Optimization Design of Building HVAC Systems Based on Digital Twin Technology

Daoran Zhang

Anhui Zhuyuan Engineering Technology Co., Ltd., Hefei, Anhui, 231500, China

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Abstract: As the problem of building energy consumption is becoming more and more obvious, and people's demand for indoor environment comfort is increasing, the optimal design of building heating ventilating and air conditioning (HVAC) system becomes extremely urgent. This article focuses on the optimal design of building HVAC system based on digital twinning technology. Firstly, this article expounds the research background, purpose and significance, and points out the limitations of traditional design methods. Through in-depth analysis of digital twin technology and the basic theory of building HVAC system, it shows that this technology is feasible and advantageous for HVAC system. Then the paper introduces the process of building HVAC system model construction based on digital twinning technology in detail, covering digital representation of physical entities, virtual model construction and data collection and transmission. Then, the optimization design strategy based on this model is put forward, the optimization goal is clear, the key influencing factors are analyzed and the optimization method is formulated. The practical case shows that this optimization design strategy can effectively improve the energy efficiency of the system, reduce energy consumption by about 15%-20%, and improve indoor comfort, which provides a feasible method for the optimal design of building HVAC system.

1. Introduction

Under the background of global advocacy of energy saving and emission reduction and people's increasing demand for indoor environment comfort, the optimal design of building HVAC system is particularly critical [1]. The performance of HVAC system is directly related to the energy efficiency and operating cost of buildings [2]. Traditional HVAC system design methods are mostly based on experience and simplified models, and it is difficult to accurately respond to the complex and changeable building environment and user needs, resulting in low system operation efficiency and high energy consumption [3].

Digital twin technology has emerged in many fields with its excellent ability of high-fidelity simulation, real-time monitoring and dynamic optimization of physical entities in virtual space [4] Introducing digital twin technology into the optimal design of building HVAC system is expected to break through the limitations of traditional design and achieve a significant improvement in system performance [5]. By constructing the virtual model corresponding to the physical entity and with the help of real-time data interaction, the HVAC system can be accurately simulated and analyzed, and the operation performance of the system under different working conditions can be predicted in advance [6].

At present, the research on the application of digital twin technology in the field of architecture is increasing gradually, but the in-depth exploration on the optimization design of HVAC system is still relatively scarce. Some studies only stay at the theoretical level, lacking practical case verification; However, some applications fail to fully tap the potential of digital twin technology, and the optimization effect is not satisfactory [7]. In view of this, it is of great theoretical and practical significance to study the optimal design of building HVAC system based on digital twin technology. On the one hand, it is helpful to improve the theoretical system of digital twin technology in the field of building energy; On the other hand, this study can provide practical

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optimization design methods for practical projects and help the construction industry achieve the goals of energy saving, emission reduction and sustainable development.

2. Digital Twin Technology and Building HVAC System

Digital twinning technology is a technology that comprehensively maps and simulates physical entities by digital means. It covers key technologies such as multidisciplinary modeling, big data and Internet of Things [8]. With the help of these technologies, a virtual model that is highly similar to a physical entity can be built in the virtual space, and the state, behavior and performance of the physical entity can be reflected in real time. The purpose of building HVAC system is to provide suitable indoor thermal and humid environment and air quality for buildings. The system is mainly composed of cold and heat source equipment, transmission and distribution network and terminal devices [9]. Its operation principle is that cold/heat is generated by cold/heat source equipment, which is transported to the terminal device through the transmission and distribution network to meet the requirements of indoor environment regulation. It is feasible and significant to apply digital twin technology to building HVAC system. Digital twin technology can integrate the data of each component of HVAC system, realize the fine simulation and analysis of the system, and then provide strong support for the optimal design of the system, and improve the operating efficiency and energy utilization rate of the system.

3. Digital Twinning Building HVAC System Model Based on Digital Twinning Technology

3.1. Digital representation of physical entities

To build a building HVAC system model based on digital twin technology, it is needed to start with the digital expression of physical entities, the construction of virtual models, data collection and transmission, and realize comprehensive and accurate simulation and analysis of the system.

Physical entities cover all kinds of equipment, pipes and building space of HVAC system. For the equipment, it is needed to collect its specifications in detail, such as cooling/heating power, energy efficiency ratio, air volume and wind pressure of fans. Take the common water-cooled chiller-Clemente FOCSWATER.E series as an example (see Table 1). Its refrigeration capacity, input power, refrigerant type and other parameters are the basis of accurate simulation of equipment operation. For pipelines, it is needed to clarify the information such as pipe diameter, length, material and connection mode. These parameters affect the flow characteristics and energy transfer efficiency of fluid in the pipeline. The geometric size of the building space and the thermal performance of the envelope are equally critical. They determine the indoor heat gain and cold heat demand.

