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AutoBPS-BIM: A toolkit to transfer BIM to BEM for load calculation and chiller design optimization

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Research Article

Abstract

This study developed a rapid building modeling tool, AutoBPS-BIM, to transfer the building information model (BIM) to the building energy model (BEM) for load calculation and chiller design optimization. An eight-storey office building in Beijing, 33.2 m high, 67.2 m long and 50.4 m wide, was selected as a case study building. First, a module was developed to transfer BIM in IFC format into BEM in EnergyPlus. Variable air volume systems were selected for the air system, while water-cooled chillers and boilers were used for the central plant. The EnergyPlus model calculated the heating and cooling loads for each space as well as the energy consumption of the central plant. Moreover, a chiller optimization module was developed to select the optimal chiller design for minimizing energy consumption while maintaining thermal comfort. Fifteen available chillers were included, with capacities ranging from 471 kW to 1329 kW. The results showed that the cooling loads of the spaces ranged from 33 to 100 W/m^2 with a median of 45 W/m^2, and the heating load ranged from 37 to 70 W/m^2 with a median of 52 W/m^2. The central plant's total cooling load under variable air volume systems was 1400 kW. Compared with the static load calculation method, the dynamic method reduced 33% of the chiller design capacity. When two chillers were used, different chiller combinations' annual cooling energy consumption ranged from 10.41 to 11.88, averaging 11.12 kWh/m^2. The lowest energy consumption was 10.41 kWh/m^2 when two chillers with 538 kW and 1076 kW each were selected. Selecting the proper chiller number with different capacities was critical to achieving lower energy consumption, which achieved 12.6% cooling system energy consumption reduction for the case study building. This study demonstrated that AutoBPS-BIM has a large potential in modeling BEM and optimizing chiller design.

Keywords

BIM;
building energy model;
EnergyPlus;
chiller design optimization;
AutoBPS-BIM

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Advances in Modeling and Simulation Tools

1 Introduction

The carbon emission of the building sector accounted for 32% of China's total carbon emissions in 2020. Emissions from the operation of buildings reached 2.18 Gt CO_2 in China, which occupied 60% of building sector carbon emissions (Building Energy Research Centre of Tsinghua University 2022). The heating, ventilation and air-conditioning (HVAC) systems occupied nearly 50% of building operation energy consumption. So, it is important for China that commits to achieving carbon neutrality in 2060 to reduce commercial building air-conditioning energy consumption (National Development and Reform Commission of China 2019). The HVAC system performance could be enhanced by improving the equipment itself efficiency, selecting proper equipment configuration and optimizing the system control strategy.

In the design stage, selecting the proper equipment size according to building loads had a large potential for reducing the HVAC system's operation energy consumption (Huang et al. 2018). Chillers were the biggest consumer of HVAC systems (Saidur 2009), so this study mainly focused on optimizing chiller design in the design stage. In general, the method of calculating building loads was divided into two main methods, static and dynamic methods (Gang et al.

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2015). In the static method, the building load calculation was often based on design parameters. Only the peak load was used to select equipment size, ignoring whole-year load fluctuation (DOE 2021). In the dynamic method, building whole-year load was obtained by using building performance simulation (BPS) tools, such as EnergyPlus and DeST. Then, a better system equipment size could be selected based on building loads to make the equipment work efficiently and reduce system energy consumption. For example, Cheng et al. (2017) analyzed cooling loads' uncertainties using Monte Carlo simulation in EnergyPlus to select the best configuration for the chiller plant. The result showed that the total cost of the optimized chiller plant was reduced by 17.7% compared with the conventional design. In engineering practice, most projects adopted the static method to calculate loads for convenience, leading to oversized equipment size and higher operation energy consumption (Dai et al. 2021). The modeling process of BPS was time-consuming and required expertise (Yan et al. 2015). During the modeling process, the building geometry, construction and material, internal gains, HVAC system and control logic needed to be modeled. Too many parameters were required in the modeling process, and manual modeling was error-prone. This study developed a tool that generates an energy model automatically based on the building information model and uses the dynamic method to give the building loads. Besides, most research utilized the load profile of the chiller plant to select several same chillers in a multiple-chiller plant by matching the capacity to load as closely as possible. Selecting multi-chillers with different capacities can bring more flexibility and save more energy for the chiller plant (Chen et al. 2020). When optimizing, this study considered the optimization both of the number and capacity of chillers.

Building information modeling has developed in the past few years, promising to provide enough information for modeling building energy model (de Lima Montenegro Duarte et al. 2021). In the building information model, all building information was integrated into a 3D model information database. The design team, construction unit, facility operation department and owner could work together to improve work efficiency, save resources, and reduce costs (Farzaneh et al. 2019). The BIM also can be applied in the automatic modeling of BPS tools. The automatic transformation from BIM to BEM significantly improved work efficiency in modeling (Nizam et al. 2018). For example, Wang et al. (2022) proposed a workflow for automatically generating the HVAC system of an office building based on BIM. The experiment tested workflow compared with the traditional computer-aid design process. The results showed that the BIM-based workflow reduced by 96% design time compared with the computer-aid design process. In this study, BIM to BEM transformation means transferring IFC (a popular building information file format) to the EnergyPlus model (a popular BPS tool). In general, the ideal process of transferring BIM to BEM included (Gao et al. 2019): (1) defining building location and linking weather files; (2) importing geometry, construction and thermal properties of materials, and space types from BIM; (3) getting simplified geometry complied with the geometry definition of the relevant BPS tool; (4) aggregating spaces into thermal zones based on geometry definition; (5) calculating the space loads assigned to the specific appropriate space types; (6) modeling the HVAC system and components. In related research, most studies focused on the part of these steps. For example, Yang et al. (2022) improved the geometry simplification algorithm in step (3). Honeybee (Ladybug Tools 2022) and OpenStudio Standards (National Renewable Energy Laboratory 2022) focused on model parameters setting in steps (3)–(6). Few studies developed relevant full-process automation modeling tools (Nizam et al. 2018). This study proposed a tool, AutoBPS-BIM, that could generate an energy model automatically based on the building information model and optimize the chiller design based on generated energy model. In the modeling process, setting correct envelope, internal gains, and the HVAC system was important for the correctness of BEM. Existing tools, such as Honeybee and OpenStudio Standards, were based on the USA building standards when setting envelope and internal loads, which led to unreasonable simulation results when applied to other regions. Few studies developed a tool to generate a building energy model based on Chinese building standards (Ying and Lee 2021). In this study, the Chinese building standards were integrated into the devolved tool AutoBPS-BIM, which could generate the building energy model that aligns with the requirement of Chinese building standards.

