REGRESSION ANALYSIS OF ELECTRIC ENERGY CONSUMPTION AND ARCHITECTURAL VARIABLES OF CONDITIONED COMMERCIAL BUILDINGS IN 14 BRAZILIAN CITIES

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ABSTRACT

The aim of this work was to develop a simple model to predict the electric energy consumption of office buildings artificially air-conditioned, for 14 (fourteen) Brazilian cities (Belém, Brasília, Curitiba, Florianópolis, Fortaleza, Maceió, Natal, Porto Alegre, Recife, Rio de Janeiro, Salvador, São Luís, São Paulo and Vitória). The building annual energy consumption was correlated with several architectural and constructive variables for each city analysed. Many variables were tested to seek those more important to be used to predict the electricity consumption. The variables that have been selected are the size of the building (number of floors and the shape size), the façade composition (window to wall ratio), thermal transmittance and absorptance of roof, the shading coefficient of glazing, the solar protection, façade and roof colours, occupation and electric power density (lights and equipments). The equations demonstrate good result with r^2 higher than 0.99 for most cities.

INTRODUCTION

Electric energy consumption in Brazil is divided in industrial, residential, commercial and public sectors. The energy consumed by buildings corresponds to 46% of national consumption. In 1996 the residential and the commercial sectors were the propellers of the national energy consumption growth, which was 8.6% and 7.7%, respectively, against only 1.6% of growth in industry (MME, 1997). These data are sufficient to justify specific initiatives of energy conservation in these sectors. The growth of electric energy consumption in the residential sector can be explained by new connections to the grid, since the electricity is not available to all houses, and new appliances acquisition due to economic stability achieved in 1994.

In commercial and public buildings, 64% of the energy consumption corresponds to air-conditioning and lighting (GELLER, 1994), showing the importance of design decisions in the total building electricity consumption. Studies estimate that adopting bioclimatic concepts during design stage should decrease in 30% the electric energy consumption in new buildings without loosing thermal comfort (SIGNOR, 1994).

Nevertheless, energy efficient building design is not part of the local culture. One of the reasons for that is the difficulty to assess the benefit obtained with the adoption of an energy conservation measure when designing a building. In addition, detailed hourly simulation models only can assess interactions between several measures and weather data influence. The use of such models is very complex, demanding multidisciplinary knowledge, being inadequate to run quick analyses during design stage.

In his work, GELLER (1992) concludes that investments in energy efficiency in Brazil are attractive, considering that the cost of 1kWh to residential consumers is US$ 0.100 while the cost to save the same kWh is around US$ 0.024

A research by JANDA and BUSH (1994) covering 57 countries shows that only 13 of them (including Brazil) do not have laws that impose the application of energy efficiency concepts in buildings projects.

A standard could be supported by simple equations that estimate the annual energy consumption of the building. Equations for cooling load calculations were developed to help the standard developed by American Society of Heating, Refrigeration and Air-Conditioning Engineers – ASHRAE – and the Illuminating Engineering Society of North America – IESNA – (WILCOX, 1991). In Hong Kong, the overall energy consumption of buildings was correlated to construction parameters, operation and occupation (LAM et al., 1997).

The aim of this work was to develop a simple model to predict the electric energy consumption of office buildings artificially air-conditioned.

METHODOLOGY

Detailed hourly simulation models were used to find the electric energy consumption of office buildings in 14 Brazilian cities (Figure 1). A typical pattern of operation was adopted and the influence of several architectural variables was studied.

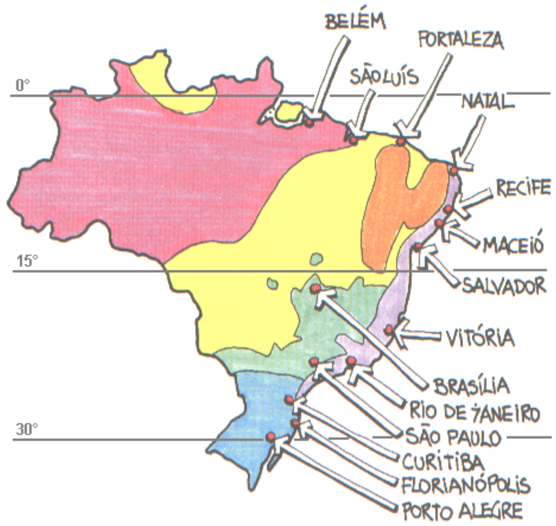

Figure 1 – The 14 Brazilian cities under analysis.