Table 1 Main Parameters of a Water-Cooled Chiller Unit

Parameter Name	Specific Value
Cooling Capacity (kW)	500
Input Power (kW)	120
Refrigerant Type	R134a
Chilled Water Flow Rate (m^3/h)	86
Cooling Water Flow Rate (m^3/h)	105
Parameter Name	Specific Value

3.2. Construction of virtual model

Virtual model construction is the core of digital twin model. Using professional modeling software, such as Energy Plus, TRNSYS, etc., combined with the digital information of physical entities to model. Taking Energy Plus as an example, the indoor and outdoor heat exchange process can be simulated based on the geometric model and envelope parameters of the building. For HVAC equipment, the dynamic simulation of equipment operation state is realized by inputting equipment characteristic curve and operation control logic. When constructing the transmission and distribution system model, the fluid flow equation is set according to the pipeline parameters to simulate the fluid flow and energy distribution in the pipe network. Different component models need to be coupled to ensure the accuracy of the whole system simulation. For example, connecting the cold and heat source equipment model with the transmission and distribution network model can simulate the whole process of cold and heat from generation to transportation to the end, and analyze the energy loss and operation efficiency of each link of the system.

3.3. Data acquisition and transmission

Data acquisition is the key link to realize digital twinning. Various sensors, such as temperature sensor, pressure sensor, flow sensor, etc., are arranged in the HVAC system to monitor the operating parameters of the system in real time. For example, temperature sensors are installed at the inlet and outlet of chilled water pipeline to obtain the supply and return water temperature of chilled water, so as to calculate the refrigeration capacity of the system. The collected data is transmitted to the data center through wired or wireless communication network. In order to ensure the stability and real-time performance of data transmission, industrial communication protocols can be adopted, such as Modbus and BACnet. Data is encrypted and verified during transmission to prevent data loss or error. After cleaning and preprocessing, the data transmitted to the data center is used to update the virtual model, realize the real-time synchronization between the physical entity and the virtual model, and provide accurate data support for the optimal design and operation regulation of the system. With the help of digital representation of physical entities, virtual model construction and data collection and transmission, a building HVAC system model based on digital twinning technology can be constructed. Figure 1 shows the model structure of building HVAC system based on digital twinning technology.

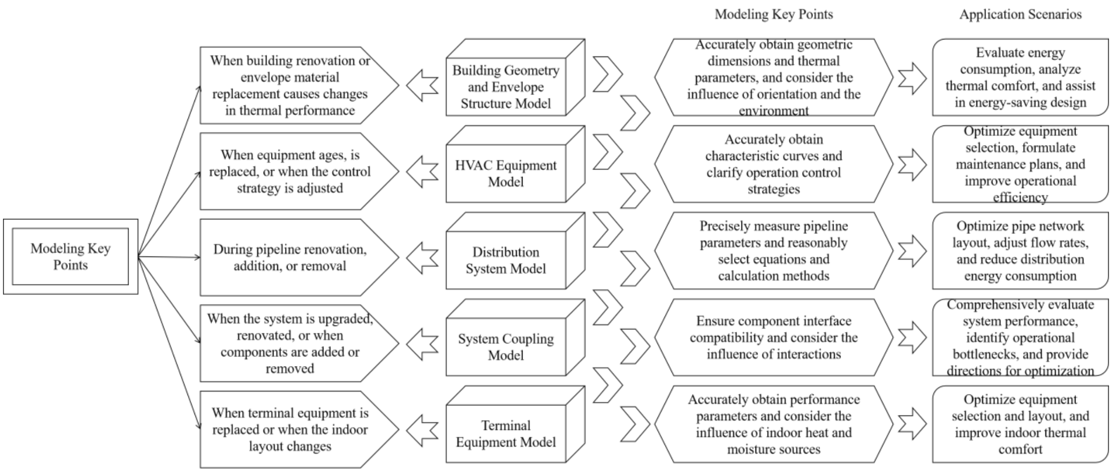

Figure 1 Digital Twin-based Air Conditioning System Model

4. Optimal Design Strategy of HVAC System

4.1. Clear optimization objectives

The primary and crucial step in optimizing HVAC systems is to clearly define the optimization objectives. The clarity of optimization objectives is like pointing out the direction for the entire optimization project, which can make subsequent work more targeted and efficient. Generally speaking, the optimization objectives of HVAC systems mainly include reducing energy consumption, improving indoor comfort, and enhancing system operational stability. Taking the HVAC system of a large commercial building as an example, the building is densely populated and has high requirements for indoor environmental quality. Setting energy consumption reduction as the key optimization objective while ensuring the comfort of indoor personnel. This is because commercial buildings usually operate for a long time, and HVAC systems consume a huge amount of energy. Reducing energy consumption not only effectively reduces operating costs, but also conforms to the current environmental protection concept of energy conservation and emission reduction. We hope to minimize energy consumption through a series of optimized designs without compromising the quality of the indoor environment.

