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Simulation Optimization of Energy-saving Techniques for Gymnasiums in Jiangxi Province Based on DesignBuilder

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ABSTRACT. Large-scale public gymnasiums in hot-summer and cold-winter zone can achieve internal and external heat exchange, maintain the indoor thermal environment, and reduce the use of air conditioning and other equipment to achieve the goal of energy savings and emission reduction by using natural ventilation techniques. With the help of DesignBuilder software, we simulate the energy consumption data of a gymnasium throughout the year in this paper using the single-factor analysis method. We then compare and optimize the ventilation strategy of the gymnasium in order to provide a case study example for the design stage of the same type of building in this region.

1 Introduction

In 2020, China's public buildings will emit around 830 million tons of CO_2, or 38% of all building carbon emissions, estimates the "*2022 China Building Energy Consumption and Carbon Emission Research Report*" (China Building Energy Consumption Research Report 2020, 2021).[1] It is clear that, although not particularly large, the stock of public buildings accounts for a sizable fraction of carbon emissions. Public buildings' energy-saving strategies can be separated into active regulation, which relies on the optimization of building equipment, and passive regulation from the building space throughout the building operation and maintenance stage. The means of achieving energy-saving targets through the design method of building space optimization can more conveniently direct the architects to make adjustments to the design only for the building's climatic conditions during the building design stage, as opposed to the active adjustment relying on HVAC and other related technical support (Zhang 2010).[2]

In this paper, starting with the design scheme of a gymnasium in Jiangxi Province, the existing ventilation and energy-saving strategies are simulated and optimized with the goal of providing a reference for energy-saving strategies enhancement at the design stage for large-scale public buildings, particularly sports buildings, in hot-summer and cold-winter zone.

2 Gymnasium foundation model extraction and parameterization

2.1 Gymnasium overview

This project is located in Ji'an City, Jiangxi Province, in China's hot-summer and cold-winter zone, with steamy summers, chilly and damp winters, and a tiny daily temperature change. The project's above-ground area is 3288.0 square meters. The main function is a basketball gymnasium, which is evenly distributed around four auxiliary rooms with transportation and toilets. The outermost circle is a corridor, which is presented as an auxiliary function wrapped around the core function. On this basis, the target project has established a cavity throughout the entire vertical space, which can be divided into the bottom air inlet, the middle ventilation cavity, and the roof air outlet by the composition of the period, which comprehensively utilizes the heat pressure to realize the heat pressure inside and outside the building, as shown in Figure 1.

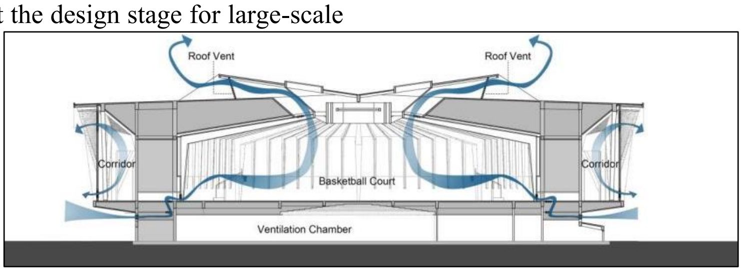

Figure 1. Vertical ventilation schematic.

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The comprehensive use of heat pressure can realize air exchange inside and outside the building and reduce the use of air conditioning, which is achievable at the design stage. In order to achieve better emission reduction, this thesis will focus on the above relevant variables for simulation, taking into account thermal comfort, energy consumption, and carbon emissions, and arrive at the optimal parameters within the range to optimize the design.

2.2 DesignBuilder energy simulation software

The gymnasium was modeled and simulated using DesignBuilder energy simulation software, which calculates loads with the help of EnergyPlus, a time-by-time simulation engine for building energy consumption. The software design built is used as a tool to assess and analyze the energy consumption of buildings. The software is used to quantify the architectural design concept to assess the energy consumption and the design can be modified to further reduce the energy consumption.[3] The heat balance method uses the exterior building surface heat balance, building body heat balance, interior surface heat balance, and indoor air heat balance equations in conjunction with each surface temperature and indoor air temperature for load calculation (Ge, Ma, Wang, 2021).[4] The model is a one-story single unit with a center-symmetric octagonal plan arrangement with a length of 76 m, a width of 62 m, a height of 9 m, and a maximum height of 16 m. The building is facing north-south. The model generated in DesignBuilder is displayed in Figure 2.