The cities were chosen by availability of climatic data. The minimum, average and maximum dry bulb temperature and relative humidity for a year are presented in Table 1 for the 14 cities under analysis.

Table 1 – Summary of climatic data for the 14 cities.

City	Dry Bulb Temperature (°C)			Relative Humidity (%)		
	Min	Ave	Max	Min	Ave	Max
Belém	20.0	26.0	35.0	44	85	100
Brasília	6.1	20.7	32.8	16	75	100
Curitiba	-2.2	16.4	31.1	28	86	100
Florianópolis	2.2	20.7	36.1	26	85	100
Fortaleza	20.0	26.5	32.2	39	79	100
Maceió	15.6	24.3	35.0	40	82	100
Natal	18.9	25.7	32.8	42	80	100
Porto Alegre	1.1	19.2	36.7	20	82	100
Recife	19.4	25.7	31.7	53	80	100
Rio de Janeiro	12.8	23.6	38.3	32	82	100
Salvador	21.1	28.6	35.0	40	76	100
São Luis	20.6	26.7	35.0	44	82	100
São Paulo	2.2	20.7	36.1	26	85	100
Vitória	11.1	23.2	35.6	34	84	100

The software chosen for this task was the VisualDOE2.6, which is a Windows interface to the DOE2.1-E. This software predicts the energy consumption of a building using a weather data file and a detailed characterization of the building under analysis, including architecture, internal loads (lighting, equipments and occupation), schedules and air-conditioning. A correlation was developed between the architectural variables and the energy consumption for each city using multiple linear regression analysis.

The first step of the study was to define the kind of building to be analysed. Office buildings were chosen as representative of commercial buildings. These buildings present behaviour easy to be modelled, since its schedules, internal loads and task are uniform.

The set of variables under analysis received special attention also. Apart from architectural and operational variables there are many parameters that influence the energy consumption of buildings. The variables selected were those that presented higher impact on the energy consumption, based on typical typology of Brazilian office buildings.

To adequate the simulations to Brazilian patterns of constructions a library of materials was created in the simulation software (RODAS, 1997). The fenestrations library already covered products manufactured in Brazil.

The first building simulated presented a rectangular shape, with 20m x 40m, 12 floors, with 3m of floor-to-floor height, and the largest façade oriented to the North. These dimensions were considered near to reality of most office building, although each building has its own characteristics, that are not easy to predict once they depend on building codes, terrain dimensions, owner necessities and architectural parameters.

The roof was modelled with 4 layers: asbestos-cement shingles, an air space, insulation and structural concrete slab. Characterizing the walls, common bricks and cement plaster on both sides were used. A WWR (Window to Wall Ratio) of 50% with single clear 3mm glazing and PF (Projection Factor) of 0.5 were considered also. Each floor was divided into 5 zones, 1 interior zone and 4 peripheral zones. Each zone was conditioned by a PMZS (Packaged Multi-Zone System) air-conditioner with EER of 10.00Btu/h/W. The air-conditioning was set to cooling mode only, because this is the common situation in Brazilian office buildings. The set-point was adjusted to 24°C and the internal load density (ILD) was 43.1W/m², that is a default value of the program, representing 21.5W/m² for LPD (Lighting Power Density), 16.1W/m² for EPD (Equipment Power Density) and 5.5W/m² for occupancy (34 occupants performing office activities). The daylight contribution was not considered in this preliminary simulation. The default values for infiltration rate (0.2 air changes per hour) and outside air (7.08 l/s/person) were adopted also.

To represent typical Brazilian conditions of occupation and operation of the building, some adjustments were made in the schedules in the software library.

With the base case defined, some simulations were carried out to detect the consumption variation as a function of the variables, such as shape of the building, height, size, orientation, floor-to-floor height, internal loads, fenestrations transmittance and shading coefficient, wall transmittance and set-point temperatures. These preliminary simulations used weather data of Florianópolis City.

In these initials simulations, each variable was changed separately. Then the variation in the electric energy consumption was credited to each variable only, although it is known that some variables are more influential when combined with other. These combinations would demand more time and were not studied. The results are listed in Table 2.

Table 2 – Preliminary simulations for sensitivity analysis.

