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OPTIMIZING THE BUILDING FORM BY SIMULATION--A PARAMETRIC DESIGN METHODOLOGY STUDY WITH INTEGRATED SIMULATION AT SCHEMATIC PHASE

Ziwei Li[1], Borong Lin[1], Shuai Lv[1] and Bo Peng[1]
[1]School of Architecture, Tsinghua University, Beijing, China

ABSTRACT

Focusing the architecture form as an objective function of many parameters, building parametric design is a novel design method widely used all over the world. The final scheme can be generated through controlling the parameters or the function relationship. But the current situation of the application is that, the energy efficiency design, ignored in schematic phase, is subject to the architecture form design. In order to combine the energy efficiency design with the parametric design, an integrated application of the building modelling software Rhino, the building performance simulation software EnergyPlus and the Most Energy Efficient Scheme Generator MEESG(Yu Qiong etal, 2011) is put forward in this paper, to achieve an integrated process from building modelling to energy consumption simulation. Firstly, a modelling procedure in Rhino has been established, and the building information output has been achieved through writing and running python script; secondly, comparison between EnergyPlus and MEESG has been performed from three aspects: computing time consumption, difficulty of combination with Rhino, relative deviation and deviation direction of simulation results; finally, the way to achieve the integrated simulation design process more efficiently is discussed and some specific technical advice is put forward.

INTRODUCTION

Parametric design theory

Under the influence of complex science, building parametric design method is based on nonlinear theory and philosophy and takes computers as aided design tools. Under this method, design scheme is taken as a function of many design parameters, and the final design scheme can be generated by controlling these parameters or controlling the function relationship. So architecture design works guided by this novel design method always appear flowing, irregular, free and soft. With the rapid development of architectural theory and building technology, this design method is gradually applied into more and more projects by many architects in modern times.

Aiming at achieving an eye-catching architectural form, some architects always take complex science theories as their design logic. As a result, the functional requirements of building are forced to fit in with the design logic which has nothing to do with architecture. Finally, the core idea of parametric design method is deviated from.

As the first step of the whole design process, the scheme design phase concentrates the main points. In this stage, the architectural form nearly takes shape, and most of the parameters related to energy consumption are selected. Many studies (de Wilde P, 2004, Hong Tianzhen etal, 2000, Augenbroe G, 2001) show that, with the promotion of design, the energy-saving space is smaller and smaller, and the cost of the same energy saving benefit is higher and higher. It is pointed that performance-based architecture design should be taken place of by performance-driven design (Xing Shi etal, 2010).

In conclusion, parametric design method and energy-efficient design method should be combined in the early stage. If building energy consumption or other single performance goal is taken as the objective function of building design parameters, the energy consumption can be reduced or the building performance can be improved by controlling the parameters or controlling the function relationship. For example, building cooling and heating energy consumption can be expressed as:

$$E = \frac{Q_{sum}}{COP_s} + \frac{Q_{win}}{COP_w} \quad (1)$$

The indoor radiation heat gain Q in summer occupies a large proportion of the cooling load Q_{sum}. So Q_{sum} could be reduced by reducing Q. Radiation distribution on building façade can be affected by characteristics of building form and building envelope, for example, the angle of rotation of each floor θ, the roof overhang length l, the window-to-wall ratio WWR and so on.

A calculation formula of steady-state load (Zeng Jianlong, 2006) through building envelope is introduced to calculate the indoor radiation heat gain in this paper. For glazing part of building envelope, the heat gain of unit area is:

$$q_{win} = K_{win} \cdot \Delta T + SC \cdot q_{solar} \quad (2)$$

So WWR and SC can greatly influence the indoor radiation heat gain.

In conclusion, Q can be expressed as an objective function:

$$Q = f(\theta, l, WWR, SC...) \quad (3)$$

The reduction of indoor radiation heat gain and an uniform radiation distribution on building façade can be achieved by controlling θ, l, WWR, and SC, thus the energy-efficient optimization design objective can be achieved.

Similarly, if the objective is to strengthen the interior natural ventilation, the objective function ventilation rate can be expressed as:

$$V = g(\Delta p, o, sa) \quad (4)$$

Δp is the wind pressure difference between the windward side and the leeward side, o represents the window's opening size, sa represents the interior spatial arrangement. Therefore good ventilation can be achieved by adjusting o and sa based on Δp.

The lighting energy consumption E_{light} can be expressed as follows if minimum lighting energy consumption is the objective:

$$E_{light} = h(d, \delta, \theta, WWR) \quad (5)$$

d represents the exterior zone depth, δ represents the window's transmittance.

