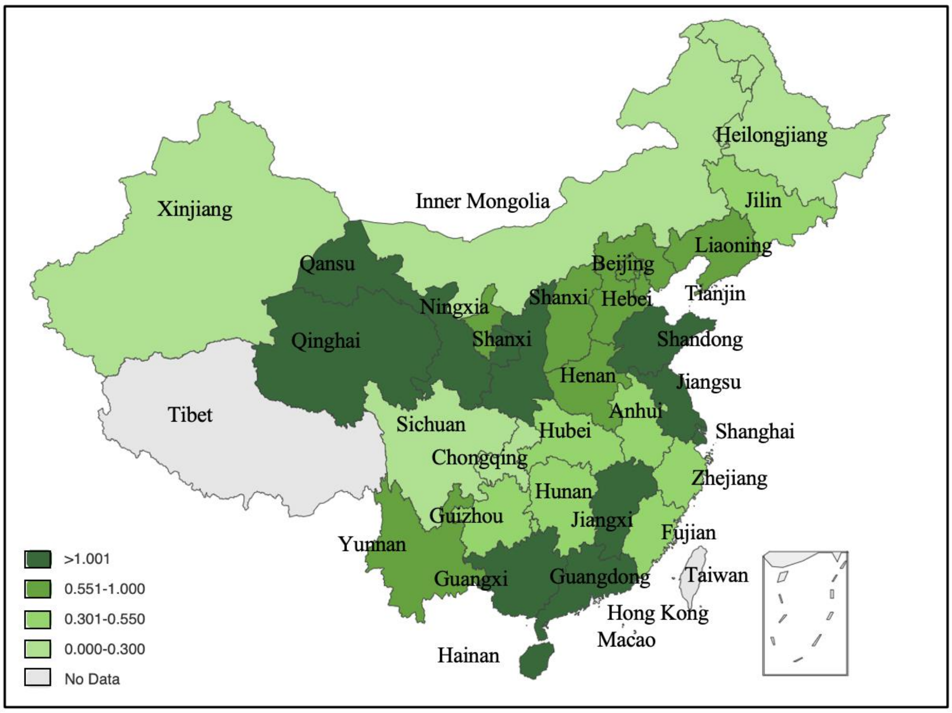

Figure 5.5 Spatial patterns of GBD efficiency in 2014.

As shown in **Figure 5.6**, there were also three core regions in 2017, but the core regions began to move west. The three core regions of GBD efficiency were the southern coastal region represented by Guangdong, the northwestern inland region represented by Qinghai and the northwestern inland region represented by Guizhou. This change revealed that the importance of reducing carbon emissions must be strengthened in GBD efficiency. Except for the core regions, some provinces performed well in GBD efficiency, e.g., Shannxi and Henan in the inland region, Liaoning and Jilin in the northeast region, Jiangsu and Shanghai in the southeast coastal region, and Guangxi in the south region.

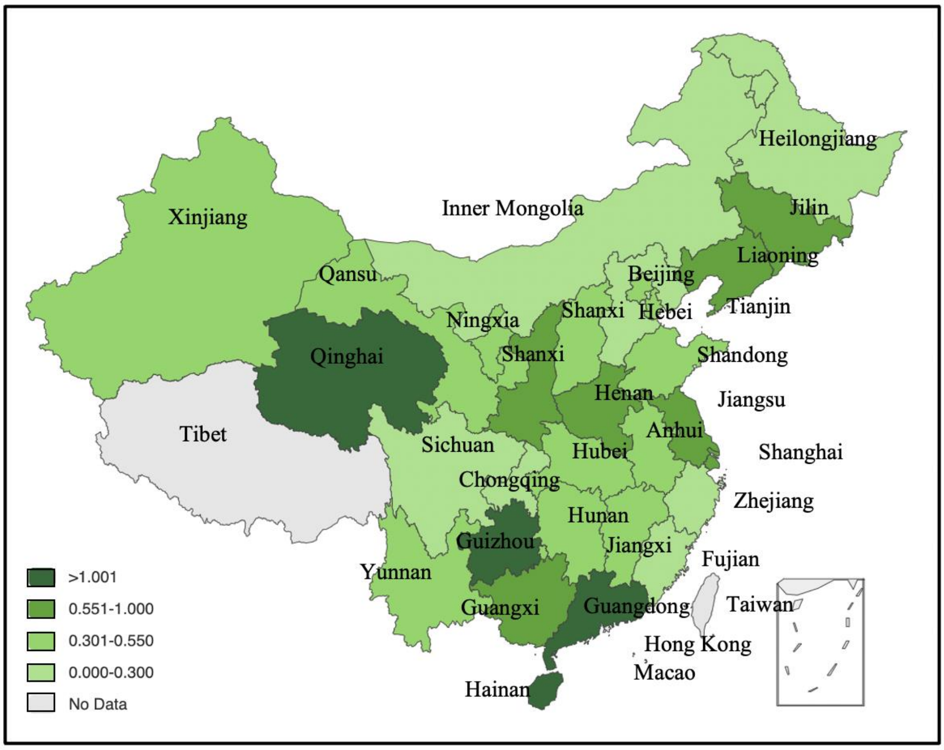

Figure 5.6 Spatial patterns of GBD efficiency in 2017.

The core regions kept changing in 2020, as shown in **Figure 5.7**. The new core regions were Jilin in the northeastern region, Yunnan in the northwestern region, and Guangdong and Jiangxi in the southern region. Although the northwest region had high GBD efficiency, the northeast showed more advantages in efficiency. Shanghai was another super-efficiency province, but the construction area in Shanghai was smaller than in other provinces. Therefore, Shanghai was not included in the core regions.

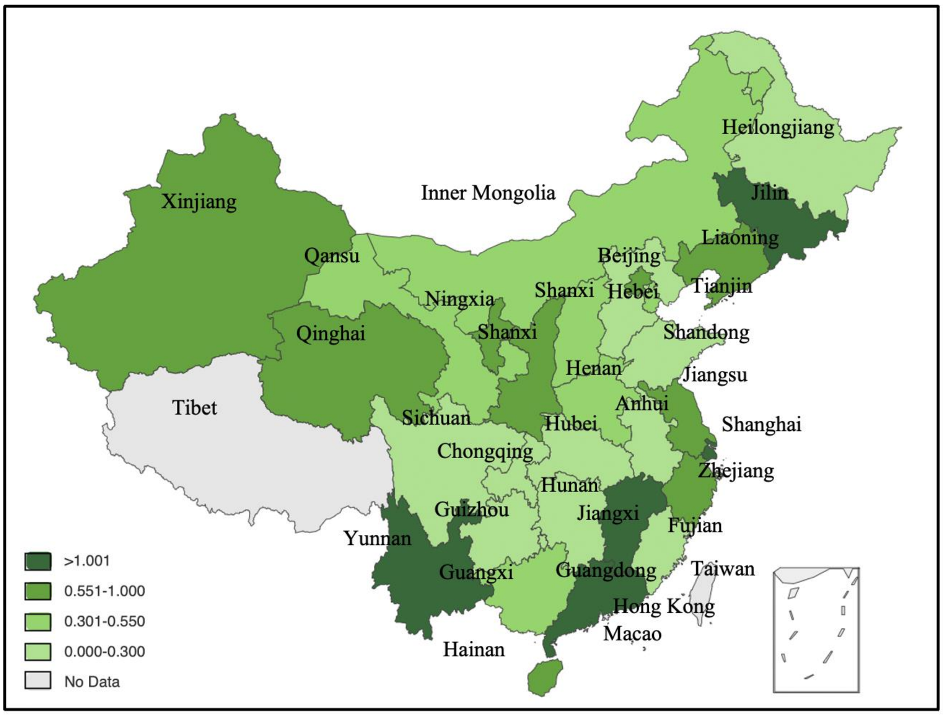

Figure 5.7 Spatial patterns of GBD efficiency in 2020.

Conclusions could be drawn from the GBD efficiency evolution. The regional GBD efficiency changed greatly in these years. In other words, the GBD efficiency in most provinces was not stable. Although there were three core regions from 2011 to 2020, core regions have been changing all the time except the core region of Guangdong. In addition, Guangdong kept high ranks in both GBD and GBD efficiency, which was the best in China. It indicates that the GBs in Guangdong has been promoted successfully. The resource allocation in GBD has been optimized, and the carbon emissions of GBs have been controlled.

According to the statistical data released by the building information platform in Guangdong, there are 5859 GBs with an area of 529 million square meters in Guangdong until 7 June 2022. The Guangdong provincial government requires local governments to incorporate GBD into the economic and social development scheme and assess the target achievement to ensure GBD. To improve GBD quality, Guangdong province requires to build high-level GBs in the Greater Bay Area and encouraged to implement high energy efficiency standards and promote low-energy buildings and net-zero energy buildings. Concerning the information platform, Guangdong is the first province to break down the barriers and establish a unified GB information platform. It is an open platform on which government updates GB information timely, including building names, locations, building types and levels.

Another striking phenomenon is a huge gap between the GBD and GBD efficiency in some provinces. GBD efficiency was decoupled from local GB Status. For instance, despite the high ranks in GBD efficiency, the GDP of Hainan and Guangxi ranked 19th and 28th among 30 provinces in 2015. The high ranks in efficiency come from the low carbon emissions. It indicates that the provinces with high GBD slowed down the speed of GB promotion, and the energy saving in these provinces is insufficient, leading to the situation with high GBD but low efficiency. There is still a long way to go for energy saving and carbon reduction in GBs.

5.5 Chapter Summary

This chapter proposed an evaluation model to assess the GBD efficiency from a macro perspective based on the DEA method. The evaluation model combined the super-SBM model with window analysis, and empirical analysis was conducted to verify the model. The GBD data from 2008 to 2020 in China were adopted in the empirical analysis. The spatial distribution and GBD evolution trends in China were further investigated. Results showed that the overall GBD efficiency significantly increased and then reduced to a stable level. Wide gaps in GBD efficiency existed between the provinces, and great changes have been observed in GBD efficiency. The spatial distribution kept three core regions with multiple centers, but the core regions, except Guangdong, have changed in these years, and the path dependency is not very high. The GBD and GBD efficiency situations were not similar in many provinces, showing high GBD but low efficiency. Reducing carbon emissions was insufficient in many provinces with high GBD, leading to this phenomenon.

CHAPTER 6 SPATIAL CORRELATIONS OF GREEN BUILDING DEVELOPMENT[6]

6.1 Introduction

Construction products are different from manufacturing products because they are produced at a fixed address and cannot be moved once the construction is completed. During the process, the construction resources are free-flowing. They are transported from other places to the construction site. Due to this characteristic, the spatial distribution of buildings is a research topic that could provide valuable references on the local building market and resource optimization. Research shows that the geographical proximity effect has a positive impact on the collaboration networks in GB projects, contributing to GBD (Qiang et al., 2021). Besides, strong spatial correlations existed among commercial GBs (Qiu et al., 2015). Although the spatial correlations of GBD have aroused researchers' attention, further investigations are needed, especially examining spatial correlations and investigating GBD network structure.

This chapter aims to propose an evaluation model to assess the spatial correlations of GBD and explore the network structure of GBD correlations. To achieve the research aim, a modified gravity model was proposed, and SNA was applied in this chapter. An empirical analysis was

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[6] This chapter is largely based upon:
Chen, L., Chan, A. P. C., Darko, A., & Gao, X. (2022). Spatial-temporal investigation of green building promotion efficiency: The case of China. *Journal of Cleaner Production*, *362*, 132299.

conducted to verify the model, and the GBD data of 30 provinces from 2008 to 2020 in China were adopted. In addition, the spatial correlation patterns and the evolutionary trend of GBD in China were explored in this chapter.

This chapter contributes to the GB body of knowledge by presenting the first investigation into GBD correlations between different regions. The findings would enable researchers, policymakers and practitioners to develop suitable and efficient policies and strategies to promote the widespread implementation of GBs.

6.2 Spatial Correlations of Green Building Development

The gravity model was used to examine the spatial correlations of GBD. The correlation network of GBD can illustrate the relationship between regions, so this chapter draws the networks of GBD correlations based on the results. The correlation networks in 2008, 2011, 2014, 2017 and 2020 are presented to illustrate the spatial patterns, as shown in **Figures 6.1-6.5**. In the figures, the size of the node represents its degree. The greater the degree of the node, the larger the node. The 0-1 spatial correlation matrix of GBD is provided in **Appendix C** (**Tables C1-C5**) for reference.

Hubei was the core province in the correlation network of GBD in 2008, as shown in **Figure 6.1**. Hubei is in central China, and it has connections with the north region (Beijing), the east region (Shanghai, Jiangsu and Zhejiang), and the south region (Guangdong). Shanghai, Jiangsu and Zhejiang belong to the Yangtze River Delta region, but Jiangsu and Zhejiang had no direct connections despite their close location. Shanghai linked Jiangsu and Zhejiang in GBD.

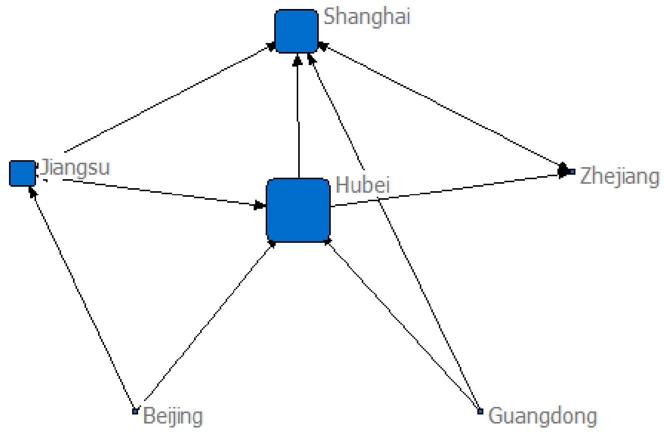

Figure 6.1 The correlation network of GBD in 2008.

As shown in **Figure 6.2**, the correlation network of GBD in 2011 had multiple core regions, which could be divided into four regions: (1) The northern region (Beijing and Tianjin). The northern region belongs to the Beijing-Tianjin-Hebei region, supported by the capital economy, but Hebei had fewer connections with other provinces. (2) The eastern region (Shanghai, Jiangsu, Zhejiang and Shandong). Shanghai was the center of the eastern region, and the center of GBD in China. Except for Shandong, the eastern region belongs to the Yangtze River Delta region, the most active and open region in Chinese economy. Similar to Hebei, Anhui is another province in the Yangtze River Delta region, but it had low connections with other provinces in 2011. (3) The southern coastal region (Guangdong). The southern coastal region includes the Pearl River Delta, one of the three major economic regions in China, and it is the gateway to the south of the country. (4) Western inland region (Chongqing). Chongqing is the only inland region playing a critical role in the development strategies of western China. Among these regions, the northern and southern regions had more influence on GBD than the southern and western regions. Therefore, it can be concluded that the GBD correlation network had two cores and two centers.

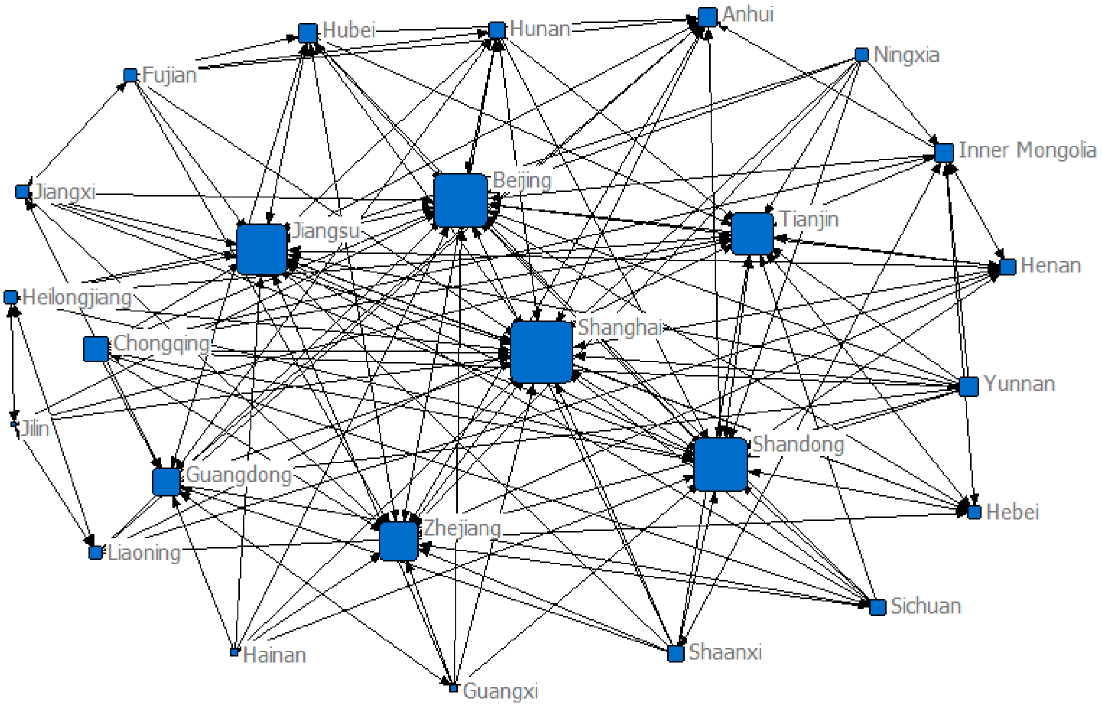

Figure 6.2 The correlation network of GBD in 2011.

Compared to the correlation network in 2011, the network in 2014 had slight differences. As shown in **Figure 6.3**, the advantages of the original western and eastern regions were obvious, while the influence of the southern region reduced slightly, and the influence of the western region declined significantly. Therefore, the GBD correlation network had two cores and one center. The western region exited the stage of GBD correlations. Some provinces stepped forward in the spatial correlations of GBD, such as Inner Mongolia, Henan, Gansu and Fujian.