Variables	Annual Consumption (kWh/m²)	Percentage change from Base Case
Base Case	141.7	0.0%
Square Shape	140.0	-1.2%
Rectangular shape with courtyard	226.2	59.6%
Size 10mx15m	205.8	45.2%
Size 20mx30m	147.9	4.4%
Size 50mx75m	114.2	-19.4%
Floor-to-floor height 2,6m	139.0	-1.9%
Floor-to-floor height 3,2m	143.0	0.9%
ILD = 10W/m^2	100.8	-28.9%
ILD = 30W/m^2	174.5	23.1%
ILD = 40W/m^2	223.8	57.9%
Orientation East-West	143.6	1.3%
WWR 30%	126.5	-10.7%
WWR 70%	153.5	8.3%
WWR 90%	169.2	19.4%
Set-point 22°C (71°F)	143.6	1.3%
Set-point 26°C (79°F)	138.7	-2.1%
Triple glazing (U = 1,06W/m^{2}K)	135.8	-4.2%
Double glazing (U = 1,32W/m^{2}K)	143.9	1.6%
Daylighting 300lux	123.2	-13.1%
Daylighting 500lux	123.3	-13.0%
Internal shading	138.5	-2.3%
One HVAC system for each zone	147.0	3.7%
HVAC - high efficiency	134.0	-5.4%
Infiltration 1,0ACH	141.3	-0.3%
Building with 6 floors	145.7	2.8%
Building with 1 floor	190.7	34.6%
Building with 2 floors	163.1	15.1%

Two cases were simulated with light sensor in the geometric centre of the perimeter zones. These sensors were adjusted to control (dimming) the artificial lighting system according to the daylight contribution, maintaining the average Illuminance at 300lux and 500lux, respectively.

Based on results shown in Table 2, some variables were excluded due to low influence on building energy consumption: square shape, floor-to-floor height, orientation, set-point temperature, internal shading, infiltration rate and glazing quantity. Although the rectangular shape with courtyard showed significant influence on energy consumption, it was not selected because is not a common practice of construction in Brazil.

The daylighting was also not selected because its complexity and variability, even though it presents a large potential for energy saving. For the same reason, the air-conditioner type and variables were not taken into account. These topics could be analysed in future studies.

The next step was to carry out the simulations covering variations of more significant parameters. The variables selected were: size of building, construction materials, WWR, PF and internal load density.

In relation to the size of the building, two variables appear: the shape and the number of floors. It was noted that the electric energy consumption is not a linear function of the shape. However, correlating the consumption with other variable, such as the External Zone Area/Total Area ratio or Façade Area/Total Area ratio, the trend is linear. Similar behaviour was detected in the number of floors. In this case, the Roof Area/Total Area ratio was adopted instead.

Then, the variables selected to be used in the equations are:

a) Roof Area/Total Area;

b) Façade Area/Total Area;

c) WWR – window-to-wall ratio;

d) PF – projection factor of windows overhangs;

e) SC – shading coefficient of glazing;

f) U_{roof} – roof transmittance;

g) α_{roof} – roof absorptance;

h) $U_{façade}$ – exterior wall transmittance;

i) α_{facade} – exterior wall absorptance;

j) ILD – internal load density.

Using 3 values for each parameter and the possible combinations, we have 3^{10} = 59,049 simulations for each city. This number is not acceptable due to the time demanding for this task. To solve this problem, a preliminary study tried to find those variables that presented linear behaviour. Decreasing to 2 values for each variable, the cases are reduced to 2^{10} = 1,024, an acceptable number.

The methodology adopted in these simulations was to change the parameter under analysis with predefined values and changing randomly the other parameters. In this way, the possibility of obtaining a linear trend by coincidence of other factors would be eliminated.

From the variables listed before, just the wall transmittance presented a non-linear tendency for the building energy consumption. To analyse this problem, some simulations were carried out using a weather file to the Belém city. This city presents an average dry bulb temperature of 26.2°C, while the Florianópolis City (used in the preliminary simulations) presents an average of 20.5°C. In addition, two new cases were inserted to better explain the phenomenon, with wall transmittance of 0.613W/m².K and 5.000W/m².K.

Considering the non-linearity of this variable, an intermediary value of wall transmittance was used to run the next simulations. The wall chosen was composed by concrete block of 19cm thickness, with U-value of 2.632W/m².K, since most wall constructed in Brazil present transmittance between 2.0 and 3.0W/m².K.

The hypothesis that 10 variables present linear tendency resulted in 1,024 simulations. However, adopting just one value of wall transmittance the number of simulations decreases to 512 for each city. Considering that there was weather data available to 14 Brazilian cities, 7,168 simulations were carried out. The values adopted for each variable are listed in Table 3.

Table 3 – Values used in the regression analysis.