In conclusion, existing research lacked full-process automation modeling tools for BIM-BEM. And no related automation modeling tools can set model parameters in line with Chinese building standards. For chiller design optimization, most research only selected the same chillers for the chiller plant to match the capacity to load as closely as possible, ignoring the chiller capacity optimization of multi-chillers. Therefore, this paper presented a tool, AutoBPS-BIM, to transfer BIM to BEM for load calculation and chiller design optimization. The generated BEM can calculate each space's heating and cooling loads under Chinese building standards' requirements. A chiller design optimization module was developed to select the proper number and capacity for the chiller. A case study with an office building in Beijing was demonstrated.

2 Methods

Figure 1 shows the overall workflow of AutoBPS-BIM, which was divided into three steps. In step (1), the BIM was exported as an IFC file. The IFC element needed for generating the building energy model was extracted. The element included building storeys, space geometry boundary, window wall ratio, and space type. Based on building geometry and standard requirements, the base EnergyPlus model was generated. In step (2), the geometry accuracy of the generated base model was analyzed. And the base energy model was compared with the energy model generated by the Revit default energy simulation tool. The base energy model was simulated to calculate each space's cooling and heating loads. And the total cooling capacity of the chiller plant was obtained for equipment size selection. In step (3), all possible chiller combinations for the total cooling capacity were given based on the chiller dataset. Then models with different chiller combinations were generated based on the base energy model and simulated by EnergyPlus. The results of different chiller combinations were analyzed from two aspects, energy consumption and equipment capacity. After analysis, the optimal chiller combination and the energy performance results were obtained and illustrated in tables and charts. The graphic user interface developed for AutoBPS-BIM is shown in Figure 2.

2.1 BIM to BEM

2.1.1 *Building geometry extraction*

Figure 3 shows the relationship between IFC elements and parameters needed for generating EnergyPlus model. The parameters of building storey height, storey elevation, space boundary coordinates, space type and window wall ratio (WWR) were needed. In an IFC file, the top-level element was *IfcBuidling*. And the relationship between the building and its storeys was defined by the *IfcRelAggregates* element. The *IfcPropertySingleValue* element defined the storey height and elevation. Each storey contained multiple spaces. The relationship between the storey and space was defined in the *IfcRelAggregates* element. In terms of spaces, the modeling process needed to know its space boundary and external wall WWR. The relationship between walls and spaces was defined by the *IfcRelSpaceBoundary* element. The wall boundary coordinates and wall area were obtained from the *IfcConnectionSurfaceGeometry* element. The WWR of each wall was equal to the window area divided by the wall area. To calculate the WWR of external walls, each wall's window area needed to be known. The window and door were associated with an opening defined by the *IfcRelFillsElement* element, and the opening was related to the wall defined by the *IfcRelVoidsElement* element. The

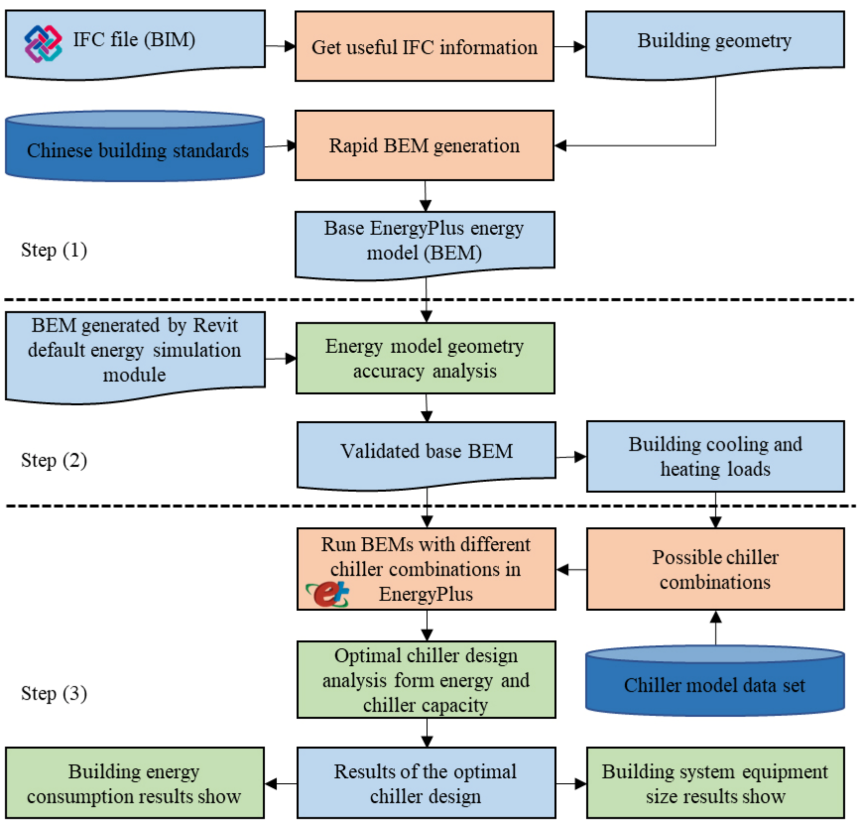


Fig. 1 Overall workflow of AutoBPS-BIM

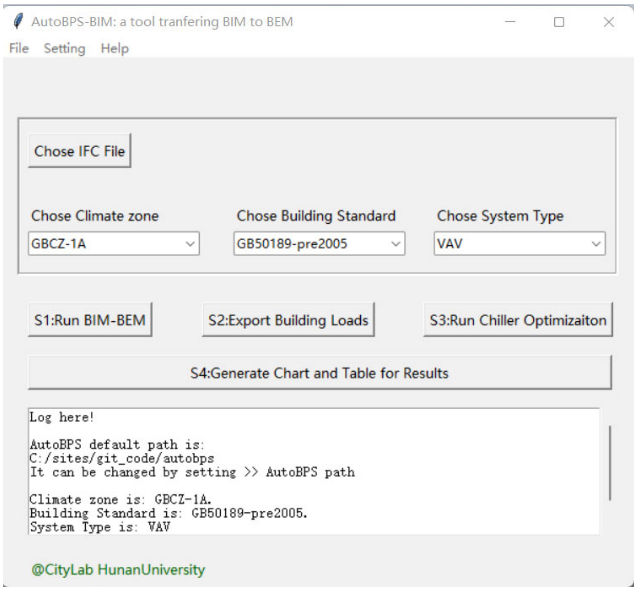


Fig. 2 Graphical user interface of AutoBPS-BIM

window area was obtained by the *IfcShapeRepresentation* element.

