Integrated Design Process for Building Climate Responsiveness

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Increasingly prominent energy and environmental problems have pushed for higher requirements for buildings' energy saving. According to the conventional energy-saving design method, the cooperative operation between architects, structural and equipment engineers and other professionals cannot run smoothly, so the energy-saving and emission reduction efficiency of the whole building cannot be improved effectively. The integrated design process (IDP) is a systematic method, which is applied in the scheme design stage and according to which the multi-level design factors of cities and buildings are considered comprehensively. It provides a concrete path of multi-specialty collaborative operation for the building's climate responsive design.

Keywords: cooperative operation ; building climate responsive design ; integrated design process

1. Introduction

The construction industry significantly impacts the environment and contributes to about 30% of global greenhouse gas emissions and 40% of energy consumption [1]. In the EU countries, 40–45% of total energy consumption comes from the construction industry [2]. In China, however, by the end of 2018, the carbon emissions of buildings in the whole life cycle accounted for 51.2% of the national energy carbon emissions [3]. Faced with the risks of energy depletion, global warming and climate change, all countries urgently need to reduce the buildings' energy consumption while maintaining a comfortable indoor thermal environment.

To cope with climate change and environmental problems, great changes must be implemented in the construction industry, and thorough improvement must be made in the process of architectural design, so that the destructive impact on the environment can be effectively reversed. For traditional buildings, attention is paid to cost, schedule and quality, while for sustainable projects, environmental protection, user health, low carbon emissions and low energy consumption must be considered [4][5]. To that end, governments should encourage the use of innovative and collaborative design processes, such as IDP [6][7]. IDP, a holistic approach, can help optimize building performance through an iterative process. In this process, all members of the design team need to cooperate from the early stage, so with IDP, the designers, contractors, suppliers and users can interact with each other more frequently [8].

Currently, the concepts of IDP in climate responsive building design are focused on the practical level. Few literature works study IDP from a theoretical perspective, such as Refs [9][10][11][12][13]; most of the studies focus on actual cases and field research and mainly discuss the design optimization methods and technical means, while ignoring the multidisciplinary cross-research relationship. Therefore, IDP in the field of climate responsive building design has a lack of guidance under a theoretical research framework.

2. Integrated Design Method Applied to Climate Responsive Buildings

2.1. Literature Analysis of Integrated Building Design Process

Based on the Web of Science database, the author created a co-occurrence diagram analysis of the relevant research hotspots in the past 10 years with "integrated building design process" as the keywords (as shown in **Figure 1**). The number of relevant documents is 5303. It is found from the co-occurrence diagram that the keywords of the research on "integrated building design process" mainly include building information modeling, public space, event-driven method, etc. Some literature works also involve keywords such as climate change, optimization, decision support system, life cycle assessment, etc.

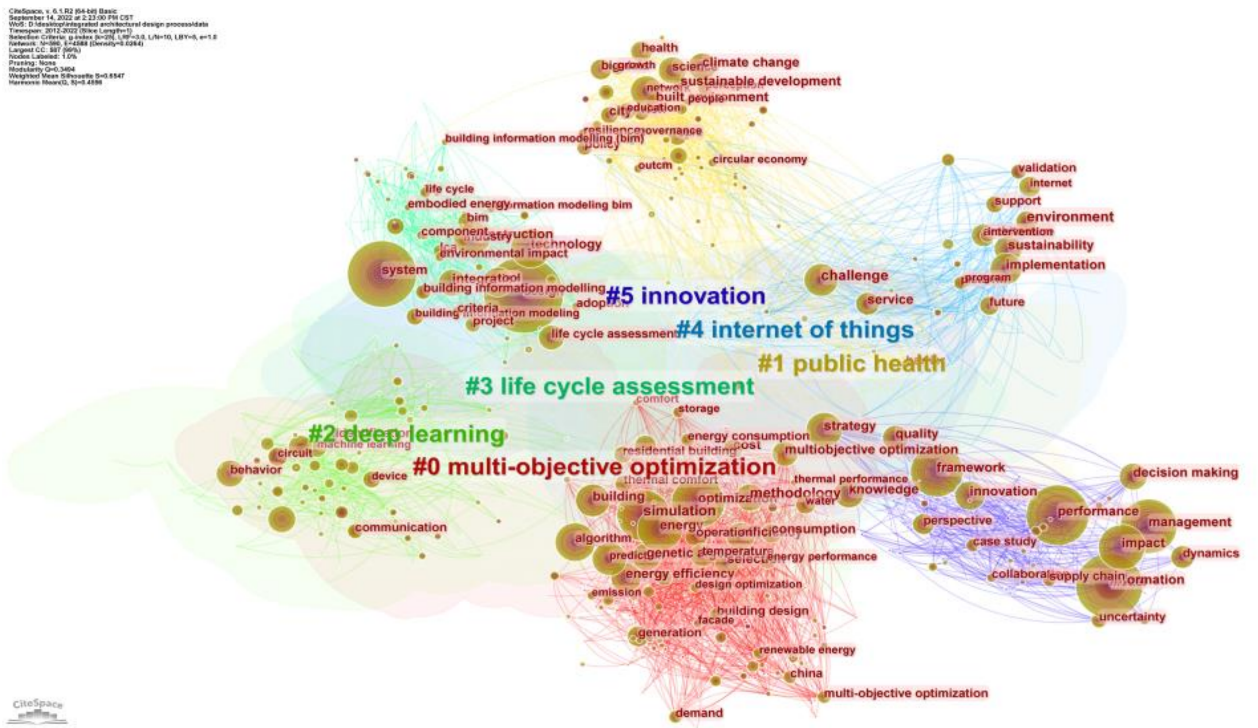

Figure 1. Analysis of keyword co-occurrence diagram of integrated building design process.