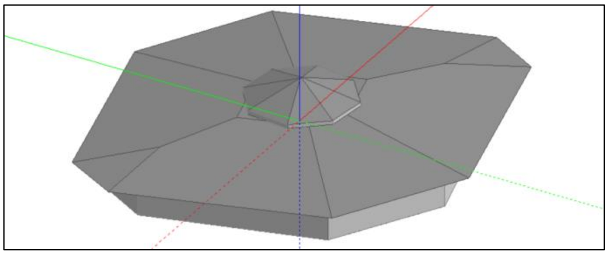

Figure 2. DesignBuilder model.

2.3 Building thermal performance

Table 1 shows the thermal parameters of the gymnasium building structure. The program is based on the overall aesthetic demand, with the outer enclosure façade using a full wrap-around glass curtain wall, which has a certain negative impact on the overall thermal environment regulation. As a result, the curtain wall is made of a high transmittance of visible light and a high reflectivity of the far-infrared double-layer LOW-E glass.

Table 1. Thermal parameters of building construction.

Structure	Designation	Thermal properties
Exterior wall	Reinforced concrete	Outer surface convective heat transfer coefficient, K=28.20 (W/m^2*K); Inner surface convective heat transfer coefficient, K=2.79 (W/m^2*K)
External window	Double-layer transparent LOW-E glass	Comprehensive glass curtain wall; Total solar transmission:0.48, Convective heat transfer coefficient, K=1.32 (W/m^2*K)
Roof covering	Aluminum magnesium alloy	Outer surface convective heat transfer coefficient, K=27.79 (W/m^2*K); Inner surface convective heat transfer coefficient, K=3.81 (W/m^2*K)
Louver	Aluminum alloy	Motor drive; Convective heat transfer coefficient, K=2.4 (W/m^2*K)
Floor	Cement+reinforced concrete+insulation layer	Outer surface convective heat transfer coefficient, K=19.88 (W/m^2*K); Inner surface convective heat transfer coefficient, K=0.34 (W/m^2*K)
Interior wall	Reinforced concrete+wood veneer	Outer surface convective heat transfer coefficient, K=19.46 (W/m^2*K); Inner surface convective heat transfer coefficient, K=2.15 (W/m^2*K)
Inner door	Wood	Convective heat transfer coefficient, K=2.18 (W/m^2*K)

Combined with the "*Energy-saving Design Standards for Public Buildings*" GB50189-2015 (GB 50189-2005, 2005),[5] the limits of the thermal parameters of the building and the thermal characteristics of the building are summarized. The shape of the body is flat, and the heated area is large. Its full wrap-around glass curtain wall with LOW-E glass is also unavoidable to the internal conduction of solar radiation. In summer, the heat storage of the building during the day may be greater than the heat dissipation at night, and the above creates the application conditions for the setting of the ventilation cavity.

3 Software simulation parameter setting

This simulation makes use of Ji'an City meteorological data from the Chinese standard meteorological database CSWD, which is available with DesignBuilder. This simulation is based on the "*Energy Efficiency Design Standards for Public Buildings*" for the main functional area, basketball gymnasium thermal comfort of the heating conditions and cooling requirements of the temperature range between 16 ~ 22℃. The summer cooling days are set for 90 days. The cooling period is from June to September. The winter heating days are set for 70 days, from November to February. Only the basketball court can be heated and conditioned, while stairwells, storage rooms, restrooms, and other areas are not.

In this paper, for the climatic characteristics of the hot-summer and cold-winter zone and the composition of this natural ventilation cavity composition, three factors affecting the energy consumption and comfort level of this building are selected, which are air inlet, ventilation path, and air outlet. A single-factor analysis is used to study the influence of each level of each factor on the building's energy consumption and carbon emissions.

