A simulation study for a low carbon consumption HVAC project using EnergyPlus

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Abstract
This paper presents how to use EnergyPlus to model a complex building by describing in detail EnergyPlus input parameters of a designing factory. It reports energy consumption, energy operation cost and environment impact of a heating, ventilation and air conditioning (HVAC) system used for space cooling and space heating in the factory. In this study, the HVAC system (System 1), a system with a nature gas boiler for space heating and a chiller for space cooling, is simulated using EnergyPlus. Moreover, the above-mentioned three indicators are calculated for HVAC System 2, the ground source heat pump system, based on the simulation results of System 1, and the annual economic and environmental benefits of the two systems were compared.

Keywords: EnergyPlus; simulation; GSHP

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1 INTRODUCTION

Energy consumption includes energy consumption due to productions, energy consumption due to transportations and energy consumption by buildings; among which, buildings consume a large amount of total society energy. In China, buildings consume \( \sim 25 - 30\% \) of the total national primary energy [1]. Moreover, heating, ventilation and air conditioning (HVAC) systems have a great contribution to the total building energy consumption to obtain a comfortable thermal environment for people living or working in those buildings or a proper condition for industrial production. In developed countries, electricity power for air conditioning accounts for 30\% of total national electricity power, whereas in China, the HVAC systems of some large industrial enterprises accounts for 40\% of the total energy consumption of those industries [2].

Buildings are divided into two categories: civil architecture and industrial architecture. In the aspect of energy saving by buildings, more attention are focussed on energy consumption of civil architecture. According to an investigation in 2008, the ratio between industrial and civil buildings in China was 53\%:47\% in total building construction investment [3]. In fact, energy consumption by large industrial buildings accounts for a considerable proportion of the total energy consumed by the society, because a large amount of energy is consumed to satisfy special thermal requirements of production or storage processes of industrial buildings.

In that there are special requirements for production or storage processes; it is obvious that industrial buildings' energy consumption and influence on environment may differ significantly than that of domestic architectures in terms of routine usage of energy, energy source composition, the environment impact and so on. To analyze the building load and the energy consumption of the industrial buildings, a comprehensive evaluation method of energy usage and environment influence of the analyzed building with different HVAC systems should be established. Building energy simulation is proved to be a reliable and effective way to evaluate the thermal condition and energy cost of a specific building. For new buildings, building energy simulation plays a significant role in performing comparison, optimization, code compliance and economic analysis of the design options [4–6].

As a result, annual and multi-year simulation consequently becomes an invaluable tool in the designing period of such buildings [7]. In this paper, EnergyPlus is used to simulate the analyzed factory with an HVAC system (System 1): a system with a nature gas boiler for space heating and a chiller for space cooling. Simulation results of the hourly building load of the analyzed factory round a year are presented, and proportions of energy consumption of main HVAC equipment and lightings are also analyzed. Then, energy consumption, energy operation cost and environment impact of the HVAC system (2), ground source heat pump (GSHP) system, are calculated based on the simulation results of System 1, and the comparison of annual economic and environmental benefits between the conventional (System 1) and GSHP (System 2) systems is carried out. Moreover, some factors affecting energy consumption are discussed, and
then several energy-saving suggestions and practical measures are proposed.

2 DESCRIPTION OF THE BUILDING

2.1 Building model
The factory is located in Nanjing city of Jiangsu Province. It has two floors of part and covers an area of 46,770 m² with a building area of 61,050 m². The architectural appearance is shown in Figure 1.

The building is divided into 14 thermal zones; of which, 9 zones are air conditioned. The isometric cut of the first (ground) floor, shown in Figure 2, has 9 zones (zone:001 to zone:009). Similarly, the isometric cut of the second floor consist of another 5 zones, shown in Figure 3. The air-conditioned zones in the factory are classified into three functional areas:

(a) Production area, includes zone:001, zone:005 and zone:013 (marked white color in Figures 2 and 3);
(b) Office area, includes zone:009 and zone:010 (marked blue color in Figures 2 and 3);
(c) Storage area, includes zone:002, zone:003, zone:004 and zone:011 (marked orange color in Figures 2 and 3).