2.2. Methodology Framework of Integrated Building Climate Responsive Design

In the system for integrated building climate responsive design, scientific and rational logical thinking ability and creative activities based on ecological rules are considered. The system not only requires strict compliance with technical rules, such as codes, standards and node structures, but also emphasizes the subjective freedom of creative design behaviors, such as site selection, layout creation and form adjustment. In addition, it also advocates professional cooperation of multi-disciplinary fields, which strengthens group coordination and encourages public participation. The integration of design content, the expansion of design scope, the systematization of design procedures and the diversification of design objectives can also be reflected in the system. The design methodology itself is developed when a systematic coordination is carried out, and the overall design contradiction is handled. Therefore, from the perspective of design methodology, integrated building climate responsive design can simplify the thinking and increase the theoretical depth of integrated design. Separately, the development of integrated building climate responsive design may more or less absorb the theoretical fruits of the modern design methodology; thus, the applied research of modern design methodology can be further expanded.

The processes of integrated building climate responsive design can be summarized into target formulation, design analysis, design hypothesis, comprehensive evaluation and internal feedback.

(1)Target formulation

The design objectives are determined based on the comprehensive consideration of various constraints, including relevant national or local design standards, policies, overall planning objectives and Party A's requirements.

(2)Information classification and synthesis

Information must be collected as much as possible to be processed collectively into a standardized and unified information source. Meanwhile, the information is classified. Then, on the basis of information acquisition and classification, the knowledge rules are explored. On this basis, an information model is built for the provision of a system model in which the component attributes, static rules and dynamic rules are integrated.

(3)Design assumptions

According to the results of design analysis, one or more hypothetical schemes are put forward properly. Here, the assumed factors mainly include the architectural and environmental factors that impact energy use, such as the surrounding buildings' shading, thermal properties of building envelope, shading, behaviors for building use, etc. These factors may correspond to certain index parameters that need to be determined according to regional or national standards.

(4)Energy consumption simulation and comprehensive evaluation

Evaluation and selection of schemes. A comprehensive solution evaluation can be performed via the use of the inventory list method or the life cycle evaluation method or the evaluation method based on the simulation of building energy consumption, so that proper solutions can be selected. In addition, in terms of the energy-simulation-based evaluation method, the comparison and synthesis of multiple solutions are also useful for the identification of the interactions between the design variables, facilitating the determination of the main design variables and guiding the design optimization of the next cycle.

(5)Internal feedback and design optimization

The internal feedback is given based on the evaluation results in the comprehensive design phrase. If the evaluation results meet the design objectives, the evaluated solution is the final optimized solution; otherwise, it is necessary to revise the connection between the variables in the information model according to the evaluation results and go through the process of "design analysis–design assumptions–comprehensive evaluation" again. Then, the process will be repeatedly circulated and optimized until a satisfactory solution is obtained.

This is an open, dynamic, cyclic solution-seeking process, which requires the involvement of professionals from various disciplines in the early stages of the project. Therefore, it is different from the conventional terminal linear route of work. The openness of the design method brings more possibilities of design optimization. Therefore, the energy efficiency obtained via the use of this method for energy-efficient design is much higher than that obtained from conventional methods.

It is important to note that the conventional energy-saving design approach is applied throughout the entire engineering design process, involving schematic design, preliminary design and design of construction drawings. Meanwhile, the integrated building climate responsive design is created to integrate the advantages of each design stage, which are then applied into the schematic design stage. This is mainly because, in the schematic design stage, when the scheme is yet to be determined, there are more opportunities for design optimization. An effective energy-saving design can minimize the building's energy use on the one hand and create a favorable environment energy-saving design at a later point.

2.3. Operational Process of Integrated Building Climate Responsive Design

Due to the constraints of the research objects in different climatic regions, different design scales, different building types and different design stages, the design objectives cannot be met. In addition, considering the many disciplines involved and the complex information links between different disciplines, the contents of the integrated building climate responsive design tend to change in multiple ways. Such dynamic nature determines the variability of the specific design process organization under the method framework. Therefore, based on the methodological framework and application practice proposed above, a preliminary exploration is conducted on the operational process organization of energy-saving integration design applicable to the design of the whole building and part of the building on the basis of energy consumption.

In the research on integrated building climate responsive design of the whole building and part of the building, much attention is paid to the building's own systems (such as envelope, equipment systems and renewable energy systems) and the impact of user behavior on the building's energy use. Meanwhile, the impact on the surrounding environment must be considered. The work procedures are as follows.

(1)Objective formulation

Generally, the design objectives are determined according to the energy-saving-based codes and policies. For example, the target status can be determined according to the energy-saving design standards of similar buildings in the region. If there is no local standard, the regional standard or even the national standard can be referred to.

Integrated building climate responsive design represents the integration of performance based on physical and visual integration, as well as a systematic synthesis of space, time, energy efficiency, economic efficiency and other multi-dimensional factors under the premise of meeting the requirements for indoor thermal comfort. Literally speaking, integrated building climate responsive design is created to save energy. Meanwhile, there must be more than one design objective due to the systemic nature of integrated design [14].

Currently, many researchers who study the fields related to building optimization use genetic algorithms for the optimization of building performance scenario by integrating rhino, grasshopper (GH) plug-ins for building performance simulation (e.g., DIVA) and GH evolutionary solver, Galapagos, including optimization of energy-efficient building skin [15], optimization of high-performance building system [16][17], building orientation optimization [18], optimization of building operations [17][19][20][21], optimization of life cycle assessment [22][23][24] and optimization of alternative energy application [25][26][27][28][29]. However, in the GH platform, Galapagos can only optimize one objective function at a time, so the data results must be reprocessed, or other evolutionary solvers of the platform, such as Octopus, must be used when multi-objective optimization problems of buildings are addressed. The objectives of the integrated climate responsive design of existing buildings should be as shown in **Table 1**.

Table 1. Optimization parameters and their associated settings of previous studies.

