Study of a simplified prediction model for daylight autonomy of office building in different daylight climate zones

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ABSTRACT
At the scheme design stage, the potential of daylighting is significant due to the saving for electric lighting use. There are some methods for lighting energy consumption prediction to optimize the daylighting design, most of which need detailed modeling and simulation process. A simplified prediction function for DA(daylight autonomy) in whole year for office building is proposed and a direct correlation has been established between DA and parameters such as orientations, ratio of window area to wall area (WWR) and perimeter area. Then the generality of coefficient in this prediction function for different daylight climate zones is analyzed. By choosing a series of typical cities in different daylight climate zones and fitting the coefficient in the DA functional relations of different WWR, this paper analyzes the variation and classification rules of the prediction function's coefficient of different cities.

KEYWORDS
Daylight climate zone, Simplified prediction model, daylight autonomy

INTRODUCTION
Daylighting can effectively decrease lighting energy which accounts for a considerable proportion of the whole in the commercial buildings. In the entire life cycle of building, the architectural scheme design stage is especially important for daylighting design. The parameters determined in this process, such as WWR and window transmission ratio, have important impact on the lighting energy consumption in the building.

However, the lack of capability of providing detailed information for simulation software in the scheme stage, and the fact that frequent change of schemes consumes more time unexpected for case study, are reasons for the reluctance of building professionals in incorporating daylighting features in their design. There are several detailed simulation tools available to evaluate the benefits of daylighting, such as ADELINE, SUPERLIT, Radiance and the integrated software based on them. But they require too much input information and time at the scheme stage. The simplified models, which could finish the dynamic calculation

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and provide reasonable energy consumption data, are suitable tools for quick analysis.

In the analysis of Lynes and Litterlefair (1990), the energy saving model is established using average Daylight Factor (DF). The paper of Krarti, Erickso and Hillman (2005) proposed a simplified analysis method to evaluate the potential of daylighting to save energy associated with electric lighting use, given perimeter area, window area, and window type. Chen Hongbin (2004) analyzed DF with the consideration of the impacts of window transmission rate, the height of the window sill and the orientation and the shade with simplified formula based on the regression equation resulted from Radiance simulation. However, these models do not have a complete consideration of the parameters, and are usually aimed to a single room, not the whole building. This paper proposed a method with a simplified prediction model for lighting energy consumption in office buildings, aimed to apply in architectural design scheme stage with quick calculation and high efficient daylighting design.

Assessment index

In this paper, daylight autonomy (DA) is introduced for evaluating the building's energy conservation potential. For DA, when its threshold value is 100lux, it equals the accumulated hours when the indoor illuminance higher than 100lux divided by the total lighting hours. Two daylight-linked control types, such as dimming control and on-off control are proposed for comparison. And the DA's values of them are different. When the indoor illuminance is lower than 100lux, under dimming control the artificial lighting will add the insufficient part, and then DA_{con} equals indoor illuminance divided by the threshold illuminance-100lux. While under on-off control, it totally relies on the artificial lighting, and DA equals zero. After getting the result of DA, the lighting energy saved by using daylighting can be easily calculated.

Methodology

The idea of this method is as flows: imports the architectural model built by ECOTECT into DAYSIM to simulate the value of DA considering different WWR, window transmission δ, and the floor height divided by the perimeter length h/r. For each value of WWR, with a linear regression, the value of DA can be demonstrated as:

$$DA = \beta_1 + \beta_2 \cdot (h/r) + \beta_3 \cdot \delta + \beta_4 \cdot (h/r)^2 + \beta_5 \cdot \delta^2 \qquad (1)$$

The coefficient $\beta_1 \sim \beta_5$ is calculated in Matlab.

However, the original research only considered simple office buildings in Beijing. Considering that daylight climate in different cities varies, daylight level will also vary. Therefore, the fitting formula for a typical city cannot necessarily be generalized to the whole country of China. Since there are too many cities in China, it is necessary to build a database for each city one by one, which is poor efficient. As a result, the superiority of this simplified prediction for DA needs further evaluation.