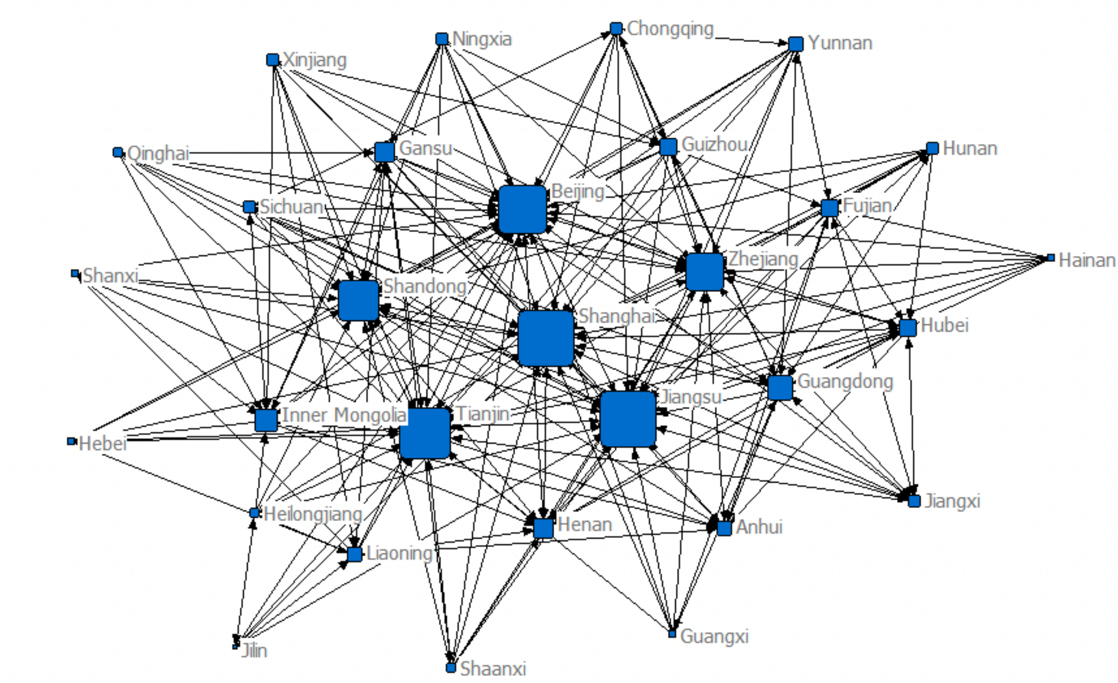

Figure 6.3 The correlation network of GBD in 2014.

Compared to the correlation network in 2014, the network structure in 2017 had no changes, as shown in **Figure 6.4**, but the scope and influence of the core regions had changed. The influence of some provinces in the core and center region has weakened in this period, e.g., Tianjin in the western region, Shandong in the eastern region and Guangdong in the southern region. At the same time, the influence of Fujian strengthened. Besides, new inland center regions appeared in 2017: the central inland region (Hubei) and the western inland region (Gansu). Therefore, it can be concluded that the GBD correlation network had two cores and multiple centers in 2017.

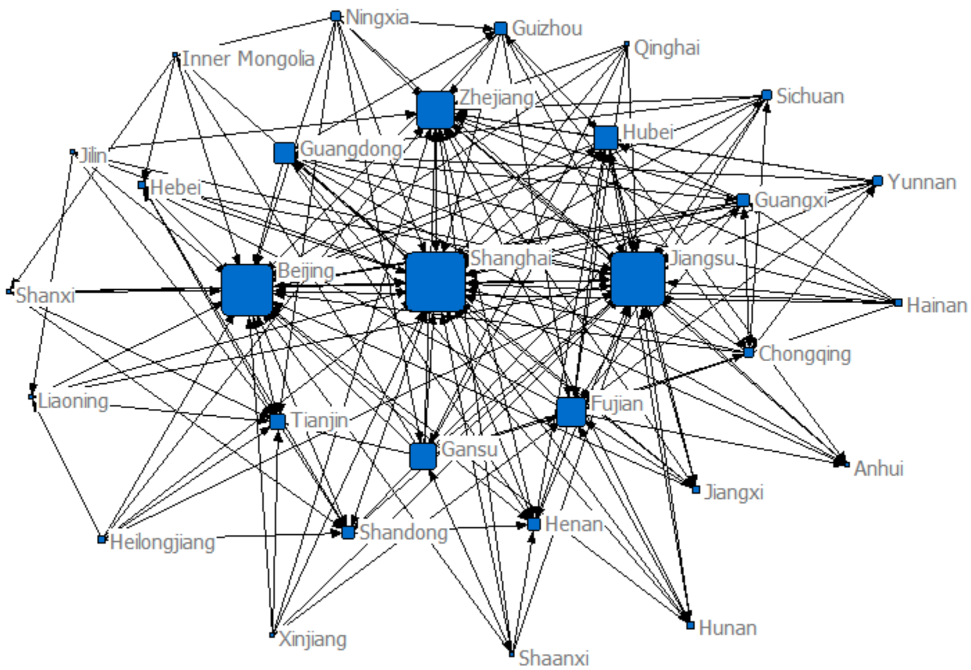

Figure 6.4 The correlation network of GBD in 2017.

As shown in **Figure 6.5**, the GBD correlation network also had two cores and multiple centers in 2020. The northern and eastern regions kept the dominant position in the spatial correlations of GBD. The critical province in the southern region had changed from Guangdong to Fujian. Hubei and Henan were two critical provinces in the central region, while Chongqing and Gansu led GBD in the western inland regions.

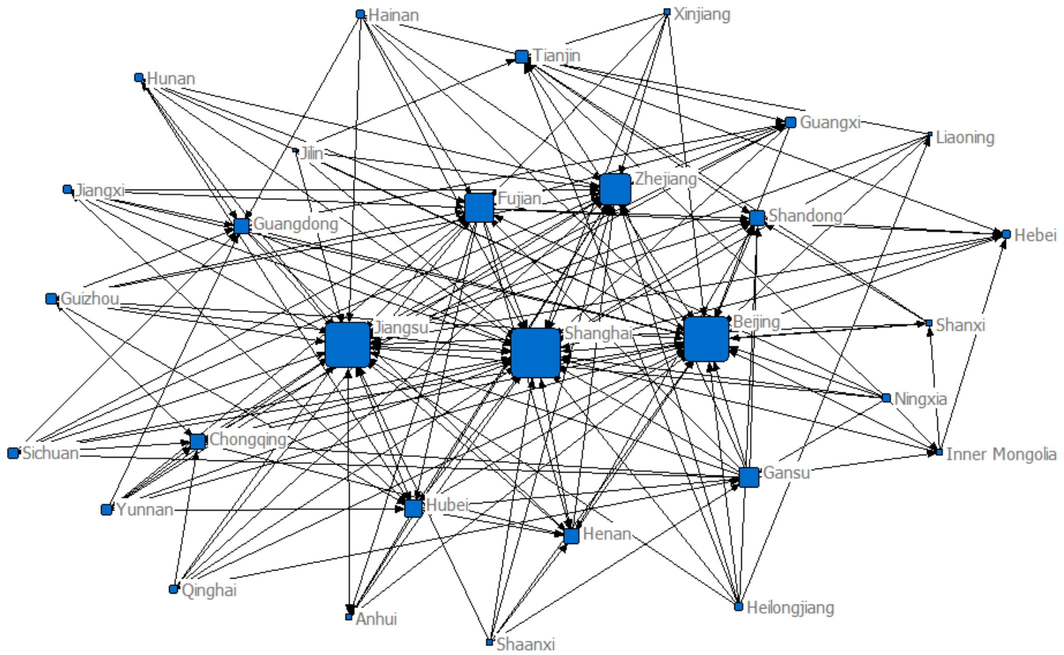

Figure 6.5 The correlation network of GBD in 2020.

A conclusion could be drawn from the patterns of spatial correlations that GBD in China was led by the northern region, represented by Beijing, and the eastern region, represented by Shanghai and Jiangsu. The evolutionary trends of GBD correlations began with one core, and then two cores appeared with multiple centers.

6.3 Results and Discussion

6.3.1 Network Structure Analysis

The network structure of the spatial correlations in GBD has been analyzed. The results are shown in **Table 6.1**, including the nodes, edges, connectedness, density, efficiency and hierarchy of the network. Among these variables, the nodes and edges of the network show the network size. As shown in the table, the GBD correlation network size increased rapidly from 2008 to 2011 and tended to be stable after 2014. The connectedness of the networks kept 1 in these years, indicating that there were edges between any nodes.

The network density shows the tight relationship between nodes in the network. The higher the network density, the better the robustness of the overall network. The table shows that the network density was the highest in 2008, while the network size was the smallest this year. Since then, the network density has remained relatively stable, ranging from 0.2 to 0.3. According to the values, the network density of spatial correlations in GBD was not very high, so the spatial correlations in GBD have a large potential to improve.

Table 6.1 Network structure variables for the spatial correlations of GBD.

Variable	2008	2011	2014	2017	2020
Nodes	6	25	30	30	30
Edges	12	162	229	194	192
Connectedness	1.00	1.00	1.00	1.00	1.00
Network density	0.400	0.270	0.264	0.223	0.221
Network efficiency	0.60	0.63	0.63	0.69	0.69
Network hierarchy	0.57	0.34	0.19	0.52	0.52

The network efficiency reflects the redundant correlations. The lower the network efficiency, the more redundant the correlations in the network. As shown in the table, high network efficiency existed in the GBD spatial correlation network, and there was a slight increase from 0.60 in 2008 to 0.69 in 2020. The network hierarchy declined after 2008 and reached the bottom in 2014. Then it gradually increased to the original values in 2020. The growth in the network hierarchy brought difficulties in integrating the regions with high and low correlations.

6.3.2 Centrality Analysis

The centrality analysis results of GBD spatial correlation networks are shown in **Table 6.2, including** degree, betweenness and closeness analysis. The degree centrality identifies the influential nodes in the network according to connections between nodes. Although the node size in **Figure 6.1-6.5** shows the degree vividly, this section provides quantitative measurements, which could analyze the node influence quantitatively. The closeness reflects the quick connect capability of the node. The betweenness of the node identifies the nodes that act as bridges in the network. These nodes are critical to the connectivity of the network.

For the degree analysis, Shanghai has always ranked first in degree centrality except for 2008, followed by Jiangsu and Beijing. Shanghai leads the surrounding areas, such as Zhejiang and Jiangsu, and the whole country in GBD because of its strong connections with other provinces. However, the land in Shanghai is limited, so its potential for GB construction is less than in other provinces. Beijing is the capital of China. It is also a political center and a metropolitan in the north of China. Tianjin is close to Beijing, but its influence in the GBD network constantly declined, from ranking fifth in 2011 to twelfth in 2020. Hebei, the other province close to Beijing, had weak correlations with other provinces. It is notable that Fujian and Gansu were getting more influence in the network. Fujian and Guangdong drive GBD in southern China, while Gansu has emerged in the network to drive GBD in the western inland regions. According to the degree, a similar conclusion can be drawn in Section 6.2. The Yangtze River region was the most critical region in the spatial correlations of GBD, leading GB construction across the country. Beijing was the center of GB construction in the north. GBD in the south was led by Guangdong and Fujian, while GBD in the west was led by Gansu and Chongqing.

Closeness analysis quantitatively examines the quick connect capability of the node. The conclusion can be drawn that the structure and evolutions of closeness kept a similar trend with the degree. Those provinces with high priorities in the degree also have advantages in the closeness centrality, such as Beijing, Shanghai, Tianjin, Jiangsu and Zhejiang. A significant difference between the degree and the closeness is that the closeness gaps were not as obvious as the degree gaps. The minimum value in the degree is 17.241, while the minimum value in the closeness is 54.717. Therefore, if the province has strong correlations with other provinces, it can also quickly connect to other provinces in the GBD correlation network.

Concerning the betweenness analysis, the betweenness of the node identifies the nodes that act as bridges in the network. These nodes are critical to the connectivity of the network. The betweenness of Beijing, Zhejiang and Guangdong was 0 in 2008, but the betweenness of all the provinces was more than 0 in the following years. The reason is that only a few provinces adopted GBs in 2008, and the spatial relationship was simple. The provinces with high ranks in the degree and closeness performed well in the betweenness. Some provinces had no advantages in the degree and closeness, but they showed advantages of acting as bridges in the network, such as Tianjin and Shandong. In contrast, Shaanxi was at the bottom of the list in 2017 and 2020, revealing its shortage in the betweenness. Fujian became more and more important in the betweenness, which ranked fifth in 2020.

Table 6.2 Centrality analysis results of GBD correlation networks.

Province	Degree					Closeness					Betweeness				
	2008	2011	2014	2017	2020	2008	2011	2014	2017	2020	2008	2011	2014	2017	2020
Beijing	40	75	75.862	82.759	86.207	62.5	80	80.556	85.294	87.879	0	11.283	9.101	15.661	18.031
Tianjin	—	62.5	79.31	34.483	31.034	—	72.727	82.857	59.184	59.184	—	5.793	9.802	1.497	1.293
Hebei	—	29.167	24.138	24.138	24.138	—	58.537	56.863	56.863	56.863	—	0.553	0.239	0.511	0.396
Shanxi	—	—	24.138	20.69	20.69	—	—	56.863	55.769	55.769	—	—	0.239	0.241	0.243
Inner Mongolia	—	37.5	44.828	20.69	20.69	—	61.538	64.444	55.769	55.769	—	1.314	1.961	0.227	0.232
Liaoning	—	29.167	34.483	20.69	17.241	—	58.537	60.417	55.769	54.717	—	0.939	1.103	0.135	0.083
Jilin	—	20.833	20.69	20.69	17.241	—	55.814	55.769	55.769	54.717	—	0.127	0.121	0.228	0.18
Heilongjiang	—	29.167	27.586	24.138	24.138	—	58.537	58	56.863	56.863	—	0.608	0.371	0.327	0.361
Shanghai	80	83.333	86.207	93.103	93.103	83.33	85.714	87.879	93.548	93.548	15	12.452	10.254	16.937	16.22
Jiangsu	60	70.833	86.207	86.207	86.207	71.429	77.419	87.879	87.879	87.879	5	6.944	10.254	13.27	13.014
Zhejiang	40	58.333	62.069	65.517	62.069	62.5	70.588	72.5	74.359	72.5	0	4.676	4.022	6.033	5.184
Anhui	—	37.5	34.483	20.69	20.69	—	61.538	60.417	54.717	55.769	—	2.386	0.985	0.106	0.084
Fujian	—	29.167	37.931	51.724	58.621	—	58.537	61.702	67.442	70.732	—	0.295	1.053	3.608	4.975
Jiangxi	—	29.167	31.034	24.138	24.138	—	58.537	59.184	56.863	56.863	—	0.529	0.358	0.162	0.167
Shandong	—	75	65.517	31.034	34.483	—	80	74.359	59.184	60.417	—	6.392	3.816	0.665	1.092
Henan	—	33.333	41.379	31.034	34.483	—	60	63.043	59.184	60.417	—	0.926	1.398	0.618	0.775
Hubei	100	37.5	37.931	44.828	41.379	100	61.538	61.702	64.444	63.043	40	1.061	0.484	1.255	0.849
Hunan	—	33.333	31.034	24.138	24.138	—	60	59.184	56.863	56.863	—	0.879	0.358	0.162	0.167
Guangdong	40	45.833	48.276	41.379	37.931	62.5	64.865	65.909	63.043	61.702	0	2.417	2.048	1.488	1.016
Guangxi	—	25	24.138	31.034	27.586	—	57.143	56.863	59.184	58	—	0.276	0.255	0.411	0.286

Note: "—" means there was no GB in this year.

Table 6.2 Centrality analysis results of GBD correlation networks (Continued).

Province	Degree					Closeness					Betweenness				
	2008	2011	2014	2017	2020	2008	2011	2014	2017	2020	2008	2011	2014	2017	2020
Hainan	—	25	24.138	24.138	24.138	—	57.143	56.863	56.863	56.863	—	0.276	0.255	0.137	0.136
Chongqing	—	41.667	31.034	27.586	34.483	—	63.158	59.184	58	60.417	—	0.905	0.237	0.321	0.698
Sichuan	—	33.333	31.034	27.586	27.586	—	60	59.184	58	58	—	0.445	0.434	0.31	0.286
Guizhou	—	—	37.931	31.034	27.586	—	—	61.702	59.184	58	—	—	0.845	0.543	0.291
Yunnan	—	37.5	34.483	27.586	27.586	—	61.538	60.417	58	58	—	0.739	0.712	0.309	0.291
Shaanxi	—	33.333	27.586	20.69	20.69	—	60	58	55.769	55.769	—	0.739	0.133	0.068	0.064
Gansu	—	—	41.379	48.276	44.828	—	—	63.043	65.909	64.444	—	—	1.191	3	1.941
Qinghai	—	—	27.586	20.69	24.138	—	—	58	55.769	56.863	—	—	0.203	0.09	0.142
Ningxia	—	29.167	31.034	27.586	24.138	—	58.537	59.184	58	56.863	—	0.449	0.296	0.583	0.429
Xinjiang	—	—	31.034	20.69	20.69	—	—	59.184	55.769	55.769	—	—	0.525	0.31	0.289

Note: "—" means there was no GB in this year.

6.3.3 Block Model Analysis

The block model was conducted to reveal regional clustering patterns in the GBD correlation network. All the provinces were classified into four blocks: the main spillover block, primary beneficial block, bidirectional spillover block and agent block. According to the frequency of provinces belonging to the blocks, a bubbling figure (**Figure 6.6**) was drawn to show the clustering patterns. The large bubble indicates that the province belonged to this block with a high frequency.

