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Review

Challenges and Future Development Paths of Low Carbon Building Design: A Review

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Abstract: Excessive carbon emissions are causing the problems of global warming and the greenhouse effect, which urgently need to be controlled worldwide. It is crucial to reduce the carbon emissions of the construction industry as it is one of the main sources. Carbon is generated at all phases of the building life cycle, including in material production, building design, and building operation and maintenance. Notably, building design has various extents of influence on carbon emissions at each phase, for which a low carbon method urgently needs to be explored. This paper aims to summarize the current status of building design through literature review considering standard systems, carbon emission calculations, and building design optimization. The challenges of building design are as follows: lack of (1) a comprehensive standard system considering different factors, (2) lack of a carbon emission calculation method for the design phase, and a (3) no real-time optimization model aiming at carbon reduction. The path of "standard−calculation−prediction−optimization" (SCPO) for future building design is proposed to address these challenges. It takes standard system as the framework, the carbon calculation method as the foundation, the prediction model as the theory, and the low carbon building as the objective. This paper can provide theoretical guidance for low carbon building design.

Keywords: low carbon building; building design; standard system; carbon emission calculation; building factor optimization

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1. Introduction

Increased fossil fuel combustion and the exploitation of finite resources are causing excessive carbon emissions, further resulting in global warming and the greenhouse effect [1,2]. If the atmospheric CO_2 doubles, the global average temperature will rise by about 3 °C [2]. It is predicted that the increase in global temperature could reach at least 1.5 °C or more by 2030–2052 due to carbon emissions [3]. Countries around the world urgently need to control carbon emissions. In 2015, the Paris Agreement was negotiated. Almost all countries and regions have pronounced low carbon emission policies [4,5]. The European Union has set a goal of achieving carbon neutrality by 2050 [4]. China is the largest carbon emitter in the world, with carbon emissions already reaching 10.251 billion tons in 2020 [6]. In response, the president of China first committed at the 75th UN General Assembly to achieve the goal of carbon peaking by 2030 and carbon neutrality by 2060 [7]. Reducing carbon emissions has become an urgent issue worldwide.

The report from the Intergovernmental Panel on Climate Change (IPCC) stated that industry, buildings, and transportation are the main sources of carbon emissions. Reducing building carbon emissions, which account for almost 40% of the total carbon emissions globally, is the key to achieving carbon peaking and neutrality [8]. The global building stock is on the rise annually. Taking Norway as an example, the building stock is predicted to increase to 448 million m^2 in 2050, which is about 20 % compared to 2020 [9]. China has about 2 billion m^2 of new construction annually, which accounts for almost 50% of the world's total [10]. It is expected that 800 million m^2 of new urban residential buildings will be built in per year by 2030 [11]. Thus, it is undoubtedly a major challenge to reduce carbon emissions in the building sector in order to achieve the goal of carbon neutrality.

Strategies have been developed in several countries and regions in order to achieve the goal of zero carbon, largely by reducing the carbon emissions from buildings [12]. The main principles are as follows: (1) making full use of renewable energy to reduce the embedded carbon emissions from the production of building materials, to building construction, to the completion phase; (2) using renewable energy and advanced energy-saving technologies to reduce the carbon emissions in the operation phase; and (3) the remaining carbon can be neutralized by means of carbon sinks or compensated carbon, in order to finally achieve the goal of low carbon building [12]. To this end, the carbon emission process of the life cycle of the building should be fully comprehended. As can been seen in Figure 1, there are seven phases in the whole life cycle, including building material production, building transportation, building design, building construction, building operation and maintenance [13], building renewal, and building demolition. Embedded carbon is generated in the phases of building material production, transportation, construction, and demolition [14], while the carbon generated in the phases of operation and maintenance is operational carbon [15,16]. The carbon emissions from building construction and operation can be up to 40% of the global total emissions [17]. Of the phases of the building life cycle, taking office buildings as an example, building operation and maintenance generates about 66% of the operational carbon, with about 27% of embedded carbon generated in the material production, transportation, and construction, and at least 7% of carbon emissions generated in the other phases [18]. This phenomenon means that each phase of the building life cycle has a diverse impact on carbon emissions.

