IOP Conf. Series: Earth and Environmental Science **182** (2018) 012017 doi:10.1088/1755-1315/182/1/012017

A Study on Daylighting Design of Urban Mid-Rise Housing from the Perspective of Carbon Emission Reduction Effect: Shanghai, China

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Abstract. Under the circumstance of rapid development, the contradiction and balance between energy consumption, carbon emission and urban living environment are increasingly become one of the problems to be solved in contemporary China. Housing has demonstrated tremendous potential to play a major role in the reduction of carbon emission, to gain a balance between reducing carbon emission and meeting increasing demand. Good daylighting is irreplaceable in improving the quality of housing and meeting the daily physiological and psychological needs of the residents. Thus, it is necessary and insightful to evaluate daylighting of housing from the perspective of carbon emission reduction. In this paper, three design control factors of window height, window/wall ratio and aspect ratio of window are studied. Several preliminary design optimization strategies based on residential lighting in Shanghai are proposed.

1. Introduction

For carbon emission of housing, it is affected by many factors. Among them, as an early phase of decision making, design plays a decisive role affecting the construction phase and use situation coming afterwards. Therefore, carbon emission should be taken into account at the initial phase of construction and also as an important design basis and standard for evaluating.

In the current situation of China, the main problems of daylighting design of urban housing mainly include two aspects: on the one hand, it just stays at the level of pandering to relevant existing building codes; on the other hand, it tends to be more blind pursuit of transparency [1]. Both of the above may cause the actual use of housing to fail to meet the design expectations and bring sensory experience and environmental problems related to energy consumption and carbon emissions [2]. In this paper, energy consumption and daylighting simulation by using design aid software combined with empirical analysis, questionnaire investigation are applied to study the daylighting design related control elements. On this basis, the optimization strategies of daylighting design of housing are proposed to try to achieve a "win-win" of carbon emission reduction and good daylighting in housing projects.

This paper is supported by the "National Natural Science Foundation of China Project: A Study on Sensitivity of Carbon Emission of Residential Building Shape Coefficient through Empirical Researches of Built Housing in Yangtze River Delta (Number.51478315)".

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2. Software Simulation

The research object of this paper is a typical middle-rise housing project in Shanghai (figure 1), using it as a reference, the software simulation study is carried out. PKPM-Daylight and PKPM-PBECA, developed and commonly used in contemporary China as design aid tools, are selected as simulation software. The research variables are window sill height, window/wall ratio and aspect ratio of window [3]. After process of modelling and parameter settings, the simulation outcomes of each variable are gathered. The main standards for daylighting condition in this research are average daylighting coefficient and daylighting distribution conditiions [4, 5].

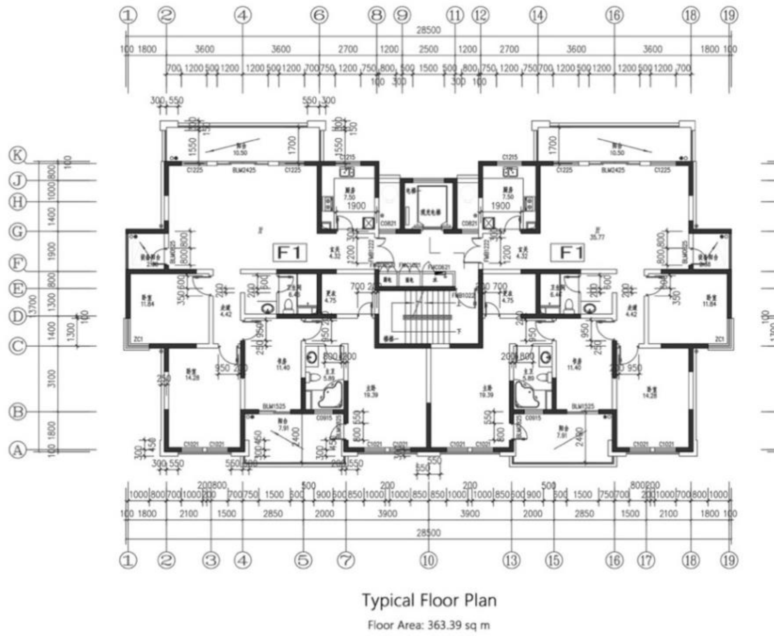

Figure 1. The typical plan of the selected middle-rise housing project.

2.1. Height of window sill

The following figures (figure 2-figure 5) show the influence of changing the height of window sill of each orientation on the daylighting coefficient and energy consumption during the use phase. It can be seen that the influence of changing the height of window sill on energy consumption is very small and can be ignored. The daylighting coefficient increases with the increase of the height of the window sill, reaching its peak value and inflection point when the height of window sill is 0.90m.

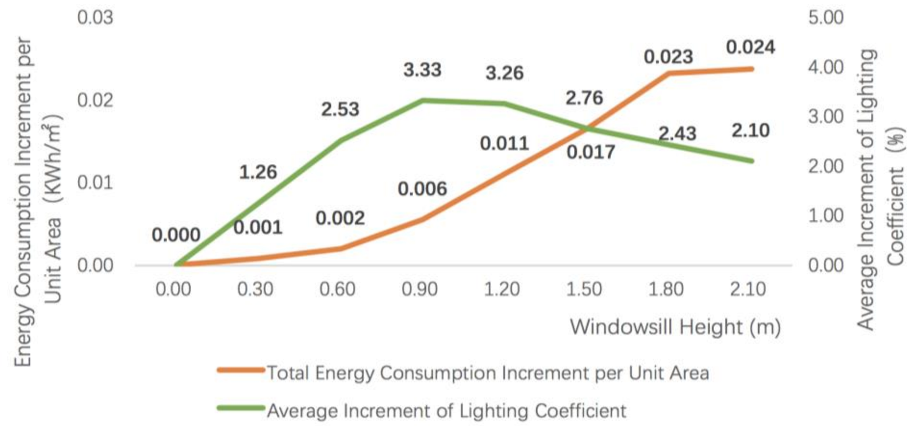

Figure 2. Increments of daylighting coefficient and total energy consumption influenced by east windowsill heights.