4 Analysis of influencing factors and results

4.1 Verification of the need for the ventilated chamber

Simulations require a driving force, which is wind, in order to have optimal mode and maximum wind circulation in the interior space.[6] This wind can be supplied by architectural elements. Figures 3 and 4 illustrate the simulation results for the stadium without and with a ventilation chamber. It can be seen that under the premise of ensuring thermal comfort if the ventilation chamber is not set up, the museum does not have the conditions for air exchange under natural infiltration. Following the installation of the ventilation chamber (Figure 3), the number of air exchanges under natural infiltration is 0.3-0.35 ac/h, indicating that the air exchange has been considerably improved.

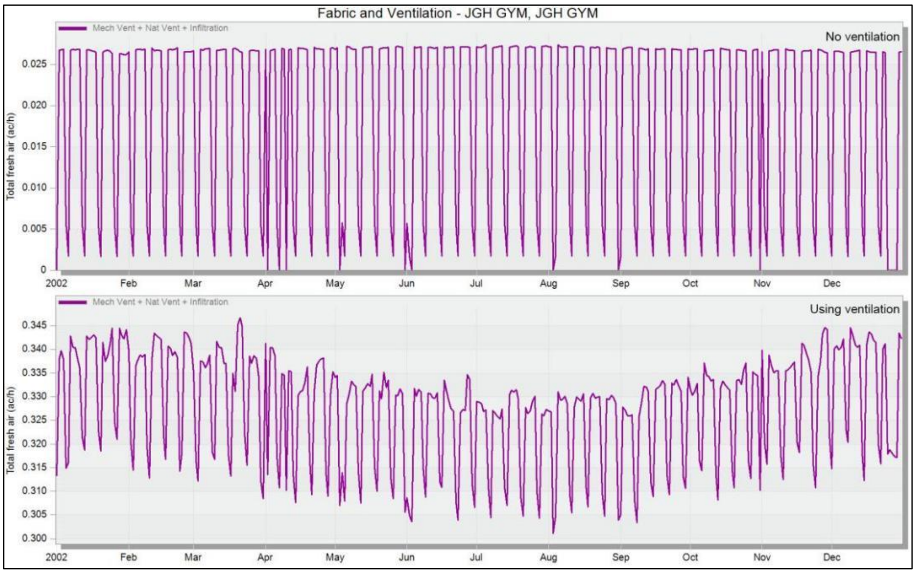

Figure 3. Ventilation number without ventilation versus ventilated chambers

As shown in Figure 4, the maximum energy consumption of the gymnasium in a single day in summer without the ventilation chamber reaches 30, 500 kWh with a long cold load phase. After using the ventilation chamber, its maximum energy consumption is reduced significantly, and the cold load period is shortened in summer. It is worth noting that the existence of the ventilation chamber may lead to a reduction in the airtightness of the building, so that the heat load from November to February also increased, but the total energy consumption of the whole year is reduced by about 600000 kWh. In conclusion, the installation of the ventilation chamber has practical significance.

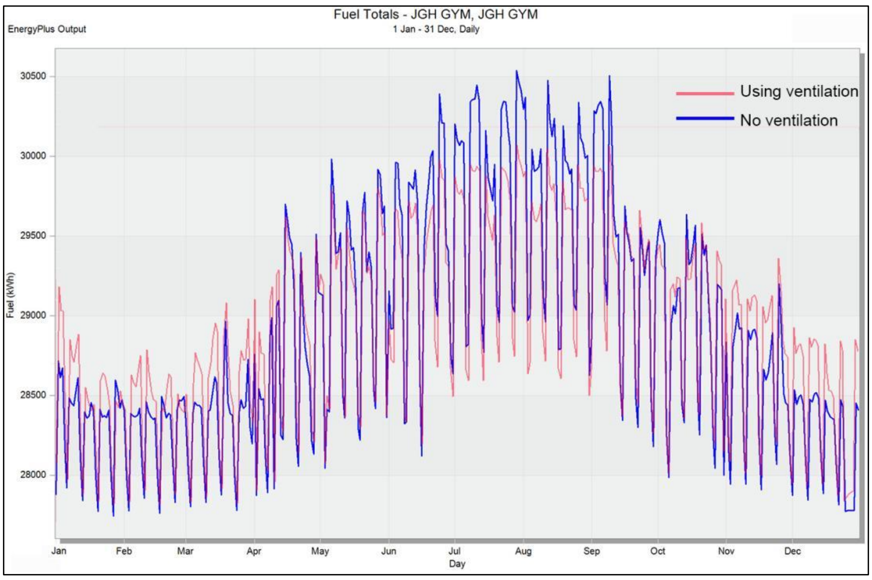

Figure 4. Simulation of annual energy consumption in unvented versus ventilated chambers

