Energy consumption simulation of the prototypical building for optimizing the orientation of building model in the simulated environment

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ABSTRACT

The objective of this project is to analyze the energy saving performance by optimizing buildings' orientation in the representative cities, such as Beijing, Shanghai, Guangzhou, Kunming and Harbin, in China. In order to estimate the annual energy consumption of buildings in different orientations, EnergyPlus is adopted as the simulation software. And the measured subentry energy consumption is used to calibrate the building models. The result of simulation indicates two valuable conclusions regarding the buildings' orientation. Firstly, if the building is located in the city such as Beijing, Shanghai or Harbin, south orientation would be the best choice; however, if the building is located in the city such as Guangzhou or Kunming, it is better to face north. Secondly, by appropriate use of daylighting and shading technology, the annual energy consumption of building can be dramatically reduced. Therefore, these technologies are worthy popularizing.

KEY WORDS: representative building, climate zone, simulation of energy consumption, building's orientation

1 INTRODUCTION

The orientation is a significant attribute of the building, influencing the building's thermal property and energy consumption level with other factors.

A number of studies have been carried out abroad and in China to analyze the optimal orientation of buildings. Odim Onuoha Odim simulated the change of indoor heat gain caused by different orientation and compared it to the practical measure, which matches the analog result well, offering a suggestion for choosing the orientation. In China, by combining the orientation and the solar heat gain, Yuan Xiang and Long Weiding researched the relation between the orientation and the building load in Shanghai and provided a transition method of it, whose result can be used for analyzing and verifying the simulation, offering support to the validity of the simulated results.

The object of this study is establishing the base model of prototypical public buildings focused on different climate zones in China, based on our country's building data and climate condition. Using simulation software, the representative energy-saving technologies ——daylighting and shading, were selected to analyzed， and the feasibility and result in different climate zones were provided.

2 METHOD

First, we established a base model of prototypical public buildings in EnergyPlus to represent different climate zones in China and calibrated its accuracy based on relevant standards and real data. Next, using the calibrated models, we simulated the year-round energy consumption of different orientation in same area, climate and building style. After the simulation, checking the validity of data, the practical effect of the orientation to the building energy consumption was quantitatively analyzed by disposing and inducing the data. Then, the relation between the orientation and building annual energy consumption was discussed, finding the cause of building energy consumption changing with the orientation in different areas and different climates.

3 ESTABLISHMENT AND CALIBERATION OF BUILDING MODEL

3.1 Modeling Approach

1) Collecting the physical parameters of the building, such as architectural shape and functions, type of building envelope (walls, structure of windows), etc.

2) Collecting energy consumption data from all parts.

3) Operating different models established in step 1) in EnergyPlus.

4) Analyzed the energy consumption trends in different orientations.

3.2 Selection of Model and Energy Consumption Data The Code for Thermal Design of Civil Buildings (GB 0176-93) divides China into five climate zones, and all of them were studied by choosing one city from each zone: Beijing (cold), Shanghai (hot summer and cold winter), and Guangzhou (hot summer and warm winter), Kunming (mild), Harbin (severe cold). The specific thermal properties of various enclosure properties used in the models and the choices of AC system in particular area are listed in Tables 3.1-3.2. Next, the process of modeling and calibrating for store + office building was introduced, and the method for other building types is much similar.

Table 3.1 Thermal characteristics of enclosure materials

Material	Density (kg/m^3)	Conductivity (W/m K)	Specific heat (KJ/kgK)
Steel-reinforced concrete	2500	1.740	0.92
Aerated concrete	700	0.220	1.05
Crushed stone concrete	2300	1.510	0.92
Cement mortar	1800	0.930	1.05
Lime-and-cement mortar	1700	0.870	1.05
Confined clay brick masonry	1800	0.810	1.05
Cement expanded perlite	800	0.260	1.17
EPS(Expanded polystyrene)	30	0.042	1.38
XPS(Expandable polystyrene)	35	0.034	1.40