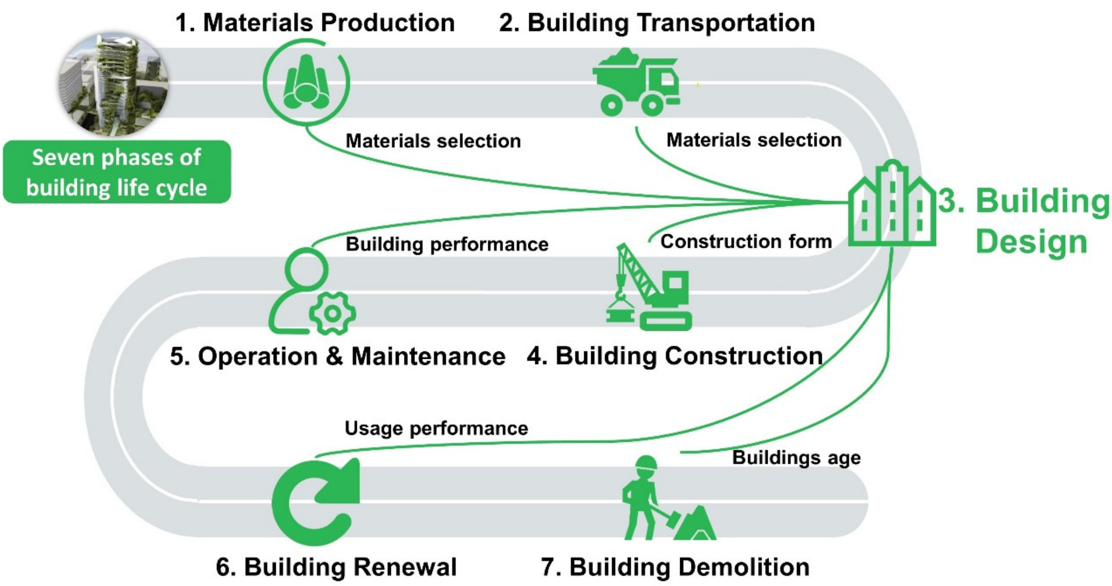

Figure 1. Seven phases of the building life cycle.

It is important to note that building design affects carbon emissions in all phases of the building life cycle to variable extents [19]. Figure 1 clearly depicts that the building design phase can determine the form of the building envelope, material selection, etc., which directly affects the carbon emits in the phases of building material production and building transportation, etc. [20]. The design of air conditioning and ventilation systems in the building operation and maintenance, and building renewal phases are based on the finalized building morphology [21]. More seriously, if the building performance is optimized by active technology or retrofitting, such as adding insulation facilities or retrofitting the original operation system [22,23], the embedded carbon emission of the building could be increased [24]. Thus, low carbon building design is crucial to reduce carbon emissions throughout the building life cycle.

At present, scholars from all over the world have fully recognized and conducted in-depth research about the impact of building design on carbon emissions [25], such as building design models and tools [26], optimization of the building design factors [27], and passive and active coupling design [28]. There are many challenges for low carbon building design in the actual application because of the complex building environment. This paper aims to summarize the current status of low carbon building design through literature analysis, and to discuss the challenges and possible developments for the future. Section 2 is the methodology of this work. Section 3 is the current status and challenges regarding research on low carbon building design. Section 4 is possible future work of low carbon building design. Section 5 is the main conclusion. This paper aims to have a guiding effect on low carbon building design.