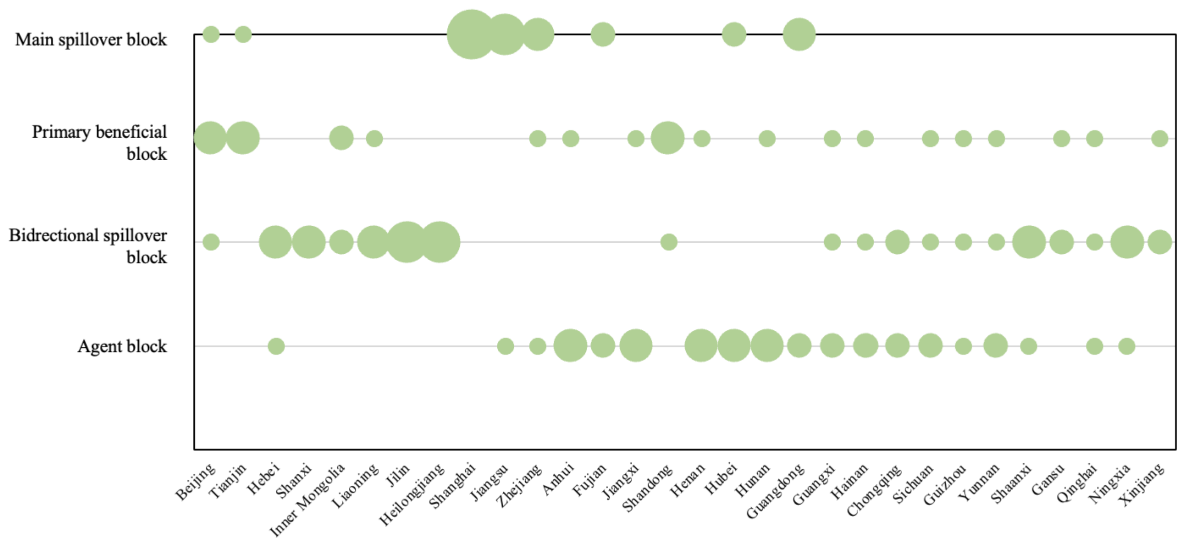

Figure 6.6 The bubble figure of block models.

It shows an obvious path dependency in the clustering patterns of provinces in the GBD correlation network. In the main spillover block, the frequency of Shanghai, Jiangsu, Zhejiang and Guangzhou is high, which belongs to the southeast and southern part of China. The spillover effects of these provinces are significant, so they promote other provinces in GBD. The primary beneficial block has more internal relationships. In this block, Beijing, Tianjin and

Shandong have a high frequency. They are geographically close to each other, and they belong to the north of China. It is an interesting finding because these provinces are not undeveloped regions, but they significantly benefit from spillover effects, which contradicts our assumptions. In our assumption, those undeveloped provinces could be the main beneficiaries of the spillover effects. This phenomenon will lead to an increasing gap between those top provinces and those bottom provinces. Hebei, Shanxi, Liaoning, Jilin, Heilongjiang, Shannxi and Ningxia belong to the bidirectional block, which means that these provinces receive many connections from other blocks and have many connections inside. The provinces had tight relationships in this block. Anhui, Jiangxi, Henan, Hubei and Hunan belonged to the agent block, which means they do not have many internal connections but have many external connections with other provinces in other blocks. These provinces are in the southeast and middle region of China. In addition, most provinces in China concentrate on the bidirectional block and the agent block.

6.4 Chapter Summary

This chapter proposed a model to examine GBD spatial correlations and investigate the correlation network in mainland China with empirical analysis. The gravity model and the social network analysis were applied in this chapter. The GBD data of 30 provinces in China have been adopted in the empirical analysis to explore GBD network structures. Results show that this model performs well in the GBD spatial correlation examination. The spatial correlation network of GBD was stable in these years, but the correlations were not tight enough. The correlations between provinces need to be improved. The network structure began with one core, and then two core regions and multiple centers emerged. Three regions have been the core regions, including the northern region represented by Beijing, the northeast region represented by Shanghai, Zhejiang and Jiangsu, and the southern region represented by Guangdong. Multiple centers included the inland region represented by Hubei, Chongqing and Gansu. The degree, closeness and betweenness of the nodes had a high similarity. The path dependence was obvious in the block model analysis.

CHAPTER 7 CRITICAL SUCCESS FACTORS OF GREEN BUILDING DEVELOPMENT IN DIFFERENT REGIONS[7]

7.1 Introduction

The term CSF was first developed by Rockart (Rockart, 1979), meaning the factors leading to the success of something. Although CSFs of GBD have been identified from different aspects by previous studies, no consensus has been achieved so far (Hwang et al., 2015; Li et al., 2019b; Qiu et al., 2017). For instance, the most critical factors in GBD included early involvement, effective collaboration, and the commitment of all participants (Venkataraman & Cheng, 2018), while Mavi and Standing (2018) had different opinions that the most important factors were stakeholder expectations, top management and sponsor support and end-users imposed restrictions. In addition, research showed that criteria and standards, clear vision, government programs, subsidies or tax reduction and existing building evaluation and policies were the critical factors in Chinese green retrofits (Liang et al., 2015). These studies were conducted in different countries or regions, leading to different conclusions.

Besides, some research investigated GBD barriers and drivers, which were also related to CSFs (Ahmad et al., 2019; Darko et al., 2017b; Olubunmi et al., 2016). For example, five categories

[7]This chapter is largely based upon:
Chen, L., Chan, A. P. C., Owusu, E. K., Darko, A., & Gao, X. (2022). Critical success factors for green building promotion: A systematic review and meta-analysis. *Building and Environment*, *207*, 108452.

of drivers identified from previous studies could provide significant reference to this research (Darko et al., 2017b). Moreover, previous review papers discussed the GB research trend, which could also provide reference to CSFs of GBD (Darko & Chan, 2016; Jagarajan et al., 2017). For example, the potential factors in GB implementation included project management and project delivery attributes (Darko & Chan, 2016b). Previous studies have conducted systematic literature reviews on CSFs, but they merely summarized factors. The quantitative method was absent in the factor analysis. Although a few studies analyzed the frequency of factors, the investigation was not deep enough. Besides, some studies have investigated CSFs of GBD in China, but the spatial perspective is lacking, which needs more attention.

This chapter aims to identify the CSFs of GBD comprehensively and prioritize them from a spatial perspective. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guideline is adopted to explore CSFs around the world, and the questionnaire survey is conducted in China. The CSFs of GBD in different countries and regions are investigated, and a further comparison is provided based on the results of the meta-analysis and questionnaire.

7.2 Critical Success Factors

The literature selection process has been introduced in Chapter 3.3.2. After the literature selection, twenty studies were included in the literature database, shown in **Table 7.1**. There were sixteen journal articles and four conference articles, ranging from 2011 to 2021. Compared to conference papers, journal articles need to get through peer review and make revisions based on reviewers' comments several rounds before publication. Conference papers tend to publish frontier research quickly, which is more concise.

Table 7.1 Basic information of selected literature.

No.	Study ID	Sample size	Reference
1	Li et al., 2011 (J) (SGP) (G)	37	(Li et al., 2011)
2	Venkataraman and Cheng 2018 (J) (W) (G)	67	(Venkataraman & Cheng, 2018)
3	Adabre and Chan 2019 (J) (W) (H)	51	(Adabre & Chan, 2019)
4	Oluleye et al., 2020 (J) (NG) (H)	74	(Oluleye et al., 2020)
5	Sang and Yao 2019 (J) (CHN) (H)	76	(Sang & Yao, 2019)
6	Tang et al., 2020 © (HK) (G)	106	(Tang et al., 2020)
7	Olawumi and Chan 2020 (J) (W) (G)	220	(Olawumi & Chan, 2020)
8	Wong et al., 2021 (C) (MY) (G)	36	(Wong et al., 2021)
9	Awaili et al., 2020 (J) (LY) (G)	20	(Awaili et al., 2020)
10	Nguyen et al., 2017 (J) (VN) (G)	215	(Nguyen et al., 2017)
11	Azeem et al., 2017 (J) (PK) (G)	103	(Azeem et al., 2017)
12	Deng et al., 2018 (J) (CHN) (G)	87	(Deng et al., 2018)
13	Li et al., 2019 (J) (NZ) (H)	26	(Li et al., 2019a)
14	Ahn et al., 2013 (J) (USA) (G)	100	(Ahn et al., 2013)
15	Yang and Yang 2015 (J) (AUS) (H)	50	(Yang & Yang, 2015)
16	Sahamir et al., 2019 (C) (MY) (HO)	82	(Sahamir et al., 2019)
17	Agyekum et al., 2020 (J) (GH) (G)	520	(Agyekum et al., 2020)
18	Wu et al., 2019 (J) (CHN) (G)	78	(Wu et al., 2019)
19	Dalirazar and Sabzi 2020 (J) (SUN) (G)	54	(Dalirazar & Sabzi, 2020)
20	Nguyen et al., 2019 (C) (VN) (G)	166	(Nguyen et al., 2019)

Among these studies, the research objectives of 14 papers are general GBs, while five papers concentrate on green residential buildings. Only one paper focuses on the green hospital. It indicates that the general GBs and green residential buildings are the mainstream in this field, especially general buildings. Most of the studies were conducted in a specific country (e.g., Singapore and Australia), while three papers conducted global research on CSFs of GBD. Only one study collected data from three countries: Sweden, America and New Zealand, reflecting the situations in Europe, North America and Oceania, respectively.

Table 7.2 Critical success factors for GBD.

Category	Factor ID	Critical success factor	Frequency
C1 Finance	CSF1	Adequate financial budget	7
	CSF2	Low cost of GBs	12
	CSF3	Effective auditing programs	5
	CSF4	Tax and fiscal incentives	5
C2 Stakeholders	CSF5	Cooperation between stakeholders	8
	CSF6	Communication between stakeholders	7
	CSF7	Early involvement of project participants	5
	CSF8	Commitment of all project participants	2
C3 Human resource	CSF9	Skilled participants	6
	CSF10	Experience in GBs	3
C4 Management	CSF11	Detailed plan	2
	CSF12	Innovative management approaches	5
	CSF13	Support from senior management	3
	CSF14	Effective feedback and troubleshooting	3
	CSF15	High motivation	3
	CSF16	Integrated design	4
C5 Technology	CSF17	Advanced machinery and equipment	4
	CSF18	Available sustainable materials	5
	CSF19	Innovative technological approaches	7
	CSF20	Software application	2
	CSF21	Available databases	3
C6 Education and knowledge	CSF22	Training	10
	CSF23	Knowledge	6
	CSF24	Demonstration projects	3
C7 Government	CSF25	Adequate incentives	7
	CSF26	Effective government policies	7
	CSF27	Regulation support	5
	CSF28	Mandatory requirements	3
	CSF29	Legislation	4
	CSF30	Comprehensive code and standard	8
C8 Research and innovation	CSF31	Research	3
	CSF32	Innovation	2
C9 Economy and industry	CSF33	Industrialization	3
	CSF34	Supply chain	2
C10 Market	CSF35	Obvious Economic benefit	4
	CSF36	Short payback period	4
	CSF37	Market demand	7
C11 Culture	CSF38	Reputation	3
	CSF39	Effective leadership	3
	CSF40	Public awareness	6

This study identified forty CSFs (shown in **Table 7.2**) and classified them into 11 categories: finance, stakeholders, human resource, management, technology, education and knowledge, government, research and innovation, economy and industry, market and culture. In these categories, it needs to further clarify the stakeholder category. Although some studies hold the opinion that stakeholders incorporate internal stakeholders (e.g., architects, contractors and consultants) and external stakeholders (e.g., governments, researchers and the public) (Lorenz & Lützkendorf, 2008), most studies focus on internal stakeholders and find that internal stakeholders play critical roles in the GB activities (Dammann & Elle, 2006; Van Bueren & Priemus, 2002). Therefore, the stakeholder category in this chapter means the internal stakeholders related to GBs. As an external stakeholder, the government is considered an independent category.

The top four CSFs in the frequency list are CSF2 “Low cost of GBs” (12 times), CSF22 “Training” (10 times), CSF5 “Cooperation between stakeholders” (8 times) and CSF30 “Comprehensive code and standard” (8 times). These CSFs are from different categories. It shows that many studies have achieved a consensus that the low cost of GBs benefits GBD.

7.3 Results of Meta-analysis

The meta-analysis conducted a quantitative study of global CSFs. The data were collected from twenty studies around the world, composing a large sample. Every CSF needs to get through the meta-analysis, so calculation processes are repeated forty times. This section demonstrates this meta-analysis process by an example of CSF2 'low green building costs' because this factor frequently appeared in previous studies (12 times).

7.3.2.1 Numerical Example

Table 7.3 shows the basic information extracted from previous studies, including the mean, SD and sample size of CSF2 in each study. The mean value shows the arithmetic average of the observations, revealing respondents' average cognition of the importance of CSFs. The SD value shows the variation or dispersion of a data set, revealing the divergence in respondents' cognition of the importance of CSFs.

Table 7.3 Statistical data of CSF2 for the meta-analysis.

Study ID	Mean	SD	Sample size
Adabre and Chan 2019 (J) (W) (H)	4.083	0.739	51
Tang et al., 2020 (C) (HK) (G)	4.180	0.906	106
Wong et al., 2021 (C) (MY) (G)	3.750	1.160	36
Awaili et al., 2020 (J) (LY) (G)	3.400	1.040	20
Nguyen et al., 2017 (J) (VN) (G)	3.950	0.970	215
Azeem et al., 2017 (J) (PK) (G)	3.250	1.178	103
Deng et al., 2018 (J) (CHN) (G)	3.920	1.010	87
Ahn et al., 2013 (J) (USA) (G)	2.620	1.406	100
Yang and Yang 2015 (J) (AUS) (H)	4.120	0.860	50
Agyekum et al., 2020 (J) (GH) (G)	4.330	0.739	520
Wu et al., 2019 (J) (CHN) (G)	3.962	1.211	78
Dalirazar and Sabzi 2020 (J) (SUN) (G)	3.704	1.057	54

Results showed that the heterogeneity of CSF2 was very high (I^2=95.501%). To reduce high heterogeneity, a random-effects model was applied. The effect size of a study was depicted as a point estimate that was bounded by a 95% confidence interval. **Table 7.4** shows the meta-analysis results, and the synthetical mean value of CSF2 was 3.786.

Table 7.4 Meta-analysis results of CSF2.

Study ID	Statistics for each study		
	Mean	Standard error	Lower and upper limit
Adabre and Chan 2019 (J) (W) (H)	4.083	0.103	[3.880, 4.286]
Tang et al., 2020 (C) (HK) (G)	4.180	0.088	[4.008, 4.352]
Wong et al., 2021 (C) (MY) (G)	3.750	0.193	[3.371, 4.129]
Awaili et al., 2020 (J) (LY) (G)	3.400	0.233	[2.944, 3.856]
Nguyen et al., 2017 (J) (VN) (G)	3.950	0.066	[3.820, 4.080]
Azeem et al., 2017 (J) (PK) (G)	3.250	0.116	[3.023, 3.477]
Deng et al., 2018 (J) (CHN) (G)	3.920	0.108	[3.708, 4.132]
Ahn et al., 2013 (J) (USA) (G)	2.620	0.141	[2.344, 2.896]
Yang and Yang 2015 (J) (AUS) (H)	4.120	0.122	[3.882, 4.358]
Agyekum et al., 2020 (J) (GH) (G)	4.330	0.032	[4.266, 4.394]
Wu et al., 2019 (J) (CHN) (G)	3.962	0.137	[3.693, 4.230]
Dalirazar and Sabzi 2020 (J) (SUN) (G)	3.704	0.144	[3.422, 3.986]
Random-effects Model	3.786	0.129	[3.533, 4.039]

The forest plot can show the results vividly, so the forest plot of CSF2 was drawn based on the meta-analysis results, as shown in **Figure 7.1**. Squares represented the mean values of CSF2 from previous studies in the figure. The diamond on the bottom of the figure represents the synthetical mean of CSF2 in the meta-analysis. A conclusion could be drawn by observing the figure. The mean values of CSF2 in these studies are close to the synthetical mean except for the study of Ahn et al. (2013). This study has a lower estimate than the average. Although this study has identified several financial barriers in sustainable design and construction, e.g., long payback periods and the first cost premium of GB projects, it holds a conservative estimate of the effect of low GB costs.

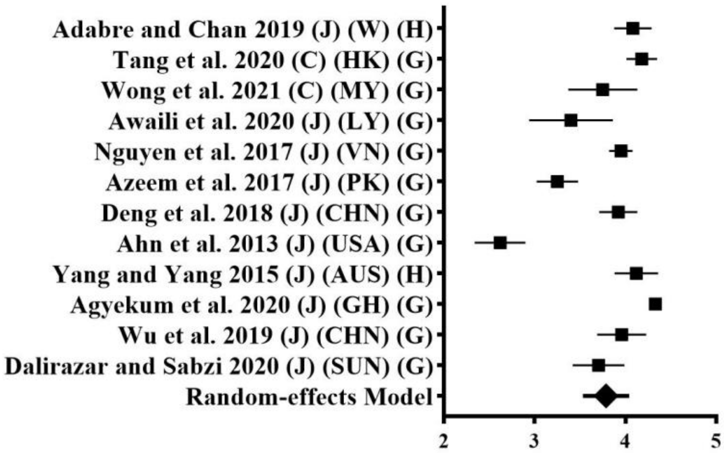

Figure 7.1 Forest plot of CSF2.

The funnel plot can show the standard error by mean for CSF2, which helps observe the publication bias in the meta-analysis. The funnel plot of CSF2 is shown in **Figure 7.2**. A conclusion could be drawn that publication bias existed because this figure is not symmetrical. It reveals that studies on the left side of the synthetical mean line are more than those on the right. Therefore, this study adopted Tweedie's Trim and Fill to provide an adjusted mean value when publication bias has affected the results.

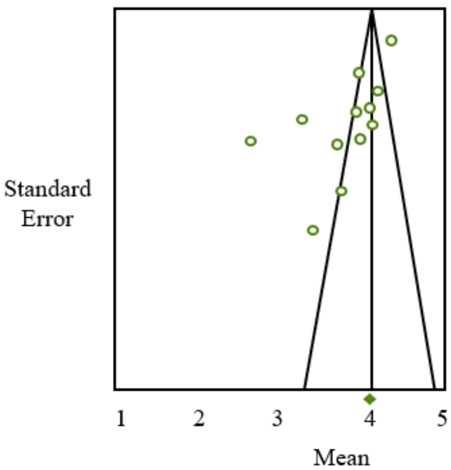

Figure 7.2 Funnel plot of standard error by mean for CSF2.

7.3.2.2 Meta-analysis Results

Meta-analysis results are shown in **Figure 7.3**, including CSFs' synthetical mean and adjusted mean (when publication bias existed). The effect sizes of CSFs are more than 3, indicating that all the factors are significant in GBD. It also proves that the CSF identification in this study was scientific and reasonable. To reduce the effects of publication bias, Tweedie's Trim and Fill was applied to reduce the effect of publication bias. Nine factors were adjusted: CSF12, CSF16, CSF18, CSF19, CSF21, CSF30, CSF35, CSF36, CSF37. Among them, three CSFs (CSF30, CSF36 and CSF12) had lower estimates, while the other factors had higher estimates.

