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OPTIMISING ENERGY CONSUMPTION IN OFFICES AS A FUNCTION OF WINDOW AREA AND ROOM SIZE

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ABSTRACT

Windows allow daylight to enter a space but they also allow for the transfer of heat gains and losses that affect the energy consumption of a building. This work optimises the relationship between window size, space dimensions and daylight to the energy consumption of the space. Models comprising of different room ratios and different room sizes were simulated using VisualDOE. The glazed areas of the rooms ranged from zero to 100% of the façade area. Energy consumption as a function of window area and room size was predicted for each model. Seven cities in Brazil and one in the UK were simulated to show the effect of climatic conditions on daylight provision and energy consumption. Resulting from the work, Ideal Window Areas for optimum energy efficiency were predicted.

INTRODUCTION

Air-conditioning and artificial lighting consume significant amounts of the energy supplied to a building, therefore it is essential that the performance of these systems be optimised in order to achieve energy savings. An important factor that can lead to savings is the amount of daylight entering a room, as this can reduce both the artificial lighting and air-conditioning load at the same time.

Large windows allow more daylight into a space and therefore the use of artificial lighting can be reduced. But large glazed areas may also allow excessive heat gains or losses into the building, which increases the air-conditioning or heating load and consequently, the energy consumption. If the windows are small, then heat gains or losses are lower, but artificial lighting may have to be used during the working day to provide the desired levels of illuminance on the working surface.

The optimum scenario is to specify a window area in which there is an ideal balance between daylight provision and the energy consumed by the artificial lighting and air-conditioning. Such a window area may be referred to as the Ideal Window Area and is the one in which the energy consumption of the room is the lowest.

OBJECTIVES

The main objectives of this work are to present a methodology to predict the Ideal Window Area for typical offices using computer simulation, and then to use the methodology to calculate the Ideal Window Area for offices located in seven cities in Brazil and one city in the UK.

METHODOLOGY

The simulation model was based on a building 10 storeys high. Five rooms were generated with the floor ratios 2:1, 1.5:1, 1:1, 1:1.5, and 1:2, as shown in plan view in Figure 1. For reference purposes, the first dimension is related to the wall where the window is located, and the window wall is the only one that is external.

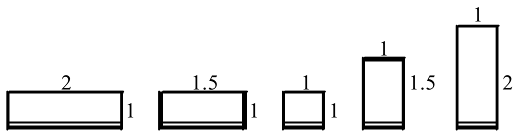

Figure 1. Floor plans of the five room ratios.

Narrow rooms (such as those with room ratios 2:1, 1.5:1 and 1:1) are usually specified by building designers in order to provide good daylight levels. This may seem appropriate, but the associated heat gains or losses are often not taken into account. Deeper rooms (with room ratios 1:1.5 and 1:2) do not usually have a good daylight supply, but experience a lower solar thermal load due to the smaller façade, which may reduce the air-conditioning load.

Each room ratio was simulated in 10 different sizes calculated as a function of the room index – as used in lighting design. Equation 1 presents the room index formula. The choice of these room indices allows a more accurate evaluation of the energy savings appropriate to each index. The energy savings are important but are not within the scope of this article.

$$K = (WD)/[(W+D)h] \qquad (1)$$

Where:
- K is the room index (non-dimensional);
- W is the overall width of the room (m);
- D is the overall depth of the room (m);
- h is the height between the work surface and the ceiling (m).

Having defined the room ratios, W can be expressed a function of D and equation 1 can be rewritten as follows:

When D = W, then W=2Kh (1.1)
When D = 1.5W, then W=(2.5/1.5)Kh (1.2)
When W = 1.5D, then D=(2.5/1.5)Kh (1.3)
When D = 2.0W, then W=(3.0/2.0)Kh (1.4)
When W = 2.0D, then D=(3.0/2.0)Kh (1.5)

Table 1 presents the room indices and room dimensions for the five room ratios. The overall height of the rooms is taken as 2.80m and the working surface as 0.75m above floor level.

Table 1. Room indices and dimensions (metres).