Variable	Value 1	Value 2	Observations
A_{roof}/A_{total}	1.00	0.10	1 and 10 floors, respectively
$A_{façade}/A_{total}$	0.14	0.70	60m x 150m and 12m x 30m, respectively
WWR	0.20	0.80	
PF	0.00	1.00	
SC	0.29	1.00	Single clear SS14 and single clear 3mm.
U_{roof} (W/m^{2}K)	0.952	4.545	Clay tile + insulation and asbestos-cement shingles
α_{roof}	0.30	0.70	Clear painting (white) and dark painting (grey)
$U_{façade}$ (W/m^{2}K)	2.632	-	Concrete block 19x19x39cm with cement plaster
$\alpha_{façade}$	0.30	0.70	Clear painting (white) and dark painting (grey)
ILD (W/m^2)	15.0	30.0	

RESULTS

The equation for Belém City

Belém was the first city analysed, and the first equation (Equation 1) was obtained considering the simple hypothesis that the variables are independent among themselves. *C* is the annual energy consumption in kWh/m².

$$C = 52.39\frac{A_{roof}}{A_{total}} + 42.93\frac{A_{façade}}{A_{total}} + 19.36WWR$$
$$-14.00PF + 7.35SC + 4.18U_{roof} + 18.67\alpha_{roof}$$
$$-13.09\alpha_{façade} + 2.9ILD \qquad \textbf{(Eq. 1)}$$

All parameters presented significant influence, but the r² for the equation 1 results on 0.8444. This value is very low to the purpose of this work, and then some associations between variables were made in order to obtain better adjustment.

The most complex hypothesis would be to combine all variables among themselves. This would result on 511 different combinations, what would be very hard to solve and not practical to use. Thus, the methodology consisted on starting with each parameter isolated and then, with coherent combinations. The influence of each parameter was tested to eliminate variables with low significance.

The first equation obtained by this new philosophy tried to group some variables. Like assured before, the roof system is very important in the consumption prediction. Thus, A_{roof}/A_{total} and U_{roof} were multiplied resulting in one only parameter ($A_{roof}.U_{roof}/A_{total}$) that represents the roof influence. The same process was taken to $A_{roof}.\alpha_{roof}/A_{total}$.

Seeking for the building façades influences, $A_{façade}.WWR.SC/A_{total}$ and $A_{façade}.\alpha_{façade}/A_{total}$ were used. The equation 2 was obtained:

$$C = -3.74\frac{A_{roof}}{A_{total}} + 10.32\frac{A_{roof}U_{roof}}{A_{total}} + 79.62\frac{A_{façade}WWR.SC}{A_{total}}$$
$$+6.29\frac{A_{façade}.\alpha_{façade}}{A_{total}} + 6.52WWR + 64.07\frac{A_{roof}\alpha_{roof}}{A_{total}}$$
$$+64.07\frac{A_{roof}\alpha_{roof}}{A_{total}} + 22.54\frac{A_{façade}}{A_{total}} - 10.85PF - 1.31SC$$
$$-0.16U_{roof} + 3.10\alpha_{roof} + 3.91\alpha_{façade} + 3.53ILD$$

(Eq.2)

This new regression results on r² = 0.9633 and differences varying from –17.6% to +16.3% between the simulated consumption and the consumption predicted by the equation. The average difference was +0.1% and the standard deviation was 6.4%. Nevertheless, some parameters did not present sufficient significance, such as $A_{façade}.\alpha_{façade}/A_{total}$, likewise some isolated variables, such as SC, U_{roof}, α_{roof} and $A_{façade}$, which lost their significance when grouped with other parameters.

In this methodology, several tests were carried out covering possible combinations until the final equation to Belém was obtained (Equation 3), with $r^2 = 0.9951$. A constant (0.19 in Equation 3) was included in the final equation to minimize errors.

$$C = 26.73\frac{A_{roof}}{A_{total}} + 21.58\frac{A_{roof}U_{roof}\alpha_{roof}}{A_{total}} + 22.90\frac{A_{façade}}{A_{total}}$$
$$+121.29\frac{A_{façade}WWR.SC}{A_{total}} - 69.39\frac{A_{façade}WWR.SC.PF}{A_{total}}$$
$$+8.34WWR - 6.57WWR.SC - 1.65PF + 3.49ILD + 0.19$$

(Eq. 3)

The minimum and maximum differences found were –7.2% and +7.8%, with average –0.1% and standard deviation 2.5%. This is the final form of the equation that will be used to the other cities.

