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FOREFRONT PERSPECTIVE

Green building research from design to operation in the past 20 years: A perspective

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The natural resources consumption has reached unprecedented levels during the past centuries. Along with the rapid urbanization crossing the world, serious environmental and energy issues have become global challenges. To address these challenges, the promotion of green building is critical because the construction industry consumes about 40% of the total energy and accounts for 30% of the total greenhouse gas emissions. The goals of green buildings is twofold: 1) enhancing indoor environmental quality (IEQ), promoting human health and productivity; 2) conserving energy, limiting pollutants and carbon dioxide emissions. Determining how to create a comfortable and healthy indoor environment while minimizing the environmental cost is the major research question for green building research. Three major principles have been proposed and used for the selection and optimization of green building technology systems: 1) local condition adaptation, 2) passive technologies first and 3) active energy efficiency optimization. Local condition adaptation, means the design of green building should consider the local conditions, including but not limited to local climate, site environment, resources, economy and culture to optimize the building planning and design. The passive technologies first refers to the construction of a built environment, through reasonable design of space and structure, natural ventilation, natural lighting and other passive technologies, green building could consume no or less energy. The active energy efficiency optimization applies supplemented and deepened technology to ensure the use of building functions throughout the year, when the passive design is not adequate to meet the indoor conditions.

The green construction projects have grown significantly in the past 20 years. The World Green Building Council announced that over 63000 projects were certificated with the Leadership in Energy and Environment Design (LEED) in 2018. At the same time, total floor areas of green constructions in China have exceeded 1 billion m^2; more than 13000 construction projects were certificated as green building in China, accounting for over 50% of the new civil buildings in urban areas [1]. The "World Green Building Trends" survey indicates a continued increase in green construction projects worldwide. Nearly half of the 2000 industry stakeholders surveyed believe that more than 60% of construction projects will be green buildings by 2021 [2].

With the growth of green construction projects, more and more attention has been attracted to the research of "Green Building". This trend can be illustrated by a literature search using the Web of Science platform. We used "Green building" as the keyword, and identified 1095 articles in the preliminary screening. We analyzed the searching result based on the publication year and country. The number of articles published in 2019 reached 106, which is 50 times more than that in 2001, indicating a continued increase of the research interests. Figure 1 shows the number of articles published in each country.

The design methods and construction technologies are key research focuses of existing studies on green building. We analyzed the publications between 2013 and 2018 of green building design methods based on the whole life cycle and their citation. The top five countries with

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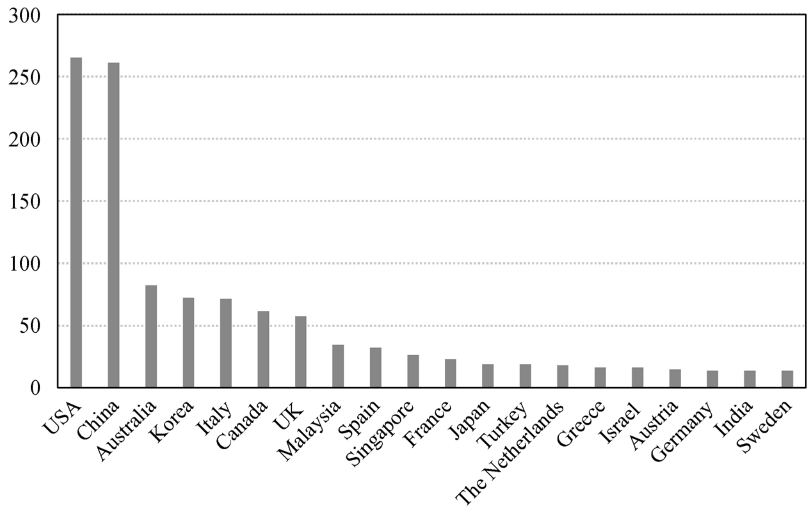

Fig. 1 Distribution of the number of green building research articles in various countries.