2. Methodology

Literature research is the main method used in this work. Firstly, the keywords of "low carbon, carbon emission, building design, embodied carbon, operation carbon, and energy saving" were searched in academic databases (i.e., ScienceDirect and Web of Science). Secondly, more relevant literature was uncovered by further searching the cited reference of the review articles. Finally, screening the literature was done according to the following three main criteria: (a) The selected publications should cover one or more of the issues related to building design, such as building form, building performance, building energy use, and building optimization. (b) The selected journals focus on the scopes of buildings, cities, building design, built environment, built engineering, etc. (c) The selected publications should be limited to the last ten years, with a focus on the relevant results from the last three to five years.

After literature screening, the traditional building design was introduced, as follows: the current status and future challenges of the possible low carbon building design path were analyzed, mainly including low carbon standards, carbon emission calculation methods, and building optimization design. The proposed low carbon building design path was summarized as well as the implementation methods of traditional building design.

3. The Status and Challenges of Low Carbon Building Design

3.1. The Traditional Building Design Process

Figure 2 illustrates the traditional process of building design, namely conceptual design, preliminary design, development design, and detailed design [29]. Conceptual design is a design concept jointly negotiated by the architect and the project client [21], which can confirm the building type, volume, functions, and main structural systems. The preliminary design details the content of the conceptual design, such as the layout of the building group, building envelope, structural system, acoustical environment, luminous environment, and air conditioning system. Development design, as a phase to supplement the preliminary design content, mainly covers detailed drawings of the building envelope, detailed layouts of the building, selection of building materials, detailed layouts of the air conditioning and ventilation system [30], detailed electrical systems, and fire safety. Detailed design is the last phase, in which the development phase design is optimized in detail using simulation software [29].

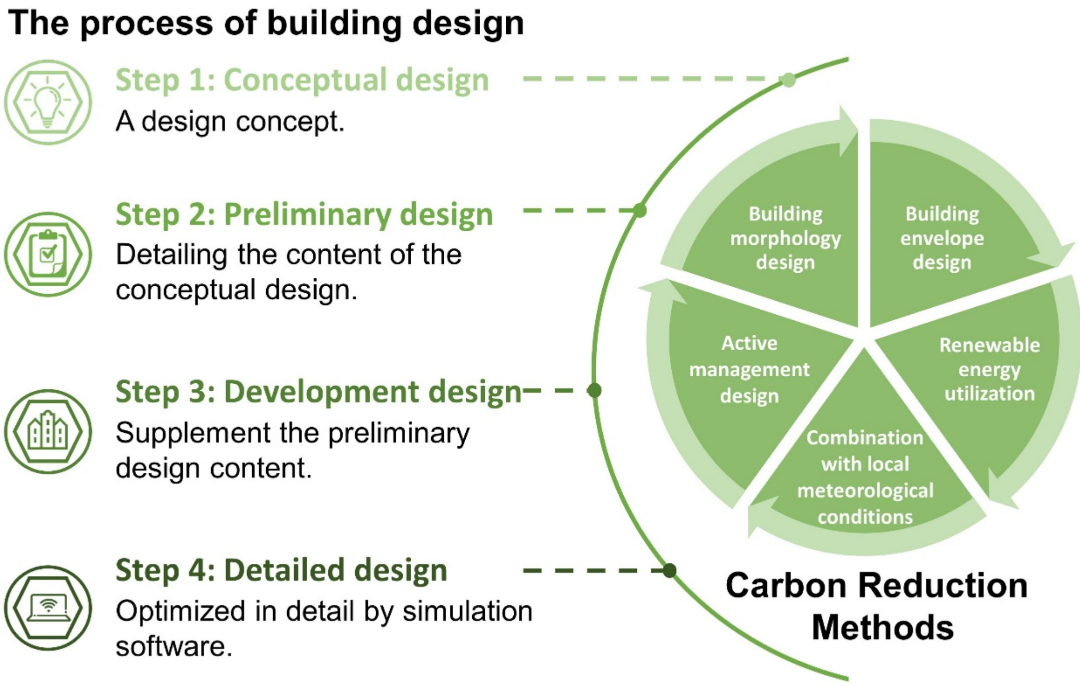

Figure 2. The process of building design and methods of carbon reduction.