K	1:1	1:1.5		1:2	
	W=D	W	D	W	D
		1.5:1		2:1	
		D	W	D	W
0.60	2.46	2.05	3.08	1.85	3.69
0.80	3.28	2.73	4.10	2.46	4.92
1.00	4.10	3.42	5.13	3.08	6.15
1.25	5.13	4.27	6.41	3.84	7.69
1.50	6.15	5.13	7.69	4.61	9.23
2.00	8.20	6.83	10.25	6.15	12.30
2.50	10.25	8.54	12.81	7.69	15.38
3.00	12.30	10.25	15.38	9.23	18.45
4.00	16.40	13.67	20.50	12.30	24.60
5.00	20.50	17.08	25.63	15.38	30.75

Each room had an incremental glazed area ranging from 0 to 100% at increments of 10% of the façade area (Figure 2). Only single clear glass was considered in the simulations. Solar protection on windows is usually needed on some building orientations in Brazil but they are not usually adopted and therefore were not included in the simulations. Each model was simulated with its window wall facing either one of the four main orientations: North, East, South, or West.

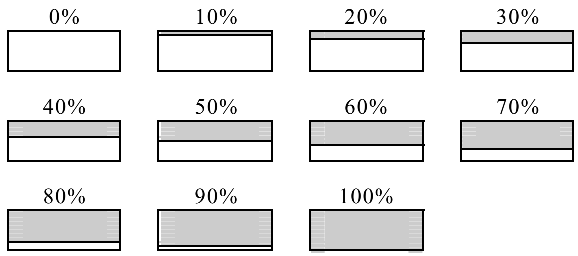

Figure 2. Window area.

Version 2.6 of the VisualDOE programme was used to run the simulations (Eley Associates, 1995). It utilises the DOE-2 calculating engine, which is a public domain programme that performs building energy analysis given a description of the climate, architecture and thermo-physical properties of the building components, operating schedules and HVAC equipment (Winkelmann et al., 1993).

The models were simulated over a whole year under local climatic conditions for the eight cities considered namely: Belém, Brasília, Curitiba, Florianópolis, Leeds, Natal, Rio de Janeiro and Salvador. The latitude and longitude of the cities are shown in Table 2. The climatic data for the Brazilian cities was obtained from the Laboratory of Energy Efficiency in Buildings, Federal University of Santa Catarina, Brazil; and the climatic data for Leeds was obtained from the British Atmospheric Data Centre.

Table 2. Latitude and longitude of the 8 cities.

City	Latitude	Longitude
Belém	-01°27’	-48°30’
Brasília	-15°47’	-47°56’
Curitiba	-25°26’	-49°16’
Florianópolis	-27°36’	-48°33’
Leeds	53°48’	-1°34’
Natal	-05°48’	-35°13’
Rio de Janeiro	-22°54’	-43°12’
Salvador	-12°58’	-38°31’

The buildings’ thermal properties (U-value and Heat Capacity) as used for the walls and roof in the VisualDOE simulations are given in Table 3.

Table 3. Thermal properties of building components.

Brazil	U (W/m^{2}K)	HC (kJ/m^{2}K)
Light walls	1.92	202
Light roof	2.22	77
England	U (W/m^{2}K)	HC (kJ/m^{2}K)
Mass walls	0.55	324
Mass roof	0.25	228

All the simulations took into account the differences in building use between England and Brazil. As for the lighting power density (LPD) it is reported that the smaller the room, the higher the LPD necessary to provide the same illuminance level as in larger rooms (Ghisi & Lamberts, 1998). Table 4 shows the lighting power density necessary to provide 500lux on the working surface.

Table 4. LPD used in the simulations.

K	LPD (W/m^2)	K	LPD (W/m^2)
0.60	22.0	2.00	13.1
0.80	18.9	2.50	12.2
1.00	17.1	3.00	11.5
1.25	15.5	4.00	10.6
1.50	14.5	5.00	10.0

The cooling set point for the HVAC equipment was assumed to be 24°C during summer for Brazil, with no heating in the winter. For the simulations run under the UK climatic conditions, a cooling set point of 23°C was assumed for summer operation condition and 20°C for winter heating.

Thus, 2200 simulations were run for each city, making a total of 17600 simulations over the eight cities.

VALIDATION

Prior to the simulations the VisualDOE programme was validated. A three-day measurement period was performed in an office space in Leeds from 7 to 9 March 2000. The energy consumption of the office was measured between 10am and 5pm in order to keep the internal temperature at 21°C and the illuminance on the working surface at 500lux. Table 5 presents the measured and simulated energy consumption of the office. WWR stands for window wall ratio.

Table 5. Measured versus simulated data.

Day	WWR (%)	Energy consumption (kWh) Measured	Simulated	Error (%)
1	65.6	10.33	9.83	-4.9
2	65.6	8.99	8.56	-4.7
3	39.0	9.80	9.41	-4.0

On day 1 the lights and the heater were kept on all the time. On days 2 and 3 the artificial lights were switched on only when the daylight levels on the work surface fell below 500 lux. On the third day, the window wall ratio was reduced from 65.6% to 39.0% by covering part of the window.

