THE USE OF COMPUTER SIMULATION TO ESTABLISH ENERGY EFFICIENCY PARAMETERS FOR A BUILDING CODE OF A CITY IN BRAZIL

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ABSTRACT

The first energy efficiency law for Brazil was presented in 2001, which required that buildings should have some energy efficiency regulation. Salvador city building code was then submitted to a study to include energy efficiency parameters related to the building envelope.

The energy consumption limits were associated with the envelope parameters using simulation and using a multi-variable regression equation developed using simulation. Twelve models were defined with the variables that influence most on energy consumption and were combined to the envelope variables resulting in the analysis of 1616 prototype buildings. This paper describes the simulations that were used to establish the limits presented in the code.

INTRODUCTION

In Brazil, electrical energy production is highly based on hydroelectric power plants. Brazil has a hydroelectric potential of 260GW and only 23% of this potential have been used (61GW) so far. The Federal Energy Balance of 2000 [MINISTÉRIO DAS MINAS E ENERGIA, 2001] showed that the electricity consumption increased from 35% in 1985 to 41% in 2000. The electricity consumption in residential, commercial and public sectors are, respectively, 64%, 94% and 91% of the total energy consumption of each sector. [MINISTÉRIO DAS MINAS E ENERGIA, 2001] 64% of the end-use in commercial and public buildings is due to lighting and cooling, and it reaches 86% in banks and office buildings [GELLER, 1991]. Energy consumption for heating is not usual in most of Brazilian states due to its mild climate. Energy consumption for cooling is electrical. Although Brazil still has a high potential of growth with clean energy production, electricity consumption is growing rapidly as Brazil still does not have a standard or a code of practice for energy efficiency in buildings.

DUFFY [1996] showed that codes and standards in Brazil could promote energy savings of about 1310TWh in 20 years (2000 to 2020), while India would save 1659TWh in the same period and Mexico 550TWh, representing reductions of 12%, 11% and 12% in 20 years, respectively. One year before, in 1995, Mexico approved its first energy standard, for commercial buildings [COMISIÓN NACIONAL PARA EL AHORRO DE ENERGÍA, 1995a] and for artificial lighting in buildings [COMISIÓN NACIONAL PARA EL AHORRO DE ENERGÍA, 1995b]. Both were based on ASHRAE Standard 90.1 [1999]. Recently, a DOE press release [DOE, 2002] stated that Mexico, United States and Canada are moving towards unifying their energy efficiency standards. This trend is already in progress in Europe, where the European directives for energy efficiency in buildings were approved in order to unify the state members standards which should present common: calculation methodologies, minimum energy efficiency requirements for buildings, certification and other proposals [EUROPEAN PARLIAMENT, 2002].

In 2001, due to an energy crisis in the country, the Brazilian Government finally passed a law that spent 10 years being analyzed in Congress, aiming to promote energy efficiency of related equipment and buildings, and made possible the creation of a committee to develop regulations for energy efficiency in buildings, such as national standards and building codes. Before such a committee could be created to develop standards for energy efficiency in buildings, the electric utility company of Salvador (COELBA) and its associated ESCO (IbenBrasil), stepped ahead and decided to propose an amendment to the Building Code of Salvador. LabEEE was responsible in analyzing parameters to be included in the Building Code to promote energy efficiency in local buildings.

Parameters to improve thermal comfort, visual comfort and energy efficiency in local buildings were included in the building code. This paper focuses on the energy efficiency parameters that were based on building performance simulation for the climatic conditions of Salvador.

Salvador is a tropical city with 2 million inhabitants located on the coast, at a latitude 12°54' South, and is the capital for the state of Bahia, Northeastern Brazil. The air temperature in Salvador ranges from 21.8° to 28.7° and the mean relative humidity is 81% [GOULART et al., 1997].