4.2 Air intake

4.2.1 Ventilation-to-wall ratios

The number of openings and energy consumption of the building were simulated throughout the year for different proportions of the inlet to the wall, with the premise of maintaining thermal comfort. Different opening ratios have a large impact on the number of openings in the building (Jintai 2016).[7] The simulation in Figure 5 shows that the larger the opening ratio is, the smaller the number of openings is required per hour. However, this makes no significant change in the total amount of air exchanged each time. In terms of energy consumption (Figure 6), the larger the opening ratio is, the less energy is consumed at each stage of the year; nevertheless, the decrease is limited, and the 80% opening ratio only saves around 400 kWh one day more than the 20% opening ratio. It can be shown that the bottom opening area mostly influences the length of the opening time, with only a slight impact on energy consumption reduction. The area of air inlet can be appropriately reduced in terms of building cost with the guarantee of ventilation effect.

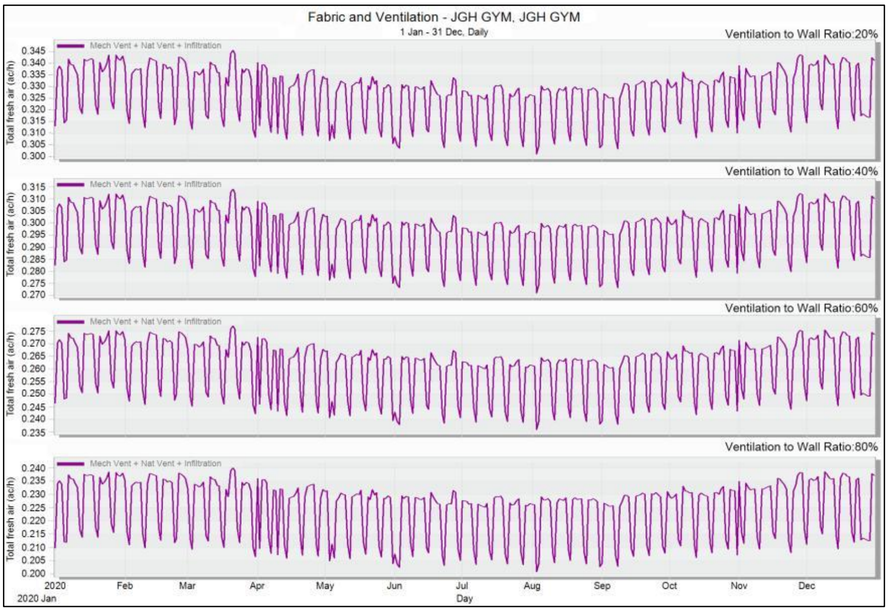

Figure 5. Ventilation times with different ventilation-to-wall ratios.

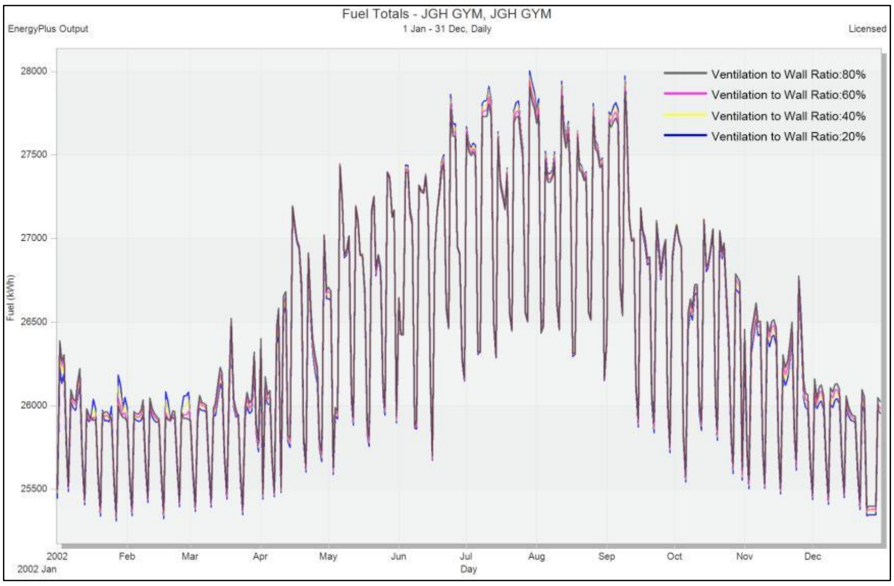

Figure 6. Energy consumption for different ventilation-to-wall ratios.