RESULTS

The energy consumptions obtained in the simulations are presented in kWh/m²/year. Due to the limitation of space, only a few examples are given.

The energy consumption as a function of room ratios is assessed first. Figures 3 and 4 show the energy consumption for the five room ratios in Florianópolis, North orientation, with room indices 0.60 and 5.00 respectively. As can be seen, the energy consumption is lower for the room ratios whose façade is smaller. But the difference in the energy consumption across the five room ratios is not so significant for rooms whose room index is larger (Figure 4). Similar results are obtained for all the other cities.

The evaluation of the energy consumption as a function of room sizes is presented next. Figures 5 and 6 show the energy consumption for the 10 room sizes (expressed by room indices from 0.60 to 5.00) in Florianópolis, North orientation, with room ratios 2:1 and 1:2 respectively.

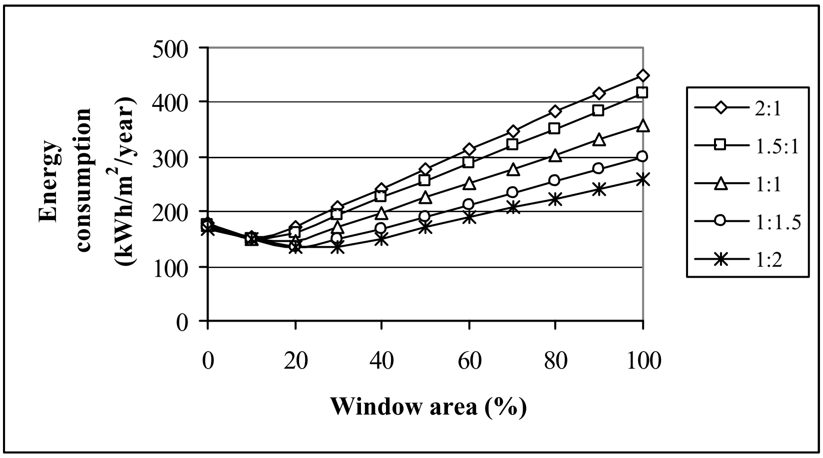

Figure 3. Energy consumption for the five room ratios in Florianópolis, North, room index 0.60.

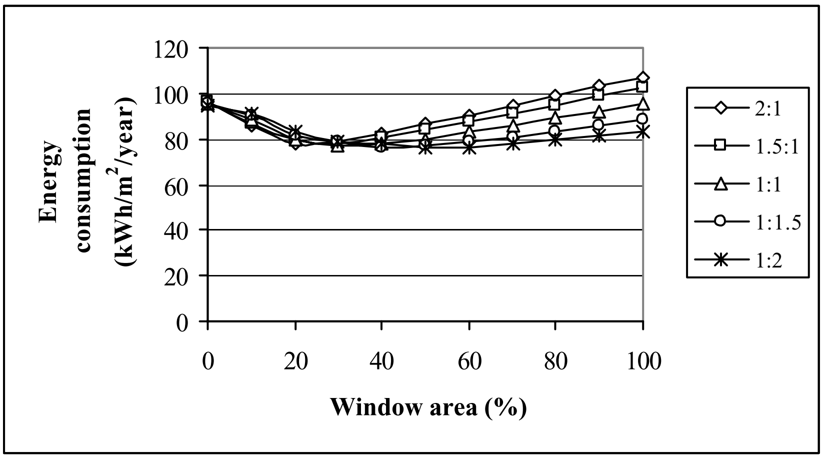

Figure 4. Energy consumption for the five room ratios in Florianópolis, North, room index 5.00.

As shown, the energy consumption per floor area is lower in rooms whose room index is larger independent of the room ratio. This is mainly due to the fact that the LPD and also the ratio of the thermal load on the façade to the space volume are lower for larger rooms (larger room indices). As the amount of solar heat entering the room depends on its façade area, the ratio of the façade area to the space volume has to be equivalent to the ratio of the thermal load on the façade to the space volume. Figure 7 shows the correlation between the energy consumption and the ratio of the façade area to the space volume. This ratio could be used as an index based on the geometry of a room to compare the impact on the energy consumption of rooms of different sizes.