The Building Code for Salvador was based on parameters presented in ASHRAE Standard 90.1 [1999], which was referred in the International Energy Conservation Code [LUCAS & MEYERS, 2000] and used in other developing countries such as Mexico; and also in Australia, which has a climate similar to Brazil's. Standard 90.1 [ASHRAE, 1999] limits were modified to better represent the local conditions. It classifies the climate of several U.S. cities and some international cities. The climates are classified by their degree-days for cooling and heating and related to one of the 26 building envelope requirements tables. Cities not analyzed in the Standard 90.1 [ASHRAE, 1999] can have their degree-days for heating and cooling calculated in order to use one of the building envelope requirements table. Salvador city climate is classified by Standard 90.1 [ASHRAE, 1999] exempting the calculation of degree-days. In the table with the requirements in which Salvador is included, U-factor for non-residential above grade walls is divided in mass walls, metal buildings, steel framed and wood framed walls. The maximum U-factor for mass walls is 3.352W/m^{2}K and for wood framed light walls is 0.513W/m^{2}K. Roofs with insulation entirely above deck have a maximum U-factor of 0.366W/m^{2}K and roofs with attics have maximum U-factor of 0.196W/m^{2}K. The maximum solar heat gain coefficient (SGHC) ranges from 0.19 to 0.25, and higher coefficients for windows oriented to south were recommended, reaching 0.61 for low Window to Wall Ratios [ASHRAE, 1999].

These thermal properties limits are quite severe for Brazilian needs. The construction components used in Brazil are different from the American components. Brazilian walls for commercial buildings are built with clay bricks or cement blocks, while American walls are composed of bricks and framed panels. Brazilian roofs are generally composed of clay tiles or corrugated asbestos cement sheets, and some commercial buildings have metal roofs. Asphalt or stones are not widely used in Brazilian roofs. Components used in Brazil are related to economic and social issues, such as use of untrained labour, material costs and customers preferences, that must be considered to establish the limits for the Building Code, the first energy efficiency regulation for buildings in Brazil. The designing of energy efficient buildings is a new concept in this country whose construction industry has not faced the energy efficiency concept yet. The limits must initially account for lower efficiencies than ASHRAE's; as building designers, builders and also the population of Salvador get used to either applying or requesting energy efficiency strategies, the thermal properties limits may be modified to promote higher energy efficiency rates. The development of the method described in this paper intends to provide knowledge of the variables to define acceptable parameters for all these particular conditions.

Two tools were used to estimate the thermal properties limits to be included in the Building Code: a multi-variable regression equation for commercial building energy consumption calculation [SIGNOR et al., 2001] and simulation using DOE 2.1–E. The regression equation was used to define the limits of WWR (Window to Wall Ratio), SC (shading coefficient) and PF (projection factor) for vertical windows oriented to north, east and south. Simulation was used to estimate the limits of thermal transmittance for walls, to investigate the influence of the building orientation on the energy consumption and to estimate the limits of WWR, SC and PF for vertical west-oriented windows.

OBJECTIVE

The main objective of this paper is to describe the methodology used to define thermal properties limits for the building envelope in the city of Salvador. It presents the differences of the limits defined in this study and the limits recommended by Standard 90.1 [ASHRAE, 1999] for Salvador.

METHODOLOGY

Energy consumption on lighting, equipment and cooling for commercial buildings was simulated using DOE 2.1-E and a multi-variable regression equation developed also from parametric simulation.

Salvador is a cooling dominated climate, external temperature often varies near the comfort conditions and solar radiation is very high, which requires the use of hourly dynamic simulation to gather better results on energy consumption estimation. The energy consumption simulations were performed to obtain site electricity end energy only, which is the main energy use in the Brazilian commercial sector.

The simulations boundary conditions are listed in Table 1. Two values for internal loads density were used, 15W/m^2 and 30W/m^2. Schedules were adjusted to Brazilian offices occupancies (eight hours) and the heating system was turned off on heating schedules.

Table 1: Boundary conditions for the energy consumption simulations.

Cooling set-point		25.6	°C
Internal loads density	Lighting	9.5 & 19.0	W/m^2
	Equipment	3.7 & 7.5	W/m^2
	Occupancy	75.4 & 37.7	m^2/person
Ventilation rate		11.7	m^3/person
Infiltration		0.2	ACH
Coil energy efficiency ratio		2.93	
Type of HVAC		Packaged multi-zone system	