If the total energy consumption E is taken as an objective function, E can be expressed as:

$$E = f(x, y, z...) \quad (6)$$

Then reduction of E can be achieved through adjusting all of the energy-related design parameters x, y, z...

Framework of this research

In order to combine energy efficiency design with building form design in schematic phase, an integrated simulation design method is put forward in this paper. The building modelling software Rhino, the building performance simulation software EnergyPlus and the most energy efficient scheme generator MEESG are integrated to achieve the following two goals:(1) "Simulating while drawing"-the scheme can be adjusted based on the energy simulation results; (2) The workload of architectural modelling in simulation software can be reduced effectively. Figure 1shows the framework of this research.

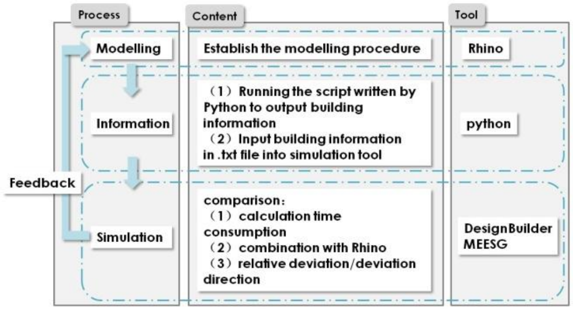

Figure 1 Integrated simulation and design process

In MEESG, parameters are divided into two kinds: one kind is given based on objective conditions of the project, and the other kind of parameters will be obtained by optimization. After setting values of the first type of parameters and setting ranges of the second type of parameters, the optimal solution with the lowest energy consumption can be generated through the energy consumption prediction model and the genetic algorithm integrated into MEESG based on AEDPM (Xiaoru Zhou, 2009), which is the theoretical basis of MEESG.

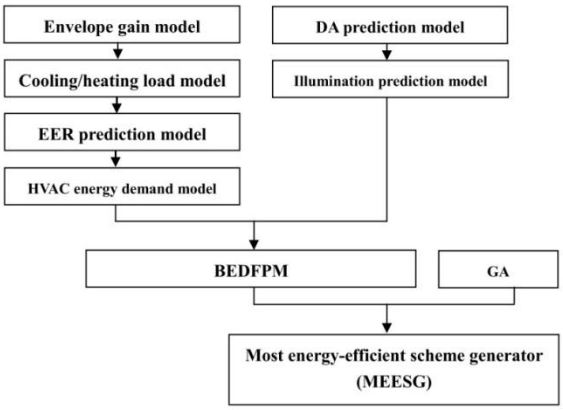

Figure 2 Frame of AEDPM

The accuracy of MEESG has been tested based on climate datas of the following four cities: Guangzhou, Shanghai, Beijing and Haerbin. For each city, the optimal solution is generated by MEESG, then n new different schemes are generated through modifying the optimal solution. Energy consumption (doesn't include lighting energy consumption) of each city's n+1 schemes is calculated by AEDPM and DeST respectively, then compared. The relative deviation of energy consumption is shown in Table 1 (Xiaoruzhou, 2009):

Table1
Relative deviation between DeST and MEESG

City	Guang zhou	Shangh ai	Beijing	Haerbi n
Relative deviation (%)	3.5	6.7	10.7	15.0

From Table 1, the relative deviations are all not higher than 15.0%. And energy simulation result shows that, when calculated by DeST, the building scheme with the lowest energy consumption is exactly the optimal solution predicted by MEESG. In conclusion, the energy consumption trend predicted by AEDPM is correct on the whole, and the order of energy consumption value of the n+1 schemes in each city is consistent with the result calculated by DeST although there are also differences.

Limited to the complexity of building energy consumption prediction model, the plan shape of optimal design schemes are all rectangle.

Although MEESG can provide a fast calculation, it is necessary to research on the relative deviation and deviation direction between the simulation results of MEESG and EnergyPlus. So, this research mainly includes the following content: (1)How to model in Rhino, then how to output the building information and edit it into a fixed format required in simulation tools; (2)Compare EnergyPlus with MEESG in three aspects: calculation time consumption, difficulty of combination with Rhino, relative deviation and deviation direction of simulation results.