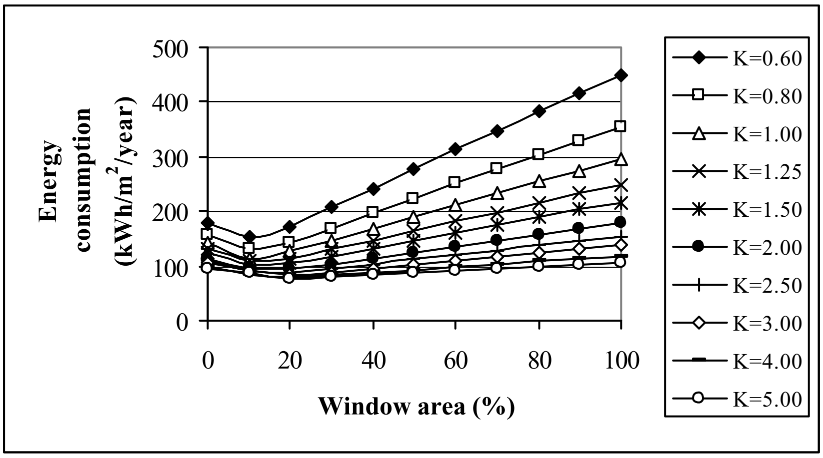

Figure 5. Energy consumption for Florianópolis, North, room ratio 2:1.

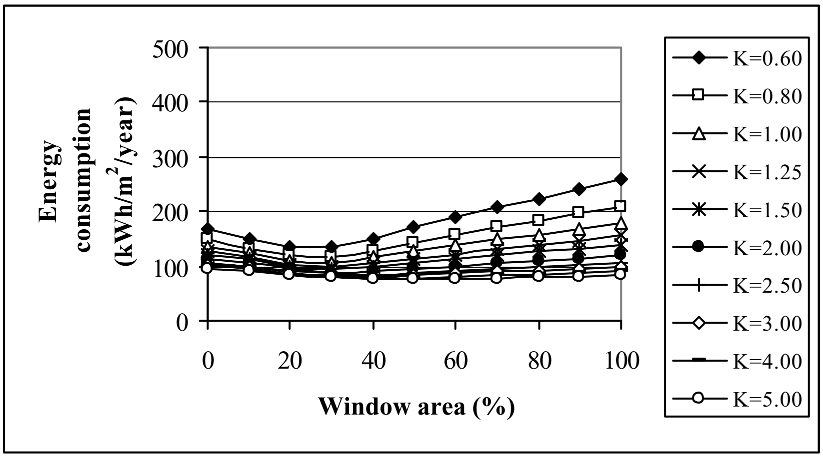

Figure 6. Energy consumption for Florianópolis, North, room ratio 1:2.

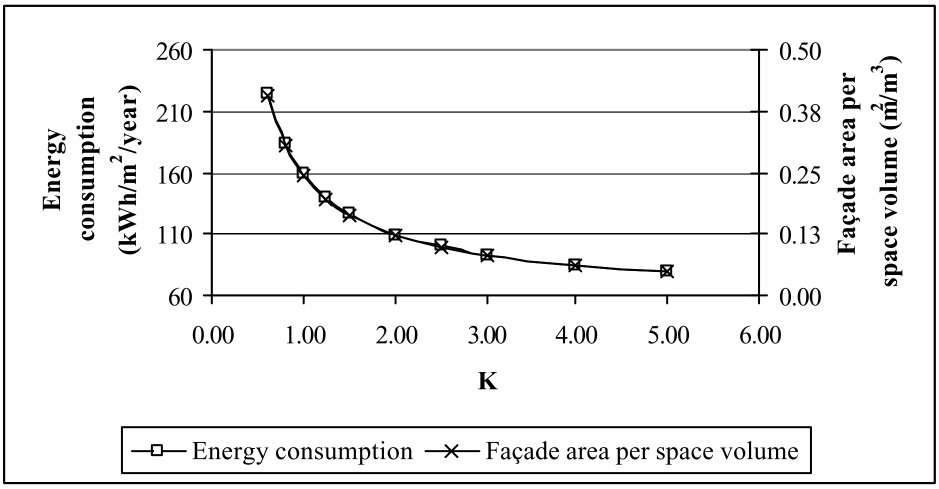

Figure 7. Façade area per space volume for Florianópolis, room ratio 1:1, North, WWR 50%.