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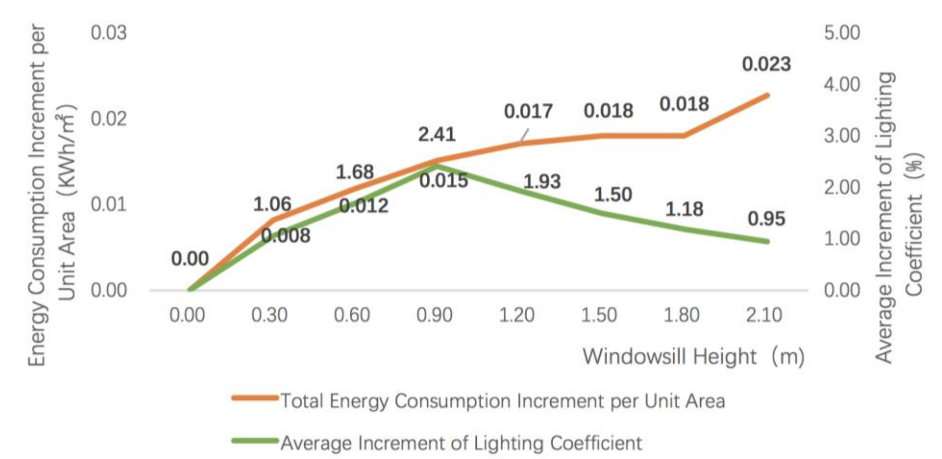

Figure 3. Increments of daylighting coefficient and total energy consumption influenced by south windowsill heights.

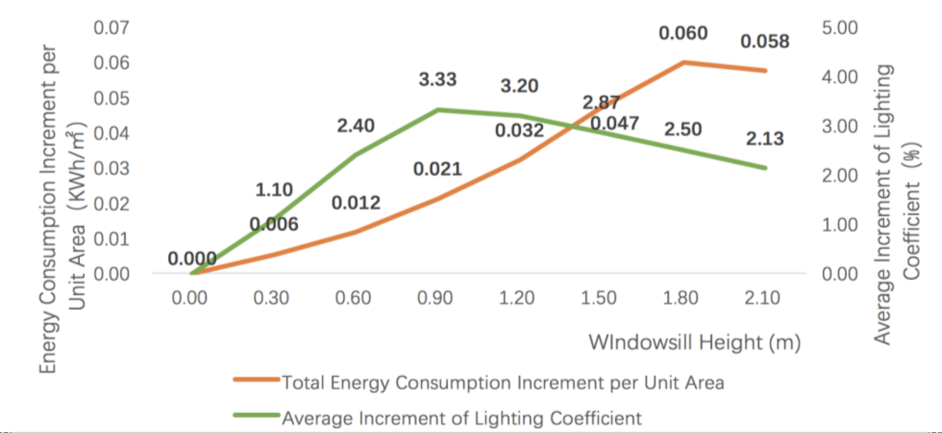

Figure 4. Increments of daylighting coefficient and total energy consumption influenced by west windowsill heights.

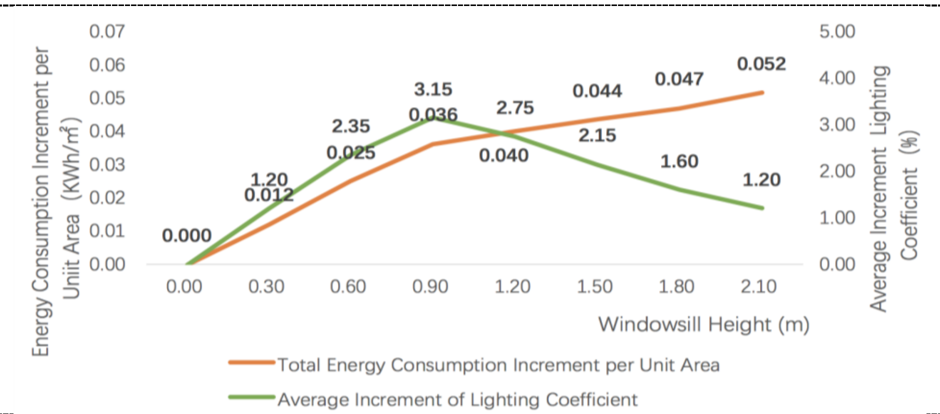

Figure 5. Increments of daylighting coefficient and total energy consumption influenced by north windowsill heights.

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2.2. Window/wall ratio

By adjusting the window/wall ratio of each orientation, that is, changing the total window area of each orientation will significantly affect the lighting effect and the energy consumption during the use phase of the house, and the increase will basically show a linear trend. In terms of orientation, when the window/wall ratio is increased, the order of the increment of carbon emissions per unit from large to small is south > east ≈ west > north, the order of the increase of indoor average daylighting coefficient is east ≈ west > north > south. Therefore, when the window/wall ratio is considered simply from the view of the lighting design of the house, it is an effective strategy to increase the window wall ratio of each orientation.

