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Performance Analysis of Application of BIM Technology and Two-Way Progressive Optimization Algorithm in Energy-Saving Design of Residential Buildings Based on BIM Technology

JES

Journal of Electrical Systems

Abstract: - The current residential energy-saving design is lagging behind, and lack of systematic design methods and scientific technical means seriously restricts process of improving quality of residential buildings in China. With development and application of digital information technology in construction field, BIM technology has brought new opportunities construction industry, and building performance data has become information basis for scientific promotion of energy conservation. This paper uses BIM technology as a platform to establish an information base of common building materials and components in Chongqing through literature research, field studies, summarization, and application practice, and to help architects make wise decisions at early design stage by using "one-click" scheme comparison and design evaluation to avoid a large number of potential energy consumption problems at a later stage, It greatly improves energy efficiency and design quality of buildings.

Keywords: BIM technology; performance analysis; residential building; energy-saving design

I. INTRODUCTION

Ecological energy-saving technology in field of construction is one of important ways to promote green development, solve outstanding environmental problems[1]. As material basis of human life, construction volume of buildings is increasing urban heat island effect and other problems[2]. In whole life cycle of building, its design, construction, commissioning, use and demolition process consumes a lot of energy, according to statistics is growing momentum[3]. In face of current economic construction and energy crisis, building energy-saving design can not be delayed, urgent need for scientific and technical means to improve its efficiency and accuracy to adapt to current fast-food residential development model, at same time, new era of residential buildings also carries demand for a more healthy and comfortable living space, accelerate building, energy-saving work is not only an important measure to achieve green low-carbon development, but also to provide people with It also provides people with a healthy resting place for body and mind[4].

Digital information technology[5] is a means to improve level of development of construction industry, quality of design, work efficiency, and comprehensive balance of quality, cost, design and other multiple dimensions at each stage. Digital technology carries information data, through editing, identification, translation and other processes

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to achieve digital information, and BIM technology as a new digital technology information tools, in recent years in construction field is widely used and practice, is clearly included in "2016-2020 construction industry information development program", "construction industry development" Thirteenth Five-Year Plan It is clearly listed in a series of national strategies and development plans such as "2016-2020 Construction Industry Informatization Development Outline", "Outline of National Informatization Development Strategy" and Technology Innovation"[6]. The national and local governments are paying more and more attention to BIM technology, constantly improving application standards and technical guidelines of BIM comprehensive training of related talents[7]. Under vigorous promotion of national and local policies, BIM technology has gradually become an means to improve quality construction projects, energy conservation and environmental protection, bringing innovation in method of residential energy-saving work [8].

II.   RELATED WORK

After outbreak of energy crisis in 1970s, building efficiency began to be widely concerned. Based on rapid development of computer technology, many foreign professionals began to explore how to use software simulation to assist in building. [9] Based on parametric design of building information modeling, study of strategies to optimize design of building façade and roof form was carried out. [10] The relationship between residential building layout and form design and building consumption is explored by analyzing role of BIM technology on environmental factors. [11] The application of BIM performance simulation of building envelope was studied. [12] The design and development application is discussed through sustainable design application of BIM technology. [13]Explored energy saving optimization strategy and energy use efficiency of residential buildings based on parameter adjustment of BIM technology. [14] Performance simulation based on Building Information Modeling (BIM) is studied to consider environmental friendliness and economic feasibility of target building and to guide program design decision. [15] Combining BIM simulation technology and value engineering, relationship between cost and energy efficiency in process of residential building design is analyzed, and BIM information model is used as a carrier to analyze and compare performance differences of different schemes based on BIM performance simulation to explore design strategies to obtain a comprehensive balance between green building assessment and cost control requirements. [16] Exploring sustainable design assessment of building projects in conceptual design stage through BIM-LEED application.

In order to realize deep development of China's construction informationization and improve informationization level of construction industry, this paper builds an open and non-visualized parameter input and information recording module for common building materials and structure information in Chongqing based on high integration capability of BIM technology for construction information, and explores energy-saving design methods suitable for characteristics of Chongqing's mountainous environment considering geographical and climatic conditions of Chongqing[17]. A BIM information model of corresponding scheme is established to test relevant control factors using energy-saving design method of BIM performance analysis, compare differences in building energy consumption caused by different strategies, and assist in screening and optimizing design scheme[18]. The results of a large number of simulation experiments are summarized, and a technical route and design method suitable for performance simulation and optimization of residential buildings in Chongqing is established[19-20].