The paper is still applied with the research method proposed by Yu.Q (2009) which is stated above. On account of an ordinary type of office building with independent window set in south, a series of typical cities that can represent different daylight climate zones are chosen for simulation to get varied fitting formulas. By analyzing the result of simulation, it may possible to establish a kind of correlation between coefficient of fitting formulas and daylight climate zones and factor of annual average illuminance.

INTRODUCTION OF SIMULATION

Simulation tool

The model of a flat office building with south independent windows as a typical example is built in ECOTECT and imported into DAYSIM for simulation. DAYSIM is a validated daylighting analysis software that calculates the annual daylight availability in arbitrary buildings based on the RADIANCE backward raytracer. It uses the Lightswitch occupant behavior model to mimic occupant use of personal controls such as light switches and venetian blinds and to predict energy savings from automated lighting controls such as occupancy sensors and photocell controlled diming systems.

Selection of city

In lighting design standard, the whole country is divided into 5 regions which adopt different standard. On the basis of the influence of daylight climate on fitting formulas, this paper chooses 9 typical cities for simulation. And corresponding information of the 9 cities are listed in *Table 1*.

Table 1. *City and its daylight climate attribute*

Daylight climate zone	*City*	*Annual average illuminance/lux*
Ⅲ	Beijing(BJ)	19122.24
	Tianjin(TJ)	17502.44
	Guangzhou(GZ)	14765.28
Ⅳ	Changsha(CS)	13690.86
	Nanjing(NJ)	15337.67
	Shanghai(SH)	16239.27
	Wuhan(WH)	14939.54
	Hangzhou(HZ)	14172.97
Ⅴ	Chongqing(CQ)	17944.02

Building model

The model is an office building with south independent windows and the floor height of the model is 2.9m. Three kinds of window transmission (0.6, 0.7, 0.8) are considered. Other parameters are listed in *Table 2.*

Table 2. *Parameters of model*

Typical WWR	*Window sill height/m*	*Window height/m*	*Window width/mm*	*Wall width between windows/mm*

0.3	0.9	1.5	1500	1200
0.4			3600	1400
0.5			4200	600

SIMULATION RESULT AND DISCUSSION

Considering 9 cities in different daylight climate zones and taking three parameters as WWR, window transmission and perimeter length for comparison, 143 cases are modeled in this paper and regression analysis is carried out based on the simulation results. Due to space limitation, typical results for the coefficients for different cities in each daylight zone are listed in *Table 3~Table 7*.

Table 3. *Regression results of TJ (Daylight climate zone Ⅲ)*

Control type	*WWR*	*β1*	*β2*	*β3*	*β4*	*β5*	*r*
Dimming control	0.3	13.37	116.71	70.55	-81.66	-35.83	0.9865
	0.4	17.43	83.74	108.73	-57.68	-71.00	0.9946
	0.5	49.03	67.31	35.25	-47.49	-16.50	0.9799
On-off control	0.3	-56.03	213.32	124.08	-145.62	-60.17	0.9923
	0.4	-63.50	167.26	226.30	-113.31	-147.33	0.9950
	0.5	-6.37	138.61	93.95	-96.46	-48.50	0.9850

Table 4. *Regression results of GZ (Daylight climate zone Ⅲ)*

Control type	*WWR*	*β1*	*β2*	*β3*	*β4*	*β5*	*r*
Dimming control	0.3	-1.1	141.1	81.8	-97.9	-40.7	0.9886
	0.4	28.7	103.2	50.3	-72.1	-23.0	0.9867
	0.5	37.6	84.4	49.0	-58.9	-23.7	0.9848
On-off control	0.3	-76.7	247.1	132.5	-166.7	-61.5	0.9937
	0.4	-40.3	203.3	105.8	-141.1	-49.5	0.9885
	0.5	-1.1	141.1	81.8	-97.9	-40.7	0.9886