Figure 2 compares the simulated consumption with the consumption predicted by Equation 3 for the first 128 models. From this graph, the tendencies of each case and set of cases with similar characteristics can be noticed.

The equations for other cities

Proceeding with the same methodology to other cities, the equation obtained confirmed that the pattern adopted could be used to all.

The Equation 4 is the generic equation to all cities under analysis, using the coefficients (**a** and **b1** to **b9**) presented in Table 4.

$$C = a + b_1\frac{A_{roof}}{A_{total}} + b_2\frac{A_{roof}U_{roof}\alpha_{roof}}{A_{total}} + b_3\frac{A_{façade}}{A_{total}}$$
$$+ b_4\frac{A_{façade}WWR.SC}{A_{total}} - b_5\frac{A_{façade}WWR.SC.PF}{A_{total}}$$
$$+ b_6WWR - b_7WWR.SC - b_8PF + b_9ILD \qquad \textbf{(Eq.4)}$$

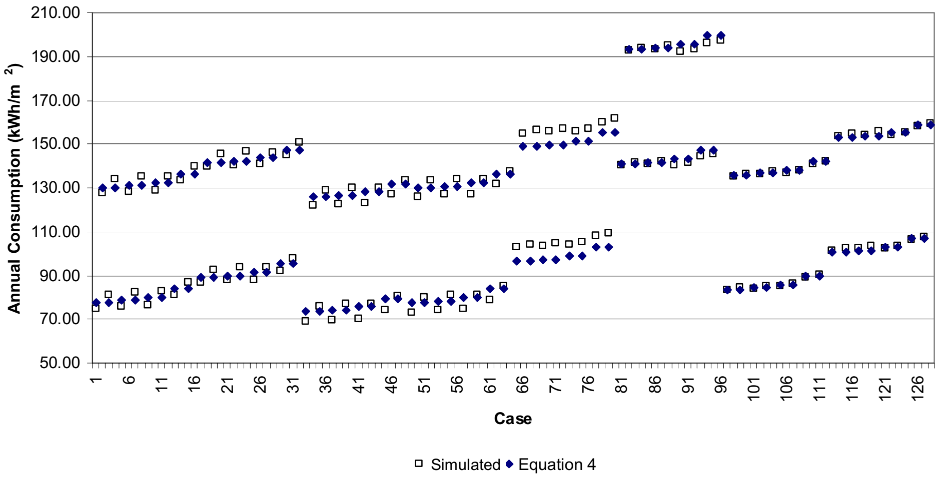

Figure 2 – Electric energy consumption simulated and predicted for Belém City.

Table 4 – Coefficients of equation 4 and the correlation factor for all cities.

City \ Coeff.	a	b1	b2	b3	b4	b5	b6	b7	b8	b9	r²
Belém	0.185	26.733	21.583	22.903	121.292	-69.388	8.335	-6.573	-1.647	3.488	0.995
Brasília	0.252	13.516	16.949	10.666	98.847	-58.360	8.030	-6.393	-0.981	3.164	0.993
Curitiba	1.226	4.109	12.881	5.555	85.425	-59.166	5.262	-4.229	-1.117	2.969	0.986
Florianópolis	0.325	21.326	18.210	15.584	117.504	-63.690	6.606	-5.301	-0.879	3.238	0.996
Fortaleza	0.902	25.670	20.342	20.998	127.444	-74.166	6.241	-4.922	-2.003	3.449	0.995
Maceió	0.355	24.916	18.170	17.291	117.206	-62.837	6.861	-5.498	-0.994	3.382	0.996
Natal	0.851	24.989	19.505	18.004	123.047	-65.808	5.833	-4.825	-1.165	3.434	0.996
Porto Alegre	0.183	19.851	17.098	13.417	102.265	-59.510	7.810	-6.098	-0.977	3.177	0.994
Recife	0.697	23.031	19.008	17.586	117.174	-64.248	6.234	-4.882	-1.785	3.400	0.994
Rio de Janeiro	0.943	33.097	18.513	22.820	111.468	-64.734	6.665	-5.485	-1.429	3.294	0.992
Salvador	0.804	39.288	25.757	28.813	150.559	-91.217	7.417	-5.959	-1.910	3.571	0.995
São Luís	-0.025	26.840	18.507	22.446	129.567	-68.928	8.563	-6.676	-1.857	3.506	0.996
São Paulo	0.459	18.560	16.729	13.960	106.629	-63.004	6.506	-5.113	-0.797	3.233	0.996
Vitória	1.008	18.509	15.908	14.864	120.067	-68.477	6.770	-5.240	-1.301	3.294	0.995

Validation of the equations

Putting the equations under test, some hypothetical buildings were simulated, with values differing from those used in the regression analysis. It was verified the equation behaviour when the input are extrapolated or interpolated.