2.1.2 EnergyPlus model generation

The EnergyPlus model generation workflow is shown in Figure 4. This workflow depended on AutoBPS-BIM, a tool developed based on AutoBPS. AutoBPS was a platform developed by Yixing Chen from Hunan university, based on OpenStudio-Standards (OSS), to automate the energy model modeling process (Deng et al. 2023). AutoBPS had 5 level methods to rapidly model single or city-scale building energy models. For example, Deng et al. (2022) utilized AutoBPS to generate urban building energy models and evaluated the saving potential of different energy conservation measures in Changsha. Yang et al. (2023) established bottom-up urban building energy models with AutoBPS and analyzed different carbon reduction scenarios of Changsha. The core module of AutoBPS was AutoBPS-OSS, which could generate EnergyPlus model based on prototype building model. When modeling, AutoBPS-OSS required three parameters (building type, building standards and climate zone). According to building type, the core module provided the relevant prototype building geometry model from the dataset. The prototype building mainly included 16 building types (Full Service Restaurant, Quick Service Restaurant, Highrise Apartment, Midrise Apartment, Hospital, Large Hotel, Small Hotel, Large Office, Medium Office, Small Office, Outpatient, Primary School, Secondary School, Retail Standalone, Retail Stripmall and Warehouse). According to building standards and climate zone, the core module set the prototype building's envelope, internal gains, HVAC system and control logic. In details of HVAC modeling, the cooling system could be the central or split air conditioner. In terms of central air conditioner, the demand side system can be variable air volume (VAV), constant air volume or fan coil unit + dedicated outdoor air system. The supply side can be chiller + boiler or heat pump system. The water system can be primary or primary-secondary pump system. According to the climate zone, the weather file for the whole year simulation was obtained. AutoBPS-BIM, developed in this study, contributed to the level 5 method, which provided a new way to generate building geometry based on the IFC file, rather than based on predefined prototype building geometry. And AutoBPS-OSS was also integrated into AutoBPS-BIM.

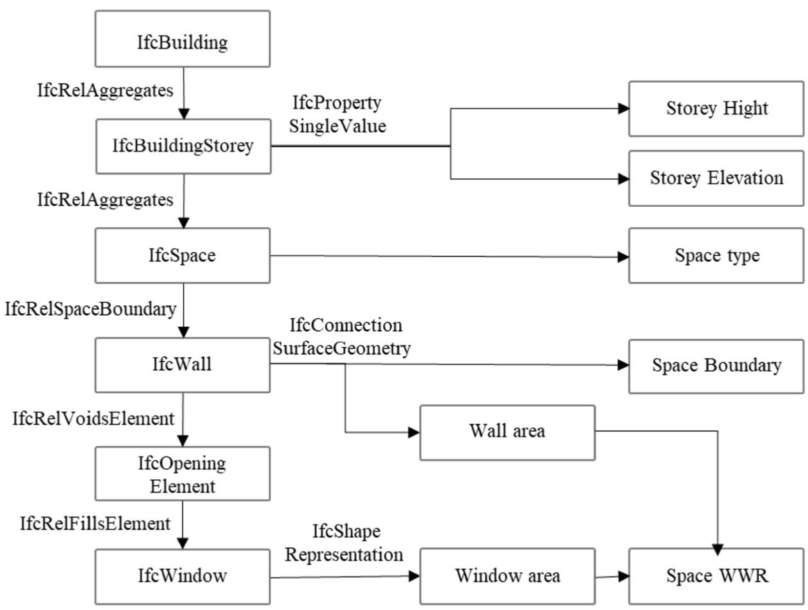


Fig. 3 Relationship between IFC elements and needed parameters

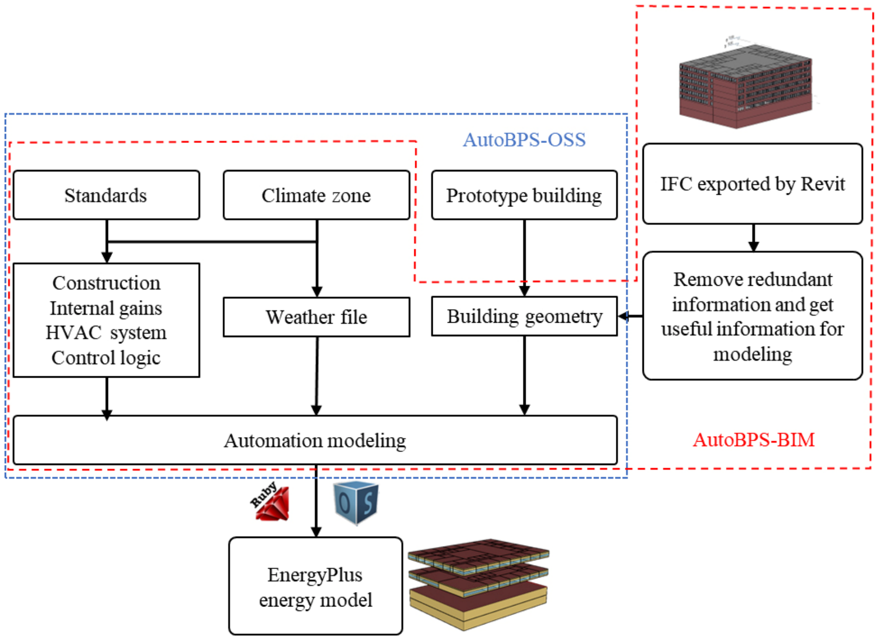
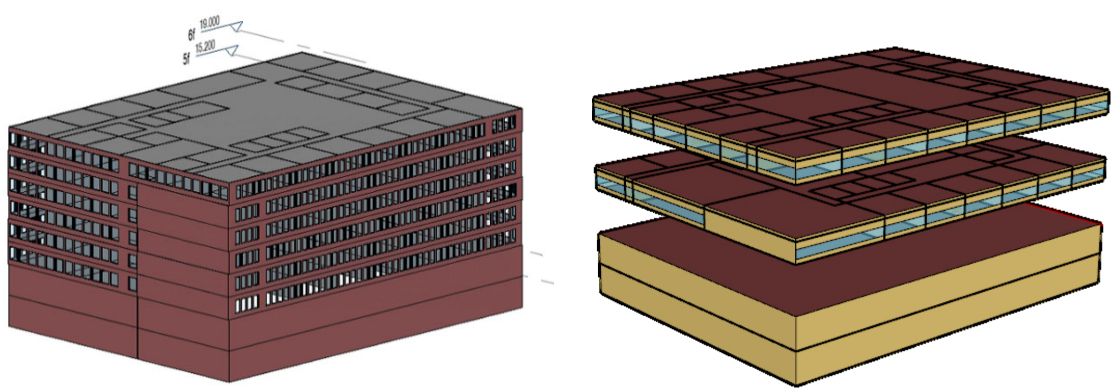