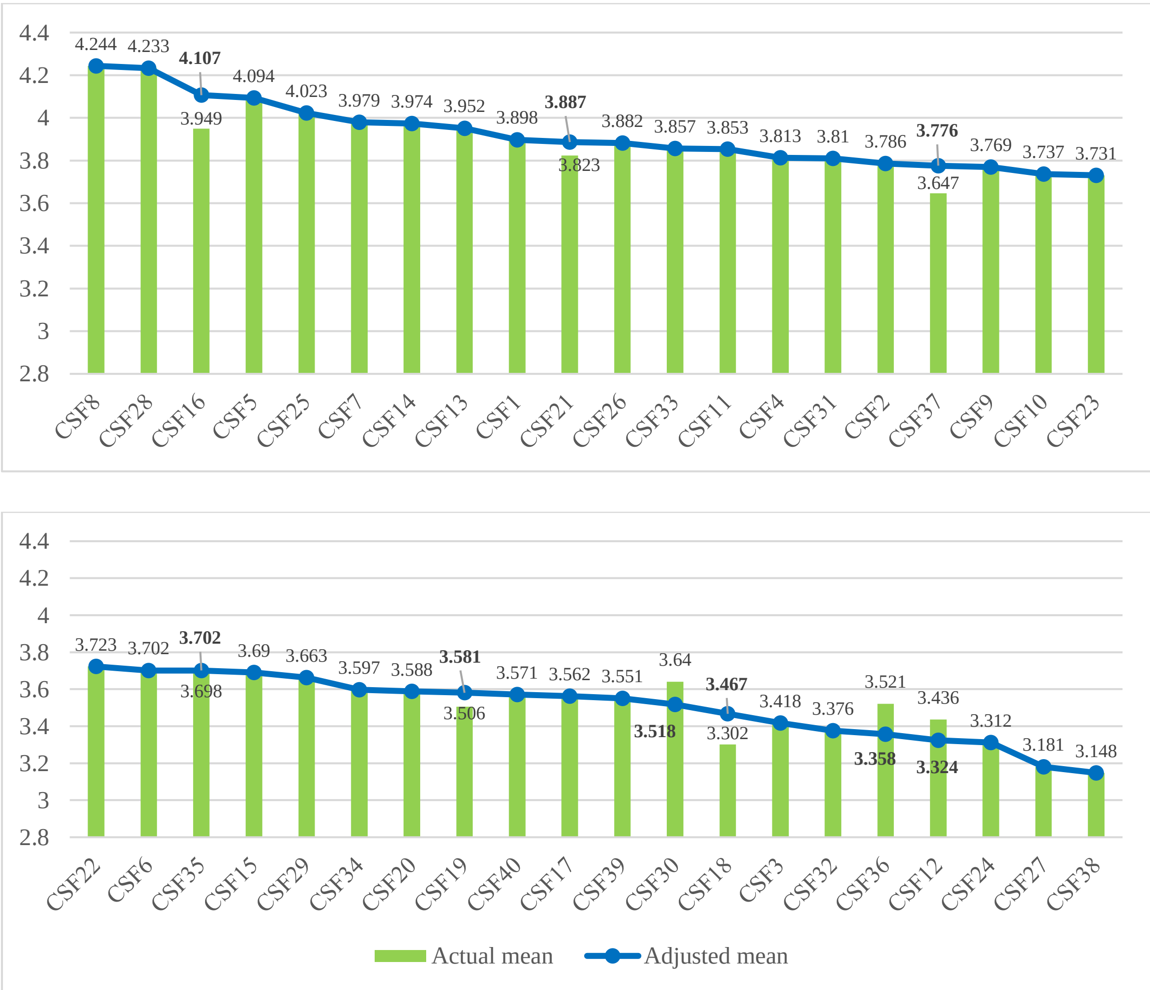

Figure 7.3 The actual mean and the adjusted mean of each CSF in the meta-analysis.

According to the original effect size, the top five CSFs are CSF8 “Commitment of all project participants” (4.244), CSF28 “Mandatory requirements” (4.23), CSF5 “Cooperation between stakeholders” (4.094), CSF25 “Adequate incentives” (4.023) and CSF7 “Early involvement of project participants” (3.979). Among these CSFs, three of them (CSF5、CSF7、CSF8) come from C2 “Stakeholder” category, while two of them (CSF25、CSF28) come from C7 “Government” category.

According to the adjusted effect size, the new top five CSFs are CSF8 “Commitment of all project participants” (4.244), CSF28 “Mandatory requirements” (4.23), CSF16 “Integrated design” (4.107), CSF5 “Cooperation between stakeholders” (4.094) and CSF25 “Adequate incentives” (4.023). Among these CSFs, two of them (CSF5、CSF8) come from C2 “Stakeholder” category, while two of them (CSF25、CSF28) come from C7 “Government” category. The other CSF comes from C4 “Management” category.

The results reveal that the existing empirical studies agree with the conclusion that stakeholders’ driving effect on GBD is obvious, including internal stakeholders and external stakeholders (governments). Internal stakeholders are the decision makers, so they have the primary responsibility in the GB construction. The internal stakeholders’ commitment and cooperation are the essential elements of GB projects. If they share the same goal and are willing to collaborate on the project, the GB practice will increase significantly.

For governments, incentive policies and mandatory policies are the two sides of a coin. The financial incentive policies (e.g., tax reduction and subsidy) take effect in a short time, and the effect of other incentives is obvious, such as simplifying the administrative procedures. Unlike incentives, mandatory policies are normally the law and regulations that stakeholders must obey, which guarantee GBD bottom line. For example, the office buildings invested by governments should comply with GB standards and apply GB labels. However, governments need to think twice before they propose mandatory requirements, guaranteeing mandatory requirements promote GBD without harming stakeholders' enthusiasm in the GB market.

The top four CSFs in frequency and significance are listed in **Table 7.5**. Only CSF5 appears in both lists. After comparing CSFs' frequency significance, it could be concluded that some CSFs (e.g., CSF2 and CSF22) appeared in previous studies many times, but their significance was not very high. It indicates that significant information could be omitted if the literature review only identifies factors from previous studies and ranks them by frequency, leading to a biased conclusion. This finding aligns with Hussein and Zayed's study, which demonstrates the merits of meta-analysis in information capture (Hussein & Zayed, 2020).

Table 7.5 Ranking list of CSFs in frequency and significance.

Rank	Frequency		Significance	
	Factor	Frequency	Factor	Mean
1	CSF2	12	CSF8	4.244
2	CSF22	10	CSF28	4.233
3	CSF5	8	CSF16	4.107
4	CSF30	8	CSF5	4.094

7.4 Results of Questionnaire Survey

The questionnaire survey aims to investigate the CSFs of GBD in mainland China and explore the geographical influence on the results. This section will present and discuss the results of questionnaire survey from the sample distribution and questionnaire results.

7.4.1 Sample Distribution

Respondents come from five types of companies or institutions, and the distribution is shown in **Figure 7.4**. Most respondents come from building construction companies (65.63%), followed by real estate companies (15.18%). The respondents from universities and research institutions only account for 0.98%, the lowest proportion.

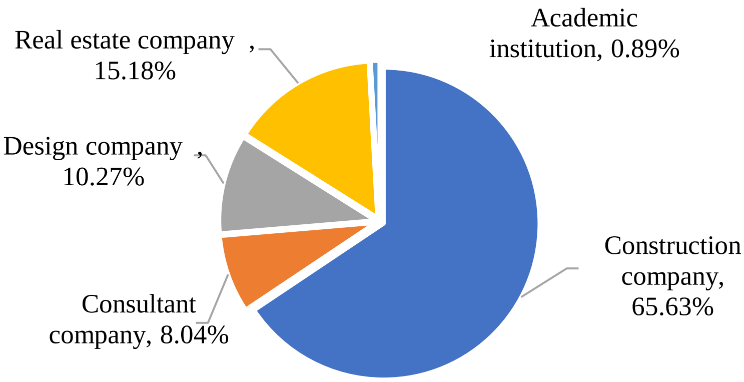

Figure 7.4 Job distribution of respondents.

The working experience distribution is shown in **Figure 7.5**. Panel (a) in this figure shows the respondents' working experience in the building industry. Most respondents have worked in this industry for more than three years. Among them, 8.93% of respondents have more than eight years of working experience. They have rich experience in the industry. About 39% of respondents are new employees in the industry. Their working experience is less than three years. Panel (b) in this figure shows the respondents' working experience in GBs. 70% of the respondents have GB working experience for less than three years. It has been 14 years since the first GB label was issued in mainland China. GBs spread fast in these years, but the proportion of GBs has a large potential to improve. Some local governments require all the new buildings in the urban area to comply with GB standards, but existing buildings in the operation stage have been neglected. It is worth noting that only 2.23% of the respondents have working experience of more than five years, which is relatively low in practice. Besides, no respondents have worked in GBs for more than eight years. Comparing Panel (a) and (b), it is found that the average working experience in the construction industry is higher than the average working experience in GBs, which is in line with reality and improves the credibility of the questionnaire.

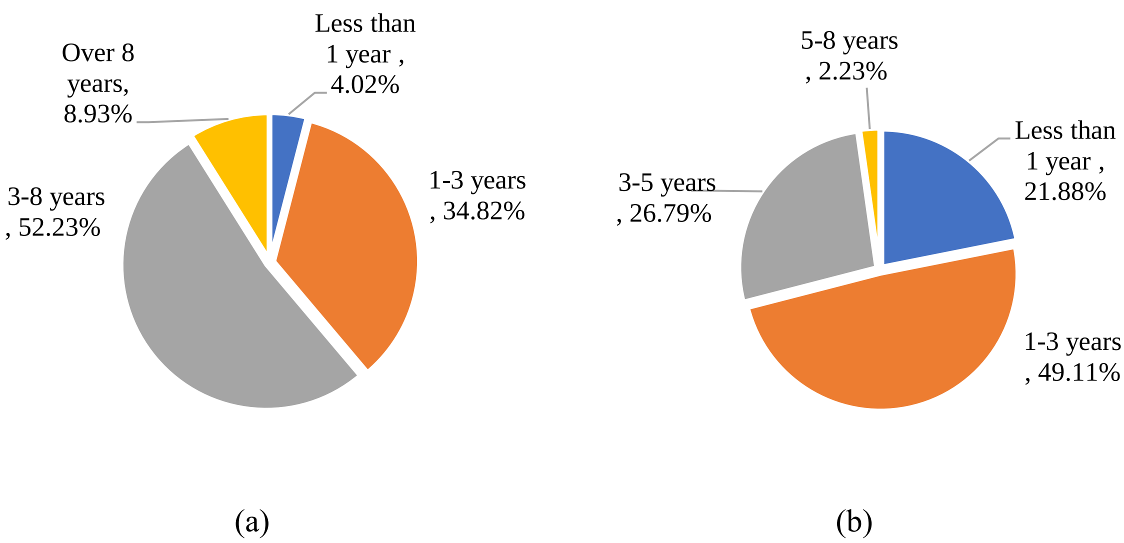

Figure 7.5 Working experience distribution in the construction industry and green buildings.

The distribution of GB types that the respondents have worked for is shown in **Figure 7.6**. Residential buildings and public buildings are the most common GBs for the respondents. The proportions of residential buildings and public buildings are similar, about 36%, followed by industrial buildings (17.14%) and mixed function buildings (10.48%). However, more public buildings apply for GB labels in practice. Taking Shanghai as an example, 152 projects obtained GB labels in 2020. Among them, there were 108 public buildings, accounting for 71.05%. 26.97% of the buildings were residential buildings, with only three industrial GBs. Respondents can select multiple items in this question. The results show that more than 80% of respondents have been involved in the work of residential buildings and public buildings.

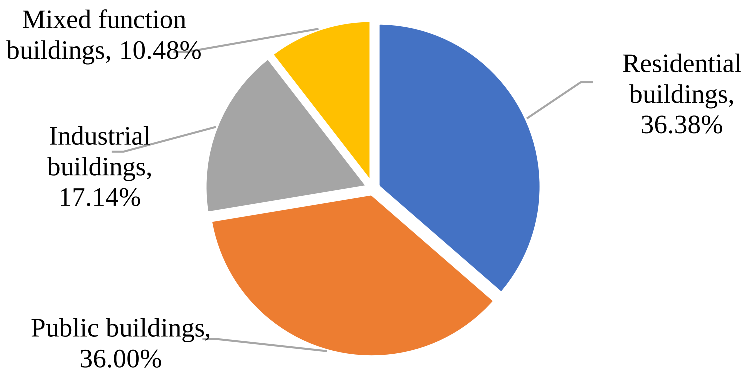

Figure 7.6 The distribution of building types.

The questionnaire was distributed through the internet, so it considered all the provinces in mainland China. After the data collection, it was found that no questionnaire was returned in Tibet. As the findings of previous chapters showed, GBD in Tibet was not satisfactory. It lacks GB practitioners in Tibet, inviting respondents is difficult in this area. In order to facilitate

GBD regional analysis, 30 provinces in mainland China were divided into seven regions according to their geographical locations: (1) The northeast region, including Heilongjiang, Jilin and Liaoning; (2) The northern region, including Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia; (3) The central region, including Henan, Hubei, Hunan; (4) The eastern region, including Shandong, Jiangsu, Anhui, Shanghai, Zhejiang, Jiangxi, Fujian; (5) The southern region, including Guangdong, Guangxi and Hainan; (6) The northwest region, including Shaanxi, Gansu, Ningxia, Qinghai, Xinjiang; (7) The southwest region, including Sichuan, Guizhou, Yunnan, Chongqing. The geographical distribution of GB projects that respondents have worked for is shown in **Figure 7.7**. Most respondents have been involved GB projects in eastern China, followed by the northern region and the southern region. The southwest, northwest and northeast regions have the lowest proportions. The total proportion in these regions is no more than 14%.

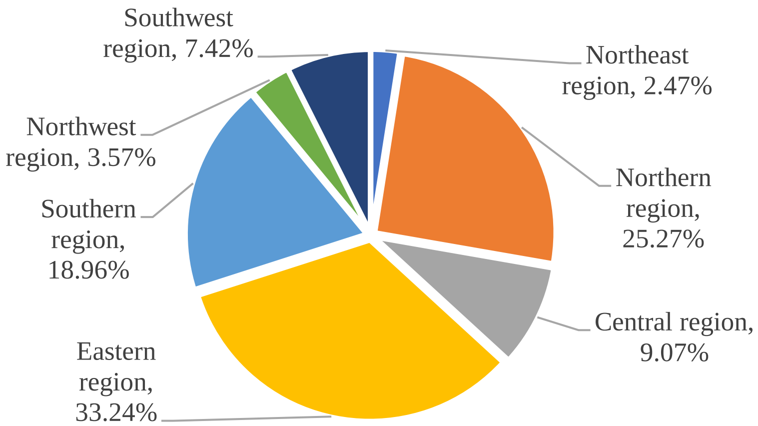

Figure 7.7 The geographical distribution of green building projects.

7.4.2 Results of Questionnaire Survey

The reliability of the questionnaire is an important indicator for the questionnaire, usually assessed by Cronbach's alpha coefficient value, ranging from 0 to 1. The Cronbach's alpha coefficient value is 0.876 in this study, revealing that the reliability of the questionnaire is acceptable.

For the questionnaire survey, the mean values of 40 CSFs are shown in **Figure 7.8**. The most important CSFs are CSF1 "Adequate financial budget," CSF40 "Public awareness," CSF13 "Support from senior management," CSF4 "Tax and fiscal incentives" and CSF26 "Effective government policies," respectively. Among the top 5 CSFs, there is an obvious gap between the first factor (CSF1) and the following factors. The importance of the other top four factors is similar. CSF1 and CSF4 are from the category of finance, which is the most effective incentive of GBD. CSF4 and CSF26 have some similarities. The tax, fiscal incentives and policies are released by governments, which proves the essential role of governments.

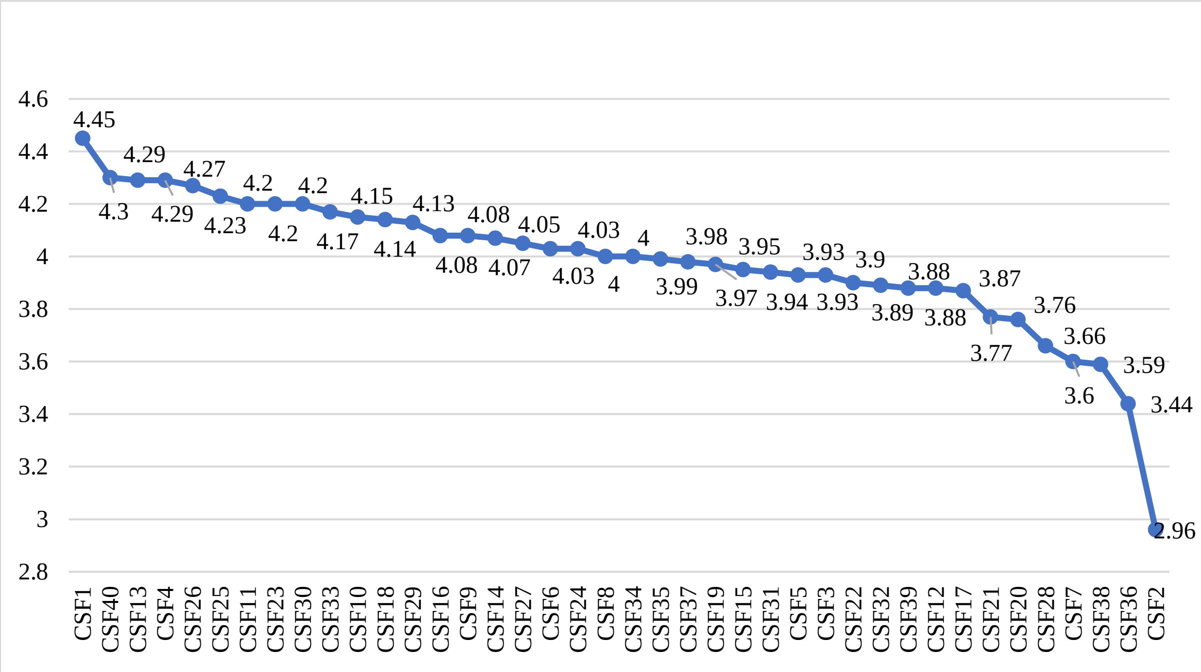

Figure 7.8 The mean value of each CSF in the questionnaire.