The multi variable regression equation was developed using detailed hourly simulation models and resulted in the combination of eight architectural variables: A_{roof}/A_{total} (roof area ratio), $A_{façade}/A_{total}$ (façade area ratio), WWR (Window to Wall Ratio), PF (projection factor), SC (shading coefficient), U_{roof} (roof transmittance), a_{roof} (roof absorptance) and ILD (internal load density) [SIGNOR et al., 2001]. SIGNOR et al. [2001] developed energy consumption equations for 14 cities using these variables. Two values were defined for each parameter to simulate 512 alternatives to detect their consumption variation. Parameters that did not present linear trends were excluded from the equation, such as wall transmittance. First investigations showed that the equation should be based on variables associations, but the hypothesis that all the variables would have to be combined among themselves would be very complex, resulting in 511 combinations, which would be very hard to solve. The equation was then developed considering the variables to be independent and the parameters were coherently combined in order to obtain better results when compared to the annual energy consumption of some simulated prototypes. The result was a multi-variable regression equation with 10 coefficients, 5 independent parameters and 12 correlated parameters with a R^2 of 0.995. Equation 1 presents the formula to calculate the annual energy consumption for Salvador [SIGNOR et al., 2001].

$$C = 0.80417 + 39.28823 \times A_{roof}/A_{total} + 25.75737 \times [(A_{roof} \times U_{roof} \times a_{roof}) / A_{total}] + 28.81267\ A_{façade}/A_{total} + 150.55861\ (A_{façade} \times WWR \times SC) / A_{total} - 91.21731 \times (A_{façade} \times WWR \times SC \times PF) / A_{total} + 7.41655 \times WWR - 5.95851 \times WWR \times SC - 1.90946 \times PF + 3.57086 \times ILD$$

(Equation 1)

Where,

C= Annual energy consumption (kWh/m^2 per year)

A_{roof}= Area of roof (m^2)

A_{total}= Total area on plan (m^2)

$A_{façade}$= Area of façade (m^2)

WWR= Window to Wall Ratio (%)

PF= projection factor (non-dimensional)

SC= shading coefficient (non-dimensional)

U_{roof}= roof thermal transmittance (W/m^2K)

a_{roof}= roof absorptance (non-dimensional)

ILD= internal load density (W/m^2)

A_{roof}/A_{total} corresponds to the number of floors while $A_{façade}/A_{total}$ corresponds to the building shape. Internal loads are related to the use of the building and were simulated using Brazilian offices occupancy, lighting and equipment schedules. These are the three parameters that most influence the annual energy consumption. The other parameters are related to the building envelope and were analyzed in order to define the limits of the Building Code to improve energy efficiency in buildings.

INFLUENCE OF THE EQUATION PARAMETERS ON ENERGY CONSUMPTION

Equation 1 was used to investigate the range of annual energy consumption of Brazilian commercial building models. It allows an instantaneous estimation of energy consumption for buildings located in Salvador because it avoids the time spent on modeling a building for simulation. The energy consumptions of 432 models were estimated by using Equation 1 to define the range of possible energy consumptions for commercial buildings. Twelve basic models were defined based on three parameters that most influence the energy consumption of commercial buildings: shape, number of floors and internal loads, as presented in Table 2. The other variables adopted in Equation 1 were based on Brazilian typologies and components mostly adopted in construction.

Table 2: Variables of the 12 basic models.

Model	$A_{façade}/A_{total}$	A_{roof}/A_{total}	ILD
1	0.14	1	15
2	0.14	1	30
3	0.14	1	35
4	0.14	0.1	15
5	0.14	0.1	30
6	0.14	0.1	35
7	0.7	1	15
8	0.7	1	30
9	0.7	1	35
10	0.7	0.1	15
11	0.7	0.1	30
12	0.7	0.1	35

These twelve models had three envelope parameters varied: roof thermal transmittance was varied from

0.952W/m²K to 4.545W/m²K, WWR was varied from 10% to 100% and SC was varied from 0.18 to 1. Projection factor and roof absorptance were assumed to be constant: projection factor remained zero at this stage of the research while roof absorptance was assumed as 0.7, a high value considering that even white-painted roofs with low absorptance become dirty with time.

Figure 1 presents the range of energy consumption estimated by using Equation 1 with Brazilian building parameters. Two models are presented in Figure 1: a model type whose energy consumption tends to be high (model 9) and a model type whose energy consumption tends to be low (model 4). Model 9 represents a small one-storey building (30m x 12m on plan) with an ILD of 35W/m², while model 4 represents a large 10-storey building (150m x 60m on plan) with an ILD of 15W/m². Each model presents the maximum and minimum annual energy consumption of its prototype buildings according to the maximum or minimum shading coefficients as a function of WWR.

In Figure 1, the energy consumption varies from 62 to 396kWh/m² per year, in buildings with WWR ranging from 10% to 100%. The energy consumption of the other models of Table 1 are located between the lines Max_Model 9 and Min_Model 4. Based on this range, the highest 50% of the energy consumption range calculated using Equation 1 was eliminated for each one of the 12 models.