SIMULATION AND EXPERIMENT

Building information output

In order to achieve real-time simulation of building energy consumption during design process, the building information must be output accurately and quickly. In addition, in order to combine with simulation tool, the format of the output building information should be similar to that of simulation input file as far as possible. Energy simulation tools in this research are MEESG and DesignBuilder (DesignBuilder and EnergyPlus are based on the same algorithm. Because it is easier to model in DesignBuilder and automatic calculation of simulation tool cannot be achieved at the present stage, so DesignBuilder is used to perform energy simulation instead of EnergyPlus in this paper).

In this paper, building information of Rhino model is output through running python script written in Rhino. One case is shown in Figure 3. The model is a two-storey building, plan size is 15m×10m, storey height is 3m， and there are four windows on the south facade. In order to output building information accurately, modelling process must follow the following four steps:(1)Pull up building body block;(2)Explode the model;(3)Copy the ground floor to the height of 3 meters vertically;(4)Frame out 4 windows on the south facade. After modelling, a txt format file which records building information can be generated through running the Python script.

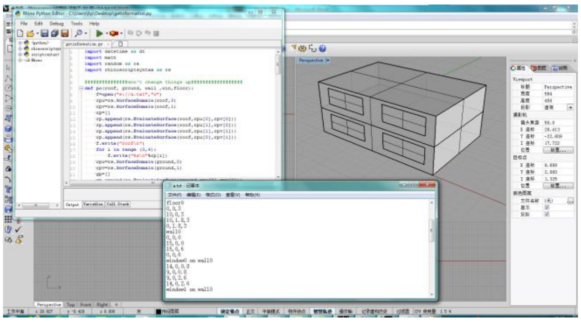

Figure 3 Modelling and information output in Rhino

Information of rectangle building is easy to obtained. And if the Python script is modified and improved, the shape of building plan can be not only rectangle, but also L, concave or other more complex shapes. Because how to make the simulation input file accurately read information from the .txt file output from Rhino is still not achieved, so comparison between MEESG and EnergyPlus is finished by manual modelling in this research.

Energy consumption simulation

The standard building model to be simulated is cuboid. Each floor is divided into five zones, one interior and five exterior zones.

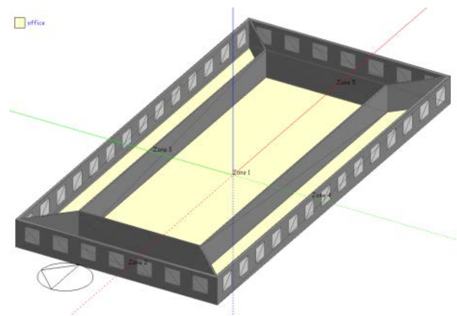

Figure 4 Building Model

Building energy simulation is performed in Beijing. Other conditions are: WWR is 0.3/0.4/0.5, the equipment heat gain is 20W/m2 or 0W/m2, the exterior zone depth is 4m/6m/8m. Building model parameter settings can be divided into 5 types (Table2 ~ Table6), pink parameters are input by drawing, blue parameters are input by choosing materials, the others are manual input parameters.

Table 2
Shape parameters

	MEESG	DB
Building area	$8000m^2$	$8000m^2$
Number of floor	10	10
Storey height	2.7m	2.7m
South side length	40m	40m
Infiltration rate	0.3ac/h	0.3ac/h

Table 3
Thermal parameters

	MEESG	DB
U-value of wall	$0.55W/m^2.K$	$0.55W/m^2.K$
U-value of window	$2.4\ W/m^2.K$	$2.4\ W/m^2.K$
SHGC of window	0.551	0.551

Table 4
System parameters

	MEESG	DB
Heating setpoint temperature	22℃	22℃
Heating set back	/	12℃
Cooling setpoint temperature	25℃	25℃
Cooling set back	/	28℃
Humidification setpoint	/	30%
Dehumidification setpoint	/	50%
Target illuminance	/	300lux

Table 5
Schedule

	Density	Schedule
Occupancy	$0.1people/m^2$	Monday to Friday: 8:00~17:00
Lighting	$11W/m^2$	
Equipment	$20W/m^2$ or $0W/m^2$	

Table 6
HVAC schedule

Heating	Nov 16th~Mar 15th
Cooling	May 21st~Sep 20th

DISCUSSION AND RESULT ANALYSIS

Computation time consumption

For the simulation model above, the calculation time of MEESG is 12s, and that of DesignBuilder is 135s, so the computational efficiency of MEESG is higher than DesignBuilder. In schematic phase, during which the building form is simple and conceptual, our goal is to compare building performance of different design schemes as quickly as possible, but not to get precise simulation results. Because the non-linear model in Rhino is always complex, and the model complexity will increase in the future, it goes without saying that a fast calculation method is preferable. Especially the goal-"Simulation while drawing", if achieved, will guide performance-oriented green building design from the start of building design. The design method proposed in this paper, which can instantly feedback calculation results, is more in line with the demand of architects. Under this method, users can get a fast and intuitive understanding of the building performance, then modify design schemes more effectively.