2.3. Aspect ratio of window

The effect of changing the aspect ratio of window, the ratio of window length to width, on energy consumption and carbon emissions is negligible in the case of the same window/wall ratio. However, from the perspective of indoor daylighting coefficient, when the window/wall ratio is less than 0.30, increasing the window width has a significant advantage over the increase of window height in increase of the lighting coefficient. The difference between these two can be nearly seven times based on the simulation results. When the window/wall ratio is greater than 0.30, the advantages of adjusting window width in increasing daylighting coefficient still exist. It is only that the difference between the two decreases gradually with the increase of window width and window height until it finally disappears (figure 6-figure 13).

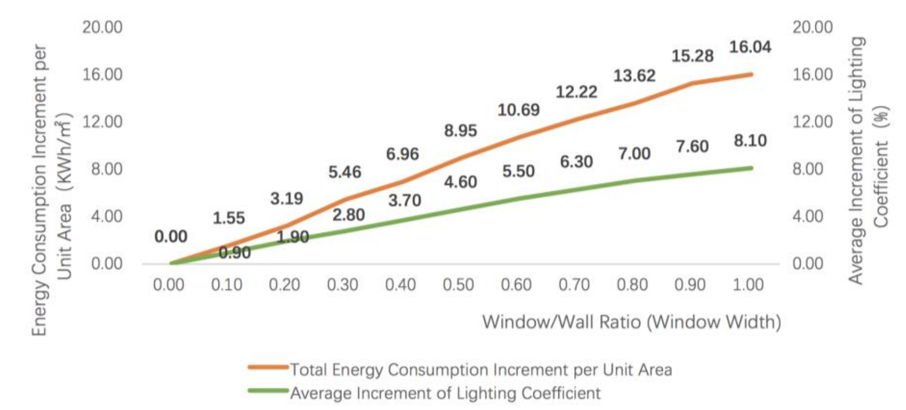

Figure 6. Increments of lighting coefficient and total energy consumption influenced by east window/wall ratio (window width).

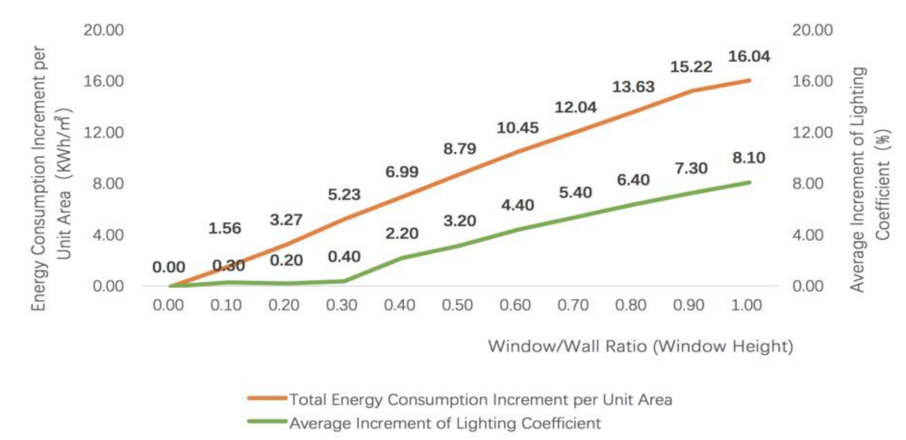

Figure 7. Increments of lighting coefficient and total energy consumption influenced by east window/wall ratio (window height).

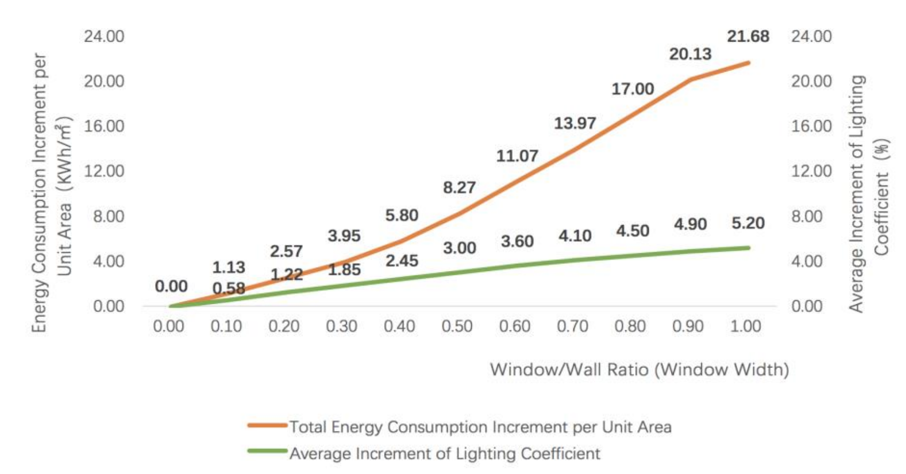

Figure 8. Increments of lighting coefficient and total energy consumption influenced by south window/wall ratio (window width).

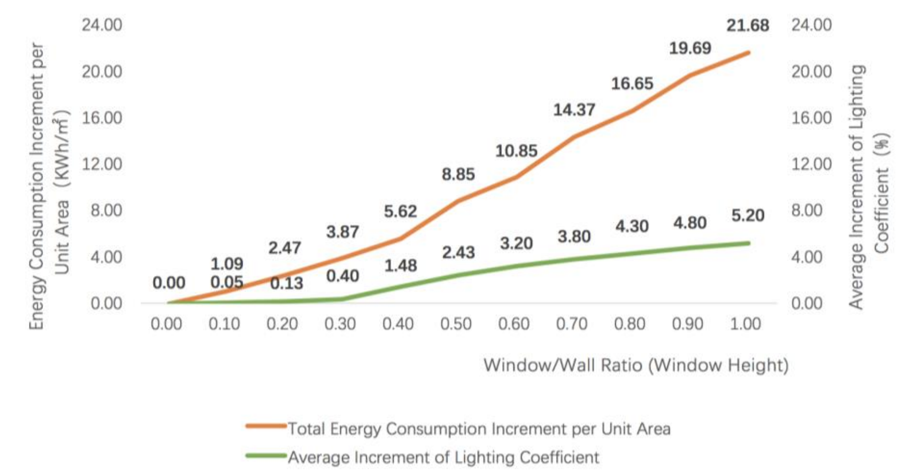

Figure 9. Increments of lighting coefficient and total energy consumption influenced by south window/wall ratio (window height).