Fig. 4 General workflow of generating EnergyPlus model

2.1.3 *Basic information and BEM result of case study*

In this study, the case study building was an office building in Beijing. The geometry of the case study building in Revit (a building information modeling tool released by Autodesk) is shown in Figure 5(a). The selected office building had 2 underground storeys and 6 overground storeys. The height of the underground and overground storeys was 5.2 m and 3.8 m, respectively. And the building's length, width and height were 67.2 m, 50.4 m and 33.2 m, respectively. Revit exported the building model into IFC2×2 format.

As shown in Figure 5(b), the office building information model has transferred into the EnergyPlus model. The selected office building was built in 2012. So, the Chinese standard of GB50189-2005 was applied for setting building parameters. And the climate zone of Beijing was the cold climate zone. This office building has six space types: corridor, closed office, main mechanical, conference, stairs and basement. Each room was set as a thermal zone to facilitate getting the whole-year load profile in the building and room level. The tool can individually model each storey. For storeys with the same layout and function types, AutoBPS-BIM allows users to model one representative storey and use a storeys multiplier to scale up the results. In terms of this office building, only four storeys were modeled in the energy model, two basement storeys, a 3rd storey and a 6th storey. The 1st–5th storeys had the same floor plan and function types, as shown in Figure 10(a). So the storeys multiplier of the 3rd storey was set to 5. Figure 10(b) shows the floor plan of the 6th storey. The basements were mainly for parking, so those storeys were considered as a single thermal zone. Table 1 illustrates the envelope system's value



(a) (b)

Fig. 5 (a) Revit model of case study building; (b) schematic of EnergyPlus model

Table 1 Details of building envelope system and internal loads

Category	Parameters	Value
Windows-to-wall ratio	South	0.45
	East	0.37
	West	0.37
	North	0.41
Construction	*U*-value of roof (W/(m^2·K))	0.45
	Roof solar reflection coefficient	0.3
	U-value of external wall (W/(m^2·K))	0.5
	U-value of window (W/(m^2·K))	2.2
	Solar heat gain coefficient	0.39
Internal gain	Lighting/equipment power density (W/m^2)	11.8/6.9
	Outdoor airflow rate per person (m^3/(h·person))	30
	Working time (Monday to Friday)	8:30–17:30

and generated energy model's internal loads. In general, AutoBPS-BIM transferred IFC to the energy model successfully and kept the building geometry details very well.

The selection of system type on the demand side was not mandatory in the Chinese building standards. Considering the high requirements of office buildings on indoor air quality, VAV systems were selected for the air system, while water-cooled chillers and boilers were used for the central plant, which is shown in Figure 6. The HVAC system was divided into two loops, the supply side loop and the demand side loop, in EnergyPlus. The VAV system was on the demand side loop. The VAV system was the all-air type of air conditioning, which provided a variable amount of air blown by the air conditioner to provide cold (warm) air. When the load of the air-conditioning area changed, the variable air volume system changed the supply air volume to cope with the indoor load and to maintain thermal comfort. Chillers and boilers on the supply side loop supplied

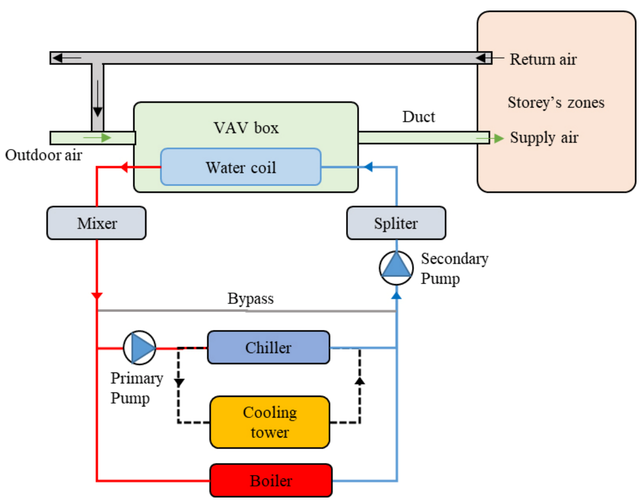


Fig. 6 Schematic of building HVAC system

chilled and hot water. Cooling towers provided cooling water for the chiller condenser. The cold (warm) media was the water, and the chilled water system was a primary-secondary pump system.

2.2 Building cooling and heating loads and model accuracy

There were two ways to ensure that the building energy model could represent the real building. One way was to calibrate the building energy model according to building measured data. Another way was to ensure that the input parameters of the energy model were correct and in line with the building standards. The former way required building measured data, so it was suitable for the built buildings. This paper discussed the energy model modeling in the design stage, so the latter way was used to ensure that the energy model was as close to the real building as possible. Revit also integrated the building energy simulation tool to generate the EnergyPlus model. The geometry accuracy of the energy model generated by AutoBPS-BIM was compared with the energy model generated by the Revit default energy simulation tool.