Meanwhile, the other five non-air-conditioned zones, such as zone:006, zone:007, zone:008 on the first floor and zone:012, zone:014 on the second floor, are marked with green color in Figures 2 and 3.

Figure 1. Isometric view of the analyzed factory.

Figure 2. Isometric cut of the first story of the analyzed factory.

Figure 3. Isometric cut of the second story of the analyzed factory.
The exterior walls of this factory have a 400-mm autoclaved aerated concrete block (ALC) layer insulated by a 30-mm expandable polystyrene board (EPS) layer, and heat transfer coefficient of exterior walls is 0.346 W/(m²·K). The exterior roofs with a U-value of 0.296 W/(m²·K) are made of a 150-mm ALC layer insulated by a 100-mm EPS layer, and a 5-mm color steel plate layer as an exterior surface. The exterior windows are insulated by double Low-e glazing glasses with the U-value of 1.364 W/(m²·K) and a solar heat gain coefficient (SHGC) of 0.482. The U-values of exterior walls and windows and the value of SHGC of windows are all shown in the file named Report: EnvelopeSummary reported by EnergyPlus.

The value of parameters such as lighting level, electric equipment level and the supply air flow rate in every zone is all derived from the design explanation of the factory.

For some parameters not determined during the design period, the following data and assumptions were made during the modeling of the factory:

1. Employees per zone floor area: three persons per 1000 m² in the production area, eight persons per 1000 m² in office area and two persons per 1000 m² in the storage area. For non-air-conditioned zones, staff in zone:006 and zone:007 is assumed to be three persons per 1000 m². The value for zone:008 (corridor) and zone:014 (plenum) is 0. The average activity level of heat gain from each person of the whole factory is 131.8 W [8].

2. The air handling system for each zone in the storage area as well as in the office area is a four-pipe fan coil system for space cooling or heating; The task air supply only for cooling is applied in zones in the production area in that there are no strict requirements of constant thermal condition and they do not need space heating, task air supply is applied. The working period of the air handling systems in the office area and in the production area is from 31 March to 31 October. To meet the strict requirements of constant thermal environment of various materials in different storage processes, four-pipe fan coil system in each zone of the storage area as an air handling system works for 24 h all year round to keep the temperature in the zone constant. The thermostat of zone:002 is set to 35°C for space heating or cooling; The thermostat of zone:003 is set to 28°C for space heating or cooling; The thermostat of zone:004 is set to 25°C for space heating or cooling for 24 h all year round.

2.2 Building operation
Because of the special requirements of the production and storage processes of the analyzed factory, most electric equipments of the production area (zone:001, zone:005 and zone:013) should be on working from 8:00 to 24:00 all year without exception. The operation schedule is the same for the office area (zone:009 and zone:010), there are three-shifts and workers take their turns to work every day. Equipments of the storage area (zone:002, zone:003, zone:004 and zone:011) must run 24 h every day of the whole year under their thermal conditions. For detailed operation schedule of lights, people and equipments of the office area, production area and the storage area, see Figure 4.

In the office area, thermostats are set to 26°C at cooling time and 18°C at heating time. In the production area, considering that zones in that area do not have strict requirements of constant thermal condition and they do not need space heating, task air supply is applied. The working period of the air handling systems in the office area and in the production area is from 31 March to 31 October. To meet the strict requirements of constant thermal environment of various materials in different storage processes, four-pipe fan coil system in each zone of the storage area as an air handling system works for 24 h all year round to keep the temperature in the zone constant. The thermostat of zone:002 is set to 35°C for space heating or cooling; The thermostat of zone:003 is set to 28°C for space heating or cooling; The thermostat of zone:004 is set to 25°C for space heating or cooling for 24 h all year round.

2.3 HVAC systems for modeling
In this section, System 1, an HVAC system with a nature gas boiler for space heating and a chiller for space cooling, simulated using EnergyPlus is described in detail.

As is introduced in InputOutputReference, which is a reference comes with EnergyPlus software, the input for SimulationControl allows the user to specify what kind of calculations a given EnergyPlus simulation will perform. For instance, the user may want to... Or the user might have all flow rates and equipment sizes already specified and desire an annual weather without any preceding sizing calculations [8]. In this model, some parameters of the main components, such
as the boilers and the chillers, are decided in order to meet the rated capacity of heating or cooling of all factory derived from the design explanation of this factory. Meanwhile, other components, such as the fans and the pumps, are dimensioned by adjusting the function of the EnergyPlus software.