Optimization Parameters	Objective Function
Heat transfer coefficients: wall, roof, floor, window frame and glazed window, heat absorption of walls, solar radiation absorption and visible light absorption, window–wall ratio, number of windows, g value of glass, transmissivity of daylight and visible light, open window area (natural ventilation), tilt angle and depth of external shading devices, type of shading, indoor and outdoor shading system, control strategy for shading devices, building shape, building shape coefficient, length–width ratio of building shape, ceiling height, building orientation, house area, airtightness/permeability, convection coefficient, and vegetation.	**Economic nature: Minimization: life cycle cost (LCC), total investment cost, building operating cost and net present value (NPV). Energy: Minimization: total electrical load, lighting energy consumption and net energy deficit (NED). Environment: Minimization: impact of life cycle environment, assessment of the impact of life cycle and carbon emissions of life cycle. Comfort: Minimization: predicted mean votes (PMV), summer thermal discomfort, winter thermal discomfort, visual discomfort, long-term percentage of dissatisfied (LPD) and predicted percentage of dissatisfied (PPD). Others: Minimization: shape coefficient. Maximization: window opening ratio, heat transfer coefficient, solar radiation, space efficiency.**
Constraints	**Algorithm**
NED ≤ 0; heating load ≤ 15 kWh/m^2; annual building energy demand ≤ 5 Mj/m^2; air exchange rate ≥ 0.6 ACH; total window width ≤ floor width. In the window areas, adequate natural lighting and ventilation must be guaranteed. Acceptable range of heat transfer coefficients of building envelope; budget constraints; constraints of design variables; maximum discomfort time fixed at 200–350 h; PMV ≤ 0.5–0.7; construction budget; life cycle cost budget.	**Generalized pattern search (GPS), multivariate optimization, particle swarm optimization (PSO), non-dominated sorting genetic (NSGA-II) algorithm, genetic algorithm, life cycle assessment (LCA), artificial neural network (ANN), particle swarm optimization based on the Hook–Jeeves algorithm, sequential search (SS), tabu search algorithm (TSA), artificial bee colony (ABC).**
Decision making/sensitivity analysis—uncertainty quantification	
Decision making: Weighted sum method (WSM), weighted product method (WPM), preference ranking based on ideal solutions, analytical hierarchical process (AHP), preference prioritization organization method for evaluation. Sensitivity analysis–uncertainty quantification: Energy price, discount rate, CO_2 emission price, climate, utility rates, setting points of heating and cooling, sensitivity of algorithm parameters, weight of objective function, decision preference thresholds, uncertainty of distributed design variables based on probability.	

(2)Information classification and synthesis

Information must be collected as much as possible, while the information is classified and processed. The collected information should include the basic information about the site and building that is required for conventional design and the information related to energy-saving building design. Such information can be divided into two categories: information about the design conditions and technical information (e.g., **Table 2**). The technology application is restrained by the design conditions, while the technical information is collected mainly to prepare for the energy simulation at a later stage.

Table 2. Classification of parameters required for integrated design.

Design Conditions	
Geographic location	Latitude, longitude and time zone of the region where the project is launched.
Climate information	Typical local annual climate involves temperature, relative humidity, wind direction, wind speed, solar radiation, etc. The EnergyPlus website already provides downloadable climate data of major cities around the world; if multiple sources are available, comparative research is required, so that the one that best matches actual conditions can be selected.
Surrounding physical environment	Topography, landforms, surrounding building envelopes and more can be obtained through external environmental research.
Base conditions	Base size, shape, layout of greenery and water bodies, etc., can be obtained through field survey of the base.
Local technical and economic conditions	The performance and price of commonly used, encouraged or restricted energy-saving products and technologies can be determined based on the relevant local standards, policy documents and market prices.
Geographical culture	A survey must be conducted to gain information about local customers, lifestyle and culture. Particular attention should be paid to symbolic characteristics of the building and human use of the building.
Regional experience in energy-saving design	Research on regional architecture or interviews with experts can be conducted to obtain information about the characteristics of building forms, spatial layout features and prototypes of energy-saving components.
Technical information	
Building materials	Physical properties of commonly used materials: heat transfer coefficient, density, specific heat capacity.
Building components	Material composition and thickness of opaque components, material composition, thickness, transmission and absorption coefficients of light-transmitting components, etc., and size and dimension of prefabricated components.
Heating and cooling equipment	The output power per unit area of rooms with different functions and the corresponding working schedule.
Indoor lighting equipment	Thermal power of illumination per unit area of rooms with different functions and the corresponding working schedule.
Indoor electrical equipment	Thermal power of indoor electrical equipment per unit area of rooms with different functions and the corresponding working schedule.
Indoor personnel	The thermal power of indoor personnel per unit area of rooms with different functions and the corresponding working schedule.
Indoor ventilation	The indoor fresh air requirement per unit area of rooms with different functions and the corresponding working schedule.

(3)Design assumptions

Many design assumptions are made within the scope of the information model. This can be achieved via different combinations of design variables. In the information model, the relevant factors that impact the building energy use under the constraints and the range of their variations are basically determined. In the design assumption stage, the values of the variables corresponding to these factors and their possible combinations are assumed, that is, different energy-saving design strategies are integrated to obtain different energy-saving design solutions. The design variables involved vary by region and building type, mainly including building orientation, envelope heat transfer coefficients of building envelope, shading coefficient of the exterior window, window–wall ratio, ventilation rate at summer nights, the COP and EER of the air conditioning system, solar photoelectric conversion efficiency, solar heat collection efficiency, etc.