Based on the EnergyPlus model, each room's heating and cooling load profile was obtained after simulation. In this step, the HVAC system was replaced by the "ideal loads air system". The "ideal loads air system" in EnergyPlus gave the amount of energy that must be added or removed from a space to maintain occupant thermal comfort, not the load on secondary equipment or energy consumption by the primary equipment. To avoid oversizing the equipment size, it needed to consider "unmet load hours" to get the ideal design cooling (heating) load when dealing with the whole-year load result. In Chinese standards, the "unmet load hours" was 50 hours for cooling loads and 1–5 days for heating loads. Based on the load profile and "unmet load hours", the space's ideal design load was decided. For example, Figure 7 shows the histogram chart of a room's ideal cooling load and design cooling load. The maximum room cooling load of whole year loads was 1381 W. The ideal

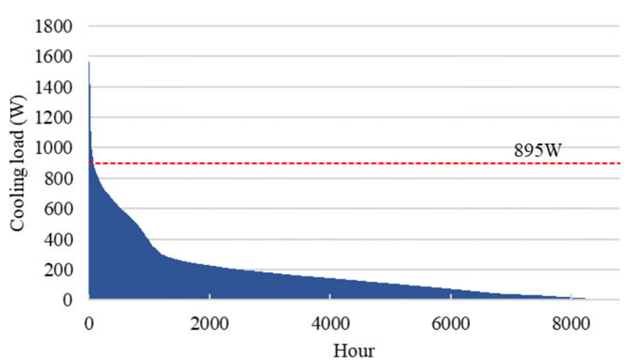


Fig. 7 Histogram chart of room's whole year ideal cooling loads

design cooling load became 895 W considering 50 unmet load hours. The rest of the rooms' ideal loads and the whole building's design cooling (heating) load were also obtained, as shown in Section 3.2.

2.3 Chiller design optimization

This study focused on cooling system optimization, especially chiller design optimization. There were few satisfied chillers and corresponding chillers combinations for the chiller design. For the case study building, the search space for possible chiller designs was small, with only 50 possible chiller combinations. Therefore, this study used the brute force method to simulate all possible chiller designs and then select the optimal design according to energy consumption.

2.3.1 *Chiller model and possible chiller design*

The design cooling capacity of the chiller plant under VAV systems was 2100 kW and 1400 kW for the static and dynamic load calculation methods. Compared with the static method, the dynamic load calculation method reduced 33% of the chiller design capacity. The percentage fluctuation of design cooling capacity for selecting chiller combinations was ±20%, from 1112 kW to 1680 kW. Fifteen chillers were selected from the EnergyPlus chiller dataset, whose rated capacity ranged from 471 kW to 1329 kW, and the reference coefficient of performance ranged from 5 to 6. The chiller performance was related to the condenser water entering temperature and evaporator water leaving temperature. In detail, the performance was determined by 15 parameters of three curves, as shown in Eqs. (1), (2), (3) and (4). All possible chiller combinations were gathered based on the selected chillers. There were 50 satisfied possible chiller combinations, as shown in Table 2.

$$C_{\text{capacity}} = a + b(T_{\text{cw,l}}) + c(T_{\text{cw,l}})^2 + d(T_{\text{cond,e}}) + e(T_{\text{cond,e}})^2 + f(T_{\text{cw,l}})(T_{\text{cond,e}}) \quad (1)$$

where: C_{capacity} is the correction coefficient of chiller power due to chiller rated cooling capacity change related to $T_{\text{cw,l}}$ and $T_{\text{cond,e}}$; $T_{\text{cw,l}}$ is the leaving chilled water setpoint temperature (°C); $T_{\text{cond,e}}$ is the entering condenser fluid temperature (°C).

$$C_{\text{EIR}} = a + b(T_{\text{cw,l}}) + c(T_{\text{cw,l}})^2 + d(T_{\text{cond,e}}) + e(T_{\text{cond,e}})^2 + f(T_{\text{cw,l}})(T_{\text{cond,e}}) \quad (2)$$

where: C_{EIR} is the correction coefficient of chiller power due to energy input to cooling output changes related to $T_{\text{cw,l}}$ and $T_{\text{cond,e}}$; equal to 1 at rated conditions.

$$C_{\text{PLR}} = a + b(\text{PLR}) + c(\text{PLR})^2 \quad (3)$$

where: C_{PLR} is the correction coefficient of chiller power due to PLR changes, equal to 1 at reference conditions; PLR, part-load ratio equal to (cooling load) / (chiller's available cooling capacity).

$$P_{\text{chiller}} = P_{\text{ref}} \times C_{\text{capacity}} \times C_{\text{EIR}} \times C_{\text{PLR}} \quad (4)$$

where: P_{chilller} is the chiller power at specific PLR; P_{ref} is the reference chiller power.

2.3.2 *Chiller sequencing control*

The sequencing control of chillers had a great impact on energy performance. The most popular sequencing control method was the "uniform part load ratio", meaning all chillers kept the same part load ratio, because it was easy and robust to implement in reality. The sequencing control method in this study also utilized the "uniform part load ratio". For instance, a sequencing control of 3 chillers was illustrated. The combination of chillers and their total capacity is illustrated in Table 3. How the chillers' capacity responds to the cooling load is demonstrated in Figure 8.

Table 2 Possible chiller combinations

	Chiller rated capacity (kW)					Chiller rated capacity (kW)			
I.D.	1	2	3	Total	I.D.	1	2	3	Total
1	1329			1329	26	541	931		1472
2	471	685		1156	27	541	1009		1550
3	471	780		1251	28	541	1023		1564
4	471	879		1350	29	541	1051		1592
5	471	931		1402	30	541	1055		1596
6	471	1009		1480	31	541	1062		1603
7	471	1023		1494	32	541	1065		1606
8	471	1051		1522	33	541	1076		1617
9	471	1055		1526	34	685	685		1370
10	471	1062		1533	35	685	780		1465
11	471	1065		1536	36	685	879		1564
12	471	1076		1547	37	685	931		1616
13	538	780		1318	38	780	780		1560
14	538	879		1417	39	780	879		1659
15	538	931		1469	40	471	471	471	1413
16	538	1009		1547	41	471	471	538	1480
17	538	1023		1561	42	471	471	541	1483
18	538	1051		1589	43	471	471	685	1627
19	538	1055		1593	44	471	538	538	1547
20	538	1062		1600	45	471	538	541	1550
21	538	1065		1603	46	471	541	541	1553
22	538	1076		1614	47	538	538	538	1614
23	541	685		1226	48	538	538	541	1617
24	541	780		1321	49	538	541	541	1620
25	541	879		1420	50	541	541	541	1623

Table 3 Chiller combinations of 471 kW, 541 kW and 541 kW

Options	Chiller A (471 kW)	Chiller B (541 kW)	Chiller C (541 kW)	Total capacity (kW)
1	Off	Off	Off	0
2	On	Off	Off	471
3	Off	On	Off	541
4	Off	Off	On	
5	On	On	Off	1012
6	On	Off	On	
7	Off	On	On	1082
8	On	On	On	1553

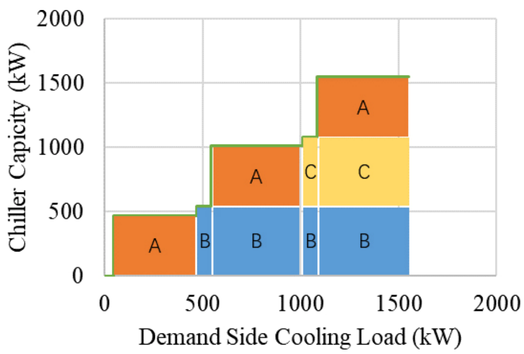


Fig. 8 Relationship between chiller capacity and demand-side cooling loads

All chillers turned off when the cooling load was lower than 47.1 kW because the minimum PLR of chiller A was 0.1.