Table 5. *Regression results of SH(Daylight climate zone IV)*

Control type	*WWR*	*β1*	*β2*	*β3*	*β4*	*β5*	*r*
Dimming control	0.3	30.82	110.32	25.32	-74.41	-4.13	0.9925
	0.4	31.29	91.92	56.47	-63.92	-28.33	0.9874
	0.5	39.76	74.79	54.27	-51.60	-28.33	0.9862
On-off control	0.3	-34.16	208.81	60.27	-139.32	-15.62	0.9936
	0.4	-28.80	182.41	100.90	-127.05	-48.67	0.9865
	0.5	-11.61	149.27	95.03	-103.69	-47.67	0.9853

Table 6. *Regression results of NJ(Daylight climate zone IV)*

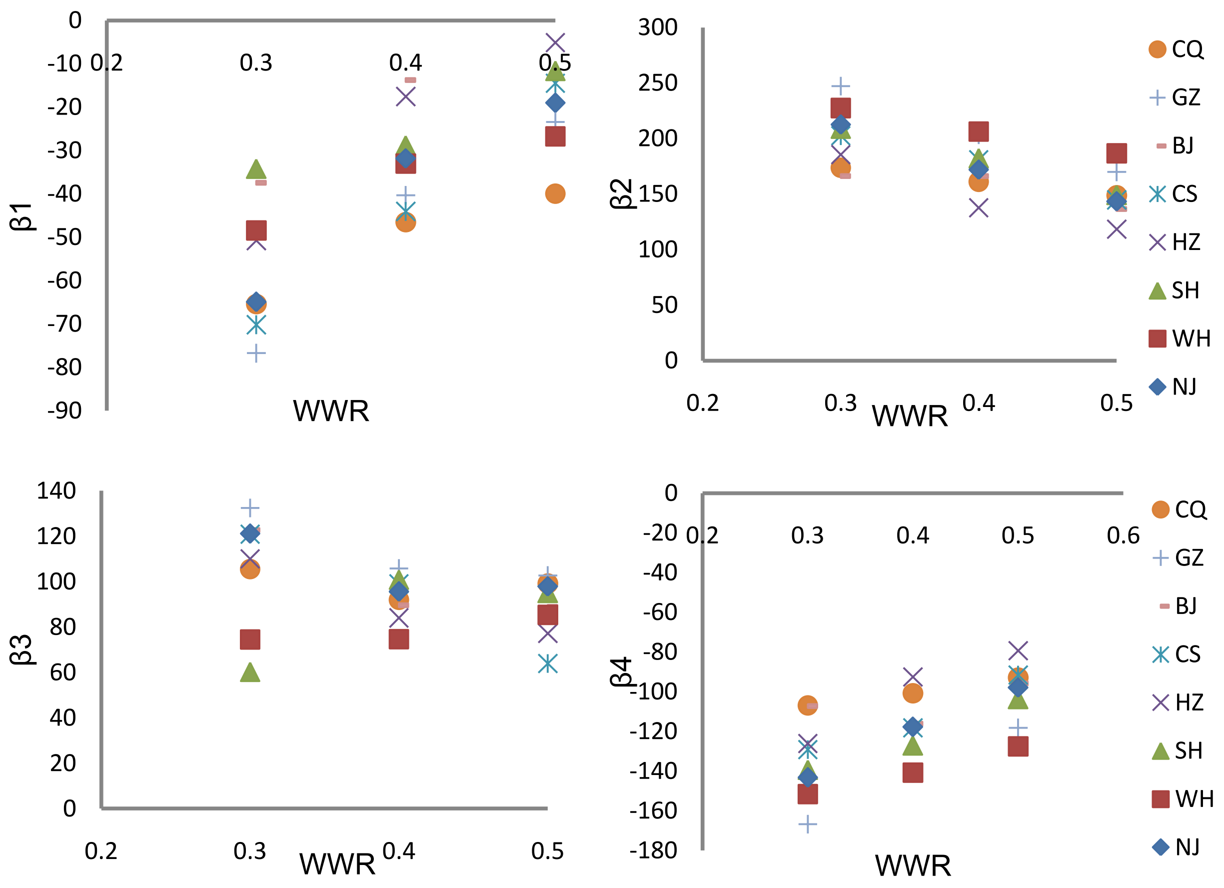
Control type	*WWR*	*β1*	*β2*	*β3*	*β4*	*β5*	*r*
Dimming control	0.3	4.3	147.6	51.3	-100.9	-22.0	0.9947
	0.4	20.6	122.3	41.4	-83.8	-17.5	0.9931
	0.5	21.5	110.2	56.1	-75.9	-28.7	0.9918