Finally, an assessment of the Ideal Window Area is presented. Figures 8, 9 and 10 show the energy consumption over the 4 orientations for a building in Leeds, Belém and Curitiba, respectively. In terms of energy consumption as a function of the orientation of the room, each city has a unique behaviour, as they are located at different latitudes and under different weather conditions. As expected, the energy consumption is lower for rooms facing South in the Southern Hemisphere and for rooms facing North in the Northern Hemisphere.

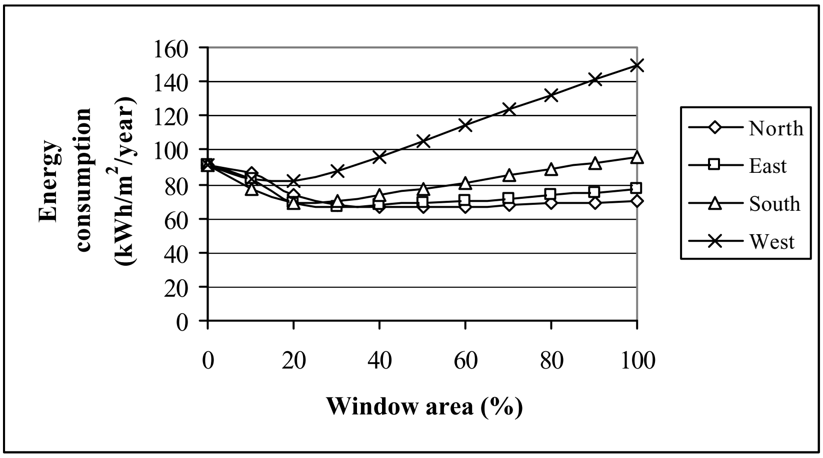

Figure 8. Energy consumption for Leeds, room index 2.00, room ratio 1:2.

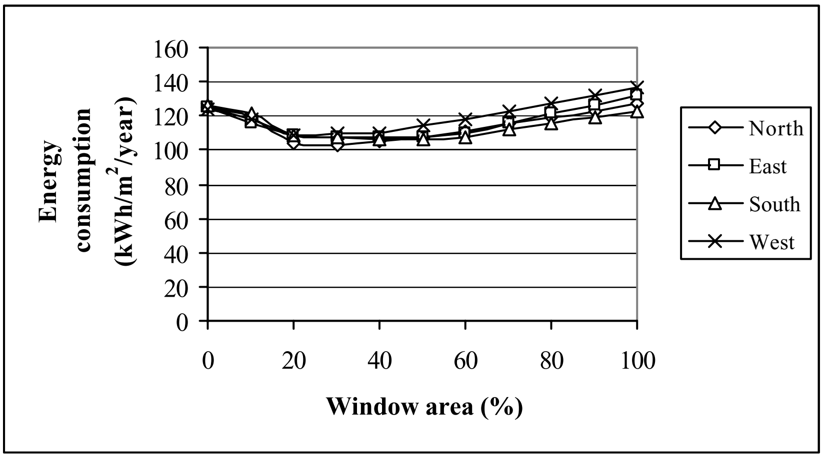

Figure 9. Energy consumption for Belém, room index 2.00, room ratio 1:2.

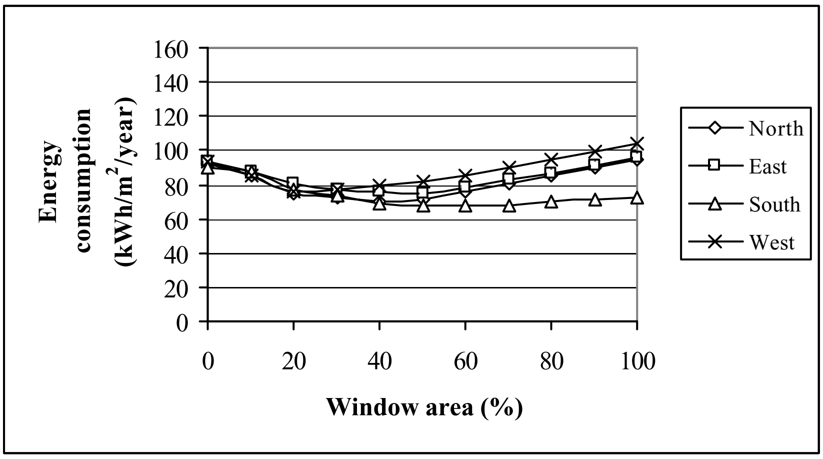

Figure 10. Energy consumption for Curitiba, room index 2.00, room ratio 1:2.