HVAC System 1 is consisted of seven main loops:

- Loop (1a): an air loop for task air cooling in zones in the production area;
- Loop (1b): a chiller water loop for making chiller water for task air supply;
- Loop (1c): a condenser loop of chiller in Loop (1b);
- Loop (2a): an air loop for cooling and heating in zones in the storage area and office area;
- Loop (2b): a chiller water loop for making chiller water for space cooling in the storage area and the office area;
- Loop (2c): a condenser loop of chiller in Loop (2b);
- Loop (2d): a hot water loop for making hot water for space heating in the storage area and the office area.

The scheme of HVAC System 1 is shown in Figure 5.

### 3 Modeling and Calculation

#### 3.1 Building energy simulation software

EnergyPlus, version 6.0, is used in building energy simulation of this modeled factory with HVAC System 1: a system with a nature gas boiler for space heating and a chiller for space cooling. The software is very powerful in the simulation of energy consumption and environment influence of a real or a designing building integrating main functions of DOE-2 and BLAST [9]. As a whole building energy analysis tool, it can simulate and precisely calculate hourly load and energy consumption all year of a building and its HVAC system.

#### 3.2 Calculation of energy consumption of the building with System 2

It is assumed that building load and energy consumption to meet the rated capacity of heating or cooling of the factory with different HVAC systems is equal. So, building load of HVAC System 1 simulated by EnergyPlus is used to calculate that of HVAC System 2: the GSHP system with a constant coefficient of performance (COP) of the heat pump using the following equation:

\[
E_{\text{ele, GSHP}} = \frac{Q_{\text{building}}}{\text{COP}}
\]

where \(E_{\text{ele, GSHP}}\) stands for yearly energy consumption of GSHP system, \(Q_{\text{building}}\) stands for yearly building load simulated by EnergyPlus and COP stands for coefficient of performance of the heat pump used in HVAC System 2. For cooling, COP is assumed to be 4.7, and for heating, it is assumed to be 4.3.
3.3 Primary energy consumption

The total yearly primary energy consumption of HVAC System 1 and HVAC System 2 is calculated using the following equation:

$$E_{\text{total}} = E_{\text{gas}} + E_{\text{electricity}} \cdot R \tag{2}$$

where $E_{\text{total}}$ stands for yearly primary energy consumption of HVAC system, $E_{\text{gas}}$ stands for yearly consumption of nature gas (for GSHP system, $E_{\text{gas}} = 0$), $E_{\text{electricity}}$ stands for yearly consumption of electrical energy and $R$ stands for primary energy consumption coefficient which is a ratio of total input energy of the energy resources (hydro, coal, oil and natural gas) and the final produced electric energy [10]. The value of $R$ is set to be 2.579 according to the calculation method provided by International Union of Producers and Distributors of Electric Energy (UNIPEDE) [11].

3.4 Operating costs

The total yearly operating costs to run a system are calculated using the following equation:

$$C_{\text{total}} = E_{\text{gas}} \cdot f_{\text{gas}} + E_{\text{electricity}} \cdot f_{\text{electricity}} \tag{3}$$

where $C_{\text{total}}$ stands for the total yearly operating costs to run each system, $f_{\text{gas}}$ stands for the specific cost of consumption of natural gas (¥/GJ) and $f_{\text{electricity}}$ stands for the specific cost of consumption of electrical energy (¥/GJ). In Nanjing, the unit price of natural gas for commercial use is nearly 3.3 yuan/m$^3$, and commercial electricity tariff is $\sim$0.8 yuan/kWh.

3.5 Carbon dioxide emission

The total yearly carbon dioxide emission during each system operation is calculated using the following equation:

$$S_{\text{total}} = E_{\text{gas}} \cdot g_{\text{gas}} + E_{\text{electricity}} \cdot g_{\text{electricity}} \tag{4}$$

where $S_{\text{total}}$ stands for the total yearly carbon dioxide emission during each system operation, $g_{\text{gas}}$ stands for specific carbon dioxide emission factor of natural gas (kg/GJ) and $g_{\text{electricity}}$ stands for the specific carbon dioxide emission factor of electrical energy (kg/GJ).