publications of this field are China, the USA, Australia, Italy, and the UK (Table 1). The top five countries cited the most are China, Spain, the USA, Australia, and Switzerland. Among them, Chinese authors published 22.83% of articles with 63.36 times cited per article, which is one of the top countries in the development of research in this filed. Figure 2 shows the cooperation network between the countries/regions. The overall cooperation between countries is limited, but cooperation between China and Australia is relatively frequent. According to the main organizations with the publications in this field (Table 2), the top five organizations are the Hong Kong Polytechnic University, the National University of Singapore, Chongqing University, City University of Hong Kong, and the University of Melbourne. The cooperation networks in Fig. 3 shows that domestic cooperation between different organizations is much more frequent than international one. Tables 3 and 4 present the main countries/regions and organizations that cite the publications, of which China reached the highest ranking in the quantities of published papers and the citing papers. This indicates that Chinese scholars have kept close attention and tracking on the research dynamics of this frontier.

This paper reviews the global studies of green buildings from the following aspects: database of buildings in life cycle, evaluation standard, performance simulation and optimization tool, pattern for building indoor environment creation, and performance monitoring and optimization. These are all hot and advanced topics of green building in research and practice in the past 20 years. The aim of this study is to critically and comprehensively review the latest challenges and trends.

1 Database of buildings in life cycle

Since the first building life cycle assessment (LCA) model was proposed in 1997 [3], researchers from different countries (Indonesia, Sweden, Spain, Italy, Japan, Australia, China, and the USA have started to explore green building performance (and/or carbon emissions) from LCA perspective. With the establishment of carbon trading

Table 1 The main counties/regions with publications on the green building design methods based on the whole life cycle

no.	country/region	quantity	ratio of quantity	times cited	ratio of times cited	citations per paper
1	China	42	22.83%	2661	35.76%	63.36
2	USA	27	14.67%	1331	17.89%	49.30
3	Australia	25	13.59%	1130	15.18%	45.20
4	Italy	15	8.15%	394	5.29%	26.27
5	UK	14	7.61%	398	5.35%	28.43
6	Singapore	10	5.43%	224	3.01%	22.40
7	Spain	9	4.89%	556	7.47%	61.78
8	Switzerland	9	4.89%	372	5.00%	41.33
9	Norway	9	4.89%	209	2.81%	23.22
10	Germany	8	4.35%	244	3.28%	30.50

Table 2 The main organizations with publications on the green building design methods based on the whole life cycle

no.	institution	quantity	ratio of quantity	T	ratio of times cited	citations per paper
1	Hong Kong Polytechnic University	18	9.78%	1021	13.72%	56.72
2	National University of Singapore	8	4.35%	205	2.75%	25.63
3	Chongqing University	7	3.80%	279	3.75%	39.86
4	City University of Hong Kong	5	2.72%	756	10.16%	151.20
5	the University of Melbourne	5	2.72%	186	2.50%	37.20
6	Central Queensland University	5	2.72%	163	2.19%	32.60
7	University of Perugia	4	2.17%	255	3.43%	63.75
8	Norwegian University of Science and Technology	4	2.17%	134	1.80%	33.50
9	Yonsei University	4	2.17%	124	1.67%	31.00
10	Swiss Fed Inst Technol	4	2.17%	94	1.26%	23.50

Fig. 2 Cooperation network between the top ten countries/regions with publications of the green building design methods based on the whole life cycle.

mechanism, countries and regions have developed their own life cycle databases of building materials, to name a few, ECO-QUANTUM in the Netherlands, Simapro in Denmark, TEAM in Canada, CASBEE in Japan, Gabi in Germany, Athena in Canada, and local database by Tsinghua University, Beijing University of technology, Zhejiang University, Sichuan University. The most commonly used database named as Ecoinvent inventory database has been constructed by Swiss government and scientific research institutions since 2000, which includes energy, materials, waste management, transportation, electronics, metal technology, etc.