III. BIM TECHNOLOGY ARCHITECTURE

BIM technology has gradually become carrier of various facilities information and resource sharing center, and its application mode can be divided into two modes according to different project application stages: one is whole life cycle application; other is phase application. whole life cycle application mode of BIM technology means that from initial stage of project until project exit, BIM technology always runs through whole life cycle of project. Mainly including preliminary conceptual planning, preliminary and deepening design, construction and completion, operation management and maintenance stages, specific application process is shown (Figure 1):
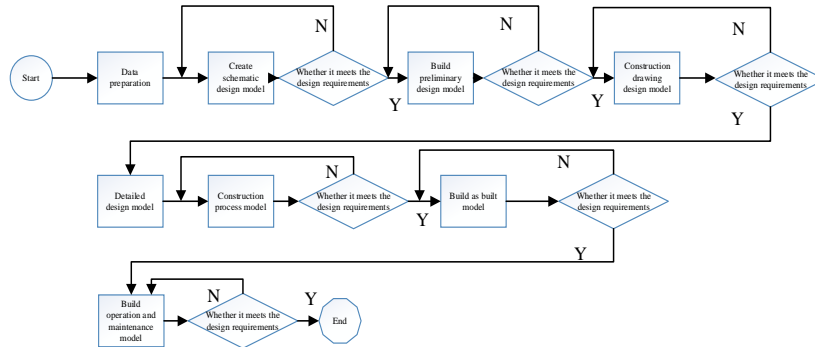

Figure 1 application process of BIM Technology in whole life cycle

The time cycle of engineering projects is generally very long, in order to facilitate project management and project advancement at each stage, generally create its applicable work mode according to nature of different stages, common design phase (concept, concept plan, preliminary design, program deepening), construction phase (construction preparation, construction implementation, completion and acceptance), design phase, for example, its specific application process is shown in Figure 2 :
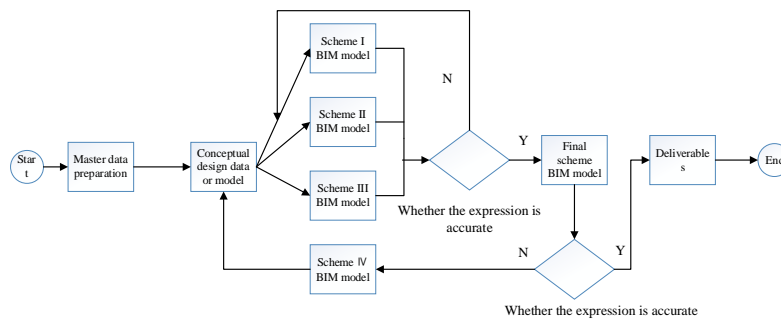

Figure 2 workflow of BIM application in design stage

BIM technology building performance analysis is a comprehensive process, different from traditional performance simulation on a single platform or a single computer, but based on BIM collaborative platform for building information integration, in different stages of architectural design according to design needs of real-time performance simulation analysis of different objectives, all performance simulation around same model, to achieve "a model of multiple uses All performance simulations are carried out around same model to achieve "one model for multiple uses". Combined with architectural design process, workflow of BIM performance analysis is shown in Figure 3.
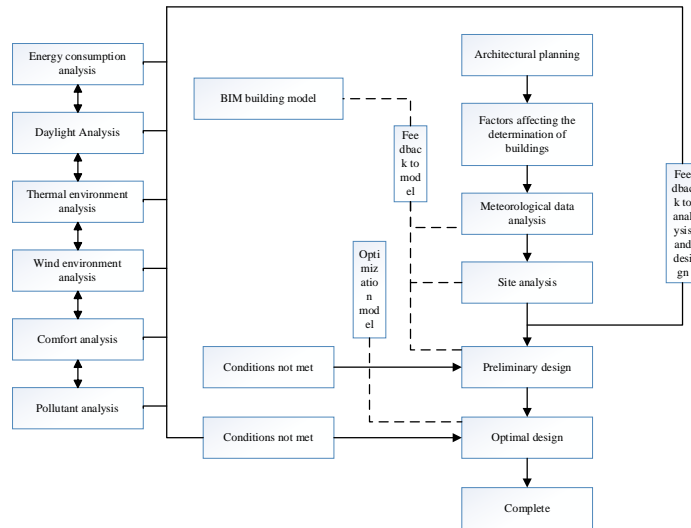
Figure 3 workflow for IBM performance analysis