In these tests, the values were set randomly, trying to represent buildings as different as possible. In this way, several values and combinations are studied, adding up to 10 buildings that had their electricity consumption simulated by VisualDOE and predicted by equations.

The results obtained were satisfactory, since many factors that influence on energy consumption were neglected in the regression analysis. For example, the building orientation was not considered in the equations but was tested in the validation (Cases 7 and 8). Schedules and air-conditioning types were the same used in the models used in the regression.

The largest discrepancy (-11.0%) was observed for Salvador city in a building with low internal load density (only 10W/m²) and Single Low Iron 3 mm glazing (SC = 1.05). The low ILD makes the building energy consumption to local climate, decreasing the equations significance. Even so, differences around 10% are not so bad, considering the good results gotten in the other tests, with average difference of less than 2%. Table 5 lists the results for Belém City.

Table 5 – Test of the equation for Belém City.

Case	Number of floors	Shape	U_{roof}	α_{roof}	ILD	WWR	PF	SC	α_{wall}	Consumption (kWh/m²)			Diff. (%)
										Simulated	Eq. 4	Diff.	
1	2	100x100	4.545	0.2	20	0.15	1.0	0.58	0.3	93.18	95.44	2.25	2.4%
2	3	20x100	0.952	0.7	10	0.50	0.0	1.05	0.7	86.44	80.65	-5.78	-6.7%
3	5	20x200	2.222	0.5	30	0.40	0.5	1.00	0.5	134.36	133.83	-0.53	-0.4%
4	15	20x20	2.000	0.3	45	0.30	2.0	0.37	0.1	171.99	170.83	-1.16	-0.7%
5	20	100x100	4.545	0.7	15	0.90	0.5	0.71	0.7	67.73	69.14	1.41	2.1%
6	2	20x40	1.786	0.1	45	0.70	1.0	0.58	0.1	188.86	193.73	4.88	2.6%
7	3	100x50	2.222	0.5	10	0.60	0.5	0.37	0.1	59.58	62.27	2.69	4.5%
8	20	100x20	1.786	0.1	45	0.20	2.0	0.29	0.3	167.86	164.53	-3.33	-2.0%
9	30	50x50	4.545	0.9	20	0.50	0.0	0.71	0.5	94.11	91.44	-2.67	-2.8%
10	10	50x50	2.000	0.7	10	0.80	1.0	1.05	0.5	58.45	56.22	-2.23	-3.8%
										Average		-0.45	-0.5%
										Standard Deviation		3.24	3.4%

CONCLUSIONS

About the equations

The obtained equations for all cities under analysis present good agreement, with r² equal or higher than 0.99. Practically all Brazilian climates are represented, as the cities are spread all over the country.

Each city has a different set of **b** coefficients due to the climate impact on building energy consumption. The internal load density present similar behaviour for all cities, as noticed in the small variation of the **b9** coefficient. The high ILD coupled with low thermal insulation of typical Brazilian office buildings decrease the influence of other architectural parameters on electric energy consumption, such as building shape, orientation and internal shading.

The equation for Curitiba City presents the worst adjustment, with lowest r² (0.986). Such behaviour can be explained by the colder climate in this city. As the air-conditioner was set to cooling mode only, in the coldest months the energy consumption is smaller and probably less dependent on the chosen variables.

The Salvador City presents the largest consumption, however it is not the hottest city. Probably, a combination of other climatic parameters (relative humidity, wind velocity, nebulosity, etc.) is determining this behaviour.

The equations presented in this work could be used as an additional tool in the Brazilian Energy Efficiency Standards to be developed.

About the models limitation

Although the equations predict the building electric energy consumption very well, some considerations must be taken into account.

Some parameters were set constant to enable the analysis, such as air-conditioner characteristics, schedules and building shape. Changing these variables would require additional studies to extend the equations.

For buildings located in urban city centres, the heat island effect was not considered as weather data are collected at peripheral areas (airports). Generally, the energy consumption for buildings located in big centres tends to be higher than the predicted by the equations.

VisualDOE limitations can also be sources of uncertainties. Problems in the algorithm can cause differences on simulated consumption and, as consequence, in the obtained equations.

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