(4)Energy consumption simulation and comprehensive evaluation

First, based on the complexity of the information model and the content of the design objectives, the suitable software tools need to be selected to simulate the building energy use and indoor environmental conditions. Software simulation can be divided into a simple mode and a specific mode. The information of the former is simple and general, and the software is modeled quickly, while in terms of the information of the latter, specific, accurate and complete information sources are required, and the modeling process is very complex and time consuming. The simple model is often used for qualitative comparison at the early stage of scheme design, while the specific model is usually used for quantitative evaluation at a later stage of the design. In terms of the scheme evaluation of this period, the environmental and economic benefits of energy-efficient design are required to be considered in a comprehensive manner, or the expert system is introduced, or the public are invited to participate.

(5)Internal feedback and design optimization

In the traditional architectural design process, there is no integrated system approach in the early stage of scheme generation and the later stage of scheme ending. Traditionally, architectural design is always judged based on the architect's experience, and the architect's cognition of the design determines whether the expected goals can be achieved in the project. With a large number of complex variables in the design, it is difficult to achieve the optimal goal if only the architect makes his/her own subjective judgment. As today's architectural simulation technology sees further development, the designers can be effectively assisted in decision making, so that the uncertain guesses in the design can be eliminated to a certain extent, and the design solutions can be evaluated quantitatively. However, these procedures are complex, and the data required to be input are detailed. It is difficult to obtain them in the early stages of the design, so the relevant schemes can only be evaluated in the later stages of the design. Most decisions that have a significant impact on energy consumption are made in the early design stage, making it difficult to effectively assist in the building climate responsive design only via the use of these simulation programs in the traditional design process.

In previous studies, the use of optimized search methods based on building environment simulation [30][31] is proposed. A Monte Carlo simulation framework is established based on building simulation tools to perform the uncertainty analysis and search for input parameters. The automated means are used to solve the problem of the input parameters being difficult to determine in the traditional sense. Optimization is a process in which the best combination of different solutions is sought while a given constraint condition is met. In the execution of optimization, decision variables, objective functions and constraints are needed. The following Formula (1) demonstrates the optimization process in a general mathematical sense.

$$\min_{x \in R_n} f(\mathrm{X}) \mathrm{g}_i(x) \le 0, i = 1, 2, \ldots, m \& l_j(\mathrm{X}) = 0, j = 1, 2, \ldots, p \quad (1)$$

Here, X represents different decision variables, and the f(X) is the objective function. The constraint conditions are gi(x)≤0,i=1,2,…,m and lj(X)=0,j=1,2,…,p. Determining the decision variables, the objective function and the constraint conditions is the most important part of the optimization process. Different optimization algorithms can be selected according to the classification of different objective functions and constraint conditions.

Pareto optimality is the classical model for multi-objective optimization [19][20], and its core thinking is an extreme objective under the premise of minimum objective conflict. The Pareto optimal solution is a set containing solutions that are no better than any others. In other words, different solutions cannot be compared with each other. The multi-objective optimization often ends up not with a unique optimal solution but a set of Pareto optimal solutions.

If the minimization value of the objective is required, there are two feasible solutions x1,x2∈S. When Formula (2) is workable, the x1 is called the Pareto optimal solution (≻)x2

$$\begin{aligned} F_i(x_1) &\le f_i(x_2), \forall i \in \{1 \ldots k\} \\ F_i(x_1) &< f_i(x_2), \exists i \in \{1 \ldots k\} \end{aligned} \quad (2)$$

Formula (2) indicates that all of the objective functions corresponding to the x_1, are no greater than the value of the objective function of x_2. In f(x1), there is a value that is absolutely lower than f(x2). When the maximal solution is required in the objective function, the expression will be changed into Formula (3)

$$\begin{aligned} F_i(x_1) &\ge f_i(x_2), \forall i \in \{1 \ldots k\} \\ F_i(x_1) &> f_i(x_2), \exists i \in \{1 \ldots k\} \end{aligned} \quad (3)$$

The integrated analysis process based on parametric simulation and optimization of building performance consists of two parts and three steps, as shown in **Figure 2**. The data collection step and the generation step constitute part 1: design prototype generation. The optimization step constitutes part 2: design optimization. In part 1, specific design parameters are collected, such as building form factors, window–wall ratios, etc., and default parameters contained in the design, such as the constraint parameters used to generate the design prototype. In part 2, the architectural design prototypes generated in part 1 are optimized. This process facilitates the formation of a series of optimized architectural design solutions that designers can evaluate, select and further develop. For building climate resilient design, the result is a building design solution with high thermal comfort and low energy and cost, which can be specified in the process shown in **Figure 3**.

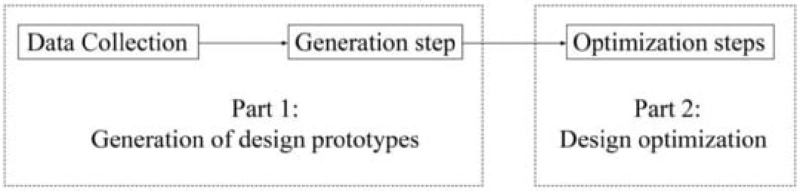

Figure 2. Basic steps of design generation and optimization.

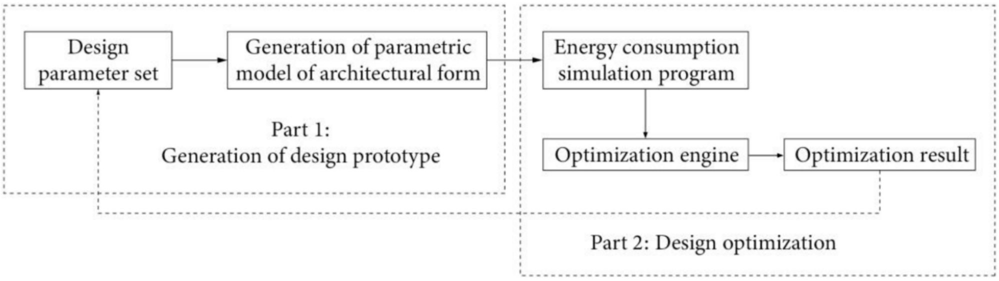

Figure 3. Simulation-based modeling process for building form generation and optimization.