Table 3.2 HVAC systems for different building in particular city

	Beijing	Shanghai	Guangzhou	Kunming	Harbin
High-rise housing	Split air conditioner + district heating	Split air conditioner	Split air conditioner	Split air conditioner	Split air conditioner + district heating
Hospital	VAV+FCU	VAV+FCU	VAV+ FCU	VAV+ FCU	VAV+ FCU
Hotel	Split air conditioner + central heating	Split air conditioner	Split air conditioner	Split air conditioner	Split air conditioner + central heating
Store + office	VAV+ FCU	VAV+ FCU	VAV+ FCU	VAV+ FCU	VAV+ FCU

3.3 Establishment of the Typical Office Building Model

In this research, the studied store + office building was 29 stories high and 84,000 m^2

in gross area. The 1-4 floors were store and the 5-29 floors were office. The building is facing south, and the window-wall ratios of all exposures were 65 percent. The first-floor height was 6 m and the second-fourth floors heights were 4.8 m. In order to match the requirement of cooling the inner area and heating the outer area, the AC system is arranged according to inner and outer area, with 10 m in depth of outer area. For the office part of 5-29 floors, each height was 3.6 m, and the tower building outline is a square with a side length of 50 m. For the same reason, AC system was divided into two partitions, with 5 m in depth of outer one.

For HVAC systems, malls and office buildings' summer air-conditioning design temperature is set to 24 ℃, winter heating design temperature of 20 ℃. The parameters are listed in Table 3.3 (P_l: Lighting power; P_e: Equipment power).

The store part of this building adopts VAV system, and the office area using FCU along with an independent air manner system (FCU totally handle the load). Cold and heat source is electric refrigeration unit + gas-fired boilers, while the water system is a primary pump system whose flow is invariable. The capacity and matching of different systems in selecting process is calculated by EnergyPlus automatically.

Table 3.3 Indoor setting for typical office building model

Functional zone	Operating time	Fresh air(m^3/h*p)	Occupant density (#/m^2)	P_l (W/m^2)	P_e (W/m^2)
Store	9 a.m.-10 p.m.	30	4	8	10
Office building	9 a.m.-10 p.m.	30	9	8	13

3.4 Building Data Taking the store + office building in Beijing for example, the process of verification and calibration for the model was described. The energy consumption data used for calibrating was sourced from Development of China's Building energy efficiency in 2009, measured and analyzed by Tsinghua University.

As the building model consists of store and office building, the standards of two types should be weighted according to the area. For this model, store gross area is 25,600 m^2 and office 62,500 m^2, and the energy consumption standard after weighting was listed in Table 3.4.

Table 3.4 Data of energy consumption, Beijing（kWh/㎡・a）

Type	Air condition	Heating	Lighting	Plant	Lift	Others	Total
Store	110	33	65	10	14	0.2	232.2
Office	30	50	22	32	3	1	138
Calibrating	53.3	45	34.5	25.6	6.2	0.77	165.4

3.5 Calibration of the Models Using standard such as the Federal Energy Management Project (FEMP), it was established that an acceptable simulation could have at most an error of 10 percent between the measured yearly energy consumption data and the simulated data. In order to verify the calibration process, the building models' simulated data on yearly energy consumption per unit area was compared to that of the source data. After numerous calibrations, all errors are within allowance band, which means that these models can be used to further research.

4 OPTIMIZING THE ORIENTATION OF BUILDING

4.1 Sensitivity of the Orientation to Energy Consumption in Different Buildings Due to the different types and functions, some buildings' energy consumption changes dramatically with orientation, while others do not show the sensitivity. To get this orientation sensitivity, the energy consumption changes with direction were simulated in this study, the result was detailed in Table 4.1. The due south corresponds 0° in this table and rotating clockwise, and it also fits to what follows in the paper. The blue cell indicates the least energy consumption of this building type while the red one means the largest. The relative difference rate can be calculated by this formula:

$$\text{Relative difference rate} = \frac{\text{largest energy consumption value} - \text{least energy consumption value}}{\text{largest energy consumption value}}$$