An adequate financial budget is a prerequisite to ensure GB construction. As mentioned in the literature review, GB construction has a higher cost than traditional buildings. For example, the average price of green houses is about 6.4% higher than traditional houses. GBs with high levels have higher energy efficiency and higher construction costs. Eventually, GB users pay high costs, but they benefit from the economic and environmental benefits brought by GBs, such as the cost saving in energy during the operation period. For construction companies and real estate companies, the high GB cost is a burden, and the payback period is too long. Meanwhile, they cannot benefit from GBs in the operation stage, so the financial issues determine the decision.

Public awareness of GBs is not very high in China. Many people have little GB knowledge. They believe GBs are buildings with many green plants on the roof and walls. The energy-saving attribute has not yet been noticed. Moreover, as potential consumers, people are unaware of GB benefits to their health. For instance, GBs could increase the comfort of the living environment, including thermal comfort, acoustic comfort, light comfort and air comfort, which is beneficial to consumers' physical and mental health. Lacking public awareness is one of the reasons for insufficient purchasing willingness. Therefore, improving public awareness of GBs helps stimulate GB consumption and promote the prosperity of the GB market.

Support from senior management is a direct factor in GBD. Governments have been promoting GBD through various measures, but for the practitioners, the command from the boss or the senior management staff is more important, and it needs to be executed immediately. In this questionnaire survey, most respondents only work in the construction industry for 3-8 years and work in GB projects for 1-3 years, which means they are junior practitioners in their companies. Therefore, respondents may not have a deep understanding of GBD, but the commands and support from senior management are essential in their work.

The government has released various policies to stimulate GBD. Tax reductions and subsidies belong to financial incentives. For example, Shanghai established a foundation to support demonstration projects of energy-efficiency buildings and GBs in 2020. if the demonstration project can be certified with a GB label with two stars, it will get a subsidy of 50 yuan per square meter. The subsidy increases to 100 yuan if the project has a three-star GB label. The financial incentives provided by the government compensate for the high GB construction cost. In addition to financial incentives, the government has released other policies to promote GBD.

For example, the central government released the *Green Building Action Plan* in July 2020. It stipulates that the proportion of new GBs in urban areas should reach 70% by 2022. As a result, local governments are taking active actions to achieve this target. As a country with a strong government, China releases GB policies with wide and deep influence, so respondents consider the effective government policy a high-rank CSF.

7.5 Discussion

7.5.1 CSF Comparison between China and the World

The meta-analysis collects data from previous empirical studies on the same topic. It synthesizes many questionnaire data, so the sample size is large in the meta-analysis, leading to accurate results. Compared to the meta-analysis, the questionnaire survey has a smaller sample size, but it is more targeted because it is conducted in mainland China.

This research conducted a meta-analysis and questionnaire survey to investigate and compare CSFs of GBD around the world and in mainland China. The meta-analysis collected a total of 2168 samples from the published empirical studies, covering 4 global studies, 9 regional studies in Asia, 4 regional studies in Africa, 2 regional studies in Oceania, and 1 regional study in North America. The questionnaire survey collected 224 samples from 30 provinces in mainland China. The results of the meta-analysis and the questionnaire survey were compared to analyze the similarities and differences in CSFs of GBD from a spatial perspective. It also provides a foundation for the following chapter to construct a driving mechanism of GBD.

The mean values of CSFs in the meta-analysis and questionnaire survey are compared, as shown in **Figure 7.9**. All the mean values are more than 2.7, indicating that the CSF identification is scientific and effective. Compared with the meta-analysis, the mean values of CSFs in mainland China are generally higher than the global results, revealing that respondents in China have a higher sense of identity in the CSFs. Some CSFs have similar trends, while some have obvious differences.

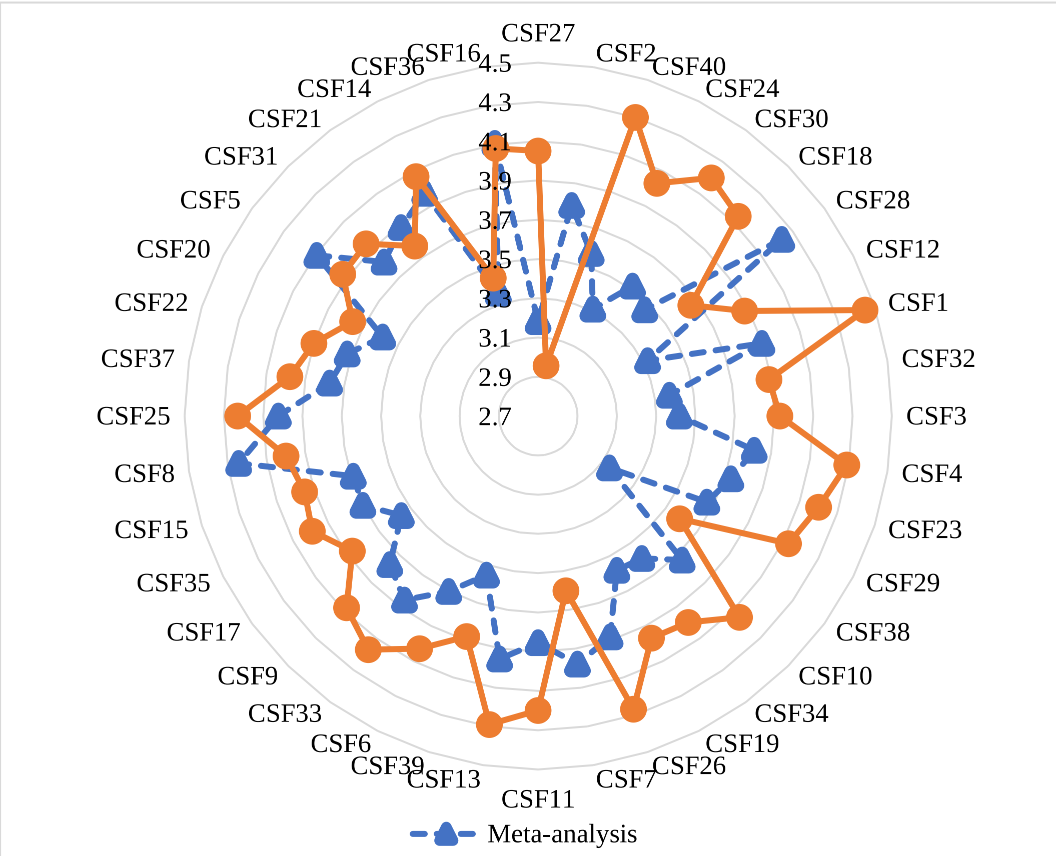

Figure 7.9 The comparison of mean values in the meta-analysis and questionnaire survey.

Among the differences between CSFs around the world and in China, the largest difference in absolute mean values is CSF27 "Regulation support." The mean value of CSF27 is 3.181 in the meta-analysis, ranking 39th, while it is 4.05 in the questionnaire survey, ranking 17th. Surprisingly, CSF28 “Mandatory requirements,” from the same category as CSF27, is on the contrary. The mean value of CSF28 is 4.233, ranking second in the meta-analysis, but it is only 3.66 in the questionnaire, ranking 36th.

The different driving forces of GBD lead to this result. China has a strong government, following the "strong state" mode, which means the government has strong administrative power and occupies a critical position in GBD. The discussion on the “strong state” and the “weak state” has become a hot topic in academia. Researchers demonstrate that a strong state can fully allocate resources to ensure a stable country, promoting economic growth and social development. Meanwhile, the strong state has been criticized for excessive government intervention in the economy, affecting the market's resource allocation. China is exploring how to handle the government and market relationship properly. This issue is also the core of economic system reform. Moreover, China proposes to combine "strong state" with "strong market", with a clear boundary between the government and the market, and fully comply with economic principles.

The mandatory requirements of GBD from the government have been implemented in China. These requirements promote GBD effectively. At the same time, they bring pressure on the practitioners in GB activities. Therefore, respondents tend to relieve the mandatory burden from the government and choose a weakened expression of “Regulation support”. The meta-analysis collected the global sample. Compared with China, administrative power is weak in other countries. Therefore, it is believed that strengthening the mandatory requirements from the government is necessary for GBD.

CSF1 “Adequate financial budget” ranks ninth with 3.898 in the meta-analysis and ranks first with 4.45 in the questionnaire survey. It is found that no matter in any country, the budget is a critical factor for GBD. The cost premium of GBs mainly appears in the construction stage, so an adequate financial budget is the basis of GB construction. The financial incentives for GBs have various forms. For instance, the UK invested £50 million in housing refurbishment in 2020 and developed a funding scheme of £1 billion to improve building energy efficiency. In Germany, the government provided around 2.5 billion euros for building renovations. In Japan, buildings with carbon reduction technologies and energy-saving retrofits can apply for financial subsidies. In Australia, GB developers can get a tax reduction, and a GB fund was set up to subsidize renewable energy.

The project budget is particularly important for China. The administrative promotion power is strong. However, consumers are unwilling to pay the cost premium due to weak market demand. Other sustainable products also face the same dilemma. To relieve the financial burden of GB projects, many provinces in China have released various policies to provide subsidies for GBs. A two-star GB project in Beijing could receive a subsidy of 50 yuan per square meter, and a three-star GB project could receive a subsidy of 80 yuan per square meter. GBs in Hubei could be rewarded in the plot ratio. One-star, two-star and three-star GBs could increase the plot ratio by 0.5%, 1% and 1.5%, respectively.

CSF40 “Public awareness” ranks 29th with 3.571 in the meta-analysis and ranks second with 4.3 in the questionnaire survey. Public institutions and non-profit organizations organize many activities to increase public awareness. The purpose of these activities is to help the public learn more about GBs and make the public aware of their duties and responsibilities to protect the environment, which is more important. At present, the public awareness of GBs in China remains low, and the public has little knowledge of GBs, leading to the phenomenon that potential consumers hesitate to buy GBs. It affects the acceptance of GBs in the market, leading to low GB demand.

7.5.2 CSF Comparison between different regions in China

The provinces in China were classified into seven regions. This section investigates the difference in CSFs in different regions of China. The top ten CSFs in each region were selected and presented in **Figure 7.10**, 20 CSFs in total. Among these factors, seven regions have similar cognitions on the importance of CSF1 “Adequate financial budget”, CSF11 “Detailed plan”, CSF25 “Adequate incentives” and CSF40 “Public awareness”. These four factors are in the top ten list in each region. CSF1 and CSF40 are discussed in the previous section. CSF11 is a management method to keep the GB activities on track. Most of the respondents (65.63%) are from construction companies in the questionnaire survey, so they are familiar with the management methods in construction sites. According to their work experience, the respondents believe a detailed work plan is essential in the GB project. Meanwhile, the respondents hope that the government could release more incentives, so they could get more benefits through GB activities. That is the reason why CSF25 ranks high. This measure is effective because it could improve practitioners' enthusiasm to build GBs. The results of the questionnaire survey also support this opinion.

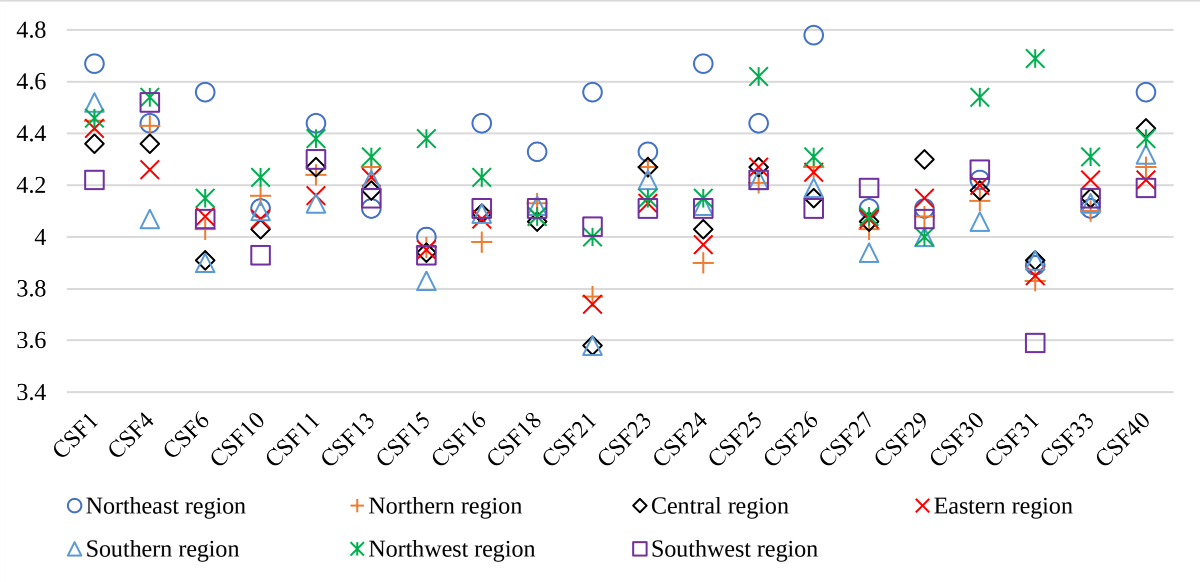

Figure 7.10 The comparison of CSFs in different regions.

Some regions have different estimates of the importance of CSFs. The northeast region has higher estimates of all CSFs, such as the CSF6 "Communication between stakeholders", CSF21 "Available databases", CSF24 "Demonstration projects" and CSF26 "Effective government policies". The northwest region has a similar situation, but they prefer other factors, such as CSF15 "High motivation", CSF30 "Comprehensive code and standard" and CSF31 "Research". Contrary to the northeast and northwest regions, the estimated value of the southwest region is lower, such as CSF1 "Adequate financial budget", CSF10 "Experience in GBs", CSF31 "Research". On the one hand, the differences in estimates reflect the perceptions of different regions on CSFs of GBD that are formulated under different regional economic and social conditions. On the other hand, the sample sizes of the northeast, northwest and southwest regions are small in the subgroup, which may lead to biased results. The number of samples in these three regions only accounts for 2.47%, 3.57% and 7.42% of the total sample, about 13.46% in total.

Different regions have different preferences for CSFs of GBD. The northeast region tends to improve GB culture, education and knowledge. In the cognition of GB practitioners in the northeast region, the popularity of GBs is not enough. First, public awareness is not enough. Second, experienced practitioners are lacking. This phenomenon is in line with the GBD of the northeast region. The pace of the GB promotion is slow in this region. This conclusion proves the GBD and efficiency results in Chapters 4 and 5.

The northern region, the central region, the eastern region, the southern region and the southwest region tend to CSFs in the finance category. It indicates that most regions in China face the dilemma of limited GB budgets, affecting the success of GB activities. Although GB activities have strong positive economic externalities, the rising costs and budgets have been the most direct problems for practitioners. Financial support is one of the most effective strategies for promoting GBD. As mentioned above, most provinces have adopted policies to subsidize GBs, which is an effective measure to alleviate the difficulty of construction budgets.

The northwest region pays more attention to the CSFs of GBD in the research and innovation category, especially the GB research. The GB field has rich literature covering GB standards, policies, management strategies, and technologies. However, it has a large potential to integrate GB research and practice, applying new GB technologies into the industry.

According to the results, the CSFs of GBD in the technology category are neglected. GB technologies are an important indicator to distinguish GBs from traditional buildings, and they are the prerequisites to realizing energy saving and emission reduction in GBs. GB technologies need more attention because they lead to cost premiums. Reducing the costs of GB technologies is essential to solving the problem of GB premium. Practitioners do not realize the importance of GB technologies because it is not the main task of their work. In addition, the GB technology system needs to be improved. As China has a vast territory and large climate differences, it is necessary to consider the local needs when constructing the GB technology system. Besides, GB design should consider the regional culture and climate, and the GB technology application should consider regional ecological culture to achieve the goal of combining architectural art with the environment.

7.6 Chapter Summary

This chapter followed the PRISMA framework, identified CSFs of GBD through a systematic review, and investigated CSFs quantitatively by the meta-analysis and questionnaire survey. The CSFs in different regions were compared, including CSFs around the world and in mainland China, and CSFs in different regions of mainland China. The results show that the top 5 CSFs in the meta-analysis are "Commitment of all project participants," "Mandatory requirements," "Integrated design," "Cooperation between stakeholders" and "Adequate incentives," respectively. CSFs in the management and government categories dominate in the top list. Meanwhile, the top 5 CSFs in the questionnaire survey are “Adequate financial budget,” “Public awareness,” “Support from senior management,” “Tax and fiscal incentives” and “Effective government policies”, respectively. CSFs in the finance category are the most direct drivers of GBD in China. After comparing CSFs from a spatial perspective, it is found that the public awareness of GBs is lower in China. Financial factors in most regions in China ranked high in importance. Besides, the northeast region tends to improve GB culture and knowledge, while the northwest region prefers to increase GB research and innovations.

CHAPTER 8 DRIVING MECHANISM OF GREEN BUILDING DEVELOPMENT AND IMPROVEMENT STRATEGIES

8.1 Introduction

The "14th Five-Year Plan" period is a critical period for China to achieve the goals of carbon peaking and carbon neutrality. As the traditional construction industry consumes a large amount of energy and emits carbon dioxide emissions, the transformation and upgrading in the construction industry are significant. GB is an innovative initiative in the construction industry. It has obvious advantages in environmental protection and saving energy, water, and land. This chapter identifies the internal and external stakeholders in GBD, integrates research results of previous chapters and establishes the driving mechanism of GBD. The strategies were proposed in this chapter to improve GBD in mainland China.

8.2 Driving Mechanism of Green Building Development

8.2.1 Stakeholder Analysis

Stakeholders are individuals or groups that influence an organization to achieve its goals (Yang & Zou, 2014). Promoting GBD requires joint efforts from all stakeholders, but conflicts exist among stakeholders. As shown in **Figure 8.1**, GBD stakeholders can be divided into internal stakeholders and external stakeholders.