The Ideal Window Area for each room was obtained by using data similar to that given in Figures 8 to 10. The Ideal Window Area is plotted as a function of room index in Figure 11. This shows there is a linear increase of the Ideal Window Area as the room indices increase. A best-fit straight line is shown through the data points for each orientation. Equations representing the best-fit were then used to calculate the Ideal Window Areas given in Tables 6 to 13. The tables show the Ideal Window Areas for each room size, room ratio, and orientation for each city. In the tables N stands for North, E for East, S for South, and W for West.

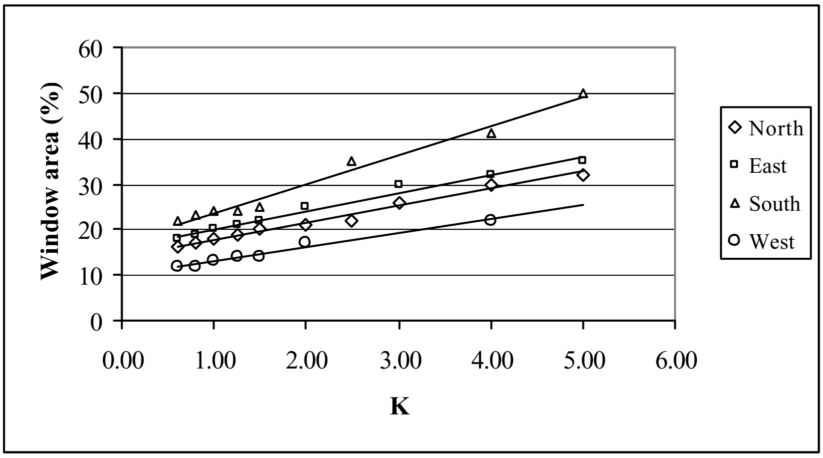

Figure 11. Ideal Window Area versus room index for Florianópolis, room ratio 1:1.

Table 6. Ideal Window Areas for Leeds, England (% of the façade area).

K	2:1				1.5:1				1:1				1:1.5				1:2			
	N	E	S	W	N	E	S	W	N	E	S	W	N	E	S	W	N	E	S	W
0.60	16	11	10	7	19	12	11	7	16	16	11	7	18	20	11	8	23	20	14	9
0.80	18	12	11	7	20	13	11	7	18	17	12	7	21	21	12	9	26	21	14	10
1.00	19	13	11	8	21	14	12	8	20	17	12	8	24	22	13	10	29	23	15	11
1.25	21	13	11	8	23	15	12	8	23	18	13	9	27	24	14	11	32	25	17	12
1.50	23	14	12	9	25	16	12	9	26	20	14	10	31	25	16	12	36	27	18	13
2.00	27	16	13	10	28	19	13	10	31	22	15	11	37	28	18	14	43	31	20	15
2.50	30	17	14	11	31	21	14	11	37	24	17	13	44	31	20	15	50	35	22	18
3.00	34	19	14	12	34	23	14	12	42	26	18	14	51	34	22	17	58	39	25	20
4.00	41	22	16	14	40	28	16	14	53	31	21	18	65	40	27	21	72	47	29	24
5.00	49	25	18	16	47	32	17	17	64	35	24	21	79	46	32	25	87	55	34	29

Table 7. Ideal Window Areas for Belém, Brazil (% of the façade area).

K	2:1				1.5:1				1:1				1:1.5				1:2			
	N	E	S	W	N	E	S	W	N	E	S	W	N	E	S	W	N	E	S	W
0.60	11	12	14	10	12	11	14	11	14	13	17	11	18	19	22	14	19	20	26	18
0.80	12	13	15	11	13	12	15	12	15	14	19	12	19	20	24	15	21	21	28	19
1.00	12	14	16	12	14	13	16	13	15	15	20	12	20	20	25	16	22	22	30	21
1.25	13	15	17	13	14	14	18	14	16	16	22	13	21	21	27	18	24	23	33	23
1.50	14	16	17	13	15	15	19	15	17	17	23	14	22	22	29	19	25	24	35	24
2.00	15	18	19	15	17	17	21	17	19	18	26	16	24	24	33	22	29	26	40	28
2.50	16	20	21	17	18	19	24	19	21	20	30	17	26	26	37	25	32	28	45	31
3.00	17	21	23	19	20	21	26	21	23	22	33	19	28	27	41	28	36	30	50	35
4.00	20	25	26	22	23	25	31	26	27	26	39	22	32	31	49	34	42	34	60	42
5.00	22	29	30	26	26	29	36	30	31	30	46	25	36	34	57	40	49	38	70	49

Table 8. Ideal Window Areas for Brasília, Brazil (% of the façade area).