Table 4.1 Annual energy consumption per sq.m（kWh/（㎡·a））

Region	Type	0°	10°	30°	60°	90°	120°	150°	180°	210°	270°	300°	330°	350°	relative difference rate
Beijing	store+office	**129.17**	129.46	130.37	**130.81**	129.19	130.37	130.80	129.18	130.37	130.81	129.19	130.36	130.80	1.20
	housing	50.21	49.76	50.24	51.11	**51.73**	51.70	50.64	50.62	50.61	51.52	51.52	50.93	**49.74**	3.80
	hospital	99.64	97.66	99.88	103.39	**104.47**	103.52	100.00	97.96	99.40	102.99	104.11	103.12	**97.23**	6.90
	hotel	165.00	163.50	166.81	171.35	172.14	**172.98**	171.71	170.70	171.38	172.28	171.39	168.84	**163.06**	5.70
Shanghai	store+office	**122.26**	123.49	124.09	124.62	122.18	124.04	124.62	122.22	124.07	124.63	122.20	124.08	**124.66**	1.90
	housing	**29.26**	29.34	29.80	30.34	**30.93**	30.14	29.46	28.94	29.71	30.57	30.44	30.76	29.99	5.70
	hospital	**85.64**	86.96	89.18	93.07	**93.98**	92.48	88.73	85.64	88.65	92.60	93.59	92.27	88.57	8.80
	hotel	**195.82**	196.14	197.76	201.25	203.14	**203.08**	200.38	199.08	199.68	202.02	202.13	200.56	197.21	3.50
Guangzhou	store+office	125.92	125.96	128.31	**127.91**	125.94	127.59	127.39	**125.91**	126.50	127.90	125.92	127.58	127.39	1.60
	housing	33.43	33.33	34.18	34.49	**34.59**	34.43	33.61	**33.35**	34.09	34.44	34.63	34.52	33.72	3.60
	hospital	92.63	92.79	93.75	96.54	**101.20**	100.03	97.02	**92.55**	96.57	99.30	100.71	99.45	94.06	8.50
	hotel	139.29	139.43	140.41	141.87	**142.26**	141.84	140.24	**138.90**	140.08	141.57	142.11	141.82	140.36	2.30
Kunming	store+office	82.51	82.54	**84.60**	83.34	82.24	84.35	84.07	**82.51**	83.41	83.80	83.52	83.22	82.92	2.40
	housing	24.05	24.06	24.63	24.73	**24.74**	24.65	24.19	**24.04**	24.30	24.65	24.73	24.62	24.14	2.90
	hospital	63.15	64.21	66.98	69.17	69.86	**68.94**	64.24	**62.57**	65.98	68.07	69.24	68.57	66.69	9.20
	hotel	63.34	63.40	63.96	64.88	**65.21**	65.01	64.12	**63.33**	63.98	64.81	65.10	64.87	64.01	2.90
Harbin	store+office	**172.45**	172.73	173.31	173.81	174.15	174.48	**174.69**	172.47	174.76	174.58	174.31	173.93	173.51	1.30
	housing	52.87	51.84	53.18	55.72	**57.54**	57.86	56.35	55.33	56.40	57.48	57.12	55.47	**51.59**	10.30
	hospital	160.23	157.80	160.00	161.72	162.71	**163.08**	161.43	157.30	160.62	162.17	162.83	162.19	**156.51**	4.00
	hotel	279.26	277.51	280.05	284.81	288.91	**290.77**	289.26	287.59	288.41	288.73	287.04	283.89	**277.00**	4.70