Combination with Rhino

In order to compare the difficulty of combining MEESG with Rhino and EnergyPlus with Rhino, building model parameters required in the two simulation tools are summarized in this paper. For MEESG, building model information includes the following 10 parameters: building area, storey height, number of floor, WWR (east/south/west/north/roof), building orientation(- π /4, - π /8, 0, π /8, π /4), atrium area ratio, south-to-west length ratio of atrium(1/3, 2/3, 1, 3/2, 3/1), atrium/courtyard position(center/south/west/north/east), atrium/courtyard type(atrium/courtyard), exterior zone depth. For EnergyPlus, vertex coordinates of each piece of building envelope(wall/partation/roof/ceiling/floor/window) must be written into an .idf file in accordance with a fixed format.

Parameters read from Rhino model conclude vertex coordinates of wall, floor, ceiling, roof and window. And parameters required in MEESG can be calculated according to parameters read from Rhino model. In addition, it is easy for MEESG to read data from excels. But because the text structure of .idf file is much more complex and strict, it is difficult for EnergyPlus to read information from the .txt file output from Rhino model.

Relative deviation and deviation direction

Table 7
Energy consumption when equipment heat gain=20W/m², exterior zone depth=4m (kWh/m² • a)

WWR	Tool	heat	cool	light	total
0.3	DB	18.20	24.27	15.35	57.82
	MEESG	19.52	21.44	16.54	57.50
0.4	DB	18.20	24.27	14.83	57.30
	MEESG	19.99	22.66	13.76	56.41
0.5	DB	18.37	28.24	13.52	60.13
	MEESG	20.55	24.25	13.76	58.56

Table 8
Energy consumption when equipment heat gain=0W/m², exterior zone depth=4m (kWh/m² • a)

WWR	Tool	heat	cool	light	total
0.3	DB	23.25	17.29	15.35	55.89
	MEESG	19.05	13.49	16.54	49.08
0.4	DB	23.03	19.39	14.83	57.25
	MEESG	19.57	14.72	13.76	48.05
0.5	DB	23.17	21.20	14.61	58.98

	MEESG	20.01	16.30	13.76	50.07

Table 9
Energy consumption when equipment heat gain=20W/m²,exterior zone depth=6m (kWh/m² • a)

WWR	Tool	heat	cool	light	total
0.3	DB	18.27	23.75	12.69	54.71
	MEESG	19.44	21.43	15.02	55.89
0.4	DB	18.22	25.14	11.32	54.68
	MEESG	19.49	22.48	10.59	52.56
0.5	DB	18.37	27.43	10.44	56.24
	MEESG	19.93	23.81	8.41	52.15

Table 10
Energy consumption when equipment heat gain=0W/m²,exterior zone depth=6m (kWh/m² • a)

WWR	Tool	heat	cool	light	total
0.3	DB	22.98	16.85	12.69	52.52
	MEESG	19.09	13.49	15.02	47.60
0.4	DB	22.82	17.85	11.32	51.99
	MEESG	20.40	14.53	10.59	45.52
0.5	DB	22.94	20.58	10.44	53.96
	MEESG	21.57	15.87	8.41	45.85

Table 11
Energy consumption when equipment heat gain=20W/m²,exterior zone depth=8m (kWh/m² • a)

WWR	Tool	heat	cool	light	total
0.3	DB	17.80	23.85	14.84	56.50
	MEESG	21.16	21.75	16.26	59.17
0.4	DB	17.98	25.24	10.46	53.69
	MEESG	21.95	22.87	12.12	56.94
0.5	DB	18.28	26.91	8.28	53.46
	MEESG	22.57	23.98	8.27	54.82

Table 12
Energy consumption when equipment heat gain=0W/m²,exterior zone depth=8m (kWh/m² • a)

WWR	Tool	heat	cool	light	total
0.3	DB	22.02	16.88	14.84	53.75
	MEESG	20.52	13.80	16.26	50.58
0.4	DB	22.18	18.43	10.46	51.08
	MEESG	21.70	15.07	12.12	48.89
0.5	DB	22.56	20.17	8.28	51.00
	MEESG	22.56	16.18	8.27	47.01