It should be noted that in terms of the simulation prediction at the urban scale (urban planning and urban design), the information about the building layout, energy supply and even the surrounding physical environment of larger scope is needed; in terms of the simulation prediction at the indoor environment level, the information about room layout, interior decoration and equipment system operation is needed.

2.4. Software Platform for Integrated Building Climate Responsive Design

In addition to the basic design software, such as AutoCAD, SketchUp, 3DMAX, etc., there are four other types of digital tools for integrated building climate responsive design: the first type refers to the integrated simulation design platforms, such as design platforms based on BIM [32][33][34] technology; the second type involves assessment software for energy consumption and environmental impact, such as BEES, Athena, EQUER, etc. [35][36]; the third type represents simulation technologies for complete energy consumption, such as EnergyPlus, ESP-r, DOE-2, etc. [37][38][39]; and the fourth type is auxiliary professional analysis software, such as AirPak, Radiance, Weather Manager, ENVI-met, etc. [40][41][42][43][44][45].

The internationally recognized PHPP software is the only software approved by PHI for passive building design simulation. PHPP, developed by PHI, is used to calculate the load and energy of passive buildings. The scheme follows a built-in German passive building certification standard [46]. In China, other simulation software programs, such as DeST [47] and eQUEST [48][49], are used for the year-round energy simulation. DeST was developed at the Institute of Environment and Equipment, Tsinghua University. The state space method is adopted, and AutoCAD is used as the graphic interface to analyze building thermal characteristics and calculate the annual hourly load and building energy consumption. The simulation results of DeST are consistent with those of DOE-2 and EnergyPlus developed by the United States Department of Energy.

In addition, an increasing number of researchers based on the Rhino/Grasshopper parametric platform use environmental analysis plug-ins Ladybug and Honeybee to conduct the analysis on building environment and energy consumption modeling. The application of this workflow can be seen in **Figure 4** below.

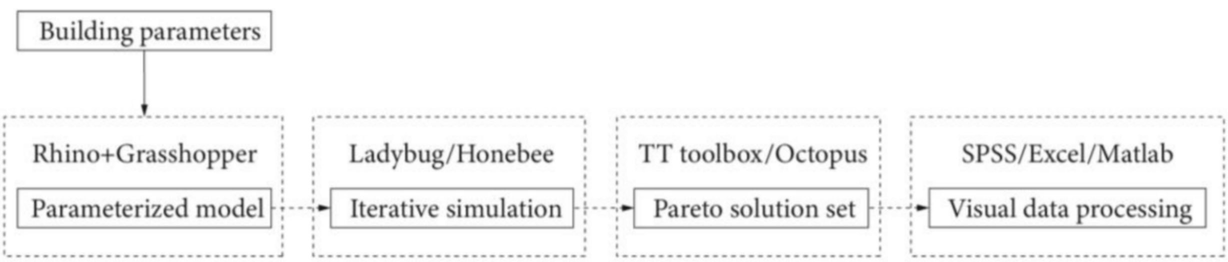

Figure 4. Parametric building optimization process.

Grasshopper is a parametric plug-in of the modeling software Rhinoceros 3D. In the Grasshopper program, one can create a program only by dragging the parameter command component into the canvas and connecting the input and output of the components in different logical orders. Grasshopper, as a graphic algorithm editor, provides a new method of expanding and controlling the 3D design and modeling process. For example, complex geometry is generated through mathematical functions. In addition, complex models are driven and quickly changed according to the environmental performance algorithms under predefined modeling logic [30][31].

Ladybug and Honeybee, the plug-ins of Grasshopper, are free computer applications that support environmental design. They connect 3D computer-aided design (CAD) interfaces to Daysim and Radiance, the light environment analysis software, and the verified simulation engine EnergyPlus. Daysim and Radiance are widely used in the analysis and evaluation of the light environment of buildings. Via the simulation of the real physical environment, the light environment can be predicted, and the impact of direct light, diffuse light and ground-reflected light on indoor natural lighting can be comprehensively calculated. They are suitable for different sky environments all year round, such as sunny sky, overcast sky and cloudy sky.

EnergyPlus is a building dynamic simulation software for energy consumption developed by the U.S. Department of Energy and Lawrence Berkeley National Laboratory on the basis of the features and functions of BLAST and DOE-2.1E. It is designed to provide integrated (load and system) simulation to achieve the accurate prediction of energy, temperature and comfort. EnergyPlus is the most widely used tool in the current building energy analysis and research. It can simulate the heating, cooling, lighting, ventilation and other energy flows and humidities of buildings. It is especially suitable for simulation of the dynamic behavior strongly influenced by thermal inertia [50][51]. The simulation process of this software is illustrated in **Figure 5**. EnergyPlus has irreplaceable advantages over some other simulation software (as shown in **Table 3**).