On-off control	0.3	-48.41	227.45	74.50	-151.59	-28.67	0.9966
	0.4	-33.00	206.28	74.67	-140.76	-32.33	0.9939
	0.5	-26.69	186.68	85.38	-127.53	-41.83	0.9922

Table 7. *Regression results of CQ(Daylight climate zone V)*

Control type	*WWR*	*β1*	*β2*	*β3*	*β4*	*β5*	*r*
Dimming control	0.3	-21.4	134.7	86.6	-86.3	-40.2	0.9978
	0.4	-1.1	116.5	66.3	-75.4	-29.0	0.9969
	0.5	5.3	105.6	68.1	-68.7	-31.7	0.9959
On-off control	0.3	-65.4	173.8	105.5	-106.9	-44.5	0.9994
	0.4	-46.5	161.2	92.0	-100.8	-37.8	0.9988
	0.5	-39.9	148.8	99.2	-92.9	-44.5	0.9980

Comparison of coefficient of DA fitting formulas for all cities is shown in *Figure 1*.



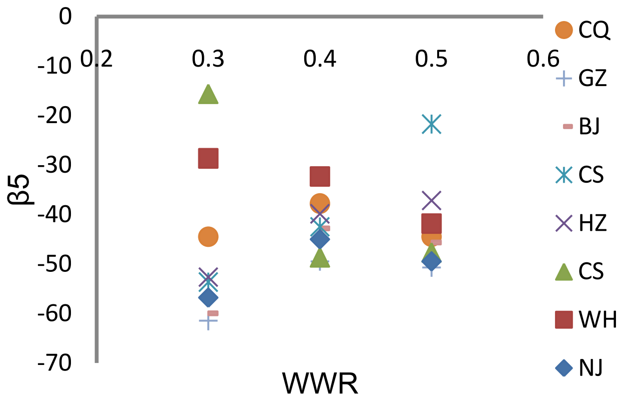


Figure 1. *Coefficient of β-WWR for all cities*

From the figure above, the coefficient of these cities in 3 different zones cannot be easily distinguished and classified by daylight climate zone on the diagram. As 5 cities of Zone Ⅳ are chosen, coefficients of these cities' empirical formulas are analyzed alone as *Figure 2*.