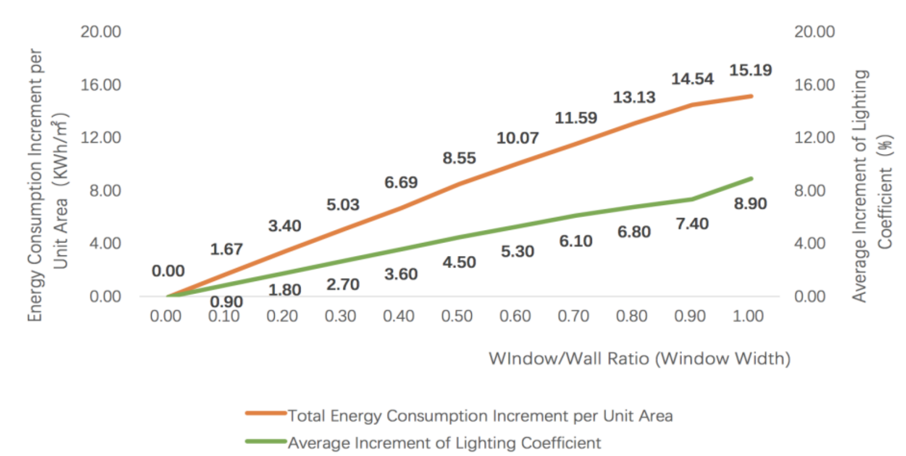

Figure 10. Increments of lighting coefficient and total energy consumption influenced by west window/wall ratio (window width).

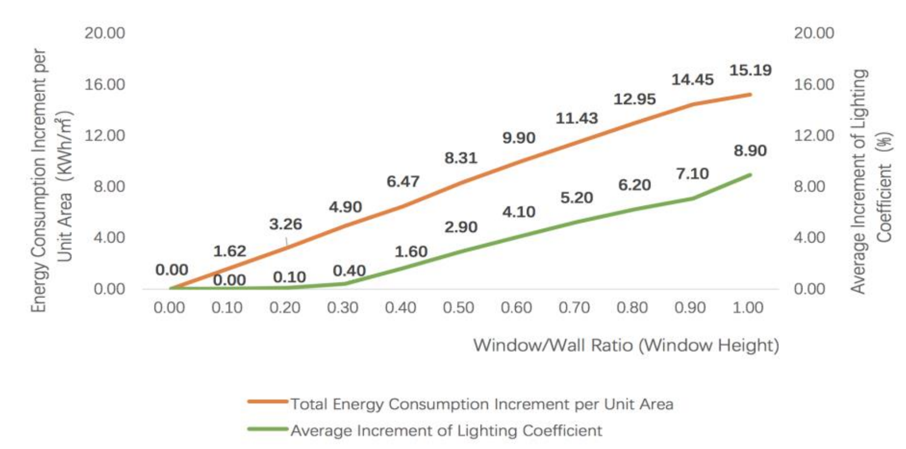

Figure 11. Increments of lighting coefficient and total energy consumption influenced by west window/wall ratio (window height).

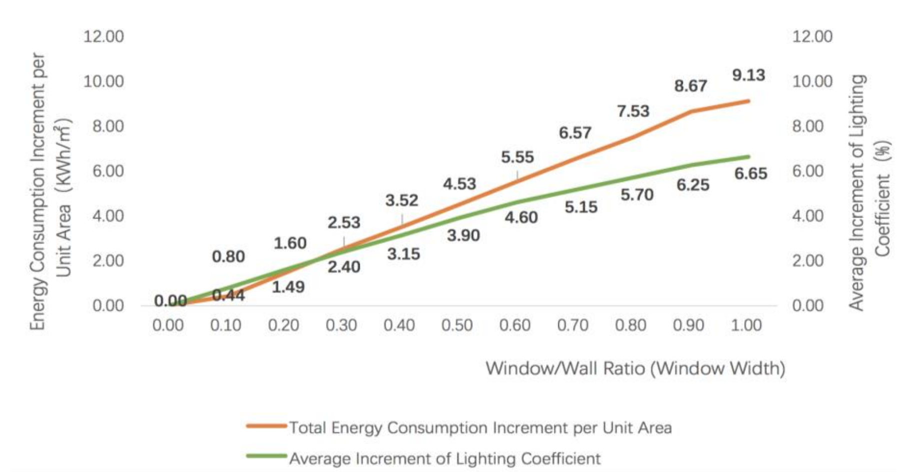

Figure 12. Increments of lighting coefficient and total energy consumption influenced by North window/wall ratio (window width).