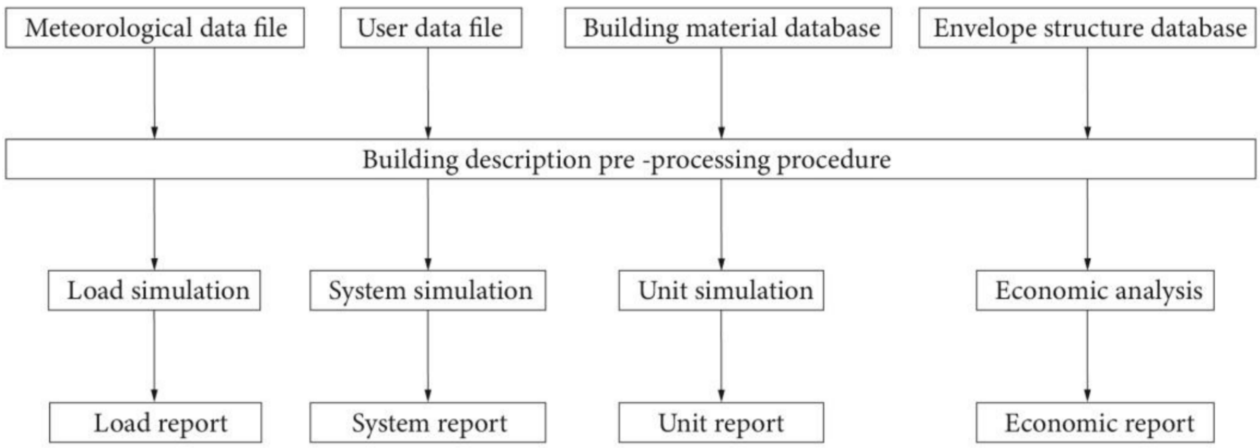

Figure 5. Operation logic of EnergyPlus simulation.

Table 3. Comparison of EnergyPlus with other software.

Comparison Contents	EnergyPlus	DOE-2	BIAST	IBLAST	DeST
Integrated simulation and iterative solutions	Yes	No	No	Yes	Yes
User’s self-defined time step	Yes	No	No	Yes	No
Output interface	Yes	No	No	No	No
Self-defined output reports	Yes	No	No	No	Yes
Calculation equation of room heat balance	Yes	No	Yes	Yes	Yes
Calculation equation of building’s heat balance	Yes	No	No	No	Yes
Convective heat transfer calculation of internal surfaces	Yes	No	No	Yes	Yes
Long-wave mutual radiation between inner surfaces	Yes	No	No	No	Yes
Heat transfer model of neighboring chamber	Yes	No	No	No	Yes
Humidity calculation	Yes	No	No	Yes	Yes

Comparison Contents	EnergyPlus	DOE-2	BIAST	IBLAST	DeST
Thermal comfort calculation	Yes	No	No	Yes	No
Radiation model of sky background	Yes	Yes	No	No	Yes
Calculation of window model	Yes	Yes	No	No	Yes
Solar transmittance distribution model	Yes	Yes	No	No	Yes
Daylight model	Yes	Yes	No	No	No
Calculation of water cycle	Yes	No	No	No	Yes
Circulation of air supply and air return	Yes	No	No	No	Yes
User's self-defined air conditioning equipment	Yes	No	No	No	Yes
Calculation for the concentration of hazardous particulate matter	Yes	Yes	Yes	No	Yes
Interface with other software	Yes	No	No	No	Yes

EnergyPlus has a simulation kernel but has no visual interface suitable for user modeling operation. Therefore, the integrated operation logic can be realized if the OpenStudio is linked with Grasshopper's plug-ins: Ladybug and Honeybee.

On the basis of modeling and performance analysis, if Octopus—a plug-in of Grasshopper—graphical parametric modeling environment is adopted, the optimization search of building environment parameters can be easily carried out. The general optimization process is divided into three parts: parameter gene, parameter model and optimization objective, namely, input parameters, performance simulation and simulation results.

Via the operation procedures shown in **Figure 4**, the interactive operation and optimization integration of building model and environmental analysis can be realized. The data concerning the changes of geometric model parameters in Grasshopper will be updated in the environmental analysis software in real time. The iterative simulation of the model is driven by the optimization engine. Different geometric and environmental input parameters and corresponding output result parameters of the analysis target are recorded, thereby generating an "input–output" table.

2.5. Evaluation and Decision-Making Methods of Integrated Building Climate Responsive Design

The evaluation method of integrated building climate responsive design is mainly used to evaluate the performance optimization of buildings. The evaluation results are used to screen and optimize the design schemes and to guide the internal feedback to correct the information model.

International evaluation methods of building performance can be roughly divided into four categories, namely: the prescriptive index method, the list method, the life cycle evaluation method and the evaluation method based on building energy consumption simulation or calculation. Among them, the prescriptive index method is the method according to which the evaluation is conducted based on the prescriptive indices of key engineering parameters stipulated in the energy-saving standards and specifications, such as the heat transfer coefficient, window–wall ratio and shape coefficient of the external envelope stipulated in the building energy-saving design standards. According to the list method, the key problems are listed in the form of a list. Different problems or categories of problems will have weight values. According to the problem scores and weight values, the final score can be calculated, and then, the building rating can be provided with reference to the grading standards. According to the life cycle evaluation method, an inventory analysis of the material and energy flows of buildings is conducted based on the basic framework of life cycle evaluation. Then, a comparative evaluation is generated. The evaluation method based on building energy consumption simulation or calculation is the evaluation method based on the energy consumption value calculated via the simulation software or calculation method for building energy consumption.

In the prescriptive index method, the limits of important energy-saving parameters are specified in the form of indicators. Although these indicators are obtained through analysis on the basis of a large number of engineering practices and scientific research works, this method still greatly limits the "communication" between the parameters. Therefore, there is no possibility of integration, and the method is not suitable as an evaluation method for integrated building climate responsive design. Comparatively speaking, the latter three kinds of evaluation methods are more flexible and adaptable. They can be used as an evaluation method for integrated building climate responsive design because of the "communication" between parameters and their characteristics of integration. It should be noted that different evaluation methods have different conditions of application, evaluation contents, evaluation objectives and auxiliary tools, so attention should be paid to a reasonable selection of these methods according to the actual situation.

(1)List method

According to the list method, the most widely used environmental assessment method, questions are posed on the key issues or criteria. Based on the weight values given to these issues and criteria, the final total score can be calculated. This method is relatively straightforward and operational but requires the user to know the project well enough; in addition, it allows different questions to complement each other, i.e., if the score of one question is low, that of another will be high enough, so that the final total score will not be decreased. However, the biggest problem with the list method is how to ensure the objectivity of the weighting factor. The unified view is yet to be found. In addition, subjective factors make it difficult to reconcile the contradictions between national standards and local adaptations. Nevertheless, considering its excellent operability, it is still an effective method for constructing a building evaluation index system, as shown in **Table 4** of the relevant literature.