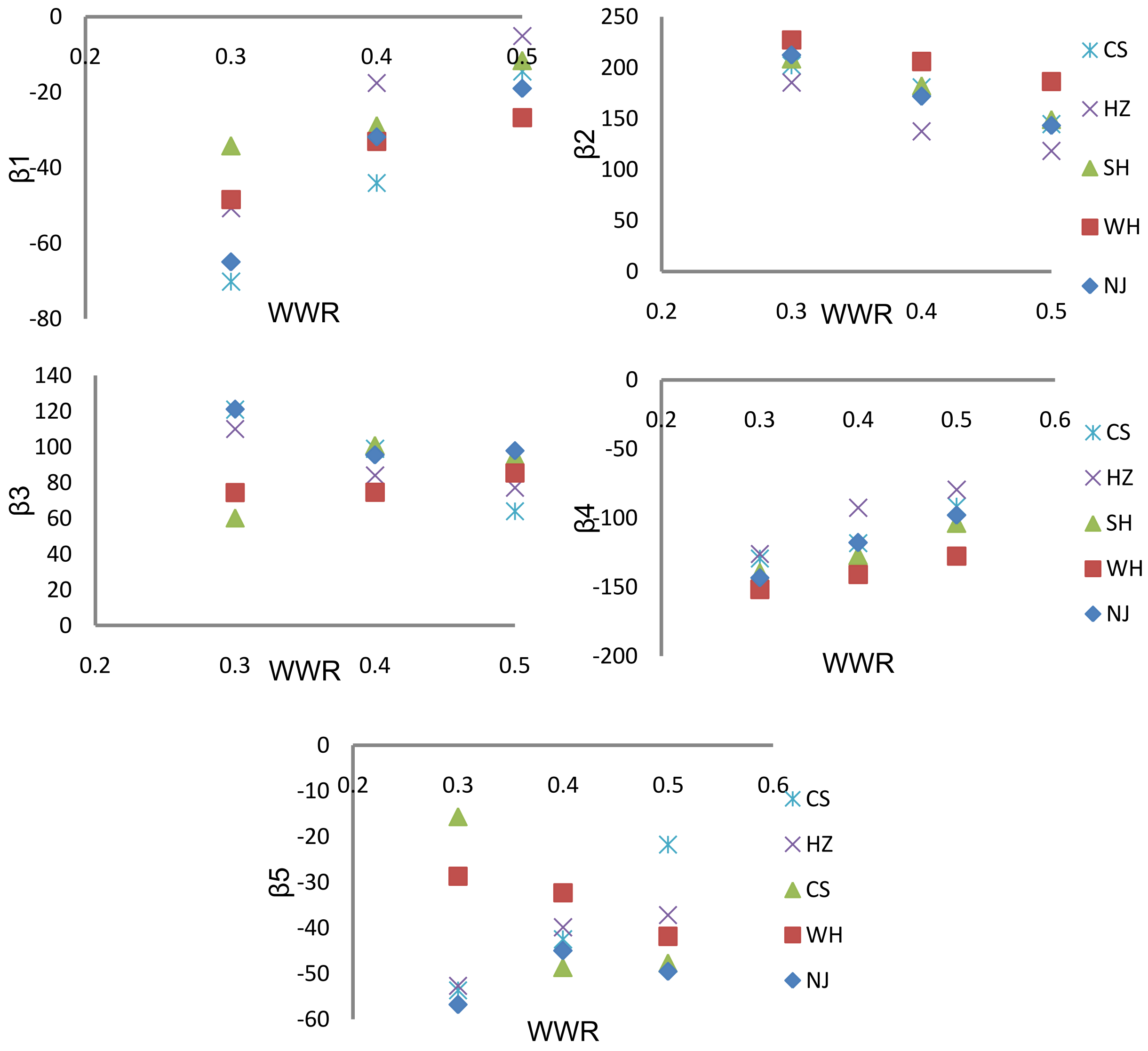


Figure 2. *Coefficient of β-WWR for cities in daylight climate zone Ⅳ*

Even though the variation trend of β for different cities approaches the same, the difference of these coefficients for different cities, especially β_4, under some WWR, cannot be ignored. If apply an empirical formula of one city to others, for example like that of BJ to others, the errors are shown in *Table 8* due to space limitation.