It is necessary to carry out a low carbon design system in the mentioned design process, aimed at low building carbon emissions.

(1) Low carbon design standards are needed to provide constraints in the conceptual design phase, such as renewable energy utilization [31–33] and local meteorological conditions [34,35]. The local climate type, dominant wind direction and speed, solar radiation, and other meteorological conditions should be taken into account, as well as local renewable energy sources such as wind, solar, geothermal, and biomass energy.
(2) In the preliminary and development design phases, carbon emission calculation methods are needed to compare the carbon emissions of different design alternatives. Building carbon emissions are needed to calculate, in real-time, when the design of building morphology (i.e., the block-scale building height, layout, density, green space ratio, building area, and volume and orientation of an individual building [36–39]) and building envelope (i.e., roof, external wall, internal wall, window-to-wall ratio, and shading [40–42]) should be changed.
(3) It is necessary for active regulation of low carbon optimization design in the detailed design phase, such as for air conditioning systems [43], lighting systems [44], etc.

Thus, the standard system, carbon emission calculation, and optimal design should be integrated into the building design process, considering the five carbon reduction methods of building morphology design, building envelope design, renewable energy utilization, combination with local meteorological conditions, and active management design (shown in Figure 2) [26]. The status and challenges of the standard system, carbon calculation, and optimal design are discussed as follows.

3.2. The Status of Low Carbon Building Design

As shown in Figure 3, this paper describes the status of low carbon building design from three aspects, namely (1) the standard system of low carbon building design, (2) the calculation methods of carbon emissions, and (3) the optimal building design.

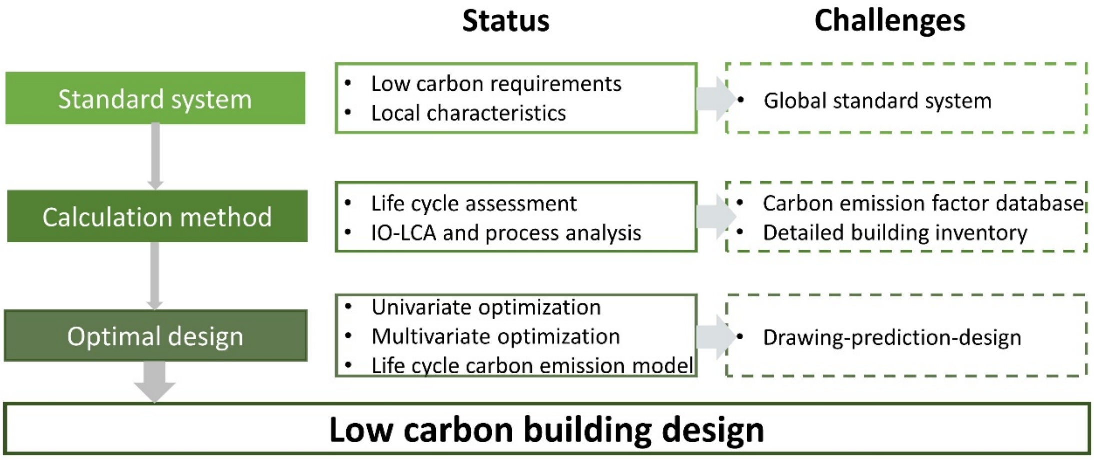

Figure 3. The statues and challenges of low carbon building design.

(1) The standard system of low carbon building design: Developed countries in North Europe and North America established related policies at an early stage, and have built numerous low-carbon buildings. Europe formulated the European Energy Technology Strategic Plan in 2008 [45]. The United States developed the Leadership in Energy and Environmental Design (LEED) [46]. These countries have been leading in the field of green and low carbon buildings, and are further exploring new technologies and new routes for "zero energy and zero carbon" buildings. Green buildings with a low energy consumption and high comfort are emerging gradually.