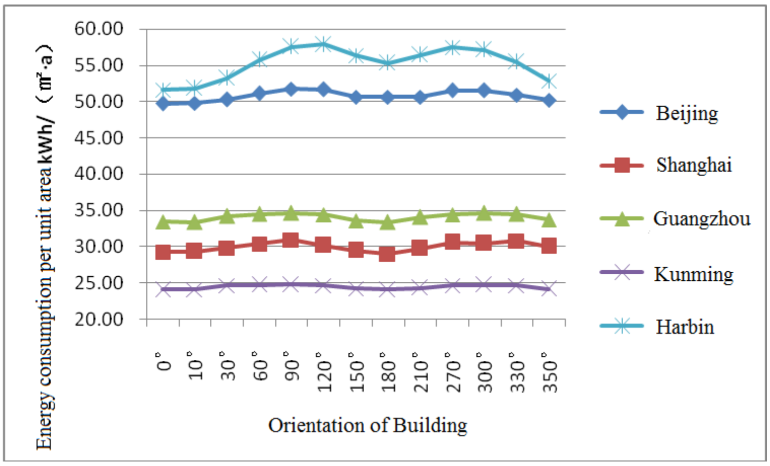
Then, we can find that the energy consumption doesn't change dramatically with the orientation changing when it comes to the store and office building. In contrast, a significant change can be seen in hospital, housing and hotel. The reasons of the phenomenon are concluded as follows. First, this type of building has a high axial symmetry level in its outline, which makes a narrow range of change for solar radiation, thus the difference caused by sunshine is small and the sensitivity to orientation decreases. Second, the inner part and corresponding function were simplified while modeling, leading to the situation that the inner functional partitions are highly symmetrical. In addition, the orientation affects the load caused by solar radiation mostly, which belongs to external load. But in buildings such as store and office, there are many people, equipment and lights, making the internal load so large, and the effect of the change in orientation become small.

In sum, due to the inferior effect caused by orientation in store or store + office buildings, the meaning of orientation optimizing is not as great as expected. Furthermore, the locations of these buildings are always in downtown, which restricted the choice of designer. So, we ignored the orientation optimizing in these buildings.

4.2 Optimizing the Orientation of Residential Building, Hospital and Hotel

4.2.1 Optimizing the orientation of residential building For residential building, the energy consumption-orientation curve is showed in Figure 1. Then we can analyze the results as follows.

Figure 1 Energy consumption-orientation curve



There is an obvious difference should be noticed: the optimal orientation of buildings in Harbin, Beijing and Shanghai is between the south by east 5°-15°, which conforms to our common sense, but the optimal orientation of Kunming and Guangzhou buildings is between ±5° of north, which conflicts our experience.

For the residential building of the model, one structural feature is that the living rooms, whose loading is the most of the building, located on the same side so that the large windows can be set in the external wall of the living room, thus it is good for lighting and ventilation. Meanwhile, bed rooms, toilets and kitchens were located on another side. In simulation, the heat caused by personnel, equipment and lighting in living room and bed room was compared in Figure 2. Take Shanghai for example, the energy consumption and annual cooling and heating load changing trend with the change of orientation was showed in Figure 3. What should be noted is that there's no heating in winter, Shanghai, thus the heating load in winter is 0.

Figure 2 Heat source distribution

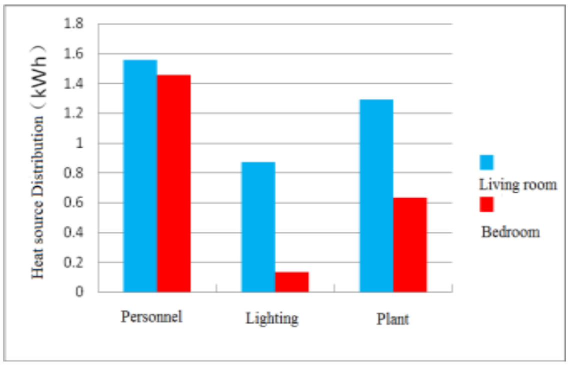
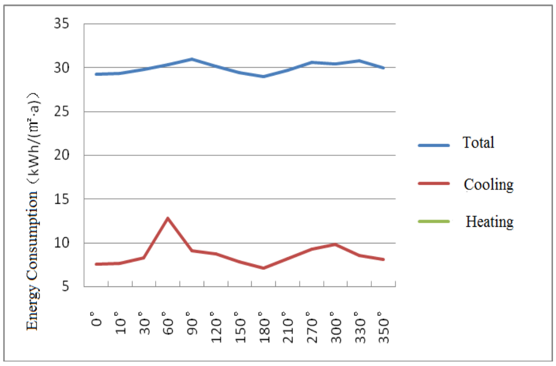


Figure 3 Load changing trend



In Shanghai, the side area where living room located can get plenty of sunshine when orientation is 350°, which causes two results. First, under directly violent sunlight in summer, the cooling load will increase. Second, heating load in winter can decease due to the solar radiation. These two factors influenced the building load in different time of year and the reducing of heating load is larger than the increasing of cooling load, which means choosing southbound orientation can reduce the energy consumption. So, for cities with high requirement of heating in winter such as Shanghai, Harbin and Beijing, south is the optimal orientation.