2 Evaluation standard

Current green building design is mainly carried out under the guidance of green building evaluation standards. With the development of green buildings in various countries, countries have also explored their own green building evaluation standard, such as LEED launched in 1997 in the USA, BRE Environmental Assessment Method (BREEAM) launched in 1990 in the UK, Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) in Germany, Comprehensive Assessment System for Built Environment Efficiency (CASBEE) in Japan, and Green Building

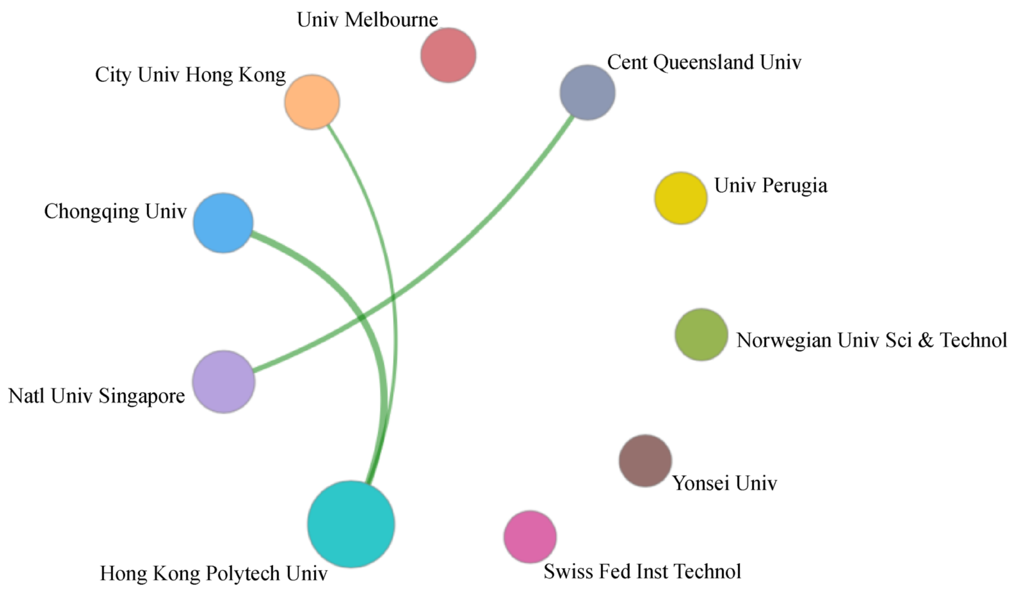

Fig. 3 Cooperation network between the top ten organizations with publications of the green building design methods based on the whole life cycle.

Table 3 The main counties/regions citing publications on the green building methods based on the whole life cycle

no.	country/region	citing quantity	ratio of citing quantity	mean year
1	China	1429	28.43%	2017.4
2	USA	766	15.24%	2017.0
3	UK	518	10.31%	2017.1
4	Australia	502	9.99%	2017.1
5	Italy	471	9.37%	2016.9
6	Spain	333	6.63%	2017.1
7	Germany	235	4.68%	2017.2
8	Canada	205	4.08%	2017.4
9	South Korea	201	4.00%	2017.1
10	France	195	3.88%	2016.8

Table 4 The main organizations citing core publications on the green building design methods based on the whole life cycle

no.	institution	citing quantity	ratio of citing quantity	mean year
1	Hong Kong Polytechnic University	208	21.73%	2017.3
2	Tsinghua University	104	10.87%	2017.6
3	Chongqing University	94	9.82%	2017.5
4	Chinese Academy of Sciences	81	8.46%	2017.2
5	National University of Singapore	78	8.15%	2017.2
6	City University of Hong Kong	71	7.42%	2016.4
7	Tongji University	67	7.00%	2017.4
8	Yonsei University	66	6.90%	2016.4
9	Shenzhen University	66	6.90%	2017.3
10	University of Perugia	61	6.37%	2016.3

Evaluation Standard in China, etc. Another significant trend in the past decades is health has gradually become an important theme in green buildings. For example, the World Health Organization (WHO) has established "15 standards for healthy housing". Different countries have developed their own system to achieve the health targets. The United States has set up a national healthy housing center and guided the housing construction with the "healthy home" construction plan, and lunched the building standard certification "WELL". France has developed healthy housing by means of legislation and policy support. Canada will issue E certificate to housings whichever could meet the requirement in both health and energy conservation. Japan has published the book "Declaration of healthy residence" to guide the construction and development of residential buildings. In China, the healthy building evaluation standard was issued in 2018, as well as more health provisions included in the revised Green Building Evaluation Standard (published in 2019). Overall, the trend of standard development demonstrates the focus on the relationship between the building and its occupancies, by integrating the evaluation indexes of air, water, nutrition, light, fitness, comfort, and spirit into a set of standard system.