2.3.3 Equipment size and energy consumption

The results of system equipment sizes and energy consumption were obtained to help designers improve building design. After chiller design optimization, the optimal design was found. The results demonstration took the optimal design as an example and focused on the cooling system. The cooling system of the case study building utilized the VAV system on the demand side. Each storey had an air handling unit (AHU). So, the equipment sizes of each storey's AHU, chillers, cooling towers and boiler were given. The bar and pie charts were adopted to analyze the system's energy consumption. The results of HVAC system equipment sizes and building energy consumption for optimal design were illustrated in Section 3.4.

3 Results

3.1 Model geometry accuracy comparison

Figure 9 compares the 6th storey floor plan of the energy model generated by the Revit default energy simulation module and AutoBPS-BIM. As shown in Figure 9(a), some space boundaries were mismatched. There was a gap between

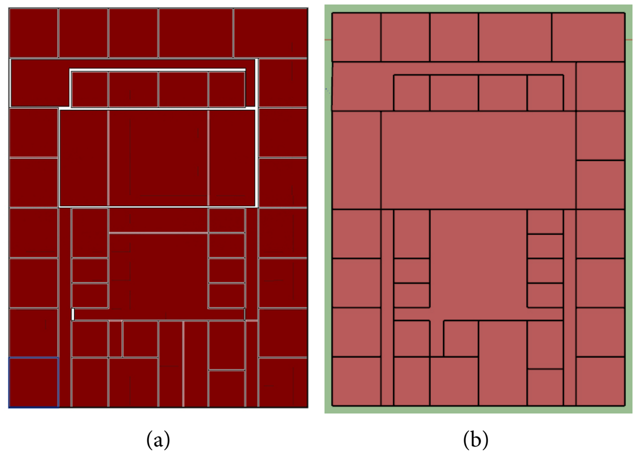


Fig. 9 Comparison of the 6th storey spaces' boundaries connection: (a) generated by Revit default energy simulation module; (b) generated by AutoBPS-BIM

the outside wall of the adjacent spaces. Revit dealt with the boundaries of simple rectangular rooms well. The mismatched space boundaries occurred at the boundary of the non-rectangular polygon spaces. The mismatch between neighbor spaces' boundaries led to partial or error simulation results. In terms of AutoBPS-BIM, it considered the space boundary matching problem of polygonal rooms. As shown in Figure 9(b), the wall boundaries of all spaces matched very well without gaps. In a word, AutoBPS-BIM dealt with the space boundary connection between spaces very well.

3.2 Building cooling and heating loads results

Each room's ideal cooling and heating design load for each storey was obtained. Limited to paper space, it was difficult to show all results. So, as an example, the rooms' cooling design loads of the 1st–5th storeys and heating design loads of the 6th storey with floor plan were selected and shown in Figure 10 to illustrate the ability of getting each room's design loads. Figure 11 and Table 4 show all rooms' cooling and heating design loads for the 1st–5th storeys and the 6th storey. The cooling design loads for all rooms ranged from 33 to 100 W/m^2 with a median of 45 W/m^2, and the heating design loads ranged from 37 to 70 W/m^2 with a median of 52 W/m^2. In a word, the developed tool could give the building loads to facilitate system design.

3.3 Chiller optimal design results

3.3.1 Overall energy performance analysis

The cooling system's energy consumption consisted of the energy consumption of chillers, pumps and fans. Figure 12 is the boxplot chart illustrating the relationship between cooling system energy consumption and chiller number.

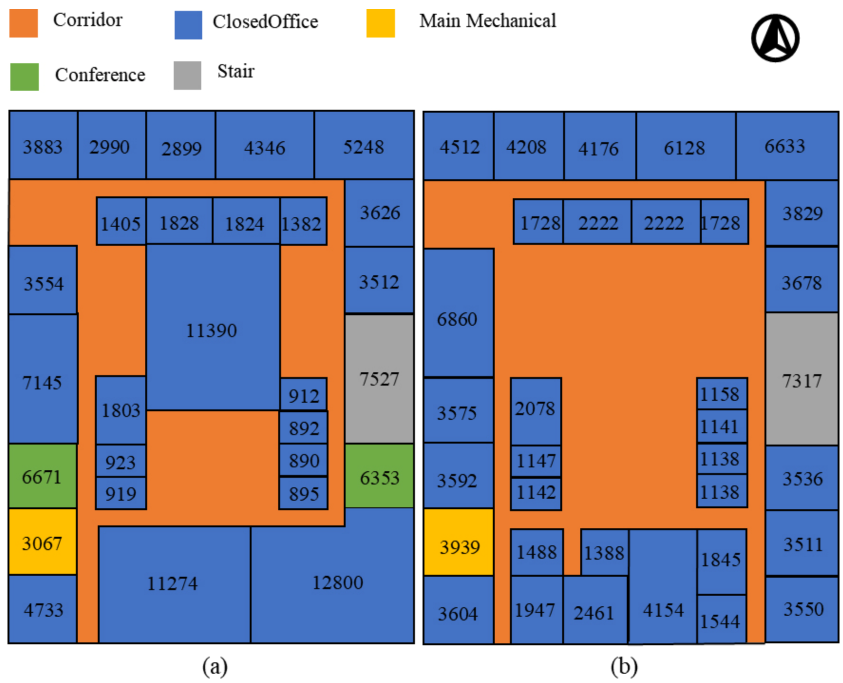


Fig. 10 Building floor plan with loads results: (a) cooling loads for 1st–5th storeys (W); (b) heating loads for 6th storey (W)