Table 13
Relative deviation of energy consumption between MEESG and DesignBuilder (%)

d	WWR	Equipment heat gain=20W/m²			
		heat	cool	light	total
4m	0.3	7.26	-11.67	7.77	-0.55
	0.4	9.84	-6.65	-7.21	-1.55
	0.5	11.86	-14.12	1.75	-2.62
6m	0.3	6.43	-9.78	18.37	2.16
	0.4	6.96	-10.58	-6.45	-3.88
	0.5	8.50	-13.21	-19.45	-7.28
8m	0.3	18.84	-8.81	9.55	4.73
	0.4	22.09	-9.40	15.84	6.06
	0.5	23.50	-10.88	-0.09	2.54

Table 14
Relative deviation of energy consumption between MEESG and DesignBuilder (%)

d	WWR	Equipment heat gain=0W/m²			
		heat	cool	light	total
4m	0.3	-18.05	-21.98	7.77	-12.18
	0.4	-15.04	-24.09	-7.21	-16.08
	0.5	-13.65	-23.11	-5.79	-15.10
6m	0.3	-16.93	-19.96	18.37	-9.37
	0.4	-10.60	-18.59	-6.45	-12.44
	0.5	-5.97	-22.90	-19.45	-15.04
8m	0.3	-6.82	-18.26	9.55	-5.89
	0.4	-2.18	-18.25	15.84	-4.29
	0.5	0.00	-19.76	-0.09	-7.83

Relative deviation can be calculated by the following formula:

$$\frac{E_{MEESG} - E_{DB}}{E_{DB}} \times 100\% \qquad (7)$$

From Table 7 ~ Table 14, total energy consumption calculated by MEESG is lower than that calculated by DesignBuilder except for 3 cases (Table13). For these 3 cases, the exterior zone depth is large but WWR is small.

Heating deviation increases with exterior zone depth and equipment heat gain increasing and WWR decreasing. It changes from -18.05% to 23.50%。

Cooling deviation is negative for all cases, when exterior zone depth is 4m, equipment heat gain is 0W/m², WWR is 0.4, cooling deviation can be -24.09% (Table 14). Cooling deviation increases with exterior zone depth increasing.

Lighting deviation increases with WWR decreasing and exterior zone depth increasing. Especially when exterior zone depth is 6m, lighting deviation can be up to 18.37% (Table 14).

Because lighting energy consumption prediction model integrated in MEESG is obtained from a large number of accurate simulation results by Ecotect and Daysim. So further research on lighting energy consumption between DB and MEESG has been performed.

Lighting energy consumption can be divided into exterior lighting energy consumption and interior lighting energy consumption (Table 15~Table 17).

Table 15
Lighting energy consumption when exterior zone depth=4m (kWh/m^2 • a)

WWR	Tool	Interior	Exterior
0.3	DB	28.15	1.93
	MEESG	28.67	5.35
0.4	DB	28.15	1.38
	MEESG	28.67	0.00
0.5	DB	28.15	0.01
	MEESG	28.67	0.00

Table 16
Lighting energy consumption when exterior zone depth=6m (kWh/m^2 • a)

WWR	Tool	Interior	Exterior
0.3	DB	28.15	4.95
	MEESG	28.67	9.71
0.4	DB	28.15	3.54
	MEESG	28.67	3.56
0.5	DB	28.15	2.63
	MEESG	28.67	0.53

Table 17
Lighting energy consumption when exterior zone depth=8m (kWh/m^2 • a)

WWR	Tool	Interior	Exterior
0.3	DB	28.15	11.60
	MEESG	28.67	14.57
0.4	DB	28.15	7.17
	MEESG	28.67	9.86
0.5	DB	28.15	4.96
	MEESG	28.67	5.49