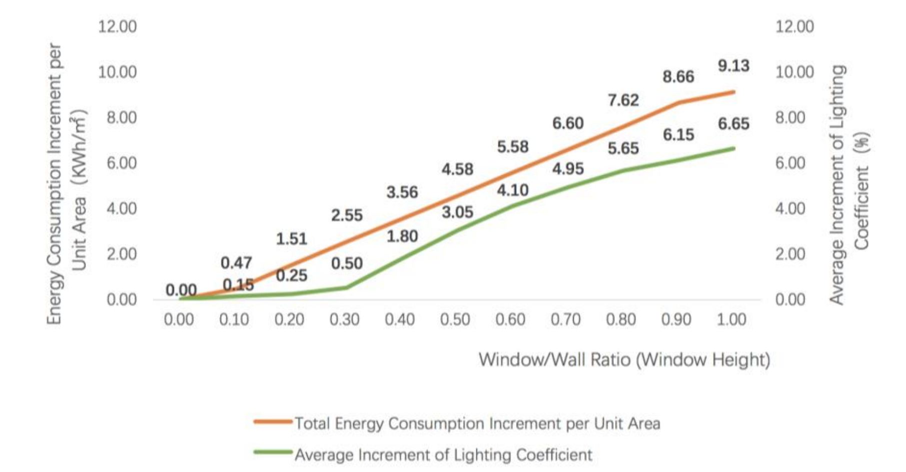

Figure 13. Increments of lighting coefficient and total energy consumption influenced by North window/wall ratio (window height).

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3. Calculation of Carbon Emissions

The carbon emission calculation system of this paper is derived from Carbon Emission Calculation Standard CECS 374-2014 in China [6]. On the basis of this specification, the scope of carbon emission units studied in this paper is reduced to the following two aspects which have the highest correlation with residential lighting, and the sum of the two is the number of residential carbon emissions in the whole life cycle (formula 1):

$$\Delta E=\Delta E_M+\Delta E_U \quad (1)$$

In this formula, ΔE is the change of carbon emission ($kgCO_2eq$) in whole life cycle due to residential lighting related variables; ΔE_M is the change of carbon emission ($kgCO_2eq$) caused by relevant lighting design variables of production, construction, demolishing and recycling phase of residential building; ΔE_U is the change of carbon emission ($kgCO_2eq$) in the operation phase of residential building due to residential lighting design variables. Among them, ΔE_M can be calculated by consulting the Athena Eco Calculator for Residential Assemblies database. ΔE_U can be simulated and calculated by PKPM-PBECA energy consumption software.

3.1. Calculation of carbon emissions in use phase

According to the national grid emission factors released by the National Climate Change Agency of the National Development and Reform Commission, the carbon emission can be calculated by bringing the energy consumption into the following formula 2 and formula 3:

$$\Delta E_U=EF_E\times\Delta C_E \quad (2)$$

$$EF_E=(EF_{grid,\ OM,\ y}+EF_{grid,\ BM,\ y})/2 \quad (3)$$

ΔE_U represents the carbon emission change of residential building in use phase ($kgCO_2eq$); EF_E represents the grid baseline emission factor in Shanghai area ($kgCO_2eq/KWh$); ΔC_E represents the annual total energy consumption difference of residential building in use phase (KWh); $EF_{grid,\ OM,\ y}$ represents the electricity marginal emission factor of the regional grid ($kgCO_2eq/KWh$); $EF_{grid,\ BM,\ y}$ represents the capacity marginal emission factor of the regional grid ($kgCO_2eq/KWh$).

Table 1. Regional power grid division of China

Region	Provinces and Cities
East	Shanghai, Jiangsu Province, Zhejiang Province, Anhui Province, Fujian Province

Table 2. Regional grid emission factor of China, 2015

Regional Grid	$EF_{grid,OM,y}$ ($kgCO_2eq/KWh$)	$EF_{grid,BM,y}$ ($kgCO_2eq/KWh$)
East	0.8112	0.5945

3.2. Calculation of carbon emissions in use phase

As can be seen from the tables above (table 1 and table 2), Shanghai belongs to the east regional grid division. According to the data from the tables, the EF_E of east regional grid is 0.7029 ($kgCO_2eq/KWh$). With the energy consumption data taken into the formula 2 respectively, the carbon emission data is calculated. The window/wall ratio data can be considered as an average value of the counterpart of width and height. The outcomes are listed in the following tables (table 3 and table 4).

Table 3. Annual increment of carbon emissions influenced by windowsill height in use phase

Windowsill Height（m）	0.00	0.30	0.60	0.90	1.20	1.50	1.80	2.10
East ($kgCO_2eq/m^2$)	0.0000	0.0006	0.0014	0.0039	0.0078	0.0116	0.0163	0.0167
South ($kgCO_2eq/m^2$)	0.0000	0.0057	0.0084	0.0106	0.0120	0.0127	0.0127	0.0159
West ($kgCO_2eq/m^2$)	0.0000	0.0039	0.0082	0.0149	0.0227	0.0331	0.0421	0.0404
North ($kgCO_2eq/m^2$)	0.0000	0.0086	0.0176	0.0255	0.0282	0.0306	0.0331	0.0363

Table 4. Annual increment of carbon emissions caused by window/wall ratio in use phase

Window/Wall Ratio	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
East ($kgCO_2eq/m^2$)	0.00	1.10	2.27	3.76	4.90	6.24	7.43	8.53	9.58	10.72	11.27
South ($kgCO_2eq/m^2$)	0.00	0.78	1.77	2.75	4.02	6.02	7.71	9.96	11.83	14.00	15.24
West ($kgCO_2eq/m^2$)	0.00	1.16	2.34	3.49	4.63	5.93	7.02	8.09	9.17	10.19	10.68
North ($kgCO_2eq/m^2$)	0.00	0.32	1.06	1.79	2.48	3.20	3.91	4.63	5.32	6.09	6.42

3.3. The calculation of carbon emission in the phase of materialization and demolition

Each residential building needs to go through a long process of materialization, from production, manufacturing, processing and transportation of different materials and components; assembling and construction; at last, the demolition phase, which includes taking care of the remaining, recycling and so on. All of these processes are accompanied by the carbon emissions. This section will focus on calculating the carbon emission changes in the materialization and demolition phases of residential buildings caused by lighting design.