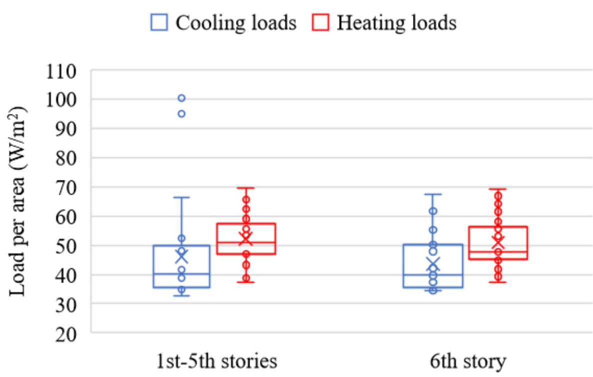


Fig. 11 Boxplot chart of rooms' design cooling and heating loads for 1st–5th storeys and 6th storey

Table 4 Rooms' design cooling and heating loads for different storeys

Item		1st–5th storeys		6th storey		All rooms	
		Cooling	Heating	Cooling	Heating	Cooling	Heating
Room's load (W/m²)	Minimum	33	37	34	37	33	37
	Average	45	52	44	51	45	52
	Maximum	100	70	67	69	100	70

Table 5 shows the annual energy consumption for all chiller numbers. The average annual cooling energy of using 1, 2, and 3 chillers were 11.91, 11.12 and 11.30 kWh/m^2, respectively. On average, the cooling energy consumption of using 1 and 3 chillers was bigger than using 2. Using 2 chillers had the lowest average energy consumption. The maximum cooling energy consumption was 11.91 kWh/m^2 when using a 1329 kW chiller. The minimum cooling energy consumption, 10.41 kWh/m^2, occurred when the chiller number was 2, whose nominal cooling capacities were 538 kW and 1076 kW, respectively. The energy consumption saving percentage between the maximum and minimum cooling energy consumption was 12.6%. It was critical to utilize the proper number of chillers rather than the more, the better.

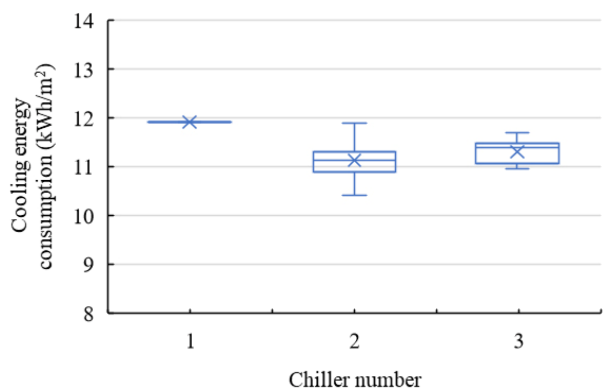


Fig. 12 Boxplot of cooling system energy consumption for different chiller numbers

Table 5 Annual cooling energy consumption for different chiller numbers

Chiller number		1	2	3
Annual cooling energy consumption (kWh/m²)	Minimum	11.91	10.41	10.96
	Average	11.91	11.12	11.30
	Maximum	11.91	11.88	11.70

3.3.2 Capacity analysis

In terms of using 2 chillers, the minimum and maximum cooling energy were 10.41 kWh/m^2 and 11.88 kWh/m^2. With the same number of chillers, selecting an appropriate chiller capacity combination had a maximum energy saving potential of 12.4%. As shown in Figure 7 in the method section, the building load fluctuated throughout the year. Selecting the chiller with different capacities made chillers operate as efficiently as possible, thus saving energy consumption. So, the relationship between chillers' capacity and energy consumption was further analyzed. Figure 13 shows the relationship between the chillers' capacity standard derivation and energy consumption. The capacity standard derivation demonstrated the variation or dispersion of chillers' capacity. For example, the standard derivation of the 780 kW and 780 kW was 0, and the standard derivation of the 541 kW and 685 kW was 72. When chillers' capacity standard derivation was 150–200 or 250–300, it got the lowest average energy consumption, 11.06 kWh/m^2. When the chillers' capacity standard derivation was 200–250, it got the highest average energy consumption, 11.36 kWh/m^2. The minimum cooling energy consumption was 10.41 kWh/m^2, and its chiller capacities were 538 kW and 1076 kW, with the capacity standard derivation of 269. For the multi-chiller plant, it was necessary to select chillers with different capacities.

3.4 Quick acquisition of equipment sizes and energy consumption results

The equipment size was calculated by the Autosize module of EnergyPlus in accordance with the relevant ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers) standards, which ensured the accuracy of the results. The equipment size of each storey's AHU is illustrated in Table 6, and the equipment size of cooling tower, chillers and boiler is demonstrated in Table 7. The rated fan power, cooling and heating capacity of each

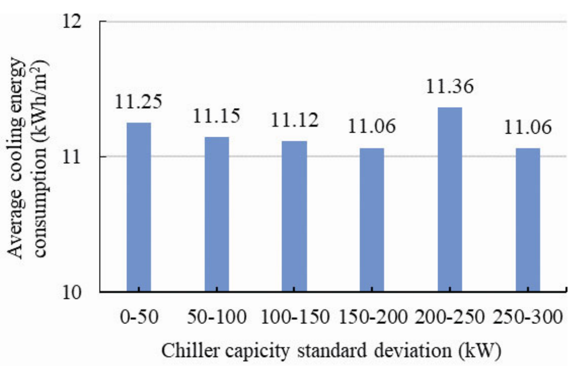


Fig. 13 Chillers' capacity standard derivation versus average cooling energy consumption

Table 6 Equipment size of each storey's AHU

AHU parameter	Storey −2nd	−1st	1st–5th	6th
Cooling coil rated capacity (kW)	117	117	232	235
Cooling coil maximum water flow rate (L/s)	5.0	5.0	9.9	10.1
Heating coil rated capacity (kW)	46	46	21	68
Heating coil maximum water flow rate (L/s)	1.0	1.0	0.5	1.5
Fan max airflow rate (m^3/s)	4.9	4.9	13.3	13.0
Fan rated electric power (kW)	12	12	31	30

Table 7 Equipment size of cooling tower, chillers and boiler

Item	Parameter	Value
Cooling tower	Nominal capacity (kW)	1547
	Design airflow rate (m^3/s)	52.73
	Design water flow rate (m^3/s)	0.11
Chiller 1	Nominal capacity (kW)	538
	Design condenser fluid flow rate (m^3/s)	0.02
	Design chilled water flow rate (m^3/s)	0.014
Chiller 2	Nominal capacity (kW)	1076
	Design condenser fluid flow rate (m^3/s)	0.047
	Design chilled water flow rate (m^3/s)	0.032
Boiler	Nominal capacity (kW)	1269
	Design fluid flow rate (m^3/s)	0.027

storey's AHU ranged from 12 to 31 kW, 117 to 235 kW, and 21 to 68 kW, respectively. AutoBPS-BIM can output all system equipment design sizes, which makes it unnecessary for designers to use other tools to calculate the equipment size.