IV.   TWO-WAY PROGRESSIVE OPTIMIZATION ALGORITHM

The objective function of building structure optimization is to find the optimal material distribution and minimize the strain under the given load, constraints and material properties. A bi-directional progressive optimization algorithm is used to optimize the model, which can be expressed as:

$$X = \left\{ x_1, x_2, \cdots, x_n \right\}^T \in \Omega \quad (1)$$

$$C = \frac{1}{2} F^T U \quad (2)$$

$$V^* - \sum_{i=1}^{n} V_i x_i = 0 \quad (3)$$

$$F = KU x_i = \left\{ x_{\min}, 1 \right\} (i = 1, 2, \cdots, n) \quad (4)$$

Where, $x_i = x_{\min}$ or 1, $x_{\min}$ is generally of order of magnitude of 10^{-3}. In order to prevent singularity of stiffness matrix K in process of structural optimization and cause abnormal calculation, optimal solution of structural optimization cannot be obtained, $x_{\min}$ cannot be equal to 0. According to above formula, as shown in following formula 5.

$$C = \frac{1}{2} F^T U = \frac{1}{2} U^T KU = \frac{1}{2} \sum_{i=1}^{n} u_i^T k_i u_i \quad (5)$$

SMIP form is introduced into original progressive structural optimization method, which sets elastic modulus of material as shown in equation 6:

$$E(x_i) = E_0 x_i^p \ (6)$$

Where, x_i represents density value of unit material, E_0 represents elastic modulus of unit material; P is penalty factor, generally taking value of 3 or greater than 3. When $x_i = 1$, $E(x_i) = E_0$ is entity unit. When $x_i = x_{\min}$, $E(x_i) \leq 10^{-9}$ is an empty element. Adding material interpolation form of penalty factor can make element material develop towards polarization and tend to E_0 or 0. The penalty factor can eliminate intermediate element to suppress appearance of checkerboard form. The expression is shown in equation 7.

$$C(x_i) = \frac{1}{2} \sum_{i=1}^{n} x_i^p u_i^T k_0 u_i \ (7)$$

Where, k_0 is stiffness matrix of entity element.

According to above formula, a beso method optimization model with penalty factor in form of material interpolation can be established. The optimization objective is strain energy of structure, and constraint is volume of structure. The structure is shown in following formula.

$$X = \left\{ x_1, x_2, \cdots, x_n \right\}^T \in \Omega \ (8)$$

$$C = \frac{1}{2} F^T U = \frac{1}{2} U^T K U = \frac{1}{2} \sum_{i=1}^{n} x_i^p u_i^T k_0 u_i \ (9)$$

$$V^* - \sum_{i=1}^{n} V_i x_i = 0 \ (10)$$

$$F = KU \ (11)$$

$$x_i = \left\{ x_{\min}, \quad 1 \right\} (i = 1, 2, \cdots, n) \ (12)$$

In two-way progressive building structure optimization algorithm, sensitivity value of a unit represents its contribution to stiffness of whole building structure as shown in Equation 13.

$$\frac{\partial C}{\partial x_i} = -\frac{p}{2} x_i^{p-1} u_i^T k_0 u_i \ (13)$$

In bi-directional progressive optimization method, value of design variable x is limited to 1 or $x_{\min}$, so sensitivity of element can be expressed as

$$\alpha_i = -\frac{1}{p}\frac{\partial C}{\partial x_i} = \begin{cases} \dfrac{u_i^T k_0 u_i}{2} & x_i = 1 \\ \dfrac{x_{\min^{p-1}} u_i^T k_0 u_i}{2} & x_i = x_{\min} \end{cases} \quad (14)$$