Residential buildings, like most other types of buildings, consist of envelop structure and supporting structure. In previous software simulations, windowsill height and window/wall ratios were adjusted based on the reference model with other parameters staying unchanged, thus, it can be regarded as no change in the supporting structure. Therefore, the carbon emissions in the materialization and demolition phases are reflected in the changes of the envelope structure.

It can be considered that changing the windowsill height does not have influence on material change. While changing the window/wall ratio results in a change of the window area and wall area due to the total area is a fixed constant for a building. Due to the fact that the materialization and demolition processes of different envelope structures are also different, the changes of the amount of different envelope structures are the main factors that change the carbon emissions of residential buildings in these phases. The envelope materials of the reference residential building are concrete block and insulated aluminium alloy window frame with double low-e hollow glazing. Thus, the carbon emission caused by window/wall ratio can be calculated by applying the formula 4, 5 listed below:

$$\Delta E_{MG}=\Delta R_O \times S_O \times C_{MC} \quad (4)$$

$$\Delta E_{MC}=(1-\Delta R_O) \times S_O \times C_{MC} \quad (5)$$

ΔR_O represents the window-wall ratio; S_O represents the envelope area of each orientation (m^2); ΔC_{MG} is the reference value of carbon emission per unit area ($kgCO_2eq/m^2$) per unit area of insulated aluminium alloy window frame with double low-e hollow glazing; ΔC_{MC} is the carbon emission per unit area of concrete block wall ($kgCO_2eq/m^2$).

The reference values for the materials used as envelope structure are obtained from the database which is widely used in the United States, the Athena Eco Calculator for Residential Assemblies, as mentioned before. This database collects a large number of homes in the United States, after conducting a huge amount of calculations and material statistics, a systematic database for carbon emission calculation is completed. The following calculation of the materialization and demolition phase will be conducted on a basis of this database.

As mentioned before, the adjustment of the windowsill height does not affect the amount of material used for the building envelope. Thus, it can be considered that different settings of windowsill height do not cause any carbon emission changes in materialization and demolition phase.

D. EXTERIOR WALLS

IN THE YELLOW CELLS BELOW, ENTER THE AMOUNT OF SQUARE FOOTAGE THAT EACH ASSEMBLY USES IN YOUR BUILDING

	WALL TYPE	WALL ENVELOPE	Square footage	Percentage of total	Fossil Fuel Consumption per ft^2 (MJ)	Global Warming Potential per ft2 (kg CO2 eq)	Acidification Potential per ft^2 (moles of H+ eq)
Average across exterior wall assemblies:					121.40	8.60	3.28
8" CONCRETE BLOCK					121.05	9.83	2.90
1	Concrete Block	Clay Brick Cladding w/ 1" Air Space R5 XPS Continuous Insulation 1/2" Gypsum Board + 2 Coats Latex Paint	0.0		120.02	10.09	3.40
2	Concrete Block	Metal Cladding R5 XPS Continuous Insulation 1/2" Gypsum Board + 2 Coats Latex Paint	0.0		194.04	15.86	5.03
3	Concrete Block	2 Coat Stucco Over Porous Surface R5 XPS Continuous Insulation 1/2" Gypsum Board + 2 Coats Latex Paint	0.0		79.48	7.07	1.83
4	Concrete Block	Vinyl Siding R5 XPS Continuous Insulation 1/2" Gypsum Board + 2 Coats Latex Paint	0.0		113.49	8.35	2.68

Figure 14. Carbon emission factor of wall per unit area in the Athena database.

E. WINDOWS

IN THE YELLOW CELLS BELOW, ENTER THE AMOUNT OF SQUARE FOOTAGE THAT EACH ASSEMBLY USES IN YOUR BUILDING

	FRAME TYPE	DOUBLE GLAZING TYPE	Square footage	Percentage of total	Fossil Fuel Consumption per ft^2 (MJ)	Global Warming Potential per ft2 (kg CO2 eq)	Acidification Potential per ft^2 (moles of H+ eq)
Average across all window types:					514.92	45.33	31.16
1	Aluminum - Operable	Low E, Argon Filled	0.0		798.29	67.63	56.56
2	Vinyl-clad Wood - Operable	Low E, Argon Filled	0.0		371.31	34.33	21.16
3	Vinyl - Operable	Low E, Argon Filled	0.0		519.25	43.69	24.85

Figure 15. Carbon emission factor of window per unit area in the Athena database.

As shown in the figures listed above (figure 14 and figure 15), it can be seen that the closet wall material is the No.3 type wall (which is concrete block, 2 coat stuccos over porous surface, R5 XPS continuous insulation). Its GWP value is 7.07$kgCO_2eq/ft^2$, which converted to a metric unit is 78.56$kgCO_2eq/m^2$; similarly, the GWP of insulated aluminium alloy window frame with double low-e hollow glazing (aluminium operable low-e double glazing) is 67.63$kgCO_2eq/ft^2$, which converted to metric units is 751.44$kgCO_2eq/m^2$.

$$\Delta E_M=(\Delta E_{MG}+\Delta E_{MC})/S_C \quad (6)$$

ΔE_M represents the change of carbon emission per unit area ($kgCO_2eq/m^2$) caused by envelope structure change in materialization and demolition phase; ΔE_{MG} represents the change of carbon emission caused by the area change of aluminium operable low-e double glazing ($kgCO_2eq$); ΔE_{MC} represents the change in carbon emissions caused by concrete block walls with XPS insulation

($kgCO_2eq$); S_C represents the total floor area (m^2). Taking the related parameters into formula 4, 5 and 6 respectively for calculation, the outcomes are listed below (table 5).