4 RESULTS AND DISCUSSION

In this section, the simulation results of annual operation of HVAC System 1, a system with a nature gas boiler for space heating and a chiller for space cooling, are reported. The hourly building loads, calculated with weather data for Nanjing, Jiangsu, are shown in Figure 6. And then, the proportions of energy consumption of each main HVAC equipment and lightings are presented in Figure 7.

Then, an energy saving and environment evaluation of the two HVAC systems based on the calculation results are also introduced in three aspects: energy consumption, energy costs and influence on the environment.

Here, those calculation results of HVAC System 2 are mainly based on COP of heat pump which is assumed to be 4.7 for cooling and 4.3 for cooling in this paper. Considering that the effect which COP of the GSHP system has on the calculation results of System 2, the calculation results of HVAC System 2 with different COP are presented in Figures 10–12 to provide a comprehensive comparison.

4.1 Results

Annual energy consumption of nature gas, electrical energy and primary energy consumption of each HVAC system is shown in Figure 8.

Annual operation energy costs of nature gas, electrical energy and the total amount of each HVAC system are shown in Figure 9.

Figure 6. Annual building load of all factories with HVAC System 1.
4.2 Discussion
As shown in Figures 8–10, the results of annual energy consumption, operation energy costs and carbon dioxide emission of HVAC Systems 1 and 2 are compared and analyzed.

Energy consumption will be analyzed and discussed by comparing all types of energy consumption in each HVAC system. From Figure 8, it may be found out that the values of nature gas energy and electrical energy for heating and cooling in HVAC System 1 are almost the same. In addition, it can be seen that the total yearly primary energy consumed by HVAC System 1 is much higher than by System 2. Consequently, HVAC system 2 has lower primary energy consumption.

Operation costs of the two HVAC systems are compared based on the data showed in Figure 9. The energy costs of System 2 are almost 33.8% of costs of System 1. That is to say HVAC System 2 needs a lower operation costs than the traditional system.

The environmental analyses refer to comparison of calculated carbon dioxide emissions of the systems as a consequence of their operation. From Figure 10, it can be concluded that carbon dioxide emission of System 2 is nearly 39.1% of that of System 1.

Calculation results of HVAC System 2 with different COP are also presented and compared in Figures 11–13. As shown in Figures 11–13, primary energy consumption,
operation costs and carbon dioxide emission of HVAC System 2 increases as the COP of the heat pump decreases. When COP drops to 1.5, calculation results of primary energy consumption, operation costs and carbon dioxide emission of HVAC System 2 go beyond the numbers of HVAC System 1 respectively and, at that situation, annual primary energy consumption of HVAC System 2 is 7.9% larger than that of HVAC System 1, annual operation costs of HVAC System 2 is 1.98% larger than that of HVAC System 1 and annual carbon dioxide emission of HVAC System 2 is 18.2% larger than that of HVAC System 1.

Finally, the analysis of the HVAC systems points out that System 2 for this factory is more efficient and more economic and has less negative impact on the environment than the traditional HVAC system—System 1. But as COP of the heat pump decreases, superiority of HVAC System 2 will decrease, when COP drops to 1.5, System 2 has no superiority compared with System 1.

5 CONCLUSION

This paper reports the results of the simulation of annual operation of a factory with HVAC System 1, a system with a nature gas boiler for space heating and a chiller for space cooling, by the building energy simulation software—EnergyPlus. Then, annual energy consumption of another HVAC System 2: GSHP system is calculated based on the results of building load of HVAC System 1 simulated by EnergyPlus. The operation of the two systems is evaluated according to its energy consumption, operating cost and pollutant emission.

Finally, it is found that System 2 for this factory is more efficient and more economic and has less negative impact on the environment than the traditional HVAC system—System 1. But as COP of the heat pump decreases, superiority of HVAC System 2 will decrease, when COP drops to 1.5, System 2 has no superiority compared with System 1. This paper points out a way to simulate energy consumption of a building with a traditional HVAC system and to calculate that of a GSHP system. Moreover, it provides an energy-saving evaluation of a building with different HVAC systems in the design period of such buildings.

REFERENCES