Table 4. Relevant literature where the list method is applied.

Farzad et al. [52]	**proposed a method of combining BIM with the Canadian green building certification system (LEED).**	**Based on the BIM platform, a model by which the LEED certification is automatically calculated is constructed. Meanwhile, the cost of the model can be calculated.**	**In this study, attention is only paid to the integration of BIM and sustainable development from the perspective of LEED. Therefore, the research results cannot go beyond LEED. The general framework of sustainable development is not produced.**
Farzad et al. [53]	**put forward a comprehensive framework that integrates BIM with green building certification system in the early design stage of the project.**	**Plug-ins for the calculation of LEED points were developed by accessing the BIM application interface (API), tools for energy analysis and lighting simulation, Google Maps and its related libraries.**	**The accuracy of the model was restricted by the number of projects. The information transmission from Green Building Studio (GBS) to plug-ins needed to be performed manually by users.**
In the study of Liyin et al. [54],	**the text-digging technology was integrated into the case-based reasoning (CBR) system to improve the decision-making efficiency of green building design.**	**Seven cases were randomly selected from seventy-one LEED cases as target cases to test how efficient the TM-CBR system is.**	**It was difficult to obtain the original data; there was a limited number of cases; there was a lack of verification of a large number of empirical data.**
In the study of Walaa et al. [55],	**both qualitative and quantitative methods were adopted. A comprehensive framework (IAF) for a green building rating and certification system was proposed.**	**In the study, a reference was provided for the development of a LEED system and different building rating and certification systems with a comprehensive framework; and interactive decision support tools, software management applications and user-friendly system interfaces were established.**	**However, in the study, the dominant position of some tools and how they impact important decisions were not clearly demonstrated; there was a lack of descriptions of iterative behaviors in the integration process in the proposed framework.**
In the study of Yingyi Zhang [56],	**the impact of parameter codes based on forms on the sustainable development of urban communities was evaluated.**	**In the study, the LEED-ND method was adopted to establish a code evaluation system based on parameter forms in order to guarantee the health of social environment and urban communities and the sustainable development of the communities.**	**The study was only conducted in Tsim Sha Tsui, Hong Kong. The findings were mainly obtained from the analysis of the Jordan Road community. In future studies, investigations of a larger scale can be conducted in different regions.**
In the study of Mohamed Marzouk [57],	**a mixed integer optimization model was developed to help architects and owners select building materials during the design phase. Meanwhile, the costs and risks involved in the selection process needed to be considered.**	**Deterministic and probabilistic cost analysis of various design alternatives can be conducted through the model developed in the study with reference to the LEED rating system based on the simulation optimization tool.**	**The study analysis was only conducted for office buildings in Egypt and only with reference to the LEED rating system; more building types will be considered, and more green building rating systems will be incorporated in the future.**

Jin Ouk Choi [58]	**developed an integrated optimization tool for LEED evaluation.**	**In the study, the LEED decision and review index (LDRI) tool was established based on the MS Excel platform and MS Access database format. The user can rank the LEED scores by performing the steps listed in the LDRI tool. The tool will automatically provide the corresponding reports.**	**Currently, no weight is assigned to each factor. In the future, the analytic hierarchy process (AHP) can be added to the model to determine the weight of factors. In addition, more factors should also be added to the tool to reflect the growing needs of owners and users.**
Elena et al. [59]	**proposed an integrated approach for energy and environmental analysis, specifically for historic building renovation.**	**An intervention strategy indicating the principal direction of historic building operations and maintenance was proposed.**	**A weakness of the study is the lack of applicability to all LEED protocols, precisely because the structure of the credits and categories in O+M is substantially different from that in most rating systems.**
In the study of Ricardo et al. [60],	**the extent to which the integrated design can effectively improve project performance and reduce environmental impacts was verified.**	**The study was conducted on three Canadian building projects that were certified by LEED and in which various environmental strategies were integrated. The study team first identified and evaluated building environmental impact strategies, then analyzed the decision-making process and measured the relationship between reference buildings, schematic design and construction documents using the life cycle assessment (LCA) tool and building energy simulation (BES).**	**The study was only conducted on projects (gold and platinum) that were certified by LEED, and no analysis was conducted on other types of green building certified projects (e.g., SbTools, Living Building Challenge, BREEAM and DGNB). The impact of full life cycle assessment metrics on integrated processes was rarely mentioned.**
In the study of Emre et al. [61],	**a method of obtaining the required number of credits in the LEED (v4) category of “energy and atmosphere” under the “optimized energy performance” credit at the lowest cost was proposed.**	**The LEED v4 credits were calculated automatically based on Excel macros via the use of energy simulation software (Sefaira), cost database (RSMeans) and BIM software (Autodesk Revit) with an office building as example.**	**It was assumed in the study that the building’s lighting and HVAC systems had been determined by the analysts. In the future studies, changes in lighting and HVAC systems can be considered. Meanwhile, a large number of scenarios can be created to obtain the desired LEED scores.**
In the study of Johnny et al. [62],	**the Delphi method and case study method were adopted to explore the potential of BIM application in the project of sustainable certified residential buildings under BEAM Plus in Hong Kong.**	**In the study, an integrated BIM-BEAM Plus assessment framework was constructed and applied to a modular apartment model for public housing in Hong Kong. It was proved in the study that 26 BEAM Plus scores can be obtained via the integrated BIM-based assessment framework.**	**The validity of the framework needs to be further verified based on real case studies. The results generated by the framework need to be compared with the real BEAM Plus scores.**
In the study of Bahriye et al. [63],	**an integrated BIM sustainable data model framework was proposed based on integrated foundation classes (IFC) in the design stage of the whole building life cycle.**	**In the study, a green building assessment tool (GBAT) was established based on the IFC-BIM integrated framework. Then, it was applied to a sample project, and the accuracy of the tool was verified via the use of the BREEAM evaluation system.**	**In the model, only materials in the BREEAM database can be used, and the material library (GML) can only be used in ArchiCAD software. The material database in the BREEAM database cannot be updated automatically.**