China's Ministry of Housing and Urban−Rural Development released the national standard "General Specification for Building Energy Efficiency and Renewable Energy Utilization" to make the calculation of building carbon emissions aiming at "carbon peaking and carbon neutral" a mandatory demand [47]. "The announcement on the issuance of the implementation plan for the in-depth development of green low-carbon leading action for public institutions to promote carbon peaking" states that the promotion of ultra-low energy buildings and low-carbon buildings should be accelerated and green buildings should be developed. Solar photovoltaic photothermic systems should be vigorously promoted. Photoelectric high-efficiency photovoltaic power generation facilities should be installed, making full use of the suitable site space, such as on building roofs and facades [48].

Several provinces and cities in China have put forward relevant development plans for low-carbon building design successively. In Shanghai, it is suggested that assembled buildings should be developed as ultra-low energy buildings, which advocate for the use of exterior wall insulation, high-performance exterior windows, and related technological innovation [49]. Sichuan Province encourages the establishment of a building energy-saving system in accordance with the local climate, humanities, and natural resources [50,51], while Yunnan Province mentions similar suggestion [52]. The Chongqing government has a standard and management system for ultra-low energy consumption buildings, further providing technical support for projects in the design and construction phases [53].

Currently, there are timely development requirements for low carbon building design in all regions. The building design is a complex issue influenced by climate, humanities, economy, culture, and other factors [54,55]. The standard system of low-carbon building design should be improved.

(2) The calculation methods of carbon emissions: Embedded carbon emissions and operational carbon emissions are generated in the life cycle of a building. In the "Standard for building carbon emission calculation" (GB/T 51366-2019) [56], the operational carbon emission calculation is determined based on the amount of different types of energy consumption and the carbon emission factors. Simulation software, such as Energy Plus, eQuest, and TRNSYS [26,40], are used as tools to calculate energy consumption. For the embedded carbon emission, life cycle assessment (LCA) is an internationally and nationally

acknowledged method [24,57–59]. Based on LCA, the input−output analysis (IO-LCA) method is widely used around the world [60–62]. It can calculate industry-wide carbon emissions by using economic input and output data, without the ability to perform specific calculations and analyses during the detailed building processes. The process analysis method [63] can overcome the limitations of IO-LCA by means of carbon emission factors for each phase, which can calculate the carbon emissions from the material production, transportation, construction, operation, disassembly, and recycling of buildings [58,59]. Specifically, the detailed process inventory for each phase is necessary for the process analysis method.

Carbon emission factors are an essential part of the calculation of embedded and operational carbon. IPCC provides a basic database of carbon emission factors. The database cannot be entirely suitable for all buildings, owing to the complex and diverse building types [64]. To be specific, more building forms and composites are gradually being proposed to meet the growing needs of high-rise buildings, resulting in carbon emission factors needing to be updated [18]. Moreover, the sources of carbon emission factors are not uniform, including the basic databases, literature, and standards [65,66]. This is an urgent issue that needs to be solved for the establishment of a standardized and comprehensive carbon emission factor database for low carbon building design.

A detailed building inventory is also crucial for the calculation, without carbon emission factors. As the building inventory information can be commonly obtained from engineering drawings, less detailed information is available on the conceptual and preliminary design phases of building design [67]. Therefore, the carbon emission calculation method should also consider the life cycle process with less inventory information [68].

(3) The optimal building design: There are three types of the optimization of low carbon building design. The first one is to investigate the impact of different factors in building design on carbon emission or energy saving (univariate optimization). Compared with active means, passive design can effectively reduce energy consumption and carbon emissions. Studies have been carried out on passive design factors for energy saving or low carbon emissions, including green roofs [69,70], window-to-wall ratios [71], and building orientation [72], which can provide sufficient theoretical support for low carbon and low energy consumption building design. However, strong interactions are exited between different design factors, causing limitations in practical applications for the univariate optimization.