Building energy consumption consisted of electricity consumption and gas consumption. The optimal chiller design case's electricity and gas consumptions were 69.8 kWh/(m^2·a) and 0.071 GJ/(m^2·a). The energy consumption and proportion of each sub-item are shown in Figure 14. Figure 15

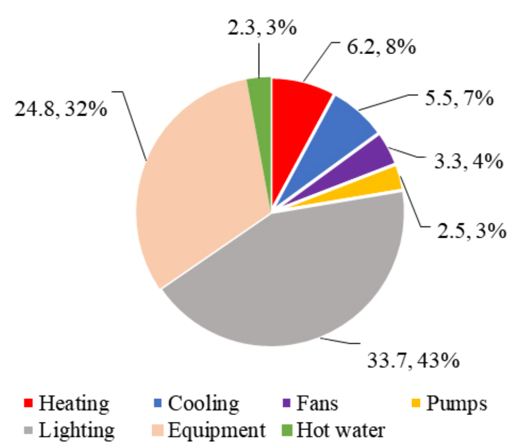


Fig. 14 Energy consumption and proportion of heating, cooling, fans, pumps, lighting, equipment and hot water

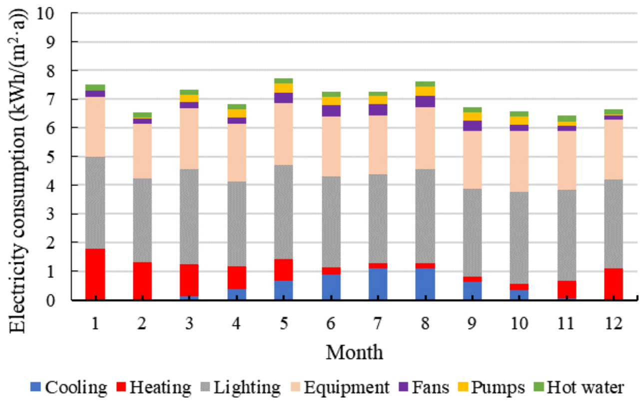


Fig. 15 Monthly energy consumption of heating, cooling, fans, pumps, lighting, equipment and hot water

illustrates the monthly energy consumption of each sub-item. The gas consumption was transferred to secondary energy, 6.2 kWh/(m^2·a), to draw the electricity and gas consumption together. Intuitive energy results can help designers understand the performance of buildings and then improve the design.

4 Discussion

4.1 Rapid BEM modeling

AutoBPS-BIM provided a workflow that can model the energy model based on the building information model rapidly. During the modeling process, the building geometry, envelope, internal gains, HVAC system and control logic needed to be assigned according to building standards. If some parameter was not given in Chinese building standards, the parameter was assigned referring to USA building standards. It caused the model results to deviate from the actual building to a certain extent. Moreover, new building standard GB 55015-2021 was released in 2021 and implemented on 1 Apr 2022, which put forward new requirements for building envelope, air-conditioning system and energy-saving measures. AutoBPS-BIM only supports Chinese building standards before 2022. For new buildings built after 2022, the energy model built by the proposed tool will not meet the latest standard requirements. The simulation results will also have a greater deviation from the real building.

4.2 Chiller optimization

AutoBPS-BIM optimized the chiller design effectively. The biggest energy consumer of HVAC systems was chillers, so this study only optimized the cooling system's chiller number and capacity. The cooling system also includes pumps, fans, cooling coils, and boilers, whose design also can be optimized. If all cooling system equipment's design is optimized simultaneously, the search space will become huge. Using the brute force method cannot effectively optimize this problem, so advanced intelligent algorithms, such as evolutionary algorithms, should be adopted. Besides the equipment size optimization, the control strategy in the operation stage also greatly influences cooling system performance, such as reinforcement learning (Zhang et al. 2022) and model predictive control. It also affected the chiller plant's operation and equipment size optimal design (Chen et al. 2022). In this study, the system control strategy was simple rule-based control. Moreover, occupancy behavior affects the building's cooling (heating) loads (He et al. 2022). And then, it affected the chiller design optimization. But, in this study, the internal loads' schedules were set as fixed schedules when optimizing the chiller design. Finally, the EnergyPlus models with different chiller number combinations were simulated case by case, which was time-consuming for the designer if applied in reality. The artificial intelligence neural network can train a black-box model based on simulated results to replace EnergyPlus (Li et al. 2022). The optimization process will become faster in the design process.

5 Conclusion

This study demonstrated a tool, AutoBPS-BIM, that could generate the EnergyPlus model based on the IFC file and building standards. Based on the generated energy model, the developed tool gave the building cooling and heating loads for each space. It also optimized the chillers' number and capacity in the design stage. Moreover, this tool also gave the building energy consumption and system equipment sizes information.

An office building located in Beijing was chosen as a case study building. The developed tool generated the building EnergyPlus model based on the building IFC file rapidly and accurately. Compared with the static load calculation method, the dynamic method reduced 33% of the chiller design capacity. The optimal chiller design was using 2 chillers with different capacities. Compared with using 1 chiller, the optimal chiller design saved 12.6% of cooling energy consumption. Selecting the proper chiller number and capacity to reduce cooling energy consumption was necessary. The developed tool also gave the system equipment sizes and energy consumption to facilitate designers to understand and improve the performance of the building.

Limited by time, AutoBPS-BIM currently only support limited Chinese building standards, and missing parameter refer to non-Chinese standards. In future work, more missing parameters of Chinese standards will be changed and added according to related literature. The latest

Chinese building standards also will be integrated into this tool. In this study, only the chiller design was optimized, and the control strategy of systems was simple rule-based control. In future work, the other cooling system equipment design will be collaboratively optimized with the chiller design. And the influence of occupancy behavior and advanced control algorithms on optimal central plant design will be studied.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contribution statement

Zhihua Chen: conceptualization, writing—original draft, methodology, investigation, software. Zhang Deng: data curation, software. Adrian Chong: writing—review & editing, supervision. Yixing Chen: conceptualization, software, writing—review & editing, supervision.

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