It can be seen from above formula that value of unit sensitivity is affected by penalty factor P. if P is large enough, sensitivity value of empty unit tends to 0. Deleting unit in this way is called "soft kill". Another method is to directly define design variable x as 0, which is called "hard kill" 5. The above formula can be simplified to

$$\alpha_i = -\frac{1}{p}\frac{\partial C}{\partial x_i} = \begin{cases} \dfrac{u_i^T k_0 u_i}{2} & x_i = 1 \\ 0 & x_i = x_{\min} \end{cases} \quad (15)$$

Where, sensitivity of cell connection point is weighted average of sensitivity of cells around connection point, as shown in Equation 16.

$$\alpha_j^n = \frac{\displaystyle\sum_{j=1}^{M} w_i \alpha_i^e}{\displaystyle\sum_{j=1}^{M} w_i} \quad (16)$$

Where, α_i^e represents sensitivity of ith unit; α_j^n sensitivity value of jth connection point, M represents number of individual cells related to sensitivity of connection point J; w_i represents weight of each cell, and its calculation method is shown in equation 17.

Where, r_{ij} represents distance between j-th connection point and i-th unit center.

$$w_i = \frac{1}{M-1}\left\{1 - \frac{r_{ij}}{\displaystyle\sum_{j=1}^{M} r_{ij}}\right\}(17)$$

In filtering region, weight w_i increases with decrease of r_{ij}, and closer cell is to node, greater weight, indicating that cell has a greater impact on sensitivity of connection point; Conversely, weight w_i; With increase of r_{ij}, effect of element on sensitivity of connection point is smalle $r_{\min} < r_{ij}$.

Convert sensitivity value of obtained connection point into sensitivity value of element, draw a circle with center of i-th element as circle center and $r_{\min}$ as radius, then use connection points contained in circular area to

calculate sensitivity value of i-th element, and calculation method is as shown in formula 18.

$$\alpha_i = \frac{\sum_{j=1}^{K} \omega(r_{ij}) \alpha_j^n}{\sum_{j=1}^{K} \omega(r_{ij})} \quad (18)$$

Where, K represents total number of connection points in $r_{\min}$; $\omega(r_{ij})$ is weight of node sensitivity. The calculation method is shown in following equation 19.

$$\omega(r_{ij}) = \begin{cases} r_{\min} - r_{ij} & r_{ij} < r_{\min} \\ 0 & r_{ij} \geq r_{\min} \end{cases} \quad (19)$$

According to above formula, closer node is to element, greater weight, indicating that node sensitivity has a greater impact on element sensitivity value, $\omega(r_{ij})$ It decreases linearly with increase of r_{ij}. when node is outside filter circle of element, node has no effect on sensitivity of element.

V. RESULTS

Construction, industry and transportation are the three major energy consumption sectors in China, and they are also important sources of greenhouse gas emissions. China's building energy consumption keeps increasing (Figure 4) China's building energy consumption has increased from 10% to nearly 30%, of which more than 97% are high energy consuming buildings. In the long run, it not only exacerbates the energy crisis, but also restricts the development of China's economy.
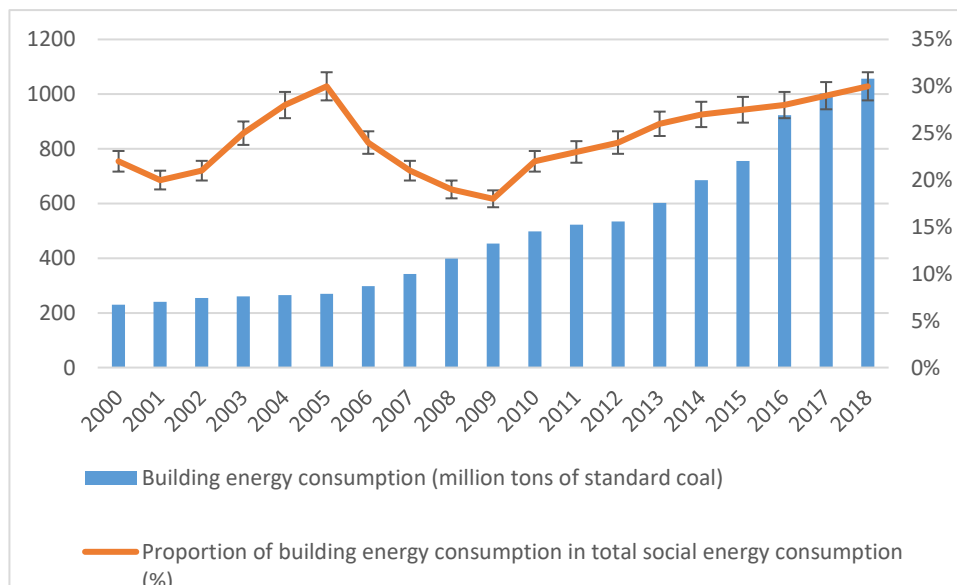