Table 5. Increment of carbon emissions influenced by window/wall ratio in materialization and demolition phase

Total Floor Area 3442.17m²			East/West Surface Area 799.22m²				South/North Surface Area 967.98m²			
Window/Wall Ratio	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
East ($kgCO_2eq/m^2$)	0.00	15.62	31.25	46.87	62.49	78.12	93.74	109.36	124.99	140.61	156.23
South ($kgCO_2eq/m^2$)	0.00	18.92	37.85	56.77	75.69	94.61	113.54	132.46	151.38	170.30	189.22
West ($kgCO_2eq/m^2$)	0.00	15.62	31.25	46.87	62.49	78.12	93.74	109.36	124.99	140.61	156.23
North ($kgCO_2eq/m^2$)	0.00	18.92	37.85	56.77	75.69	94.61	113.54	132.46	151.38	170.30	189.22

3.4. The calculation of carbon emission in the phase of materialization and demolition

According to the formula 1 proposed previously, the carbon emission changes in whole life cycle can be calculated by taking all results gathered above in materialization phase, use phase, and demolition phase. To simplify the process, the use phase is calculated as 50 years. The final results are listed as below (table 6 and table 7). As can be seen from the chart above, the carbon emission increment caused by window/wall ratio are significantly more than the counterpart of windowsill. Therefore, the window/wall ratio may be the most potential aspect that should be pay more attention to when dealing with carbon emission issues of residential buildings.

Table 6. Increment of carbon emissions influenced by windowsill height in whole life cycle (50 years)

Windowsill Height（m）	0.00	0.30	0.60	0.90	1.20	1.50	1.80	2.10
East ($kgCO_2eq/m^2$)	0.00	0.03	0.07	0.19	0.39	0.58	0.82	0.84
South ($kgCO_2eq/m^2$)	0.00	0.29	0.42	0.53	0.60	0.63	0.63	0.80
West ($kgCO_2eq/m^2$)	0.00	0.19	0.41	0.75	1.13	1.65	2.10	2.02
North ($kgCO_2eq/m^2$)	0.00	0.43	0.88	1.28	1.41	1.53	1.65	1.82

Table 7. Increment of carbon emissions influenced by window/wall ratio in whole life cycle (50 years)

Window/Wall Ratio	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
East ($kgCO_2eq/m^2$)	0.00	70.62	144.75	234.87	307.49	390.12	465.24	535.86	603.99	676.61	719.73
South ($kgCO_2eq/m^2$)	0.00	57.92	126.35	194.27	276.69	395.61	499.04	630.46	742.88	870.30	951.22
West ($kgCO_2eq/m^2$)	0.00	73.62	148.25	221.37	293.99	374.62	444.74	513.86	583.49	650.11	690.23
North ($kgCO_2eq/m^2$)	0.00	34.92	90.85	146.27	199.69	254.61	309.04	363.96	417.38	474.80	510.22

4. Carbon emission reduction potential of household behaviour influenced by daylighting design

4.1. Questionnaire Survey

The previous parts of this paper define and discuss the main influencing factors of residential carbon emissions in this research, which can be classified as the materialization and the demolishment phase and the use phase. Among them, the carbon emission of the use phase is not only related to the energy

consumption of the equipment which is determined by the physical performance of the residential enclosure structures, but also closely related to the household behaviour, like habits of using household appliance and other equipment [7]. The impact of household behaviour on residential carbon emissions is often studied isolated or ignored, systematic, comprehensive demonstration and research need to be further explored. With the research perspectives being continuous widening in recent decades, more and more scholars continue to raise awareness of energy conservation and carbon emission reduction in many areas. With sociology, behaviour, environmental psychology and other multidisciplinary fields and other more perspectives emerging, the majority of scholars are gradually study in this area deeper. Household behaviour has a potential impact on residential carbon emissions in residential buildings, which makes it worth to be explored [7, 8].
The above section outlines the impact of household behaviour on residential carbon emissions. In order to explore further, a questionnaire survey is conducted, as a supplementary study for simulation, to try to understand how residential lighting, household behaviour and emission reduction affect each other in hot summer and cold winter area [9,10]. The entire research system is enriched by analysing and summarizing the survey results, screening out the key factors.

4.2. Analysis of outcome

As for why using artificial lighting, only 11.1% of the sample preferred artificial lighting [11]. More people are forced to use artificial lighting because of the inadequate daylighting and poor lighting quality. The factors of residential design will also have a certain impact on the use of equipment. The shading, for instance, is a common method for controlling direct sunlight and radiant heat into the interior in summer times, the effect of the physical characteristics of residential buildings is without doubt. As can be seen from figure 16 and figure 17, the potential behaviour impact on household has been illustrated. In units with shading, the family members have a higher preference for passive cooling ways to enjoy a comfortable natural climate than the members living in the houses without any shading equipment. Equipped with the exterior louvers, household behaviour of air conditioning in the summer has been shown an increment proportion to open intermittently than the counterparts of the units without shading (11.11%); while the proportion of household to set a low running temperature of cooling equipment decrease significantly as well; at the same time, the proportion of household to set high temperature of air conditioning in summer is relatively high in shading residential, especially for exterior shading louvers (35.29%). On one hand, among all forms of shading types shown in the figure above, the exterior shading types such as louvers, balcony and building shape shading have more influence in changing the behaviour of setting the operating temperature of cooling equipment in summer than the interior shading form. On the other hand, conversely, when heating equipment was used in winter, the proportion of household to set operating temperatures in residential units without shading show a higher number in operating their devices intermittently (22.22%) than the counterpart of the residential units with shading.