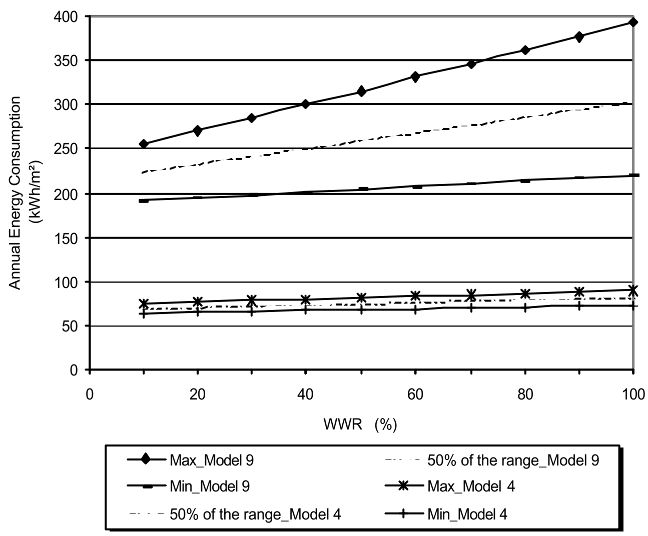

Figure 1: Maximum and minimum energy consumption for two building models presented in Table 1.

The objective was to find limits of PF, SC and thermal transmittance of roofs that would result in energy consumptions lower than the limit of 50% of the energy consumption range shown in Figure 1, for any building prototype.

THERMAL TRANSMITTANCE OF ROOFS

Equation 1 was used to analyze the influence of the roof thermal transmittance on energy consumption. The roof U-factor was varied from 0.3W/m²K to 5.0 W/m²K, as seen in Figure 2, which presents the U-factor influence on energy consumption for four models with internal loads of 35W/m².

Models 3 and 9 correspond to one-storey buildings, while models 6 and 12 correspond to 10-storey buildings. Although the influence of roof U-factor on energy consumption is higher on one-storey buildings, thermal comfort was also considered to specify one limit for the thermal transmittance of the roof for any model, no matter the number of floors.

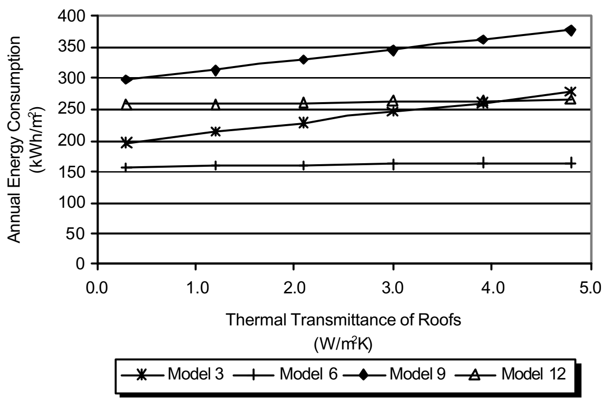

Figure 2: Influence of thermal transmittance of roofs on the annual energy consumption for models 3, 6, 9 and 12.

A clay-tile roof and an asbestos-cement roof, both without ceiling, have a similar U-factor of 4.60W/m²K. The addition of a ceiling reduces the U-factor to 2W/m²K, which is widely used in Brazil. The U-factor limit was defined as 1.2W/m²K, which corresponds to a roof with insulation or with a radiant barrier and a concrete slab, as a good practice.

Then, as seen in Figure 2, the energy consumption was reduced from 375W/m² to a maximum of 320W/m² on model 9, a reduction of 15% on the model which the energy consumption is higher. Similar savings were found on model 3, also a 10-storey model. The value of 1.2W/m²K was then adopted in all the following energy consumption estimations.

WINDOWS WWR, SC AND PF

The twelve building models shown in Table 2 had their windows properties varied in order to identify a relation between WWR and SC which would not overpass the established consumption limit. Figure 3 presents the shading coefficient variation as a function of WWR for models 3, 6, 9 and 12. The SC provided energy consumptions for each model that did not overpass their energy consumption limits.

Having found the shading coefficient limits for each model, the minimum shading coefficient limits (most severe limits found) were adopted for all the models.