Table 8. *Error between DA calculated by empirical formula of BJ and simulation*

		DA								
		δ=0.6			*δ=0.7*			*δ=0.8*		
	r	4	6	8	4	6	8	4	6	8
WWR 0.3	*BJ*	5.8%	8.2%	***12.4%***	5.3%	7.1%	***12.4%***	4.8%	6.4%	***10.7%***
	CS	***21.6%***	***27.4%***	***34.6%***	***19.3%***	***24.8%***	***31.7%***	***17.4%***	***22.7%***	***29.2%***
	HZ	***17.9%***	***18.8%***	***23.1%***	***17.4%***	***18.4%***	***21.5%***	***16.9%***	***18.1%***	***20.4%***
	WH	***15.7%***	***19.0%***	***25.2%***	***14.8%***	***17.3%***	***22.8%***	***13.9%***	***16.2%***	***21.0%***
	NJ	9.8%	***13.4%***	***20.1%***	9.9%	***13.8%***	***19.8%***	9.6%	***13.1%***	***19.3%***
	CQ	***34.8%***	***41.4%***	***48.7%***	***32.0%***	***45.1%***	***45.3%***	***29.6%***	***36.0%***	***42.7%***
	GZ	7.9%	***12.5%***	***20.9%***	6.9%	***10.6%***	***17.8%***	6.0%	9.1%	***15.4%***
	TJ	4.8%	5.7%	9.9%	4.5%	5.3%	8.7%	4.3%	5.0%	7.9%

From the table above, it can be found out that data error more than 10% count for 63.4% in total. Among them, when apply to cities located in different zones from BJ, such as CS, NJ, HZ, WH, CQ, error for all data points is above 10%, which shows that apply empirical formula of BJ to other daylight climate zones is not feasible. However, when applied to TJ and GZ which are also located in Zone Ⅲ, satisfaction rate of error<10% reached 70.4% and 100% respectively. Therefore, in order to further analyze the generalization of empirical formula, choose daylight climate zone Ⅳ as example, using formula of NJ. The result (part) is as ***Table 9.***

Table 9. *Error between DA calculated by empirical formula of BJ and simulation*

		DA								
		δ=0.6			*δ=0.7*			*δ=0.8*		
	r	4	6	8	4	6	8	4	6	8
WWR 0.3	*SH*	-4.4%	-6.0%	-9.7%	-5.1%	-7.8%	-9.3%	-5.3%	-7.8%	***-10.7%***
	CS	***13.1%***	***16.2%***	***18.2%***	***10.5%***	***12.7%***	***14.8%***	8.7%	***11.1%***	***12.2%***
	HZ	9.0%	6.2%	3.8%	8.4%	5.3%	2.0%	8.1%	5.7%	1.4%
	WH	6.6%	6.4%	6.3%	5.4%	4.1%	3.7%	4.8%	3.6%	2.1%

It can be found out from the table above that number data points where error>10% is relatively large, counts for 19%. Especially for CS, error almost distributes in the 10%~20%, which indicates that applying NJ's formula to SH, etc, is not feasible enough.

To see the result further, the feasibility of applying a typical city's formula to a whole daylight climate zone is questionable. Besides, the correlation between the coefficient and annual average illuminance is not obvious either.

SUMMARY

This paper chooses 9 typical cities in different daylight climate zones and simulates 143 cases to get results of DA in typical office buildings under different lighting control type, WWR, window transmission and perimeter length. Then prediction model for DA is established, WWR, window and perimeter length as variables. And the coefficient obtained is studied. The simulation result shows that the empirical formulas of different cities cannot be classified according to daylight climate zones. From the analysis of zone Ⅳ, it is found out that when applying formula of NJ to other city in the same zone, data points where error between DA calculated and simulated is above 10% counts for approximately 20%. Therefore, it’s possible that a database including empirical formulas for typical cities is needed. In architectural design scheme stage, different formula can be invoked in calculation according to cities.

There are still some deficiencies in this paper: lots of complex factors influence DA such as changing window area, height and location which will all lead to the variation of coefficient in empirical formula, while we do not know the sensitivity of coefficient to these factors. In order to reach more reliable conclusions, more modeling and simulation work must be done.

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