4.2.2 Air inlet opening method

The openings are divided into: grille large dark slat 0.5, grille large light slat 0.5, and Opening 0.7, whose energy consumption is simulated throughout the year as shown in Table 2. The sun radiation will be substantially lower because the air inlet is self-covered by the shape. The same air intake can be attained for different ventilation strategies by varying the number of openings times. Finally, the simulation reveals that using a grille large light slat 0.5 saves more energy throughout the year.

Table 2. Energy consumption of different opening methods

	Times. (ac/h)	Maximum single-day energy consumption. (kWh)	Minimum single-day energy consumption. (kWh)	Minimum single-day energy consumption for core area (kWh)
Grille large dark slat0.5	0.33	27641.39	25550.56	466.76
Grille large light slat0.5	0.32	27274.57	25886.73	451.28
Opening0.7	0.34	27558.01	25547.12	478.19

4.3 Internal ventilation path

This simulation uses three different ventilation paths to simulate the annual energy consumption and carbon emission of the building, which are no fixed ventilation, fixed ventilation, and ventilation rooms.

In terms of preserving room comfort, ventilation rooms outperform the other two approaches in the spring and, to some extent, during the rest of the year, save for the winter months of December (Figure 7).

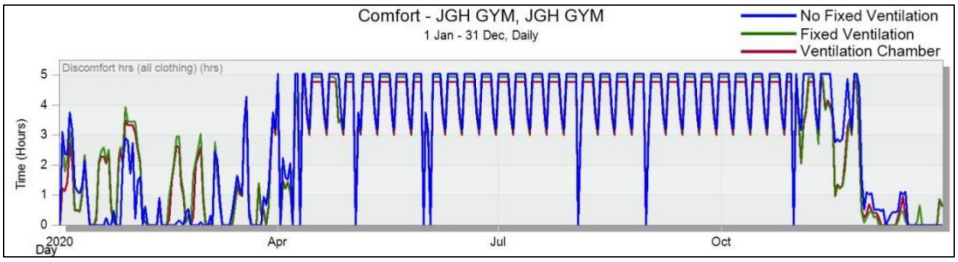

Figure 7. Space comfort for different internal ventilation paths.

As shown in Figure 8, after installing fixed ventilation ducts and rooms, the gymnasium's energy consumption is lowered in all periods, and the ventilation rooms reduce energy consumption better than fixed ventilation. The rooms, on the other hand, will develop new thermal areas, lowering the effective use of the area. When combined with Table 3, the ventilation chamber increases carbon dioxide emissions in all phases when compared to the other two approaches. In conclusion, installing fixed ventilation is a better option.