3 Building performance simulation and optimization tool

Studies and projects have shown that the scheme design phase demonstrates the greatest optimization and improvement potential of building performance scheme design phase. One simulation study demonstrated that more than 40% of energy saving potential exists in the building scheme design phrase (IEA ANNEX-30 Bring Simulation to Application) [4]. A survey of 67 European buildings showed that, among the 303 green building technologies studied in the survey, 57% of them need to be implemented in the scheme design phrase [5].

However, there is still a lack of methods, algorithms, and tools to support the performance optimization effectively in the scheme design phase. Based on five evaluation indicators (usability, intelligence, interoperability, process adaptability and accuracy), Attia and Herde [6] have compared 10 commonly used building performance simulation tools. The results indicate that the current building performance simulation tools are mainly assessment-oriented and cannot provide the real-time and dynamic decision-making support in the scheme design phase. Østergård et al. [7] summarize the barriers impeding the application of building simulation and analysis technology in the scheme design phase, including time-consuming modeling process, rapid changes of design idea, and uncertainty of input parameters. The demand of supporting real-time design decision-making is seriously ignored in most current building performance optimization design tools [6]. This cannot provide architects with fast and flexible building performance analysis capabilities.

4 Pattern for building indoor environment creation

The indoor environment usually includes four aspects: thermal (air temperature, relative humidity, radiation temperature, wind speed, etc.), acoustic (sound intensity, sound pressure, etc.), light (illumination, brightness, etc.) and air quality (CO_2, formaldehyde, VOC, particulates, etc.). Among them, the creation of thermal environment is the biggest challenges for the consideration of human comfort as well as energy saving.

Determining the appropriate indoor temperature and humidity parameters to ensure the thermal comfort of personnel is often considered as the first task of creating a comfortable indoor thermal environment. Based on heat balance model and subject tests, Fanger [8] proposed the index of PMV to predict average thermal sensation, which has been widely adopted by international thermal comfort standards. Recently, a large amount of field survey data shows that the PMV predicted value deviates greatly from the actual thermal sensation in a non-neutral case, and the prediction accuracy is low [9]. As an alternative approach, the thermal adaptation models have been established since 1990s with the consideration of regional differences in climate, geography, and culture [10]. It emphasizes the relationship between people and the environment, and brings the benefits of comfort indoor environment and energy consumption reduction.

In recent years, many researchers have conducted studies on building envelopes from the aspects of material properties, structural forms, and applicability. This is to promote the performance of building envelopes to improve the indoor lighting and thermal environment of the building and its energy consumption reduction.

The glass modification processes have been adopted in many studies to reduce solar radiation heat transmission by increasing the glass's ability to absorb or reflect solar thermal radiation, such as online or offline coating films to develop heat-absorbing glass, and developed thermal reflective glass, low-e glass and other high-performance glass. To improve the thermal insulation capacity of the non-transparent envelope structures, researchers have developed new thermal insulation materials such as vacuum insulation panels, aerogel panels, aerogel foam concrete and evaluated the moisture absorption of various materials, freeze-thaw, refractory. The energy-saving envelope structure has also been developed by various technologies, i.e., change heat storage based on phase, heat-exchange-enhanced wall based on embedded water pipes and heat pipes, passive evaporative cooling of roofs with roof rainwater, and the ideal energy-saving envelope structure concept, the method of wall thermal resistance and heat capacity distribution.