K	2:1				1.5:1				1:1				1:1.5				1:2			
	N	E	S	W	N	E	S	W	N	E	S	W	N	E	S	W	N	E	S	W
0.60	12	16	20	10	15	16	21	11	17	19	27	13	20	26	31	17	24	30	41	19
0.80	13	17	21	11	16	17	23	11	18	21	29	14	21	28	34	18	26	33	44	20
1.00	13	18	22	11	16	18	24	12	19	23	30	15	22	30	36	18	27	35	46	21
1.25	14	19	23	12	17	20	26	13	20	25	32	16	24	32	39	19	30	38	49	22
1.50	15	20	24	13	18	21	27	14	21	27	34	17	26	34	42	20	32	41	52	23
2.00	16	23	27	14	19	24	30	16	23	31	38	19	29	39	48	22	36	48	57	26
2.50	18	25	29	15	21	27	34	17	25	35	42	22	33	44	54	24	40	54	63	28
3.00	19	27	32	17	22	29	37	19	27	39	46	24	36	49	60	25	45	60	69	30
4.00	23	32	37	19	26	35	44	23	31	47	53	28	43	58	71	29	53	72	80	34
5.00	26	36	42	22	29	41	50	26	36	55	61	32	50	68	83	32	62	84	91	39

Table 9. Ideal Window Areas for Curitiba, Brazil (% of the façade area).

K	2:1				1.5:1				1:1				1:1.5				1:2			
	N	E	S	W	N	E	S	W	N	E	S	W	N	E	S	W	N	E	S	W
0.60	12	14	18	10	15	17	20	11	17	20	24	12	23	26	32	16	29	32	43	19
0.80	13	14	19	11	16	18	21	11	19	21	26	13	24	28	34	17	31	33	45	19
1.00	14	15	20	12	17	19	23	12	20	22	27	13	26	29	36	17	33	35	48	20
1.25	15	16	22	12	18	20	24	12	21	23	29	15	27	30	39	18	35	37	50	21
1.50	16	17	24	13	18	21	26	13	22	24	31	16	29	32	42	19	36	39	53	22
2.00	17	20	27	14	20	23	30	14	25	27	35	18	32	35	47	21	40	44	58	23
2.50	19	22	30	16	22	24	33	15	27	29	39	20	35	39	52	23	44	48	64	25
3.00	21	24	33	17	24	26	37	17	30	32	43	22	38	42	58	25	48	52	69	26
4.00	25	28	39	20	27	30	44	19	35	36	51	27	45	49	68	29	56	61	80	30
5.00	28	32	46	23	31	34	51	22	40	41	59	31	51	55	79	33	64	69	91	33

Table 10. Ideal Window Areas for Florianópolis, Brazil (% of the façade area).

K	2:1				1.5:1				1:1				1:1.5				1:2			
	N	E	S	W	N	E	S	W	N	E	S	W	N	E	S	W	N	E	S	W
0.60	11	15	18	10	11	15	20	10	16	19	21	12	20	25	25	15	25	26	31	19
0.80	11	15	19	11	12	16	21	11	17	19	22	12	21	26	26	16	27	27	33	19
1.00	12	16	20	11	13	17	22	11	18	20	24	13	22	27	28	17	28	29	36	20
1.25	13	17	20	12	14	18	23	12	19	21	25	14	24	28	30	17	29	31	38	21
1.50	13	18	21	12	15	19	24	13	20	22	27	15	25	29	32	18	31	32	41	21
2.00	15	20	23	14	17	20	26	15	21	24	30	16	27	31	36	20	34	36	47	23
2.50	16	21	25	15	19	22	28	16	23	26	33	18	30	34	40	22	37	40	53	25
3.00	18	23	26	16	22	24	30	18	25	28	36	19	32	36	44	23	40	43	58	26
4.00	21	27	30	19	26	28	35	21	29	32	43	22	37	41	52	27	45	50	69	29
5.00	24	30	33	22	30	31	39	24	33	36	49	25	42	46	59	30	51	58	81	33

Table 11. Ideal Window Areas for Natal, Brazil (% of the façade area).