The second is the multi-objective optimization of building design factors. Construction cost and energy consumption are the commonly used objective functions [73,74]. Low energy consumption and low carbon building design can be achieved by finding the optimal objective [17,27,75]. However, this refers more to the carbon emissions of operational energy consumption [28], which are not enough to indicate the actual carbon emission reduction [76]. Life cycle carbon emissions should be considered in low carbon building design [77]. Many scholars have conducted research on the life cycle carbon emission calculation model of buildings, which is also the research content of the third type.

Generally, in the research of the carbon emission model of buildings, the carbon emission database for life-cycle should first be established [78]. Secondly, the model can be constructed by machine learning and regression fitting, etc. [79–82]. The current database construction mainly includes research statistics and energy consumption simulation [26,29,57,83]. Research statistics require continuous statistical data over several years or months, for which it takes more time to build a database of carbon emissions. The existing building design optimization is time-consuming and investment heavy. It is necessary to explore a fast and convenient optimization method for low carbon building design.

3.3. The Challenges of Low Carbon Building Design

As shown in Figure 3, based on the analysis of the status of the standard system, the calculation method, and the optimal low carbon building design, several challenges in the development of low carbon building design are present.

The first challenge is the lack of a global perspective design standard system. China's building stock is relatively high, with various climate characteristics [84], population densities, economic levels, and human characteristics [54]. There is an urgent need for low-carbon buildings to consider multiple factors and develop novel design approaches for different characteristics [85], which consider the spatial form of buildings and being low carbon as the common optimization objectives.

The second challenge is the lack of carbon emission calculation methods applicable to the design phase. The existing calculation methods of embedded and operational carbon require a comprehensive database of carbon emission factors and detailed process inventories [56]. The current database of carbon emission factors needs to be improved in order to be applicable to more building types [18]. The information in the detailed process inventory is assumed, which may differ from the actual construction and operation process information, further affecting the accuracy of the calculation of building carbon emissions [68,86]. Hence, in order to reduce the difference between the design and operating phase, exploring a calculation method applicable to the design phase remains a great challenge.

The third challenge is the lack of real-time optimization methods in the design phase aiming at low carbon emissions. Low carbon building design should take into account the building morphology, for example circulation space, open space and aesthetics, floor area, floor layout, floor height, building volume, building orientation, and fenestration, as well as windows, doors, shading and exterior walls, etc. [74]. Each factor affects the carbon emission directly or indirectly [87]. Moreover, there is the problem of the design process being the time-consuming and this needs to be optimized [81]. Low carbon building design needs to use convenient and fast optimization methods, i.e., drawing−prediction−design, which can provide accurate guidance for building design.

4. Possible Future Work

As shown in Figure 4, the design standard system of "spatial regulation" and "performance regulation" for low carbon green buildings that can adapt to various climatic characteristics will be established in future work. The standard system of building design can provide the low carbon constraints for the conceptual design phase, as well as low carbon concepts for climate and renewable energy adaptation. Specifically, this includes building morphology design, envelope design, low carbon material selection, balancing control between light and heat, passive−active coupling design, indoor humidity independent control, etc.