Figure4 proportion of building energy consumption in total social energy consumption

China's urbanization rate has been increasing, reaching 59.58% by end of 2018, and annual new construction area exceeds total annual area of all developed countries, especially construction area of residential buildings has

climbed sharply (Figure 5), and in recent years has been occupying first place in total construction volume. From 6.652 billion square meters in 2001, accounting for 21%, to 27.9 billion square meters in 2014, accounting for 44%, volume of residential construction has increased more than threefold. At same time, energy consumed by residential buildings has also increased, such a large construction base, such high building energy consumption, constantly aggravating social energy crisis and environmental burden, solving problem of residential building energy consumption is a challenge that must be broken in process of sustainable development in China.
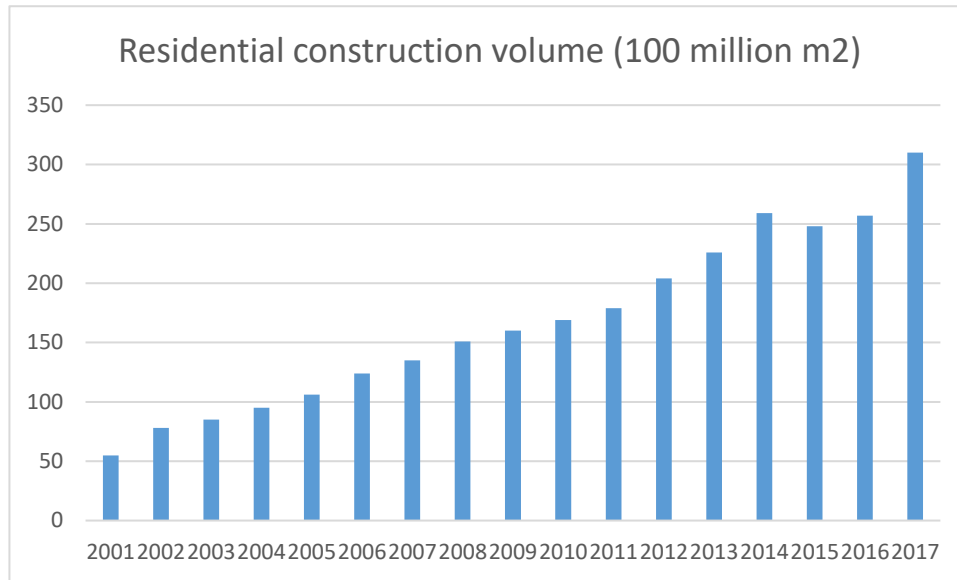

Figure 5 annual construction area of residential buildings (urban residential buildings) in China