Figure 3 shows that the most severe SC limit occurs for models 6 and 3. The SC of one of these two models could be adopted as the SC limit for all the other models. The analysis was made with the twelve models. Later, the projection factor was included in the analysis to allow the use of glasses with higher shading coefficients. The same method used to find the SC limits was used for PF: a value of PF, as a function of SC and WWR, was obtained with the condition that the prototype's annual energy consumption would not overpass the energy consumption previously defined as a limit.

Figure 4 presents the curves and the equations for the relation between SC and PF obtained for each WWR.

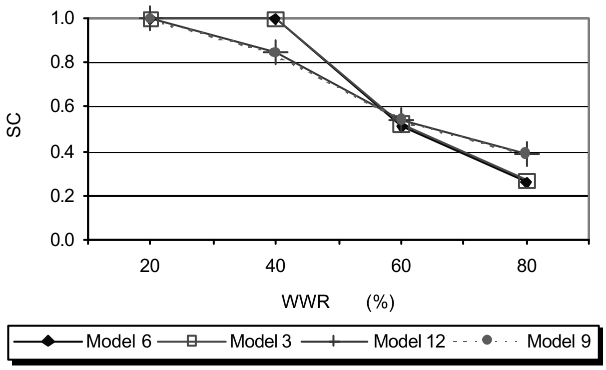

Figure 3: Shading coefficient as a function of WWR for 4 models with ILD= 35W/m².

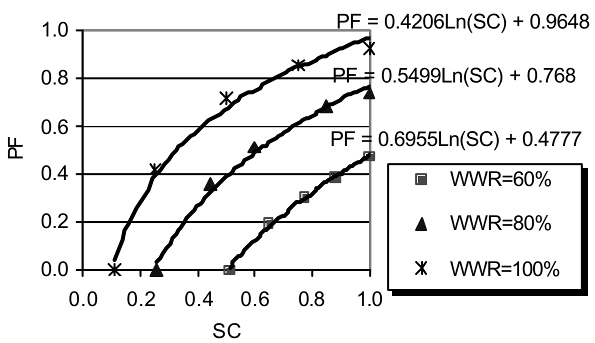

Figure 4: Projection factor as a function of SC and WWR.

Shading coefficient (SC) was converted to solar heat gain coefficient (SHGC) after its limits were defined, multipling the SC by 0.86. The maximum SHGC allowed in the Building Code are presented in Table 3 and some examples of minimum PF are presented in Table 4.

Table 3: Maximum SHGC as a function of WWR for north, east and south windows.

	WWR			
	0 to 40%	**40.01 to 60%**	**60.01 to 80%**	**80.01 to 100%**
SHGC	0.86	0.43	0.22	0.09

Table 4: Examples of the minimum PF as a function of SHGC and WWR for north, east and south windows.

SHGC	WWR			
	0 to 40%	**40.01 to 60%**	**60.01 to 80%**	**80.01 to 100%**
0.86	0	0.48	0.77	0.96
0.60	0	0.23	0.57	0.81
0.47	0	0.06	0.44	0.71
0.43	0	0	0.39	0.67
0.26	0	0	0.11	0.46
0.22	0	0	0	0.38

BUILDING ORIENTATION INFLUENCE ON ENERGY CONSUMPTION

The Standard 90.1 [ASHRAE, 1999] recommended a specific SHGC for south-oriented windows. Other models were simulated using DOE2.1-E in order to identify the building orientation influence on energy consumption.

Despite the recognition of lower energy consumption in prototype buildings with south-oriented windows, 134 simulations showed that the energy consumption for buildings with west-oriented windows presented significant differences. Figure 5 presents the energy consumption differences of small prototype buildings with their window wall facing either one of the four main orientations: north, east, south or west.

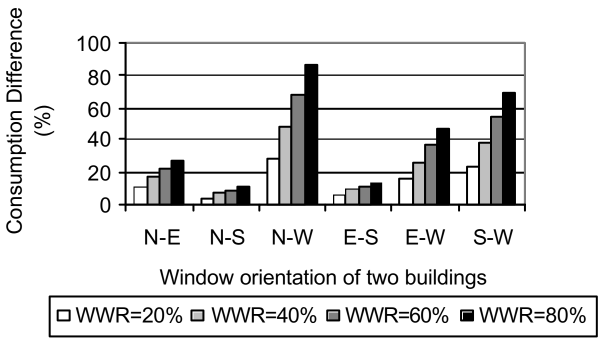

Figure 5: Energy consumption differences between two buildings with window wall facing different orientations.