In order to make the optimization objectives more operable and measurable, a quantitative target of achieving an energy consumption reduction rate of 15% -20% has been set, as shown in Table 2. Before optimization, the total energy consumption was 500000 kWh/year, and after optimization, the target is set at 400000-425000 kWh/year; Before optimizing the refrigeration energy consumption, the target is 300000kWh/year, and after optimization, the target is 240000-255000kWh/year; The pre optimization target for heating energy consumption is 150000 kWh/year, and the post optimization target is 120000-127500 kWh/year. Meanwhile, it is expected that indoor comfort can be improved by 10-15%. The main equipment involved in this optimization measure includes cold and heat source equipment, water pumps, fans, etc. For the refrigeration and heating processes, it also involves chiller units, cooling towers, boilers, air source heat pumps, etc.

Table 2 Energy Consumption Comparison of HVAC System Before and After Optimization

Comparison Item	Energy Consumption Before Optimization (kWh/year)	Target Energy Consumption After Optimization (kWh/year)	Energy Reduction Rate (%)	Expected Indoor Comfort Improvement (%)	Major Equipment Involved in Optimization Measures
Total Energy Consumption	500,000	400,000-425,000	15-20	10-15	Heat/Cold Source Equipment, Water Pumps, Fans
Cooling Energy Consumption	300,000	240,000-255,000	15-20	-	Chillers, Cooling Towers
Heating Energy Consumption	150,000	120,000-127,500	15-20	-	Boilers, Air-Source Heat Pumps

4.2. Analyze key influencing factors

In-depth analysis of the key factors affecting the performance of HVAC system is the basis for formulating effective optimization strategies. The accuracy of load forecasting has a significant impact on system energy consumption and comfort. Factors such as personnel activities and external climate conditions of buildings will lead to dynamic changes in load. For example, during the high temperature period in summer, the solar radiation increases and the indoor cooling load increases. The equipment operation strategy is also very important. The combination mode of start-stop time and operation frequency of different equipment directly affects the system energy consumption and operation effect. The hydraulic balance of transmission and distribution system can not be ignored. If the hydraulic imbalance of the pipe network, it will lead to uneven cold and heat in some areas, reduce indoor comfort and increase energy consumption.

4.3. Formulate optimization methods

Based on the digital twin model, many optimization methods can be adopted. By simulating the operation performance of the system under different working conditions, the analysis process can reveal the influence degree of each factor on the optimization goal. For example, system operators can observe the changes of system energy consumption and indoor temperature by changing the number of running cold and heat source equipment and load distribution. Intelligent algorithms can be used in the optimization process, such as genetic algorithm, particle swarm optimization and so on. Taking the genetic algorithm as an example, the algorithm designer can take the system equipment parameters, operation strategy, etc. as gene codes, and realize the search for the optimal solution through operations such as selection, crossover and mutation. In practical application, the actual operation data can be used to calibrate and verify the model, thus improving the reliability of the optimization results.

Aiming at the HVAC system of an office building, the digital twin model simulation shows that the fresh air operation mode in transition season can significantly reduce energy consumption. At the same time, the frequency conversion control strategy of water pump is optimized, and the speed of water pump is adjusted in real time according to the end load, so as to realize energy saving of transmission and distribution system. The operation shows that the energy consumption of the optimized system is reduced by about 18%, which achieves the expected optimization goal and effectively improves the overall performance of the system. By defining the optimization goal, analyzing the key influencing factors and using scientific optimization methods, the optimal design strategy of HVAC system based on digital twin model can improve the energy efficiency and indoor comfort of the system.

5. Conclusions

This article focuses on the optimal design of building HVAC system based on digital twin technology, and has achieved a series of results. The research shows that the digital twin technology provides an innovative way for the optimal design of HVAC system. By constructing a digital twin model covering digital representation of physical entities, virtual model construction and data acquisition and transmission, the accurate simulation and analysis of the system are realized. Based on this model, the optimal design strategy is defined, and the key influencing factors such as load forecasting and equipment operation strategy are analyzed, and the system performance is improved by simulating different working conditions and intelligent algorithm optimization. The case shows that the energy consumption of the system is significantly reduced and the indoor comfort is improved, which proves the feasibility and effectiveness of the optimization strategy.

However, there are still some limitations in this study. On the one hand, in the data acquisition process, the accuracy and stability of some sensors may affect the data quality, and then have a subtle impact on the accuracy of the model. On the other hand, the actual building environment is complex and changeable, and the simulation accuracy of the model needs to be further improved when dealing with extreme working conditions or special building structures.

With the continuous development and integration of digital twin technology and related technologies such as sensors and big data, it is expected to achieve more accurate model construction and optimization. Further research can consider expanding the application scope of the model, enhancing its adaptability to complex building environment, and further improving the ability of data acquisition and processing.

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