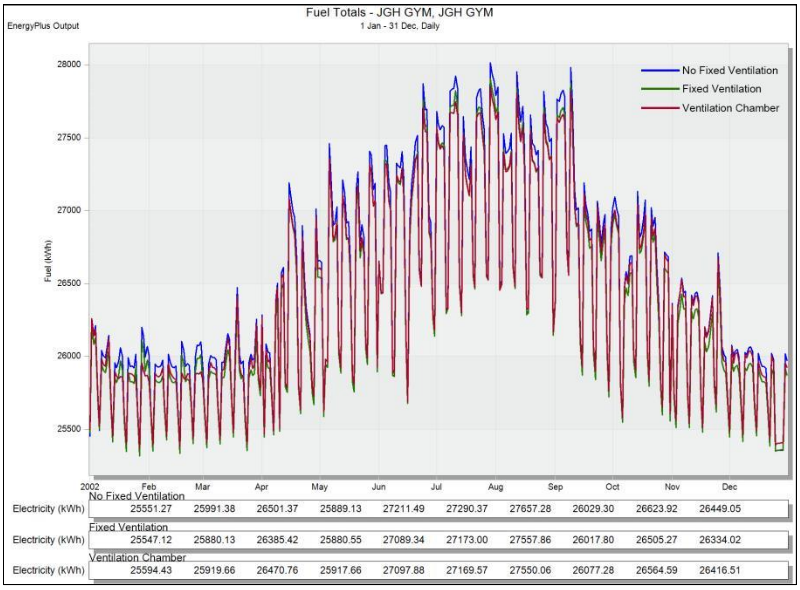

Figure 8. Energy consumption for different internal ventilation paths.

The rooms, on the other hand, will develop new thermal areas, lowering the effective use of the area. When combined with Table 3, the ventilation chamber increases carbon dioxide emissions in all phases when compared to the other two approaches. In conclusion, installing fixed ventilation is a better option.

Table 3. CO_2 emissions from different ventilation paths

	Jan	Feb	Apr	May	Jun	Jul	Aug	Oct	Nov	Dec
No Fixed Ventilation	15484	15750	16060	15689	16490	16538	16760	45774	15774	16028
Fixed Ventilation	15482	15683	15990	15684	16416	16467	16700	15766	16062	15958
Ventilation Chamber	15510	15707	16041	15706	16421	16464	16695	15802	16098	16008

4.4 Air outlet

The height of the air outlet directly determines the size of the thermal pressure difference, which in turn determines the effectiveness of ventilation (Yin 2010).[8] At the same time, the distance from the air outlet to the eaves of the large roof will also have an impact on the air outlet rate. The best air outlet is chosen by simulating and comparing the energy usage and carbon emissions of various heights.

Table 4 displays the particular energy consumption values, which show that the annual energy consumption of the gymnasium with increasing height shows a declining tendency, but the magnitude is not very significant.

Table 4. Simulation of energy consumption at different heights and depths

Height, Depth	Jan	Feb	Apr	May	Jun	Jul	Aug	Oct	Nov	Dec
9.5 m, 0.5 m	25555	25887	26414	25897	27100	27181	27565	26033	26523	26538
9.5 m, 1.0 m	25552	25885	26406	25893	27102	27184	27574	26027	26517	26350
9.5 m, 1.5 m	25549	25882	26397	25890	27104	27187	27580	26023	26513	26341
10.5 m, 0.5 m	25546	25880	26386	25883	27097	27182	27574	26018	26507	26334
10.5 m, 1.0 m	25550	25883	26396	25887	27096	27179	27567	26023	26512	26342
10.5 m, 1.5 m	25553	25887	26405	25891	27095	27157	27562	26028	26518	26351
11.5 m, 0.5 m	25540	25876	26336	25874	27092	27178	27565	26008	26491	26316
11.5 m, 1.0 m	25547	25880	26385	25881	27089	27173	27558	26018	26505	26334
11.5 m, 1.5 m	25550	25884	26395	25885	27088	27170	27554	26023	26511	26343

This could be because the functional requirements of the building basketball gymnasium have reached a height restriction of 9 m, which exceeds the range that can be influenced by adjusting the height. By adjusting the distance from the air outlet to the gable end, energy consumption can be reduced to a small extent. The closer the distance to the gable end is, the more obvious the effect is. The combination of 11.5 m height and 0.5 m depth is ideal in the comparison. In this scenario, the heat balance energy consumption of each building component is indicated below (Figure 9).

Figure 9. Heat balance energy consumption.

5 Conclusion

The simulation of the annual energy consumption of a gymnasium in Jiangxi Province by DesignBuilder revealed that the ventilation chamber utilized in the design stage has a positive impact on reducing energy consumption.

The ideal program combination is determined using three characteristics of simulation optimization: The air inlet uses the grille big light slat 0.5, which takes up 20% of the wall surface; fixed ventilation ducts are installed in the interior; and the outlet is installed at a height of 11.5 m above ground, 0.5 m away from the roof gable. It is measured to be 10% lower than the pre-optimization energy consumption in this scenario.

This simulation optimization method has practical usefulness during the architectural design process. This generalized approach can serve as a guide for comparable public structures in hot-summer and cold-winter zone.

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