(N-E) represents the differences in energy consumption between a building with north-oriented windows and a similar building with east-oriented windows. (N-S) represents the differences in energy consumption between a building with north-oriented windows and a similar building with south-oriented window, and so on. It is possible to verify that the energy consumption differences are significant between buildings with west-oriented windows, no matter the WWR of 20% or 80%. The highest energy consumption difference between a prototype with its windows oriented to west and a prototype with its windows oriented to other direction is about 18% (WWR= 80%), while the lower energy consumption difference is about 7% (WWR= 20%). No significant differences were found between prototype buildings with south-oriented windows. Note that Standard 90.1 [ASHRAE, 1999] allows higher SHGC for south-oriented windows and do not consider any different SHGC for west-oriented windows.

The prototype buildings were then simulated to find a pattern in the annual energy consumption differences. These differences would indicate the value of the shading coefficient that should be used on west-oriented windows to neutralize the energy consumption differences between buildings with windows on the north façade and buildings with windows on the west façade. South or east-oriented windows would present a similar behavior of north-oriented windows since no significant energy consumption differences were found between these prototypes. The SC that would partially compensate this energy consumption difference was 0.4, reducing the differences in 18% only. A reduction in the SC from 1 to 0.4 was considered to be enough due to the high costs of low SC glazing.

New limits were then defined for the west orientation based on a significant decrease on shading coefficient values and were converted to SHGC. The projection factor was also corrected for west-oriented windows. Table 5 presents the new proposed SHGC for west-oriented windows: note that no changes were made on small windows (WWR from 0 to 40%) and Window to Wall Ratios higher than 80% and without any solar protection (PF>0) were banned for the west façades.

Table 5: Maximum SHGC as a function of WWR for west-oriented windows.

	WWR			
	0 to 40%	**40.01 to 60%**	**60.01 to 80%**	**80.01 to 100%**
SHGC	0.86	0.17	0.09	-

THERMAL TRANSMITTANCE OF EXTERNAL WALLS

As the thermal transmittance of external walls was excluded from the development of Equation 1, simulations were performed using DOE 2.1-E in order to analyze the influence of wall thermal transmittance on the energy consumption.

Two types of external walls were simulated: mass walls and light walls. Both of these types had their U-factor modeled ranging from 0.273W/m²K to 5.263W/m²K. Figure 6 presents the energy consumption variation as a function of the wall thermal transmittance. The energy consumption varies from 83kWh/m² per year to 230kWh/m² per year. Although energy consumption tends to increase as the thermal transmittance increases, there are some energy consumption decreases on both light and mass walls lines. The energy consumption of prototype buildings with external mass walls tends to significantly increase only when walls U-factor are higher than 3.7W/m²K. This U-factor corresponds to a solid clay-brick wall, widely used in Brazil since the 16th century. The energy consumption of prototype buildings with external light walls is similar to the energy consumption of prototype buildings with external mass walls when the prototype building external light walls have a U-factor of 1.2W/m²K. This energy consumption of prototype buildings with external light walls presents a significant increase when their walls have a U-factor higher than 0.5W/m²K.

The light walls represent the class of new materials and components that are becoming used in the Brazilian construction industry, although the clay or concrete-block walls are still widely used. For mass walls, no limitation was imposed, as 3.7W/m²K represents a 10cm solid brick wall, but for light walls higher insulation was required (U=1.2W/m²k) in order to keep the energy consumption similar to the mass walls as can be seen in Figure 6.

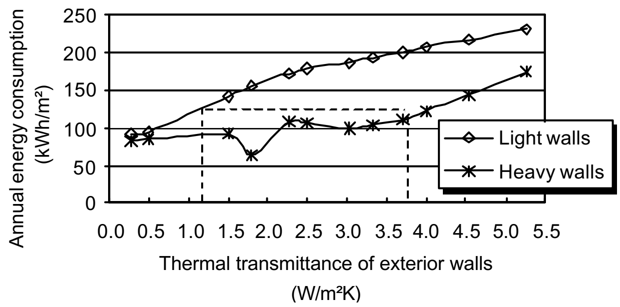

Figure 6: Energy consumption as a function of external wall transmittance.