A comprehensive evaluation system consists of several elements: evaluation purpose, evaluator (development agency), evaluation object, evaluation index, weighting coefficient, comprehensive evaluation model and evaluation result. The core elements of the evaluation system include determining the evaluation indicators, selecting the scoring methods, determining the weighting coefficients and creating a comprehensive evaluation model. A good evaluation index system should be equipped with comprehensive and integrated evaluation indices, a scientific and rational scoring method, an objective and reasonable weighting system, an operation-friendly evaluation model, and an accurate and effective evaluation result expression.

Internationally, many studies are conducted on green building evaluation systems, which have been strongly supported by the governments of various countries. The famous evaluation systems include BREEAM of the U.K., LEED of the U.S., CASBEE of Japan, GBTool of Canada, etc. China is also going to introduce a new version of green building evaluation standards. The theoretical and methodological achievements of these evaluation systems provide valuable experience for the development of evaluation systems for building energy-saving design.

(2)Life Cycle Assessment

Life cycle assessment (LCA) is a method of evaluating the resource consumption and environmental impact of products, systems and services throughout their life cycle, including the inception and the ending. In 1969, the Midwest Resources Institute in the U.S. conducted a study on product packaging, marking the first step of LCA research; by the mid-1980s, research on LCA methodology gradually emerged, and LCA methodology was widely used in design, industry and marketing; by the 1990s, The Society of Environmental Toxicology and Chemistry (SETAC) explicitly introduced the concept of "life cycle assessment". Since then, the International Organization for Standardization (ISO) has developed a series of LCA standards (ISO 14140 series). According to ISO's LCA methodology, LCA should include the following steps: definition of the objectives and scope, inventory analysis and impact evaluation. The relevant literature is shown in **Table 5**.

Table 5. Relevant literature where the LCA is applied.

Thais et al. [64]	**developed a framework for environmental impact assessment within the design life cycle.**	**In the article, two different whole building environmental impact assessment (EIA) tools are analyzed, including life cycle assessments (LCA) and green building rating systems (GBRS).**	**A software tool or framework needs to be developed to support designers in conducting whole life cycle EIA throughout the design process.**
In the study of Ahmad et al. [65],	**BIM and LCA tools were integrated with a database for designing sustainable building projects.**	**In the study, an integrated BIM-LCA model was described to simplify the process of sustainable design, build inter-operable design and analysis tools, and assist designers in quantifying the environmental impacts of design solutions.**	**The main disadvantage of the model is that it cannot be applied in the detailed design stage of a building project, as only information on commonly used components is stored in the database, with the information on a large number of green building materials uninvolved. In addition, the model is not fully integrated with automation, and some steps still require manual adjustment by the user.**
In the study of Mohammad et al. [66],	**an evaluation model of integrating BIM and LCA was established.**	**Based on the ISO 14040 and 14044 guidelines in the existing database, the BIM-LCA integrated analysis framework was established with Autodesk Revit as the BIM-LCA program and applications of Green Building Studio and Tally in Revit as tools.**	**In the future, more parameters of building materials will be included in the study to assist in evaluating the energy consumption, carbon dioxide and environmental impact of different building materials in the whole life cycle of buildings.**
Maria et al. [67]	**developed a multi-objective optimization model to obtain the minimum design parameters of greenhouse gas emission and life cycle cost in building operation.**	**Based on DAKOTA, TRNSYS and multi-objective genetic algorithm (MOGA), the multi-objective optimal designs were compared with typical houses in four climatic regions of Greece as examples.**	**In the study, attention was only paid to residential buildings and only under the climatic conditions in Greece. In the future, more different types of buildings will be considered, and more architectural design parameters will be included.**
In the study of Hae Jin Kang [68],	**a decision support tool suitable for early design stage was constructed to evaluate the performance and cost of CO_2 emission reduction. A program with a database was developed.**	**In the study, a decision support tool was developed to comprehensively evaluate and compare the environmental and economic impacts in the early design stage, so as to achieve effective decision making. The tool could be used to improve the realization and popularization of nZEB, so that the evaluation results could be obtained quickly and simply, and the comprehensive performances of design alternatives could be compared.**	**The evaluation tools developed in the study are only suitable for the early design stage. In the future, more evaluation decision-making methods can be added to the building operation stage.**
Farshid et al. [69],	**by combining the multi-objective optimization method with the BIM design process, solved the trade-off decision problems in implied energy and operational energy.**	**The design prototype was developed with a low-energy residential building in Sweden as an example. The best design scheme for the use of LCE of the building was found through the trade-off calculation of implied energy and operational energy.**	**Further study needs to be conducted to reduce the time cost of calculation and expand the design framework, so that more design variables are covered, such as the geometry of the building, etc.**

Like the life process of all the other products, the life process of a "building product" includes six stages: planning, design, building, test, operation and recycling. It represents the unification of the time process and "information flow change", as well as a process of diversified information and circular flow. As a systematic information processing method, the whole life cycle evaluation method can be directly used for the economic and environmental performance assessment of buildings. Meanwhile, the energy-saving performance of buildings needs to be evaluated comprehensively based on the results of energy consumption simulation or calculation. The LCA of a building requires the creation of a detailed inventory of the inputs and outputs of building materials and resources during the building process. Then, on this basis, an evaluation of the associated environmental impacts and resource consumption is conducted. Recommendations and alternatives for improvement are proposed.

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