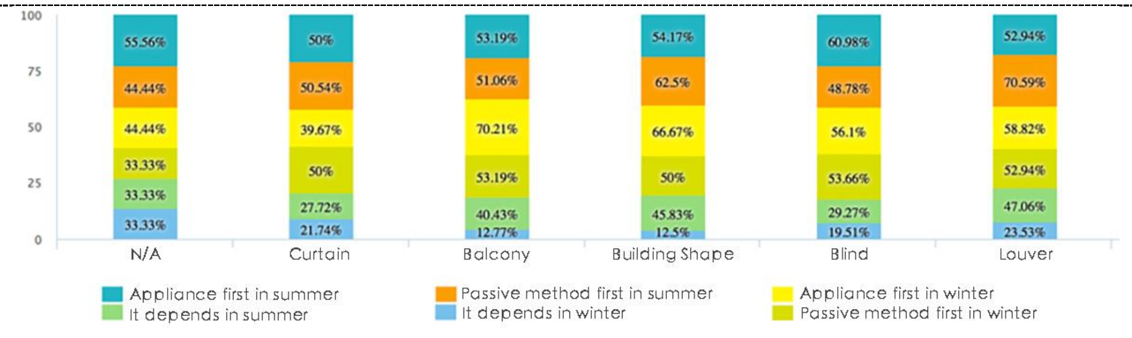

Figure 16. Shading and cooling, heating preference.

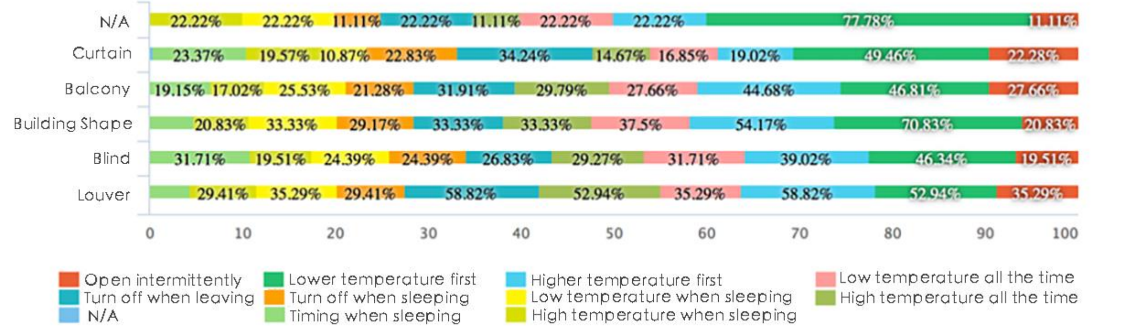

Figure 17. Shading and behaviour of cooling equipment.

5. Summary

The research work of this paper is conducted by applying simulation, empirical study, field investigation and research and so on. Through the quantitative analysis, the possibility of carbon emission reduction in residential lighting design is discussed in a certain framework. The main conclusions are summarized as follows.

(1) Height of windowsill. Based on the simulation and empirical research, when the window area is a fixed value, the most cost-effective approach to improve the indoor lighting coefficient is to increase the height of the windowsill appropriately, and the effect gets to the best when height of the windowsill reaches about 0.90m; after this turning point, the lighting coefficient goes down with height of the windowsill increasing; the evenness of indoor daylighting distribution improved with the height of the windowsill increasing; as for the carbon emission consideration, with the increment of indoor lighting coefficient, the carbon emission increment is so small that can be ignored. Combining these two aspects, design an appropriate windowsill height can be an efficient way in residential design for improving indoor lighting conditions to some extent without causing significant carbon emission increment, which is a suitable sustainable design strategy under the context of carbon emission reduction. And the recommendation height for windowsill is 0.90m.

(2) Window/wall ratio. By adjusting the window/wall ratio of different orientations, that is, changing the window area in each direction respectively when the total area of each direction is a fixed value, the residential lighting efficient will be significantly affected. Increasing the window/wall ratio is a direct way to improve the residential lighting condition, but it is also accompanied by a considerable increment in carbon emissions in both use, materialization and demolition phase. And the growth rate between the carbon emission increment and lighting coefficient shows a linear correlation; taking the direction of the window into consideration, the order of carbon emission increment per unit is south > east ≈ west > north; the order of average daylighting coefficient increment is east ≈ west > north > south. The recommendation window/wall ratio for south direction can be summarized as 0.40-0.50.

(3) Aspect ratio of window. When the window/wall ratio is a fixed value, or in other words, the total area of window is a fixed value, the carbon emission increment caused by changing the shape of window in each direction is almost negligible. However, the shape of window does make a notable difference when it comes to the indoor lighting coefficient distribution. When window/wall ratio is less than 0.3, increasing the window width has significant advantages for increasing the lighting coefficient compared with increasing the window height, the difference between these two is almost up to 7 times; while window/wall ratio is more than 0.3, the advantages of adjusting the window width in increasing the indoor natural daylighting effect still exist, but the differences between these two gradually decrease. Given the carbon emission can be ignored for adjusting the shape of the window, which in most situations, widths and heights in residential buildings, if other design conditions permit, the better design strategy of improving lighting from the carbon emission perspective is to increase the window width first instead of increasing the window height. Especially when the window height or the height of windowsill is below 30% or less of the floor height.

In addition, through a series of qualitative analysis of questionnaire survey, it can be concluded that residential lighting design has the potential to reduce carbon emissions by influence the household behaviour toward the operation of cooling and heating equipment, such as proper shading design will affect the cooling habits and reduce household reliance on cooling equipment so that it will reduce carbon emission in use phase to some extent.

In summary, the daylighting design in the context of carbon emission reduction is a relatively complicated and multi-variable comprehensive consideration. And a considerate and appropriate lighting design has many potentials in balancing carbon emissions and lighting conditions.

6. References

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Acknowledgments

I would like to express my gratitude to my beloved supervisor-Yiru Huang for this opportunity to be part of this significant research program and Clark E Llewellyn for his guidance.