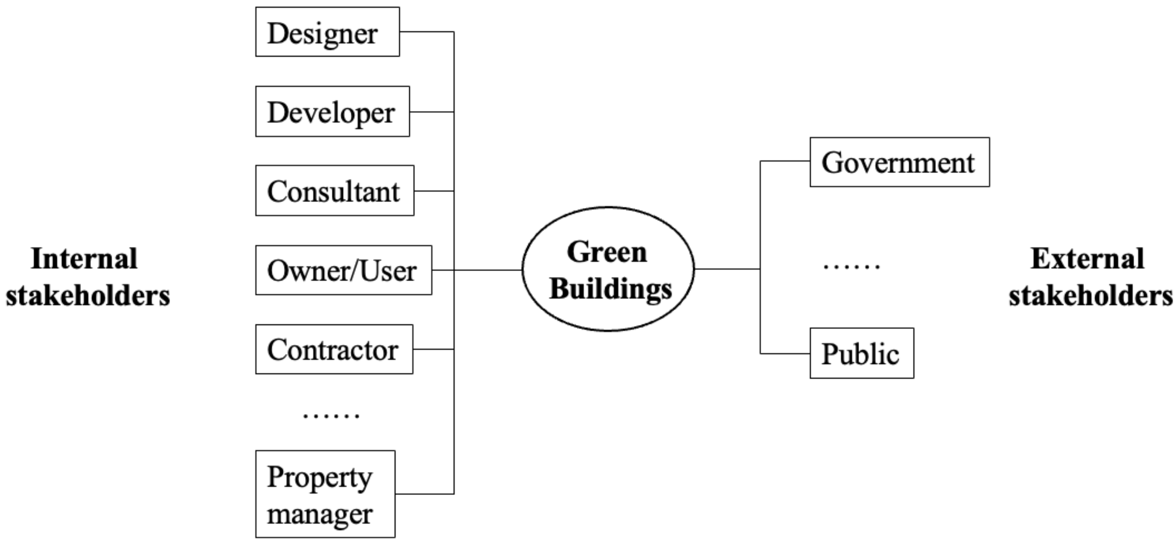

Figure 8.1 Stakeholders in GBD.

8.2.1.1 Internal Stakeholders

Internal stakeholders refer to the individuals or organizations directly involved in GB work, including designers, developers, consultants, owners/users, constructors and property managers. Designers are responsible for GB design. They consider the whole life cycle of GBs and follow GB standards. Integrated design, which has been considered a critical success factor in Chapter 7, has become the preference of designers. Developers aim to chase the maximum benefits in GB activities. High GB costs influence developers' willingness to adopt GBs, while preferential government terms motivate developers with financial support and other incentive policies. Consultants provide consulting services for GBs and offer expertise to the successful delivery of GB projects. Contractors are responsible for GB construction. Owners are the decision-makers. They have the right to decide whether to adopt GBs or not. Sometimes they are the end users of GBs. In China, the owner should clarify the requirement of GB level before construction and check the buildings after completing the construction work. Property managers undertake management tasks during the operation stage of GBs. They should set up management regulations, maintain the operation of energy-saving and water-saving facilities and equipment, and check the automatic monitoring system of heating, air-conditioning and other equipment on time. The primary condition to ensure GBD success is that all stakeholders take responsibility.

Many interactions exist among GB stakeholders. The collaboration between stakeholders is critical to promoting GBD. Trust is the foundation of stakeholders' collaboration, and keeping promise is the basic line. Good communication between stakeholders ensures smooth information exchanges, meaning the accurate task connection between different stakeholders. Since GB stakeholders are involved in the project at different time points, early involvement in the task helps stakeholders catch more information of the projects, such as the schedule and procurement management. With respect to stakeholder management, developing detailed plans, effective feedback and troubleshooting help complete GB tasks better. Support from senior management is essential in the decision-making and GB project implementation. The command from the senior management is the most direct work instruction, which guides employees in a clear direction.

8.2.1.2 External Stakeholders

Although external stakeholders do not directly participate in the GB construction and operation, they significantly influence GBD, which cannot be neglected. This section summarizes the two main external stakeholders in GBD: the government and the public.

The government is the supervisor of GB construction and the important GB promoter. Governments promote GBs to improve our society and enhance citizens' well-being. Governments in China are divided into the central government and the local government. The central government formulates the policies around the country, points out the GBD direction and supervises the local governments in the implementation. The local governments are responsible for developing detailed guidelines and regulations and then implementing them. Governments have administrative departments in charge of the construction industry, regulating all GB activities.

Government promotion is effective in GBD, which reflects in two aspects. The first is that government incentives encourage internal stakeholders to construct GB. The second is the mandatory regulations, which provide the bottom line of GB construction.

Meanwhile, governments formulate various GB standards and norms and set up GB regulation systems, clarifying the primary responsibility of stakeholders and setting benchmarks for GBD.

The public needs sustainable construction products and services. They are consumers or potential consumers of GBs. GBD satisfies people's need to improve their living environment and aspires for a better life. As mentioned in Chapter 7, GB public awareness and public participation are not very high in China. However, the public is the ultimate beneficiary of GBD. First, GBs save energy and protect the environment, which benefits the public in the environmental aspect. Second, GBs save energy in the operation stage, reducing building operation costs, including electricity and heating costs, which benefit the public in the financial aspect. In addition, GBs provide a safe, healthy and comfortable living environment for the public.

8.2.2 Driving Mechanism of Green Building Development

After identifying the stakeholders in GBD, this section investigated the relationship between CSFs and proposed a driving mechanism of GBD based on CSF analysis, as shown in **Figure 8.2**.

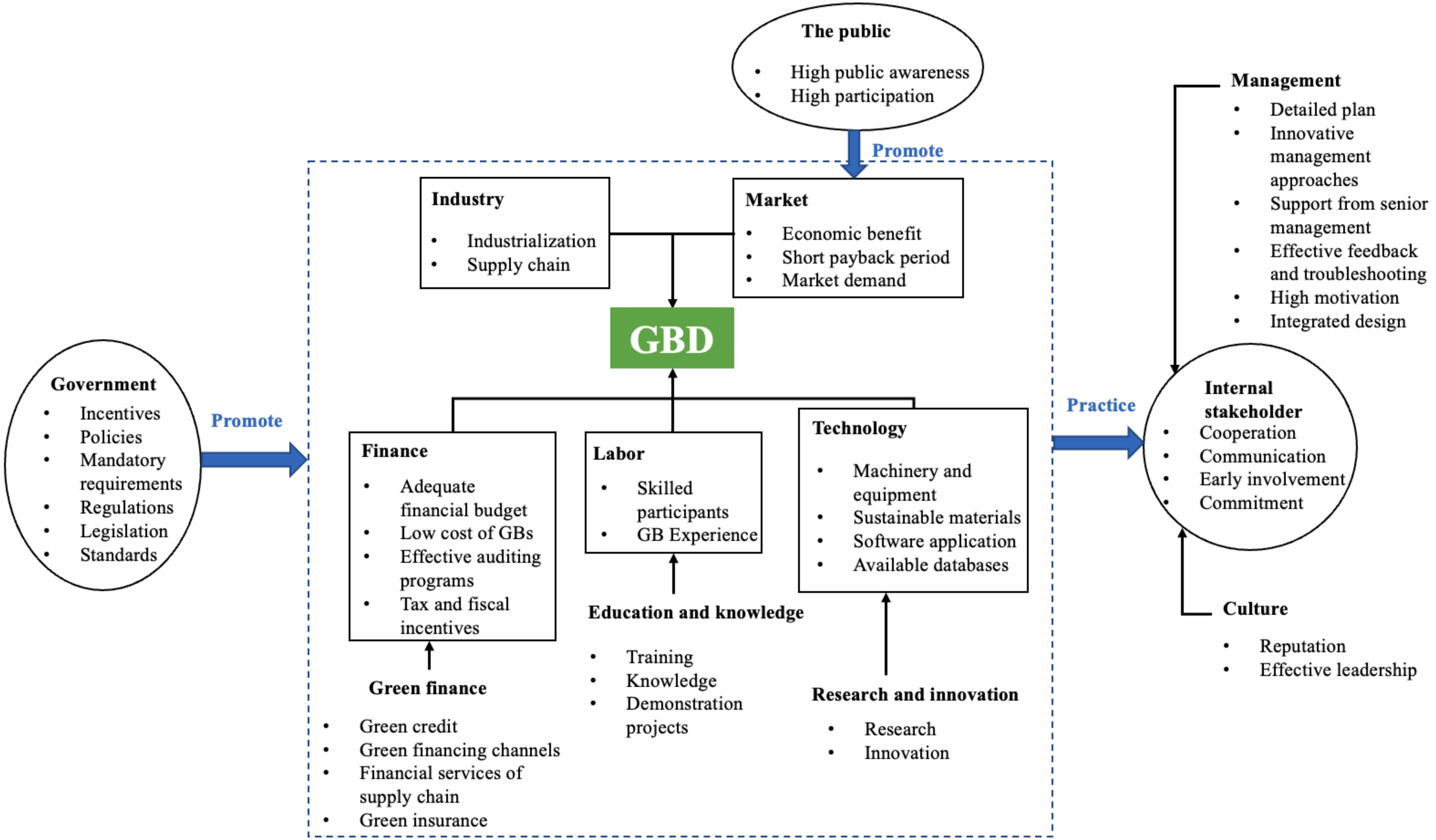

Figure 8.2 Driving Mechanism of GBD.

According to the stakeholder analysis, GBD participants include governments, internal stakeholders and the public. The government promotes GBD by formulating various incentives, policies, mandatory requirements, regulations, legislation and standards. High public awareness can increase the public willingness to pay for sustainable initiatives in buildings. High public participation can promote the improvement of green technologies, which positively affects GBD. Internal stakeholders directly get involved in GB activities. Completing GBD tasks is the fundamental responsibility of internal stakeholders, including the management and cultural factors discussed in Chapter 7. Besides, stakeholder interactions are important, including cooperation, communication, early involvement and commitment.

The GB industry and GB market are the two aspects of GBD. Industry development and market development complement each other. GB industry not only includes the design and construction services of GBs but also requires related and supporting industries to provide products and services (Allen & Potiowsky, 2008). For example, GB construction need materials (e.g., wood, sand, gravel and asphalt) and heating, ventilation and air conditioning (HVAC). Governments encourage GBs adopt GB materials, so the industrialization of GB materials has brought new economic vitality to many cities (e.g., Yuxi in Yunnan province and Liaocheng in Shandong province). At present, GB industrialization in China still has large potential. The supply chain, another critical success factor for the GB industry, is a complex logistic system that could deal with materials and deliver the product with the highest efficiency. The key point of GB industrialization is to set up the supply chain and develop the upstream and downstream industries of GBs. It helps optimize the GB industry's resource allocation and promotes standardized GB products.

Setting up the GB market aims to draw attention to the economic attributes of construction products and fully show the advantages of GBs in the market to improve the economic benefits and shorten the payback period of investments. The GB economic benefits are essential elements in the GB market, which attracts stakeholders in the decision-making stage. Besides, it is necessary to increase GB demand in the market. In the past few decades, China has fully promoted GBD from the supply side through incentive and mandatory policies, but consumers' willingness was neglected from the demand side, resulting in unbalanced circumstances between GB supply and demand. Strong demand benefits the GB industry to be more competitive and helps improve technical standards for products, which are the foundation of a mature market (Colgan & Baker, 2003). The public is the potential GB consumer. Improving their awareness of GBs will help expand their demand for GB products. Although GBs contribute to operation cost reduction, this advantage is hard to attract occupants' interest. Occupants are more likely to choose those comfortable and healthy buildings. Therefore, only improving building energy efficiency is insufficient to earn competitiveness for GBs.

The driving mechanism of GBD has three bases: finance, labor and technology. On the base of the finance, the first is to ensure that the project budget is sufficient. Green finance can provide financial support for GB projects, including green credit products, green financing channels, financial services for supply chains, and green insurance services (Akomea-Frimpong et al., 2022). The government's subsidies and various financial policies can also alleviate the shortage of project budgets, including tax reduction, plot ratio incentives, and preferential loan interest rates. GB cost premiums are mainly from GB technologies. Reducing GB costs should consider reducing the cost of GB technologies.

The labor base provides human resources for GBD. Adequate and appropriate human resources guarantee the smooth running of GB construction. USGBC proposed LEED credentials to improve proficiency in GB areas. Over 203,000 professionals have passed the exam and earned LEED credentials (USGBC, 2022). There is no GB credential for GB practitioners in China. Rather than setting a benchmark for human resources, China is prone to cultivate experienced and skilled professionals for GB construction and management through education and training.

On the basis of technology, except for common approaches such as improving machinery and equipment, GB materials should be encouraged. As innovative building materials, GB materials are the materials that meet the standards of "health," "environmental protection," and "safety" (Sharma, 2020). GB material production adopts clean production technologies, reducing carbon emissions and waste. Furthermore, some GB materials are recycled products of construction waste. The application of GB materials enhances the environmental benefits of GBs, saves resources, and benefits residents' health. In addition, it is necessary to promote the application of information technology in the GB field, such as promoting the application of 5G, Internet of Things, artificial intelligence, construction robots, and other technologies in GB construction (Debrah et al., 2022; Tushar et al., 2018). Besides, it encourages to apply BIM technologies in the GB design, construction and operation, which benefits information sharing among stakeholders (Chang & Hsieh, 2020). Moreover, data platforms, such as the building energy consumption monitoring platform and the GB label management platform, could be set up to collect building data. Universities and research institutions are the main contributors to GB research and innovations. Research on GB technologies is prevalent in universities and research institutions (Darko et al., 2017c; Nelms et al., 2005; Kong & He, 2021). Besides, transferring GB technologies from research institutions to building enterprises is vital to GBD. It needs cooperation work between the two sides (Yin & Li, 2018).

8.3 Improvement Strategies for Green Building Development

Based on the research results, this section proposed strategies to improve GBD in mainland China, including improving GB standard, coordinating GBD and GBD efficiency, strengthening spatial correlations of GBD and solving the financial dilemma of GBD.

8.3.1 Improving the Green Building Standard System

Since the promulgation of ESGB in 2006, GBs in China have a history of more than ten years. Although GBD in China has reached many achievements in the past years, it also faces some problems. At present, the scope of GB standards in China is still relatively narrow, and the standard system of GBs needs to be improved. The system of GB standards in China is shown in **Figure 8.3**.

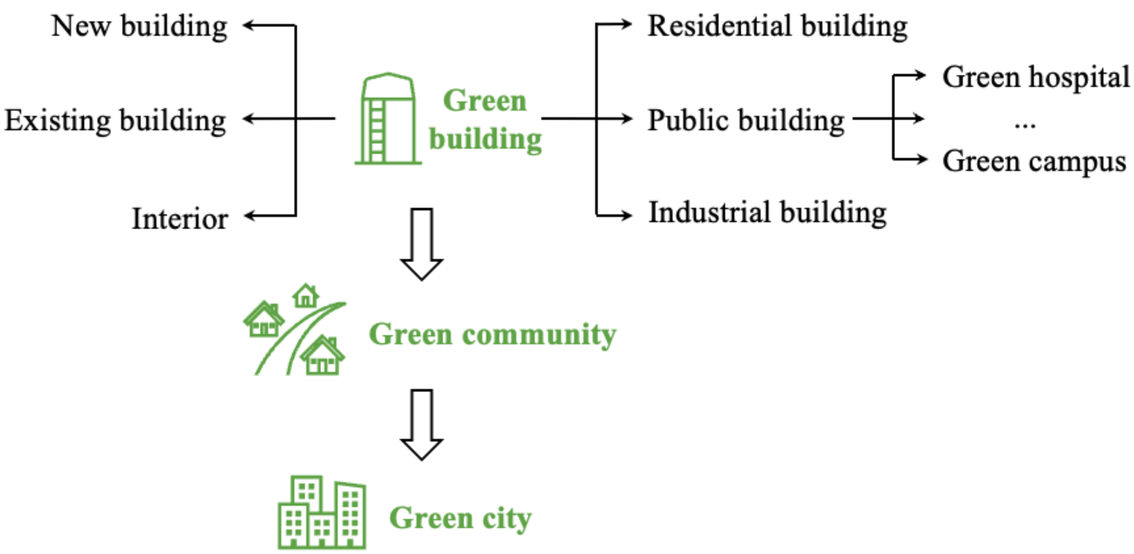

Figure 8.3 GB standard system in China.

It needs to promote the greening of multiple building types for a single building. According to the classification, GBs can be divided into new GBs, existing GBs and green interiors. Currently, new buildings are the main trend of green construction. The standards of new buildings are comprehensive. In contrast, although the GB standard for existing buildings has been implemented for many years, greening existing buildings is difficult. According to government statistics, out of the 1,345 GBs evaluated by the Science and Technology and Industrialization Center of the Ministry of Housing and Urban-Rural Development, only more than 20 GBs belong to the energy-saving renovation of existing buildings. The green retrofitting implementation in existing buildings faces the challenge of unclear responsibility classification during building operation. Green retrofitting works involve many stakeholders, leading to many conflicts in retrofitting. However, China has a large stock of existing buildings, revealing enormous energy-saving potential. In addition, the green interior emphasizes the decoration, transformation and renovation of interior spaces, which is also an essential part of GBs. The *Assessment standard for green interior decoration (T/CBDA 2-2016)* has been implemented since 2016. The interior decoration impacts occupants' health. This standard focuses on optimum material/resource utilization and contributes to reducing air pollution.

According to the building functions, GBs are divided into residential buildings, public buildings and industrial buildings. Most residential buildings comply with ESGB, while industrial buildings have a specific standard. Public buildings can be divided into subgroups, such as green hospitals and green campuses (Tan et al., 2014). China releases GB standards for different building types. Improving the GB standard system needs refining building standards. **Table 8.1** summarizes GB-related evaluation standards. The standard system incorporates green industrial buildings, green office buildings, green stores, green hotels, green exhibition buildings, green booths, green campuses, green hospitals, green railway stations and green industrial buildings of the tobacco industry. Except for national standards and industry standards, many provinces in China have released local standards for GBs. The standards for individual GBs are various and complex, which may confuse users in the application (Ye et al., 2015). In addition, the contents of standards largely overlap. It is necessary to integrate GB standards and formulate a systemic scheme.

Table 8.1 Evaluation standards for buildings.