The construction industry is pillar of China's economic development, and its total output value is increasing year by year and maintaining a good growth trend (Figure 6). With popular application of digital information technology in construction industry, way of thinking of using information and data-aided design is changing inherent mode of traditional design industry, and information integration role of BIM technology for architectural design is valued and continuously applied in all stages of construction projects to promote project process in an orderly manner with work mode of collaborative design, which improves design efficiency and design quality, and its three-dimensional visualization of dynamic design The 3D visualization of dynamic design process significantly reduces problems of errors, omissions, touches and shortages at a later stage. More importantly, use of BIM technology brings innovation in method of building energy saving, which can be used throughout whole life cycle of building design, especially in early stage of building creation, real-time dynamic simulation, and feedback performance evaluation results provide timely and accurate quantitative data for building energy saving, which is real practice of building sustainability. However, due to late start of China's construction information technology, breadth of popularization and application depth is far from enough, level of information technology in construction industry is low, average level of utilization of information technology in construction industry is 0.03%, and international average level of 0.3% is about 10 times (Figure 7). Therefore, to speed up deep use of building information technology, break through traditional mode, is key to improve energy-saving work.
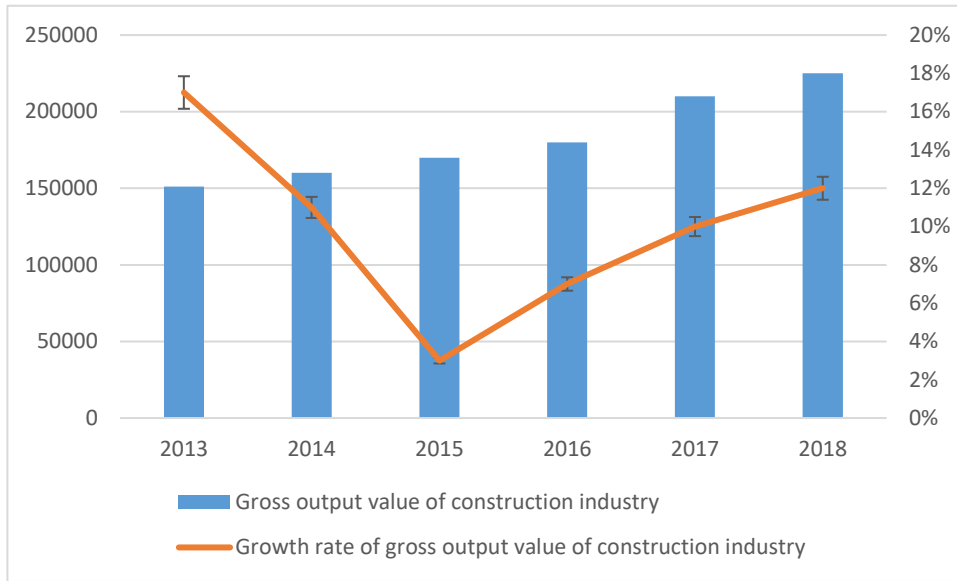
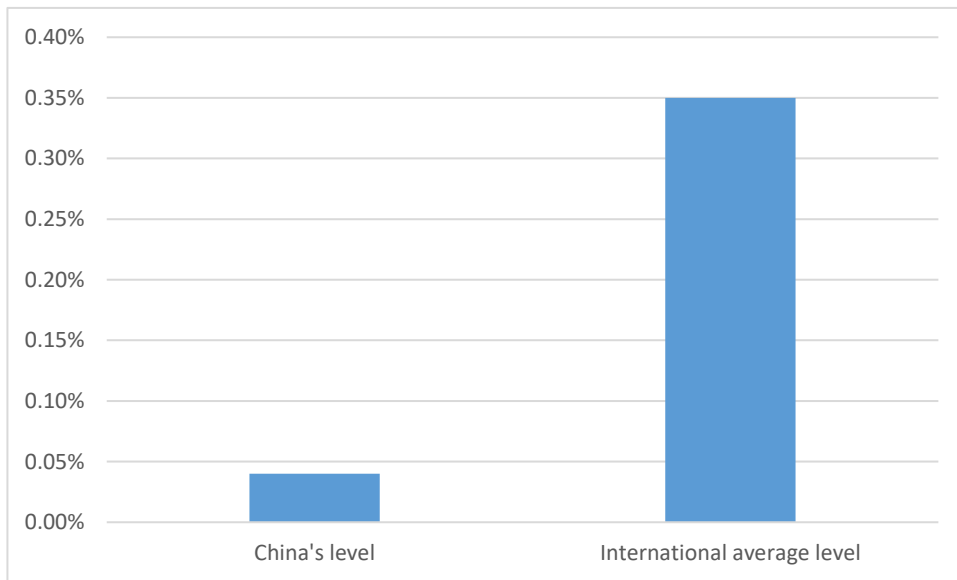**Figure 6 gross output value and growth rate of China's construction industry**