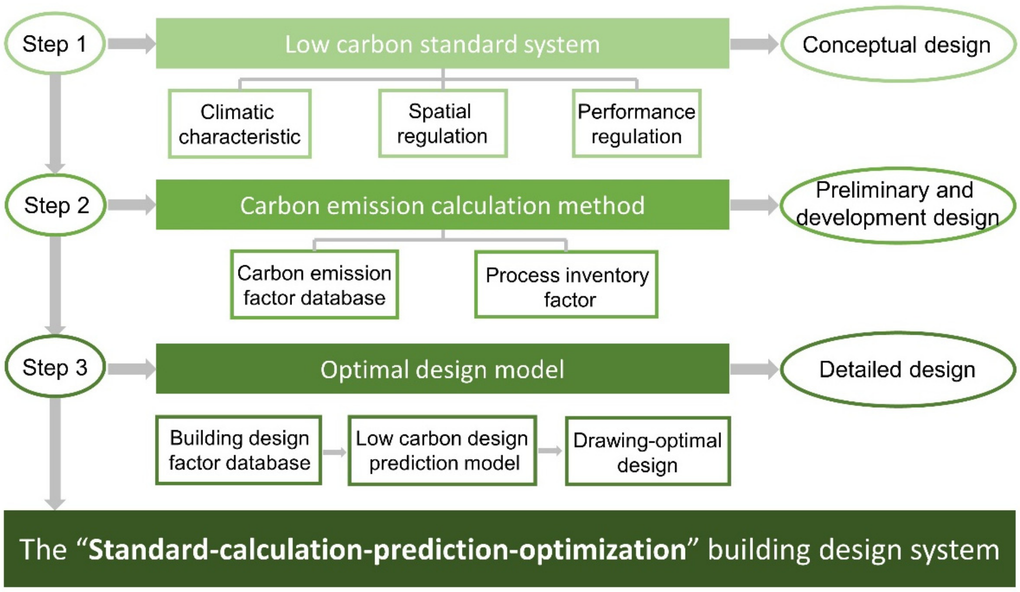

Figure 4. Possible future work for low carbon building design.

Then, based on the low carbon building design standard system, the carbon emission calculation methods applicable to the design phase will be explored in future work. Real-time and rapid calculation of building carbon emissions, important for evaluating design alternatives, will be used for different design alternatives during the preliminary design and development design phases. A comprehensive database of carbon emission factors will be built to meet the needs of different climatic conditions, building types, and building heights, etc. In addition, the carbon emission calculation in the design phase will meet the demand of incomplete content of inventory information in future research. Based on the carbon emission factor and the process inventory database, a convenient and fast carbon emission calculation method should be formed to facilitate the rapid assessment of carbon emissions in the design phase.

In the final step, building design in the future will be optimized through the design model. The design parameters will be accurately quantified to minimize the building carbon emissions. Firstly, different climate zones and building types are used as the first boundary conditions. Site area, floor/area ratio, and building height limits should be used as the second boundary conditions. The building orientation and window-to-wall ratio should be used as the third boundary conditions. The influence of each building design factor on carbon emission should be constructed, further contributing a comprehensive database of design factors. Secondly, a low-carbon design prediction model will be constructed through big data analysis and machine learning methods based on the above boundary conditions. Finally, building design drawing software, including Computer Aided Design (CAD) and Building Information Modeling (BIM), will be coupled with the low carbon design prediction model, forming a design pattern so that buildings can be optimized immediately after drawing.

5. Conclusions

This paper reviews the current status of the building standards system, carbon emission calculation methods, and building design optimization in the traditional building design process. The main challenges are as follows: (1) the lack of a comprehensive standard system for different climate zones, space, and performance requirements in the building design phase; (2) the existing carbon emission calculation methods lack a comprehensive database of carbon emission factors, which are not applicable to the design phase without a detailed process inventory; and (3) not being able to optimize building design factors based on real-time carbon emissions during the drawing process in the design phase.

Possible future work in building design should examine dealing with the above-mentioned challenges. A standard design system integrating spatial building information and low carbon performance needs to be formed, which is a constraint framework for the traditional conceptual design phase. A convenient carbon calculation method based on a comprehensive carbon emission factor database and a process inventory factor database should be explored, which is significant for the preliminary and development design phase. The prediction model will be proposed for detailed design using machine learning methods. Specifically, the spatial-low carbon standard system, carbon calculation method, prediction model of building design, and the optimal design of low carbon will be the framework, the foundation, the theory, and the objective, respectively. The system of "standard−calculation−prediction−optimization (SCPO)" will provide precise guidance for future building design.

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