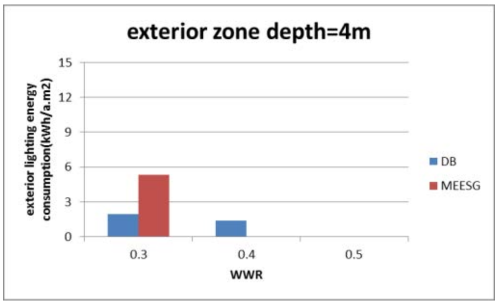

Figure 5 Exterior lighting energy consumption when exterior zone depth=4m

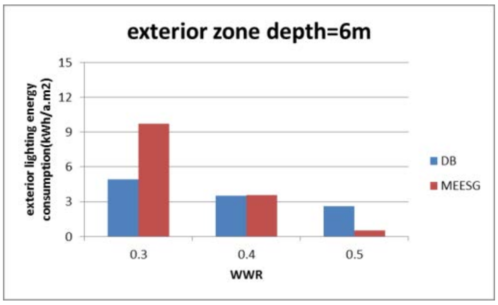

Figure 6 Exterior lighting energy consumption when exterior zone depth=6m

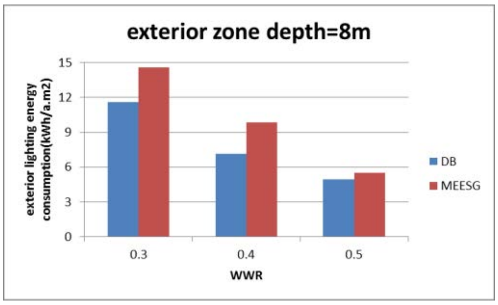

Figure 7 Exterior lighting energy consumption when exterior zone depth=8m

Lighting energy consumption division results show that:

(1)Interior lighting energy consumption is obtained by multiplying lighting density by working hours, so interior lighting energy consumption calculated by the two methods are nearly equal.

(2)Exterior lighting energy consumption calculated by MEESG is much higher than that calculated by DB. Exterior lighting deviation increases with exterior zone depth decreasing, so when exterior zone depth is constant, lighting deviation will increase with the proportion of exterior area increasing.

(3)Compared to DB, the parameter WWR has a greater impact on exterior lighting energy consumption calculated by lighting energy prediction model integrated in MEESG.

CONCLUSION

It is pointed out that, although building parametric design method is widely used today, the energy efficiency design is subject to the architectural form design in schematic phase. In order to combine energy efficiency design with parametric design in schematic phase, an integrated application of Rhino, EnergyPlus and MEESG is put forward, and an integrated simulation and design process has been established in this paper.

In the aspect of information output, a modelling procedure has been established in this paper. After modelling, the building model information can be output through python script written in Rhino. In the aspect of energy simulation, aiming at evaluating the possibility of combination MEESG and EnergyPlus with Rhino, the comparison between MEESG and DesignBuilder has been performed in three aspects: calculation time consumption, difficulty of combination with Rhino, relative deviation and deviation direction of energy simulation results.

In conclusion:

(1) MEESG has a big advantage over DesignBuilder in an integrated application because a shorter time will be consumed when calculating the same case. And another advantage of rapid calculation is that the simulation results can be feedback, then the design can be adjusted according to the simulation results. (2) Compared to EnergyPlus, MEESG is much easier to be combined with Rhino.

(2)For the 10-storey case in this paper, simulation results show that energy consumption calculated by MEESG is lower than DB both for heating and cooling, but lighting energy consumption calculated by MEESG is higher than DB.

Further work focuses on 4 points:

(1)The python script will be modified to meet more complex building form.

(2)Heating and cooling load calculated by DB and MEESG will be divided and more detailed comparison between the 2 calculation methods should be performed. Lighting energy prediction model integrated in MEESG will be modified by more accurate simulations. In further simulations, many parameters will be altered, for example, in lighting simulation, the ambient bounces should be changed from 2 to 5, and the WWR range should be changed from [0.3,0.5] to [0.2,0.7].

(3)Compare MEESG with other energy simulation software, such as DeST, IES...

(4)Energy consumption prediction model in MEESG should be developed and applied into architecture design works with more complex shapes. The following 3 modules integrated in MEESG will be focused: body judging module, radiation calculation module, lighting energy prediction module.

NOMENCLATURE

E =energy consumption

Q_{sum}=cooling load in summer

Q_{win}=heating load in winter

COP_s =coefficient of performance in summer

COP_w =coefficient of performance in winter

q_{win}=radiation heat gain from window

K_{win}=heat transfer coefficient of window

ΔT =temperature difference

SC =shading coefficient of window

q_{solar}=radiation energy intensity on the window

Q =indoor radiation heat gain

θ =floor's orientation

l =roof overhang length

η =glazing ratio

V =ventilation rate

Δp =wind pressure difference between the windward side and the leeside

sa =interior spatial arrangement

o =window's opening size

E_{light}=lighting energy consumption

d =exterior zone depth

δ = the window's transmittance

x =first variable

y =second variable

z =third variable

E_{MEESG}= simulation results calculated by MEESG

$E_{DesignBuilder}$ = simulation results calculated by DesignBuilder

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