Figure 7 comparison of building informatization level at home and abroad

Building energy consumption in China is divided into public buildings, urban housing and rural housing. China's urbanization rate has increased from 29% to nearly 59%, and the market capacity of commercial housing has increased from 100million square meters to nearly 1.7 billion square meters. From the total construction volume of three types of buildings in 2016(Figure 8), construction area of urban residential buildings is 27.9 billion m2, accounting for 44% of total, and carbon emissions are in first place. A large number of urban residential buildings occupy less and less land, combined with special geographical environment and climate characteristics of Chongqing, this paper takes residential buildings in Chongqing, i.e. urban residential buildings, as research object, and explores energy-saving design method of residential buildings in Chongqing based on BIM technology[21,22].
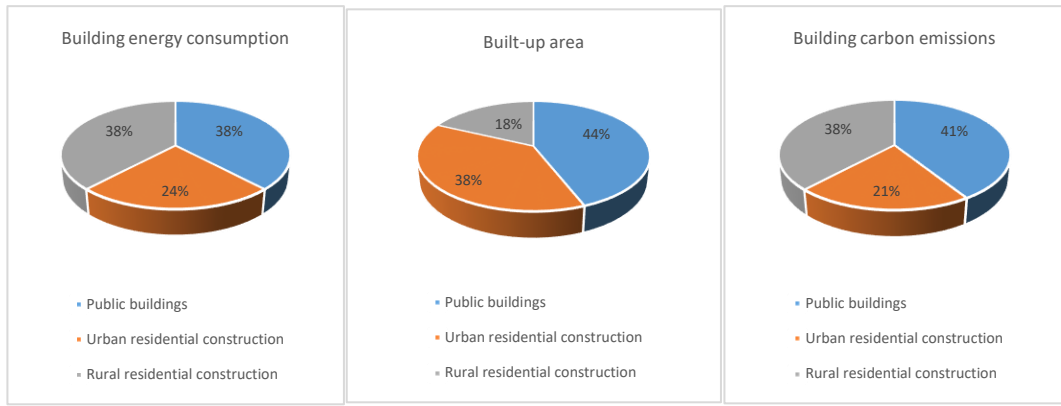
Figure 8 national building energy consumption data (2016)

The building orientation determines indoor lighting and ventilation, which in turn affects difference of building energy consumption. The best orientation of residential buildings in Chongqing is from 100 to 10°S ESE, and suitable orientation is from 30°S ESE to 30°S WSE, while unsuitable orientation is from E and W. According to research building orientation statistics can be seen (Figure 9), Chongqing residential building orientation is relatively free than northern region, often depending on overall layout of form of beautiful, that is, overall composition of beauty; or depending on form of enclosed courtyard, that is, setting of courtyard landscape; or depending on direction of surrounding roads, etc., less according to climate characteristics of Chongqing area to design, which inevitably appear bad orientation affects lighting and ventilation, building The problem of energy consumption[23,24]. In research residence, about 1/3 of buildings are arranged to east and west, and main living rooms are not set up with certain sun-shading measures, although there are still many residents choose, but main reason is developer's appropriate preferential policies to reduce pressure to buy, but let residents in subsequent long time to bear huge energy expenses, and environmental comfort is not met.
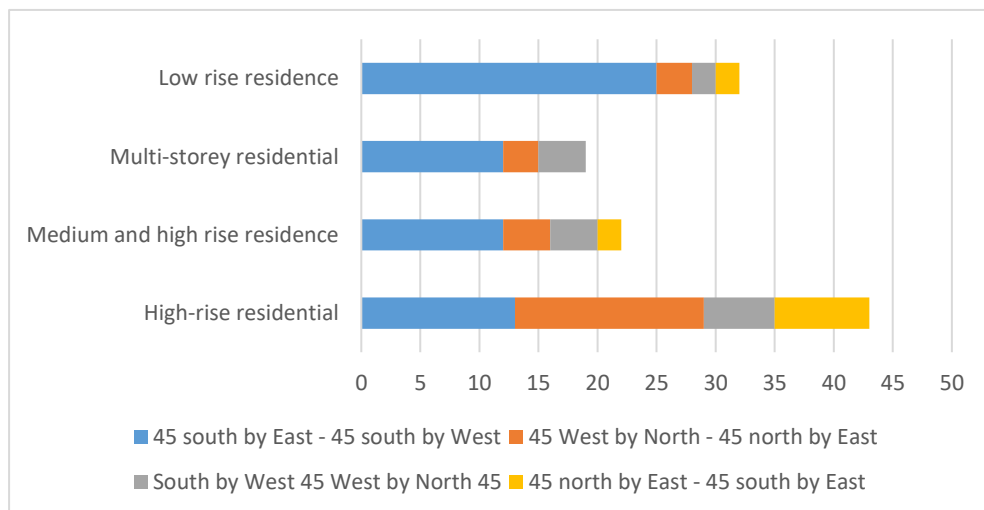