As for Kunming and Guangzhou, the least energy consumption appeared when building towards to north. Through the data table we can find that the difference of south and north is not quite much and the reason why we select north the optimal is that the cooling load is the main part of annual load due to there's no heating in winter in these cities.

4.2.2 Optimizing the orientation of hospital

For hospital, one of the characteristics is its strong functionality, leaving this type of building different from others in the aspect of building energy consumption. In one hand, the different function within hospital led to different regional load, e.g., the equipment and AC energy consumption of operating room which has a high requirement of cleanness is huge and much larger than corridor or aisle, even the personnel density is pretty high there. In another hand, the requirement of heating in winter is relatively high due to its role of providing better healing environment and higher indoor comfort level, thus the energy consumption for heating is large.

Offices, wards, operating rooms and consulting rooms were concentrated in one side of building, leading the energy consumption of equipment, heating and cooling in this side pretty large and having a big effect on energy consumption of the whole building. While toilets, corridors and staircases concentrated in another side, which are not belong to the air conditioning area, having small influence on building energy consumption.

The hospital in this model share a characteristic with residential building: a big difference exists in functional areas of building, leading the asymmetric of the load. Thus, similar to residential building, facing south is the optimal orientation when the building located in cold winter region, while in Guangzhou or Kunming, north will be better.

4.2.3 Optimizing the orientation of hotel

For hotels, the air conditioning area spread over the whole building while high geometric asymmetry level exists in every direction. At this point, when the orientation changes, the mechanism of action is similar to the room with single window described above. Thus, the optimal orientation is same to the residential building.

Note: Based on the simulated result above, the difference of annual energy consumptions when the building faced south and north is not very big, especially the residential buildings. The reason of this phenomenon is that the energy consumption of cooling and heating, which influenced by the orientation, accounts a little for the whole consumption in the civil buildings, when the sun-shading is not taken into consideration. Thus, only based on the models and data above, there is no big difference of south and north.

4.3 Analysis of Orientation Considering Sun-shading and Natural Lighting

As for the practical buildings, shading structure is common. Thus, a model with inner shutter shading was established to find the optimal orientation. The parameters of shutter were listed as follow: the shutter direction is horizontal, width is 25mm, thickness is 1mm, interval between two shutters is 18.75 mm, and the control strategy is opening with an angle of 45 ° when the daylighting condition is met and keeping closed when the sunshine is too valiant in summer. The sun-shading was put away in winter to ensure the indoor sunlight. Thus the glare is ignored in winter lighting to ensure low energy consumption. The simulated results of residential buildings, hospitals and hotels with daylighting and inner shutter shading in main occupancy space were shown in Table 4.5.

1. For cities such as Harbin, Beijing and Shanghai, the least energy consumption appeared when the building faced south. But the total energy consumption decreased with the using of daylighting and adjustable shading. The energy consumption of lighting dropped most obvious and the cooling load follows.
2. For Kunming and Guangzhou, the advantage of north in energy-saving becomes significant with the using of daylighting and sun-shading.