K	2:1				1.5:1				1:1				1:1.5				1:2			
	N	E	S	W	N	E	S	W	N	E	S	W	N	E	S	W	N	E	S	W
0.60	11	12	11	9	12	12	14	9	13	12	15	9	18	16	19	11	20	16	18	18
0.80	12	13	12	9	13	13	14	9	15	14	16	10	19	18	20	12	22	19	20	19
1.00	12	14	13	10	13	15	15	10	16	16	18	11	20	20	22	13	24	21	22	19
1.25	13	15	14	11	14	16	16	11	17	18	19	12	22	23	23	15	26	24	24	19
1.50	14	16	15	11	15	18	17	11	19	20	20	13	24	25	25	16	28	27	26	20
2.00	16	19	17	13	17	21	19	13	22	24	23	14	28	31	28	19	33	33	31	21
2.50	18	21	19	14	19	24	21	14	25	28	26	16	32	36	32	21	37	38	35	22
3.00	20	24	21	15	21	27	23	16	28	32	29	18	35	42	35	24	42	44	40	23
4.00	24	29	25	18	25	34	27	18	34	41	35	22	43	52	42	29	51	56	49	25

5.00	28	34	30	21	29	40	31	21	40	49	40	25	50	63	48	34	60	68	58	26

Table 12. Ideal Window Areas for Rio de Janeiro, Brazil (% of the façade area).

K	2:1				1.5:1				1:1				1:1.5				1:2			
	N	E	S	W	N	E	S	W	N	E	S	W	N	E	S	W	N	E	S	W
0.60	9	9	18	8	10	11	16	9	14	14	20	9	16	18	22	10	20	26	29	13
0.80	10	9	18	8	10	11	17	9	14	15	21	9	17	20	24	11	21	28	31	13
1.00	10	10	19	8	11	12	18	9	15	16	22	10	17	21	26	12	22	29	33	14
1.25	11	11	19	9	13	14	19	9	15	17	23	10	18	23	28	13	23	31	35	15
1.50	12	12	20	9	14	15	20	10	16	19	25	11	19	24	30	14	24	33	37	15
2.00	13	14	21	10	16	17	22	10	17	21	28	12	21	28	34	16	26	37	42	17
2.50	15	16	22	10	18	19	24	11	19	24	31	13	22	31	39	18	28	41	47	18
3.00	16	18	24	11	21	22	26	12	20	26	34	14	24	35	43	20	31	45	51	20
4.00	19	22	26	12	26	26	31	13	23	32	39	16	27	42	52	23	35	52	60	23
5.00	22	26	29	13	30	31	35	14	26	37	45	19	31	49	60	27	40	60	69	26

Table 13. Ideal Window Areas for Salvador, Brazil (% of the façade area).

K	2:1				1.5:1				1:1				1:1.5				1:2			
	N	E	S	W	N	E	S	W	N	E	S	W	N	E	S	W	N	E	S	W
0.60	10	9	16	7	10	11	18	8	11	16	20	9	16	17	23	10	20	21	29	11
0.80	10	10	17	8	10	11	19	8	12	16	21	10	16	18	25	11	20	22	31	12
1.00	11	10	18	8	11	12	19	9	13	17	22	10	17	19	26	12	21	23	33	13
1.25	11	11	19	9	12	12	20	10	14	17	23	11	17	20	28	13	21	25	35	15
1.50	12	12	20	10	12	13	21	10	15	18	24	12	18	21	30	15	22	26	38	16
2.00	13	13	21	11	14	15	23	12	17	19	27	14	19	23	35	17	24	29	42	19
2.50	14	14	23	13	15	16	25	13	18	20	29	16	21	24	39	19	25	32	47	22
3.00	15	16	25	14	16	17	27	14	20	22	32	18	22	26	43	22	26	35	52	25
4.00	18	18	29	17	19	20	31	17	24	24	37	22	25	30	51	26	29	42	61	30
5.00	20	21	33	20	22	23	35	20	28	27	42	26	28	34	59	31	32	48	70	36

CONCLUSIONS

Using data obtained from the simulations the following conclusions can be made.

1. Room ratios with a small façade have lower energy consumptions. This shows that narrow rooms, as recommended in daylight guides, may experience higher daylight levels, but may not have the lowest energy consumption.

2. The larger the room, the lower the energy consumption per floor area.

3. The ratio of the façade area to the space volume can be used as an index to compare the energy consumption of different room sizes.

4. The Ideal Window Area tends to be larger on the orientations whose energy consumption is lower due to the reduced solar radiation reaching them.

5. The larger the room and the smaller its façade, the larger its Ideal Window Area.

6. The Ideal Window Areas presented can be used as a guideline to improving energy efficiency in buildings.

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