Figure 9 statistical table of building orientation

Through BIM information model and performance simulation data, we can comprehensively understand movement law of local airflow (wind speed, wind direction, wind temperature, wind frequency, etc.), combine favorable resources of site, consider functional needs of building and human comfort requirements, refer to impact of different wind speeds on human indoor activities in Table 1, reasonably use angle change between building

orientation and dominant wind direction, and come up with a range of building orientation suitable for local wind environment to assist designers in proposing more suitable residential energy-saving design solutions.

Table 1 impact of wind speed on human body and indoor activities

Wind speed (m/s)	Equivalent to temperature drop (℃)	Impact on comfort
0.05	0	The air is still and I feel a little uncomfortable
0.21	1.12	Hardly feel wind
0.41	2.0	Can feel wind and feel comfortable
0.81	2.9	Strong wind is felt, but in some windy areas, when air is hot, it is acceptable
1.0	3.4	Good wind speed for natural ventilation in hot and dry areas
2.1	4.0	Good wind speed for natural ventilation in hot and humid areas
4.5	5.1	It still feels "breezy" outdoors

The BIM-based energy analysis software EcoDesigner compares different envelope materials to visually evaluate performance of each envelope material and finally determine its solution, so that building can meet design requirements and achieve good energy-saving effects. According to relevant data charts in energy consumption evaluation report, it is easy to compare energy consumption differences of different materials and structural forms in process of building envelope design, which can effectively guide energy-saving design. According to different combinations of exterior wall, exterior window and roof materials and structure forms, energy consumption simulation and analysis were carried out, and simulation results are shown in Table 2.

Table 2 energy consumption of enclosure structure with different exterior wall materials

Programme	Exterior wall	External window	Roofing	Average U value of building shell	External U value	Opening U value	Energy consumption kwh/m^2 year	co_2 emissions kg/m^2 year
1	A	A	A	2.65	1.97	3.01-3.33	125.1	21.07
2	B	A	A	2.29	1.55	3.02-3.33	116.22	19.61
3	C	A	A	1.96	1.43	3.01-3.33	108.57	19.25
4	D	A	A	1.76	1.21	3.01-3.32	107.52	18.81
5	E	A	A	1.35	0.87	3.01-3.32	103.07	18.87

Through performance analysis of BIM technology, it can quantify difference of energy consumption of various solutions for designers, and guide selection of suitable material type and structure thickness to meet design requirements and thermal performance without wasting any material, and truly realize building material saving. In use space of residential buildings, through key performance values of different areas and energy balance, it can efficiently and accurately assist designers in architectural design process to adjust unreasonable energy consumption, hitting pain points and quickly reducing energy waste in some spaces.

VI. CONCLUSIONS

China's economic construction and construction industry are closely linked, and in past two decades, year-on-year increase in construction volume has brought us rapid economic development as well as environmental crisis. Under influence of concept of sustainable development, energy-saving design of residential buildings in China has become more and more stringent, and people's physical and psychological needs for living space have also gradually increased, but because most developers regard residential buildings as commodities, design suitability of most residential buildings is low and energy-saving effect is poor. Therefore, based on high information integration capability of BIM technology, this paper explores energy saving and specific strategies for residential buildings in Chongqing through literature research and field studies on residential buildings in Chongqing, from conceptual planning stage, preliminary design stage, and program deepening stage, to provide designers with quantitative references for program selection and design decision, and assist in more energy-saving program design.

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