Category	Name	Code
National standard	*Evaluation Standard for Green Buildings*	GB/T 50378-2019
National standard	*Evaluation Standard for Green Refurbishment of Existing Building*	GB/T 51141-2015
National standard	*Evaluation Standard for Green Industrial Building*	GB/T50878-2013
National standard	*Evaluation Standard for Green Office Building*	GB/T 50908-2013
National standard	*Evaluation Standard for Green Store Building*	GB/T 51100-2015
National standard	*Evaluation Standard for Green Hotels*	GB/T 51165-2016
National standard	*Evaluation Standard for Green Exhibition Building*	GB/T51148-2016
National standard	*Evaluation Standard for Green Booth*	GB/T 41129-2021
National standard	*Evaluation Standard for Green Campus*	GB/T 51356-2019
National standard	*Evaluation Standard for Green Hospital Building*	GB/T 51153-2015
Industry standard	*Evaluation Standard for Green Railway Stations*	TB/T 10429-2014
Industry standard	*Evaluation Standard for Green Industrial Building of Tobacco Industry*	YC/T 396-2011

At first, the GB concept referred to a single building. With the development of sustainable practices, the green scope has expanded, aiming to achieve sustainability with a large scope. A green community is the spatial expansion of a single GB. It is a composite ecological space with energy saving, environmental protection, and harmonious coexistence between man and nature. The *Evaluation Specification for Green Community (DB4403/T 147-2021)* is a local standard in Shenzhen, which has been implemented since April 2021. It stipulates basic requirements, evaluation contents and approaches for a green community. However, the national standard for the green community is lacking in China. Furthermore, the green community is the foundation for the sustainable development of an entire city. The green community also needs to consider the relationship between GBs, which puts forward more requirements for space design and planning between buildings.

The ultimate sustainable goal is to build a green city, further expanding the scope of the green community. Urban planning in the new era should consider the city's function and achieve ecological harmony between the city and nature. Besides, the green city concept involves the inclusiveness and sustainability of the economy and society (Pan et al., 2020). A green city could be constructed based on multiple green communities, and it also includes GBs and green infrastructure. The ultimate aim is to achieve green and sustainable development of the cities.

8.3.2 Coordinating Green Building Development and the Efficiency

According to research results, GBD in mainland China increased fast in these years. As mentioned in Chapter 4, results show that GBD in China was uneven, which is in line with the study of Teng et al. (2019). GBD showed a three-step distribution, and GBD has strong correlations with the local economic levels. However, the efficiency assessment results in Chapter 5 demonstrate that GBD efficiency needs to improve because of the large gap between high-efficiency regions and low-efficiency regions. Compared results of Chapters 4 and 5, it is found that the convergence between high-level regions and high-efficiency regions was poor, revealing that many provinces with high GBD had low efficiency in GBD. Except for Shanghai and Guangdong, other regions with high GBD efficiency have excellent energy conservation and emission reduction performance, but their efficiency advantages are not obvious in GBD. The reason is that some regions have many GBs, but their energy conservation and emission reduction advantages were not obvious, especially during the operation period.

Recently, urbanization speed in China has slowed down. Meanwhile, the focus of urbanization has switched from pursuing construction speed to pursuing construction quality (Yu, 2021). Similar to the changes in urbanization, GBD improvement first achieves progress in quantity, then achieves progress in efficiency, aiming at improving the quality of GB activities. Without progress in quantity, the efficiency advantage has no roots. Hence, for those regions with a low GBD, achieving a robust and competitive GB cluster needs to improve the basic environment for GBD (Allen & Potiowsky, 2008), and it is supported by many elements, including releasing the regulations, policies and laws of GBD, and improving the green coverage of new and existing buildings. For instance, the Dutch construction industry achieves self-regulation by combining the "constraining" and "enabling" policies (Melchert, 2007). A long-term subsidy strategy has been optimized to promote GBs (Jiang et al., 2022), which could be applied in low-GBD regions.

Only focusing on the GB number will put pressure on greening new buildings, leading to ignoring GB energy efficiency. Therefore, to achieve a breakthrough in GBD, more attention should be paid to the energy-saving renovation of existing buildings and the green assessment of new buildings during the operation period. The effects of energy saving and carbon emission reduction should be re-evaluated in the operation stage, and governments should encourage buildings to apply GB labels during the operation. Renewable energy (e.g., solar energy and wind energy) could be combined with other types of energy or applied in storage devices (Jiang & Rahimi-Eichi, 2009). For instance, a photovoltaic system is applied to the roof to save electricity (Fan & Xia, 2018). Other alternative strategies without cost include changing the air conditioning temperature, and strategies with cost include changing the lamp, chiller and glass

(Inayati et al., 2017). Besides, GB design could consider nature wisdom and utilize architectural innovations with bionic functions, such as the natural ventilation system in termite mounds (Yuan et al., 2017). Recently, passive design has drawn much attention because of its low investment and high energy saving, including building geometry, air-tightness and infiltration performance (Chen et al., 2015).

8.3.3 Strengthening Spatial Correlations of Green Building Development

As the findings in Chapter 6, GBD spatial correlations still have large potential. Strengthening spatial correlations aims to enhance the regional spillover effect of GBD so that more regions can benefit from the high-level GBD regions' resources, technologies and knowledge (Zhou et al., 2019). The resource allocation among different regions could be optimized. An essential strategy to strengthen GBD spatial correlations is to improve the connectivity between regions, creating basic conditions for resource flow (Ma et al., 2015). The first is the connectivity in geography, indicating more investments in the infrastructures to improve the transport routes and approaches, including constructing more roads and railways (Démurger, 2001). The second is the smooth flow of production resources under a unified economic system. The geographic distance between regions exists in reality, which cannot disappear, but the policy environment in different regions can be unified. In these years, China encouraged to build a unified national market to reduce policy barriers between different regions and realize the free flow of production resources across the country (Yang et al., 2022). Meanwhile, it also reflects the full play of the market mechanism, aiming to deepen the reform in the market sector.

In addition, the regions at the edge of the spatial correlation networks need more attention. They have fewer correlations with other regions, meaning they cannot enjoy the spillover benefits. Improving the spatial correlations between these regions and other regions is an effective strategy to strengthen the overall network correlations. Furthermore, if the regions on the edge have a far geographical distance from the central regions, the effect is not significant when strengthening their direct correlations. In this case, priority should be given to improving the one or two provinces with more regional advantages, considering it a regional center to support neighboring provinces and enhance GBD around the country. For example, Chongqing and Gansu are the regional centers to support other southwest and northwest provinces, respectively.

8.3.4 Solving the Financial Dilemma of Green Building Development

According to the CSF analysis of GBD (Chapter 7), it is found that financial factors are the most direct drivers of GBD in China. Therefore, insufficient investments in GB construction is a critical challenge needed to be first addressed. This section proposed three strategies.

The first strategy is to attract investments. *The Opinions on Accelerating the Construction of a National Unified Market* issued by the central government in China proposed to break the market segmentation and promote the flow of commodity elements in the unified national market, including investments (The state council, 2022). This policy implementation reduces investment barriers but needs to improve GB economic benefits and shorten the payback period to attract more investments. Studies have shown that GBs have lower costs in operation but higher construction costs than traditional buildings (Vyas & Jha, 2018; Zhang et al., 2017a; Uğur & Leblebici, 2018). However, the value-added advantages of GBs are not obvious at present. The task in the next stage is to improve the return on the GB investment.

The second is to increase government subsidies and incentives. GB financial subsidies have been the most direct and effective policy incentives (He et al., 2021). The government needs money to continue the subsidies, which is not applicable to those regions with limited money to provide subsidies. Therefore, those regions could adopt incentives in other forms, such as tax reduction, floor area ratio incentives and reduction or exemption of urban ancillary fees, which increase stakeholders' willingness to invest GBs.

The third strategy is to encourage green finance to raise funds for GB construction. The main products of green finance include green credit, green bonds and green insurance (Akomea-Frimpong et al., 2022). At present, the support of green finance is insufficient for GBs. Few GB projects raise money through green finance, and there are a small number of green bonds. Before financial institutions support GB projects, they need to collect information and analyze the value relationship between the performance of GBs and building assets. Currently, it is difficult to quantify the values, so it is hard to confirm the price of green financial products. The specific operation rules of green financial products still need to be refined.

8.4 Chapter Summary

This chapter identified GBD stakeholders and proposed a driving mechanism of GBD based on the CSF analysis. Moreover, this chapter discusses the strategies to improve GBD, including improving the GB standard system, coordinating GBD and GBD efficiency, strengthening spatial correlations of GBD and solving the financial dilemma of GBD.

CHAPTER 9 CONCLUSIONS AND RECOMMENDATIONS

9.1 Introduction

This chapter reviewed the research objectives and summarized the findings of this research. Moreover, this chapter demonstrated this study's contributions, including theoretical contributions and practical implications. Limitations of this study were reported and addressed, and future research was proposed in the end.

9.2 Review of Research Objectives and Conclusions

This study aimed to develop evaluation models to examine GBD from three aspects, including GBD status, GBD efficiency and spatial correlations of GBD, and to explore the driving mechanism of GBD based on CSF analysis. The empirical analysis was applied to the GBD data in mainland China from 2008 to 2020, and the spatial patterns of GBD were investigated. CSFs of GBD indifferent regions were examined and compared. Therefore, this study proposed three research questions: “How to evaluate GBD comprehensively?”, “What are the spatial patterns of GBD?” and “What are the CSFs and the driving mechanism of GBD?” To achieve the research aims and answer the questions, five research objectives were established in this study:

1. To establish a GBD evaluation model from a macroeconomic perspective, and to investigate spatial patterns of GBD in mainland China;
2. To propose a GBD efficiency assessment model, and to explore spatial patterns of GBD

efficiency in mainland China;

3. To develop a model for investigating the spatial correlations of GBD between different regions, and to explore the structure of the spatial correlation network in mainland China;
4. To identify CSFs of GBD, and to quantitatively analyze and compare the global CSFs and Chinese CSFs;
5. To clarify the driving mechanism of GBD, and to develop strategies for GBD improvement based on the research results.

The research design for each objective and the research methods are shown in Chapter 3. The findings and conclusions of each objective are shown in Chapters 4-8. The main conclusions of each objective are summarized in the following.

Objective 1: The results show that the evaluation model performed well in the GBD examination. The spatial heterogeneity of GBD was high in mainland China. GBD showed an obvious three-step shape in geography, revealing that GBD in the southeastern coastal regions was better than that in the inland regions, and the inland regions were better than the western regions. Tibet was always at the bottom of GBD, and there was a large gap between Tibet and other regions. The regional collaborative advantages of the Beijing-Tianjin-Hebei, Yangtze River Delta and Pearl River Delta regions were significant. The overall evolutionary trends of GBD was an inverted "U" shape. The spatial structure of GBD changed from "points" to "lines." Then it tended to be stable while the integration ability was enhanced, followed by a slight degradation.

Objective 2: The results show that the GBD efficiency assessment model is effective. The GBD efficiency in mainland China also had high spatial heterogeneity, and the efficiency was affected by the local carbon emissions. From the overall trend, the GBD efficiency increased rapidly, then fell and fluctuated. For individual provinces, the GBD efficiency was not stable. It showed a leaping trend in some cases. The spatial distributions of GBD efficiency kept three core regions and multiple centers, but only the southern coastal region represented by Guangzhou was in the core regions all the time. Other core regions changed fast. Significant differences between GBD and GBD efficiency existed in the spatial distribution. Except for Guangdong and Shanghai, the regions with high GBD were weak in energy saving and carbon emissions, which means that their ability to reduce carbon emissions cannot catch up with the speed of GBD.

Objective 3: The results show that the model effectively analyzes the spatial correlation network of GBD. The GBD spatial correlation network in mainland China had a large scale, with high accessibility and stability but insufficient density, indicating the spatial correlations of GBD in mainland China were inadequate. The network structure began with one core region and evolved into two core regions and multiple centers. The northern region represented by Beijing and the eastern coastal region represented by Jiangsu, Zhejiang and Shanghai, firmly occupied the core position. In contrast, the southern region represented by Guangdong was gradually flattened in the hierarchy. The inland region has gradually raised, supporting GBD in the central and western regions.

Objective 4: The global GB practitioners pay more attention to the CSFs in the government and management categories, while the practitioners in mainland China believe the financial factors are the most direct drivers of GBD. The comparison between global CSFs and Chinese CSFs shows that the international awareness of government-related factors is higher due to the different political systems. Comparing CSFs in different regions of China, most regions have a higher demand for financial factors. Besides, the northeast region tends to improve GBD with CSFs related to culture, education and knowledge, while the northwest region tends to CSFs related to research and innovations.

Objective 5: The driving mechanism of GBD, constructed based on the GBD evaluation and CSF analysis, contains three bases: finance, labor and technology. The market and industry are the two inseparable aspects of GBD. The government, internal stakeholders and the public are involved in driving GBD. The strategies for GBD improvement in mainland China are proposed, including improving the GB standard system, coordinating the scale and efficiency of GBD, strengthening spatial correlations of GBD and solving the financial dilemma of GBD.

9.3 Research Contributions

9.3.1 Theoretical Contributions

The theoretical contributions of this study are as follows:

- It expands the scope of GB research. Existing studies in this field mainly focus on the micro levels of GBs, such as the research on GB delivery and performance optimization in GBs. Few studies concentrate on GBD and discuss GB activities from a macro perspective, such as the GB industry and the resource optimization for GB construction. Besides, only a few previous studies conducted the spatial investigation of GBD. Based on the economic geography theory, this study investigated GB economic activities through evaluations and CSF analysis from a spatial perspective. Furthermore, it explored the spatial correlations, contributing to the knowledge of GBs.

- It enriches GBD theory. This study proposes a theoretical research framework for measuring GBD from three aspects: the status, the efficiency and the correlations. The logic flow follows the thought that GBD needs to achieve the development in quantitative, then achieve the development in quality. Rich spatial correlations benefit GBD by enhancing the exchanges of GB experience and resources. In addition, it proposes an analysis framework for CSFs of GBD in different regions and compares the CSFs from a spatial perspective. The driving mechanism of GBD is explored based on the relationship between CSFs, which contributes to GBD theory.
- It applies new research methods in the GB field. This study optimizes the research methods in each part, promoting the progress of research methods in the GB area. In GBD evaluation, the entropy method is applied in the catastrophe progression model, aiming to objectively determine the importance of indicators. In the GBD efficiency assessment, the Super-SBM model is combined with window analysis to examine the dynamic efficiency that could be compared in different years. Moreover, the SNA method is applied in the research on spatial correlations of GBD, and meta-analysis is adopted to analyze the CSFs

of GBD, which are innovative in the GB field.

9.3.2 Practical Implications

This study also provides practical implications for GBD. First, the models help identify regions with unsatisfied GBD, including low GBD, efficiency and correlations. These regions affect the overall GBD. Identifying these regions will help the government to formulate targeted policies to improve the progress of low-development regions, thereby promoting the overall improvement of GBD. Secondly, this research explores the spatial pattern of GBD in mainland China, which benefits the government in understanding the current status of GBD from a spatial perspective and grasping the dynamic development patterns. Effective measures could be taken to narrow the spatial gaps of GBD, promoting the regional balance and regional coordination of GBD. Meanwhile, it benefits GB stakeholders to understand the local GB market and provide references for practitioners in investment decision-making, project bidding and other GB activities.

9.4 Limitations and Future Research

This study has some limitations which should be addressed and improved in future research. First, not all official data on GBs could be found after 2015. Although this study made great efforts to collect GB data from government websites, reports and databases, some data were still unavailable. This study applied mathematical models to process the missing data, including GM(1,1) model and LSTM model, but the accuracy of the results will be better if the data is available. In recent years, China has advocated establishing a unified GB information platform. The platform will provide the GB data and achieve the transparent management of buildings with GB labels. Therefore, future research will analyze GBD thoroughly based on the available data.

Second, this research conducted empirical studies on the provinces in mainland China, so the spatial scale is wide. Future research may consider investigating GBD patterns in different spatial scales, such as countries, cities and more microscopic spaces in the cities. It may lead to new analysis and hence shed new light on the GB knowledge. Comparing GBD in different countries benefits the understanding of the global trend of GBD. The GB spatial research in communities or cities helps formulate the planning and construction strategies for green communities or green cities, reflecting the extension of the GB concept, which is necessary to achieve sustainable cities.

Third, this study mainly constructed the driving mechanism of GBD with a theoretical framework. No mathematical models were applied to examine the driving mechanism. Future research may examine the driving mechanism using quantitative approaches based on the meta-analysis and questionnaire survey results, such as the system dynamics method and structural equation model.

Furthermore, to reduce carbon emissions significantly and achieve carbon neutrality, researchers could pay more attention to the operation stage of existing buildings, not the newly constructed buildings. Some existing buildings in China have been in service for many years. They complied with previous building standards, which may not meet new building energy requirements. The energy efficiency retrofitting of existing buildings is an urgent task, but organizing the retrofitting initiatives has many obstacles, such as the high cost, split incentives, and lack of policies. Moreover, new technologies and innovations can bring new opportunities to improve building energy retrofitting, which is a valuable topic for future research.

APPENDICES

Appendix A Green Building Rating Systems

Table A1. GB rating systems in various countries.