Table 4.4 Energy consumption with and without daylighing and sun-shading

Item			Beijing	Shanghai	Guangzhou	Kunming	Harbin
With daylighting and sun-shading	Residential buiding	Least energy consumption	47.56	28.34	28.36	21.07	50.99
		Orientation	S	S	N	N	S
	Hospital	Least energy consumption	95.26	82.14	72.54	58.26	155.2
		Orientation	S	S	N	N	S
	Hotel	Least energy consumption	158.8	184.19	132.5	58.55	216.1
		Orientation	S	S	N	N	S
Without daylighting and sun-shading	Residential buiding	Least energy consumption	49.74	29.26	33.35	24.04	51.59
		Orientation	S	S	N	N	S
	Hospital	Least energy consumption	97.23	85.64	92.55	62.57	156.51
		Orientation	S	S	N	N	S
	Hotel	Least energy consumption	163.06	195.82	138.90	63.33	277.00
		Orientation	S	S	N	N	S

The conclusions can be attained as follow:

(1) Choosing north as the orientation can dramatically reduce the energy consumption of cooling and lighting relative to south. The reason can be summarized that the window faced north has the diffuse reflection instead of direct solar radiation, reducing the solar heat gain. And another benefit of this is it can avoid the glare, which makes the daylighting time increased, thus reducing the energy consumption of lighting, as Table 4.5 shows.

Table 4.5 Available daylighting hours of different orientation (hr)

	Facing south	Facing north
Kunming	1114.5	1988.25
Shanghai	1021.75	1629.25

(2) As for cities such as Kunming and Guangzhou without heating in winter, no significant increasing on heating load appeared when the building faced north even it caused the decreasing on heat gain in winter. Thus, the load of heating in winter didn't increase obviously.

Due to these reasons, the advantage of north with daylighting and sun-shading building in Kunming and Guangzhou become significant.

5 CONLUTIONS

In this paper, four types of building in five cities (corresponding to 5 climate zones of our country) were selected to study the relation between orientation and building energy consumption. And the suggestive optimal orientation of the different buildings was provided. From the results of this study, we have drawn the following conclusions:

1. For store buildings, optimal orientation has little significance in reducing the energy consumption and there is no optimal orientation. Thus the orientation is often decided by the situation of the actual project. In contrast, it has practical significance that selecting a propel orientation for the buildings such as housing, hospital and hotel. Widely speaking, the orientation should be carefully selected when the building has the

features as follow:

(1) Obvious difference exits in the distribution of building's geometric shape, envelope properties, and materials, and the axisymmetrical level is low;
(2) The distribution of function, personnel and equipment of building has dramatic difference in every direction;
(3) Substantial load of AC system was caused by heat transfer and radiation via envelope, without much internal load.

2. When heating requirement of the building is high (cold regions, severe cold regions, hot summer and cold winter region), the optimal orientation is south (in the south by east between 0° ~10° , according to the actual situation), as the Table 5.1 shows.

Table 5.1 Optimal orientation of the building

Region	Beijing	Shanghai	Harbin
Orientation	350° (south by east 10°)	0° (south)	350° (south by east 10°)

3. When heating load is low but cooling load in summer is high (mild regions, hot summer and warm winter), the optimal orientation is north, as the Table 5.2 shows.

Table 5.2 Optimal orientation of the building

Region	Kunming	Guangzhou
Orientation	180° (north)	180° (north)

4. For residential buildings, due to the cooling and heating load is not very high, the reducing in energy consumption caused by orientation changing is not obvious if not take the day-lighting and sunshade into consideration.
5. The energy-saving effect of optimal orientation becomes obvious if the day-lighting and sun-shading were used in the building. And for Kunming and Guangzhou, the advantage of north relative to south is visualized (natural lighting time in north increased by 60% to 80% than south).

References

Odim Onuoha Odim, Experimental Studies Of Comfort Levels of East-west And North-south Solar-oriented buildings In A Warm-humid Climate, 2008.4

Yuan Xiang, Long Weiding, Analysis and Transformation of orientation in forecast of cooling load in regional building, 2009.6

Building Energy Research Centre Tsinghua University P R China, Development of China's Building energy efficiency in 2009

US Department of Energy Office of Energy Efficiency and Renewable Energy. DOE/ GO210200020960 M &V guidelines : measurement and verification for federal energy project s[S] . Version 2. 2 ,2000

International Performance Measurement and Verification Protocol (IPMVP), Volume 1, March 2002

ASHRAE Guideline 14—2002, Measurement of Energy and Demand Savings, ASHRAE Standards Committee June 22, 2002