Over the last few years, some researchers have applied new active cooling and heating technologies to building envelopes, such as installing thermoelectric materials in the envelope. For example, installing sky radiant cooling materials on the roof uses the natural low temperature cold source of outer space to actively cool the building. It cannot only reduce the thermal load of the envelope, but also provide active heating and cooling. These new active cooling and heating technologies have strengthened the functions of the building envelope, but further research is necessary.

It has been found that the centralized air conditioning systems widely used in practice could cause various problems, such as low efficiency of heating and cooling sources, high energy consumption of system transmission and distribution, high quality and low utilization, and offset of cold and heat. Recently, studies have focused on excluding heat and humidity sources of different temperature grades and heat in the room to find suitable thermal-humid environments to meet the demand. The independent temperature and humidity control systems were proposed for cooling and dehumidification. Based on these studies, new indoor environment creation methods were explored, such as the corresponding indoor terminal method and air humidity treatment device. The methods have become an important measure to assess the adaption of local conditions in the process of creating indoor thermal-humid environments, which make full use of natural cooling sources and use various effective heat recovery methods.

5 Monitoring and optimization

Collecting comprehensive, real, and reliable building operational data are essential for green buildings' research and the premise, when analyzing the characteristics of the operational performance. There are several test methods and standards, regarding how to collect the operational performance data of buildings. For example, American Society of Heating Refrigerating and Air-conditioning Engineer (ASHRAE)/Chartered Institution of Building Services Engineers (CIBSE)/ United States Green Building Council (USGBC) in the USA has published Performance Measurement Protocols (PMP) for commercial buildings [11]. The test method has been categorized into three levels according to the monitoring cost and level of precision: beginner, intermediate, and advanced.

To collect various environmental parameters in field studies, large amount of expensive measuring instruments were utilized. Often instruments are limited to test only one or several physical parameters. Although this method can solve the problem of simultaneous acquisition of multiple parameters, it will bring many difficulties and inconveniences in practice. This results in complicated equipment system with high cost, not to mention the waste of time and human resources. Recently, the methods and tools of indoor environment measurement have also made great progress due to the development of the Internet of Things, wireless sensing and other technologies.

The integrated design of multiple environmental parameter sensors reduces the cost and volume of the device significantly, which simplifies the on-site implementation [12]. Meanwhile, the wireless transmission technologies such as Zigbee, Wi-Fi, 3G/4G, provide cloud service for real time environmental data analysis. The data can be viewed online and downloaded remotely, which enhance the efficiency of long-term monitoring [13]. In addition, occupants' satisfaction surveys in green buildings have been conducted along with the measurements of physical environment. Some existing efforts include the Building Use Studies Occupant Survey (BUS), Cost-effective Open-Plan Environments Project (COPE), and Occupant Feedback Tools of the Office Productivity Network (OPN) in the UK; Centre for the Built Environment survey (CBE) and Building Assessment Survey and Evaluation (BASE) in the USA; Health Optimization Protocol for Energy-efficient Buildings (HOPE) in Europe.

Through analyzing large amounts of data, two similar conclusions have been drawn. First, there is a huge gap between the actual energy consumption and the designed value of green buildings. The energy consumption conservation of some green buildings is less than expected in the design stage. Second, there is a lack of research and limited data sets on the objective measurement of indoor environment parameters for green buildings. The correlation between subjective and objective data of the indoor environment of green buildings needs more analysis.

6 Summary

The promotion and development of green buildings provides a promising solution to the current energy and environmental challenges we are facing. In the recent years, the focus of green buildings has shifted from "quantitative improvement" to "occupant-oriented" "qualitative improvement". Meanwhile, the advancement of information technology, energy and materials has created cutting-edge tools for planning, design, construction, operation and maintenance of green buildings. In this paper, we have identified several trends and urgent needs for the future development of green buildings. It includes the new method of cross-disciplinary whole life cycle collaborative design from monomer to urban scale, AI-assisted optimization design, performance-oriented digital design, healthy building/smart building design, active and passive integrated equipment terminal design and development and application of new materials, etc.

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