NO.	Continent	Countries	GB Standard
1	Europe	Finland	PromisE
2	Europe	France	Haute Qualité Environnementale (HQE)
3	Europe	Germany	Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB)
4	Europe	Italy	Protocollo Itaca
			GBC Home
			GBC Historic Building
			GBC Quartieri
			GBC Condomini
5	Europe	Portugal	Lider A
6	Europe	Spain	VERDE
7	Europe	United Kingdom	Building Research Establishment's Environmental Assessment Method (BREEAM)
8	Europe	Sweden	BREEAM-SE
			Citylab
			GreenBuilding
			Miljöbyggnad
9	Europe	Latvia	BREEAM-LV
10	Europe	Norway	BREEAM-NOR
11	Europe	Netherlands	BREEAM-NL
			DGBC Woonmerk
			GRESB
12	Europe	Denmark	Green Key
13	Europe	Ireland	Home Performance Index (HPI)
14	Europe	Switzerland	Swiss DGNB System
15	North America	United States	Leadership in Energy and Environmental Design (LEED)
			Green Globes
			ILFI Zero Energy and Zero Carbon
16	North America	Canada	BREEAM Canada

			LEED Canada
			Green Globes
17	South America	Brasil	Alta Qualidade Ambiental (AQUA)
			LEED Brasil
			GBC Brasil CASA
18	South America	Colombia	CASA Colombia
19	Asia	China	Evaluation Standard of Green Building (ESGB)
20	Asia	China (Hong Kong)	Built Environmental Assessment Method Plus (BEAM Plus)
21	Asia	China (Taiwan)	Ecology, Energy saving, Waste reduction and Health (EEWH)
22	Asia	Japan	Comprehensive Assessment System for Building Environmental Efficiency (CASBEE)
23	Asia	Israel	Israel Standard 5281 (IS-5281)
24	Asia	Singapore	Green Mark
25	Asia	Malaysia	Green building index (GBI)
26	Asia	Philippine	Building for Ecologically Responsive Design Excellence (BERDE)
27	Asia	India	LEED India
			Green Rating for Integrated Habitat Assessment (GRIHA)
			Indian Green Building Council (IGBC)
28	Asia	Indonesia	GREENSHIP
29	Asia	Turkey	Ecological and Sustainable Design in Buildings (B.E.S.T)
30	Asia	Sri Lanka	GreenSL
31	Asia	South Korea	Korea Green Building Certification (KGBC)
32	Asia	Pakistan	Pakistan Green Building Guideline (PGBG)
33	Asia	United Arab Emirates	PEARL (Abu Dhabi)
34	Oceania	Australia	Green Star
			National Australian Built Environment Rating System (NABERS)
35	Oceania	New Zealand	Green Star NZ
			Homestar
			NABERSNZ
36	Africa	South Africa	Green Star SA
			Excellence in Design for Greater Efficiencies (EDGE)
37	Africa	Kenya	Green Star SA Kenya

Appendix B Questionnaire

Dear Sir/Madam,

Invitation to participate in a survey on regional green building development

We humbly invite you to participate in a joint Ph.D. study between The Hong Kong Polytechnic University and Tongji University, entitled "Evaluation Models and Driving Mechanism of Green Building Development: A Spatial Perspective". This questionnaire survey aims to investigate the critical success factors of green building development in mainland China.

Please complete the questionnaire by ticking "✓" in "☐" based on your knowledge and your experience with green buildings. Be assured that all of the responses and information we collect will be kept in the strictest confidence and only used for academic purposes.

Thank you for your participation and your valuable time. If you have any questions, please email Ms. Linyan Chen at linyan.chen@______________.

Yours sincerely,

Linyan Chen (Ph.D. candidate)

Department of Building and Real Estate, Hong Kong Polytechnic University

School of Economics and Management, Tongji University.

Critical Success Factors of Green Building Development in Mainland China

Section A: Background Information of Participant

Q1. Which types of company do you work for? (Note: Single choice)

☐Construction company ☐Consultant company ☐Design company

☐Real estate company ☐Academic institution ☐Other (Please clarify):________

Q2. How long have you been working in the construction industry？(Note: Single choice)

☐Less than 1 year ☐1-3 years ☐3-8 years ☐Over 8 years

Q3. How long have you been working related to green buildings? (Note: If respondents choose "Never", the questionnaire jumps to the end.)

☐Never ☐Less than 1 year ☐1-3 years ☐3-5 years ☐5-8 years ☐Over 8 years

Q4. Which province are the locations of green building projects that you have worked for? (Note: Single choice or multiple choice)

☐Beijing ☐Tianjin ☐Hebei ☐Shanxi ☐Inner Mongolia ☐Liaoning ☐Jilin ☐Heilongjiang ☐Shanghai ☐Jiangsu ☐Zhejiang ☐Anhui ☐Fujian ☐Jiangxi ☐Shandong ☐Henan ☐Hubei ☐Hunan ☐Guangdong ☐Guangxi ☐Hainan ☐Chongqing ☐Sichuan ☐Guizhou ☐Yunnan ☐Shaanxi ☐Gansu ☐Qinghai ☐Ningxia ☐Xinjiang ☐Tibet

Q5.Which types of green building projects have you worked for? (Note: Single choice or multiple choices)

☐Residential buildings ☐Office buildings ☐Industrial buildings ☐Mixed function buildings ☐Other (Please clarify): __________

Section B: Critical Success factors of regional green building development in China

Please indicate the level of importance of each critical success factor of green building development based on your knowledge and your working experience. Use the following scale: **1 = not important; 2 = less important; 3 = neutral; 4 = important; 5 = very important**.

Code	Critical success factors	Level of importance				
		Strongly disagree	Disagree	Neutral	Agree	Strongly agree
CSF1	Adequate financial budget	☐1	☐2	☐3	☐4	☐5
CSF2	Low cost of green buildings	☐1	☐2	☐3	☐4	☐5
CSF3	Effective auditing programs	☐1	☐2	☐3	☐4	☐5
CSF4	Tax and fiscal incentives	☐1	☐2	☐3	☐4	☐5
CSF5	Cooperation between stakeholders	☐1	☐2	☐3	☐4	☐5
CSF6	Communication between stakeholders	☐1	☐2	☐3	☐4	☐5
CSF7	Early involvement of project participants	☐1	☐2	☐3	☐4	☐5
CSF8	Commitment of all project participants	☐1	☐2	☐3	☐4	☐5
CSF9	Skilled participants	☐1	☐2	☐3	☐4	☐5
CSF10	Experience in GBs	☐1	☐2	☐3	☐4	☐5
CSF11	Detailed plan	☐1	☐2	☐3	☐4	☐5
CSF12	Innovative management approaches	☐1	☐2	☐3	☐4	☐5
CSF13	Support from senior management	☐1	☐2	☐3	☐4	☐5
CSF14	Effective feedback and troubleshooting	☐1	☐2	☐3	☐4	☐5
CSF15	High motivation	☐1	☐2	☐3	☐4	☐5
CSF16	Integrated design	☐1	☐2	☐3	☐4	☐5

CSF17	Advanced machinery and equipment	☐1	☐2	☐3	☐4	☐5
CSF18	Available sustainable materials	☐1	☐2	☐3	☐4	☐5
CSF19	Innovative technological approaches	☐1	☐2	☐3	☐4	☐5
CSF20	Software application	☐1	☐2	☐3	☐4	☐5
CSF21	Available databases	☐1	☐2	☐3	☐4	☐5
CSF22	Training	☐1	☐2	☐3	☐4	☐5
CSF23	Knowledge	☐1	☐2	☐3	☐4	☐5
CSF24	Demonstration projects	☐1	☐2	☐3	☐4	☐5
CSF25	Adequate incentives	☐1	☐2	☐3	☐4	☐5
CSF26	Effective government policies	☐1	☐2	☐3	☐4	☐5
CSF27	Regulation support	☐1	☐2	☐3	☐4	☐5
CSF28	Mandatory requirements	☐1	☐2	☐3	☐4	☐5
CSF29	Legislation	☐1	☐2	☐3	☐4	☐5
CSF30	Comprehensive code and standard	☐1	☐2	☐3	☐4	☐5
CSF31	Research	☐1	☐2	☐3	☐4	☐5
CSF32	Innovation	☐1	☐2	☐3	☐4	☐5
CSF33	Industrialization	☐1	☐2	☐3	☐4	☐5
CSF34	Supply chain	☐1	☐2	☐3	☐4	☐5
CSF35	Obvious Economic benefit	☐1	☐2	☐3	☐4	☐5
CSF36	Short payback period	☐1	☐2	☐3	☐4	☐5
CSF37	Market demand	☐1	☐2	☐3	☐4	☐5
CSF38	Reputation	☐1	☐2	☐3	☐4	☐5
CSF39	Effective leadership	☐1	☐2	☐3	☐4	☐5
CSF40	Public awareness	☐1	☐2	☐3	☐4	☐5

Appendix C Spatial Correlation Matrix

Table C1. Spatial correlation matrix of GBD in 2008

Code	P1	P2	P3	P4	P5	P6	P7	P8	P9	P 10	P 11	P 12	P 13	P 14	P 15	P 16	P 17	P 18	P 19	P 20	P 21	P 22	P 23	P 24	P 25	P 26	P 27	P 28	P 29	P 30
P1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
P2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P9	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P10	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
P11	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P17	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P19	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
P20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

P29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Note: P1: Beijing; P2: Tianjin; P3: Hebei; P4: Shanxi; P5: Inner Mongolia; P6: Liaoning; P7: Jilin; P8: Heilongjiang; P9: Shanghai; P10: Jiangsu; P11: Zhejiang; P12: Anhui; P13: Fujian; P14: Jiangxi; P15: Shandong; P16: Henan; P17: Hubei; P18: Hunan; P19: Guangdong; P20: Guangxi; P21: Hainan; P22: Chongqing; P23: Sichuan; P24: Guizhou; P25: Yunnan; P26: Shaanxi; P27: Gansu; P28: Qinghai; P29: Ningxia; P30: Xinjiang

Table C2. Spatial correlation matrix of GBD in 2011

Code	P1	P2	P3	P4	P5	P6	P7	P8	P9	P 10	P 11	P 12	P 13	P 14	P 15	P 16	P 17	P 18	P 19	P 20	P 21	P 22	P 23	P 24	P 25	P 26	P 27	P 28	P 29	P 30
P1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P2	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P3	1	1	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P5	1	1	1	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
P6	1	1	1	0	0	0	1	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P7	1	1	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P8	1	1	0	0	0	1	1	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P9	0	0	1	0	0	0	0	0	0	1	1	1	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
P10	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
P11	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
P12	0	0	0	0	0	0	0	0	1	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P13	0	0	0	0	0	0	0	0	1	1	1	1	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
P14	1	0	0	0	0	0	0	0	1	1	1	0	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
P15	1	1	1	0	0	0	0	0	1	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P16	1	1	0	0	1	0	0	0	1	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P17	1	1	0	0	0	0	0	0	1	1	1	1	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
P18	1	1	0	0	0	0	0	0	1	1	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
P19	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0	0	1	1	0	1	0	0	1	0	0	0	0	0	0	0
P20	1	0	0	0	0	0	0	0	1	1	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
P21	1	0	0	0	0	0	0	0	1	1	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
P22	1	1	0	0	1	0	0	0	1	1	1	0	0	0	1	0	0	0	1	0	0	0	1	0	1	0	0	0	0	0
P23	1	1	0	0	0	0	0	0	1	1	1	0	0	0	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0

P24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P25	1	1	0	0	1	0	0	0	1	1	1	0	0	0	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
P26	1	1	0	0	1	0	0	0	1	1	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
P27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P29	1	1	0	0	1	0	0	0	1	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Note: P1: Beijing; P2: Tianjin; P3: Hebei; P4: Shanxi; P5: Inner Mongolia; P6: Liaoning; P7: Jilin; P8: Heilongjiang; P9: Shanghai; P10: Jiangsu; P11: Zhejiang; P12: Anhui; P13: Fujian; P14: Jiangxi; P15: Shandong; P16: Henan; P17: Hubei; P18: Hunan; P19: Guangdong; P20: Guangxi; P21: Hainan; P22: Chongqing; P23: Sichuan; P24: Guizhou; P25: Yunnan; P26: Shaanxi; P27: Gansu; P28: Qinghai; P29: Ningxia; P30: Xinjiang

Table C3. Spatial correlation matrix of GBD in 2014

Code	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20	P21	P22	P23	P24	P25	P26	P27	P28	P29	P30
P1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P2	0	0	1	1	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P3	1	1	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P4	1	1	0	0	1	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P5	1	1	1	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	1	0	0	0	1	0	0	0
P6	1	1	1	1	0	0	1	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P7	1	1	0	0	0	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P8	1	1	0	0	1	1	1	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P9	0	0	1	0	0	0	0	0	0	1	1	1	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
P10	0	0	1	0	0	0	0	0	0	0	0	1	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
P11	0	0	0	0	0	0	0	0	1	1	0	1	0	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
P12	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P13	0	0	0	0	0	0	0	0	1	1	0	1	0	1	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0
P14	1	1	0	0	0	0	0	0	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
P15	1	1	1	1	0	0	0	0	1	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P16	1	1	0	0	0	0	0	0	1	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P17	1	1	0	0	0	0	0	0	1	1	1	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P18	1	1	0	0	0	0	0	0	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0

P19	0	0	0	0	0	0	0	0	1	1	0	1	0	1		1	1	1	0	1	0	0	1	1	1	0	0	0	0	0
P20	1	1	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
P21	1	1	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
P22	1	1	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	1	0	0	0	1	1	1	0	0	0	0	0
P23	1	1	0	0	1	0	0	0	1	1	1	0	0	0	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
P24	1	1	0	0	0	0	0	0	1	1	1	0	1	0	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
P25	1	1	0	0	1	0	0	0	1	1	1	0	1	0	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
P26	1	1	0	0	0	0	0	0	1	1	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0
P27	1	1	0	0	1	1	0	0	1	1	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	1	0	1	0	0
P28	1	1	0	0	1	0	0	0	1	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
P29	1	1	0	0	1	0	0	0	1	1	1	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0
P30	1	1	0	0	1	1	0	0	1	1	1	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0

Note: P1: Beijing; P2: Tianjin; P3: Hebei; P4: Shanxi; P5: Inner Mongolia; P6: Liaoning; P7: Jilin; P8: Heilongjiang; P9: Shanghai; P10: Jiangsu; P11: Zhejiang; P12: Anhui; P13: Fujian; P14: Jiangxi; P15: Shandong; P16: Henan; P17: Hubei; P18: Hunan; P19: Guangdong; P20: Guangxi; P21: Hainan; P22: Chongqing; P23: Sichuan; P24: Guizhou; P25: Yunnan; P26: Shaanxi; P27: Gansu; P28: Qinghai; P29: Ningxia; P30: Xinjiang

Table C4. Spatial correlation matrix of GBD in 2017

Code	P1	P2	P3	P4	P5	P6	P7	P8	P9	P 10	P 11	P 12	P 13	P 14	P 15	P 16	P 17	P 18	P 19	P 20	P 21	P 22	P 23	P 24	P 25	P 26	P 27	P 28	P 29	P 30
P1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P2	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P3	1	1	0	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P4	1	1	0	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P5	1	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P6	1	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P7	1	1	0	0	0	1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P8	1	1	0	0	0	1	0	0	1	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P9	0	0	0	0	0	0	0	0	0	1	1	1	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
P10	0	0	0	0	0	0	0	0	1	0	1	1	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
P11	0	0	0	0	0	0	0	0	1	1	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P12	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P13	0	0	1	0	0	0	0	0	1	0	0	1	0	1	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0

P14	1	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
P15	1	0	1	0	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P16	1	0	0	0	0	0	0	0	1	1	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
P17	1	0	0	0	0	0	0	0	1	1	1	1	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
P18	1	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
P19	1	0	0	0	0	0	0	0	1	1	0	1	0	1	0	1	0	1	0	1	0	0	0	1	0	0	0	0	0	0
P20	1	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0
P21	1	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0
P22	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1	0	0	0	0	0
P23	1	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
P24	1	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0
P25	1	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0
P26	1	0	0	0	0	0	0	0	1	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0
P27	1	1	0	0	1	0	0	0	1	1	1	0	1	0	1	0	1	0	0	0	0	1	1	0	0	1	0	0	0	0
P28	1	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
P29	1	1	0	0	1	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0
P30	1	1	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Note: P1: Beijing; P2: Tianjin; P3: Hebei; P4: Shanxi; P5: Inner Mongolia; P6: Liaoning; P7: Jilin; P8: Heilongjiang; P9: Shanghai; P10: Jiangsu; P11: Zhejiang; P12: Anhui; P13: Fujian; P14: Jiangxi; P15: Shandong; P16: Henan; P17: Hubei; P18: Hunan; P19: Guangdong; P20: Guangxi; P21: Hainan; P22: Chongqing; P23: Sichuan; P24: Guizhou; P25: Yunnan; P26: Shaanxi; P27: Gansu; P28: Qinghai; P29: Ningxia; P30: Xinjiang

Table C5. Spatial correlation matrix of GBD in 2020

Code	P1	P2	P3	P4	P5	P6	P7	P8	P9	P 10	P 11	P 12	P 13	P 14	P 15	P 16	P 17	P 18	P 19	P 20	P 21	P 22	P 23	P 24	P 25	P 26	P 27	P 28	P 29	P 30
P1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P2	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P3	1	1	0	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P4	1	1	0	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P5	1	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P6	1	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P7	1	1	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P8	1	1	0	0	0	1	0	0	1	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

P9	0	0	0	0	0	0	0	0	0	1	1	1	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
P10	0	0	0	0	0	0	0	0	1	0	1	1	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
P11	0	0	0	0	0	0	0	0	1	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P12	1	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P13	0	0	1	0	0	0	0	0	1	0	0	1	0	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0
P14	1	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
P15	1	0	1	0	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P16	1	0	0	0	0	0	0	0	1	1	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
P17	1	0	0	0	0	0	0	0	1	1	1	1	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
P18	1	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
P19	1	0	0	0	0	0	0	0	1	1	0	0	0	1	0	1	0	1	0	1	0	0	0	1	0	0	0	0	0	0
P20	1	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
P21	1	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0
P22	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0	1	0	0	1	1	1	0	0	0	0	0
P23	1	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
P24	1	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0
P25	1	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0
P26	1	0	0	0	0	0	0	0	1	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0
P27	1	0	0	0	1	0	0	0	1	1	1	0	1	0	1	0	1	0	0	0	0	1	1	0	0	1	0	0	0	0
P28	1	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0
P29	1	1	0	0	1	0	0	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
P30	1	1	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Note: P1: Beijing; P2: Tianjin; P3: Hebei; P4: Shanxi; P5: Inner Mongolia; P6: Liaoning; P7: Jilin; P8: Heilongjiang; P9: Shanghai; P10: Jiangsu; P11: Zhejiang; P12: Anhui; P13: Fujian; P14: Jiangxi; P15: Shandong; P16: Henan; P17: Hubei; P18: Hunan; P19: Guangdong; P20: Guangxi; P21: Hainan; P22: Chongqing; P23: Sichuan; P24: Guizhou; P25: Yunnan; P26: Shaanxi; P27: Gansu; P28: Qinghai; P29: Ningxia; P30: Xinjiang

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