RESULTS

The energy consumption resulted from the calculation using Equation 1 and the commercial buildings envelope limits defined for the Salvador Building Code are represented in Figure 7 for models 4 and 9. The energy consumption range for these models and Standard 90.1 prescriptive limits, whose maximum WWR is 50%, are also presented.

The Building Code maximum SC is indicated as a function of WWR that, starts at 40%, with increments of 20% (Tables 2, 3 and 4). This can be seen in Figure 7, where the energy consumption increases for the same SC, as the WWR increases, until the dashed line is interrupted by the new SC prescribed for the next WWR range.

The limits are more severe than initially planned. This happened because one model had to be chosen among the twelve models of Table 1 and its SC limits were adopted for all the eleven models. The choice was made for the more severe shading coefficient limits and applied for all commercial building typologies. This resulted in a consumption limit that excluded more than 50% of the energy consumption range. Figure 1 shows the initial plan for the consumption limits and can be compared to the final results presented in Figures 7 and 8.

The parameters defined for buildings with WWR from 80% to 100% in the Building Code are stricter than parameters defined for buildings with WWR lower than 60%. Nevertheless, ASHRAE prescriptive parameters do not even indicate any SHGC that can be adopted for WWR higher than 50%.

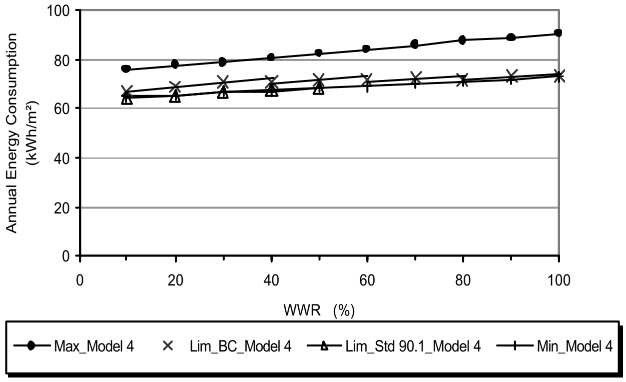

Figure 7: Energy consumption for model 4 and energy consumption limits defined in the Building Code and in Standard 90.1.

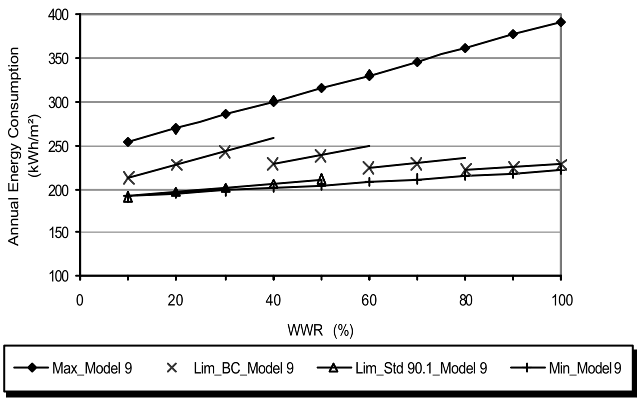

Figure 8: Energy consumption for model 9 and energy consumption limits defined in the Building Code and in Standard 90.1

Figure 8 shows that ASHRAE limits are more severe than the limits defined in the Building Code, being close to the minimum energy consumption line for model 9 while this happens to the energy consumption calculated with the Building Code limits only when WWR ranges from 80% to 100%. The envelope thermal properties limits of Salvador Building Code banned most of the cases whose energy consumption would be extremely high due to high Window to Wall Ratios.

CONCLUSIONS

An equation with eight building parameters was used to estimate energy consumption for commercial buildings in combination with simulation. This equation was developed through 512 parametric simulations for the climate for Salvador. Three parameters (A_{roof}/A_{total}, $A_{façade}/A_{total}$ and ILD) that most influence energy consumption were combined into 12 models in which the other envelope parameters were varied. The energy consumption range for Brazilian commercial buildings was estimated and consumptions limits were defined. The limits of thermal properties for the envelope were estimated based on the energy consumptions limits using Equation 1 and simulation.

Equation 1 was used to estimate the limits of thermal transmittance of roofs and solar heat gain coefficient and projection factor of vertical windows. Simulation was used to define the thermal properties limits of external walls and to investigate the influence of window wall orientation on energy consumption.

The Building Code had its parameters defined by calculating the energy consumption for 921 prototype buildings using Equation 1 and simulating 695 prototype buildings in DOE 2.1-E. The combination of Equation 1 with the further simulations reduced the number of simulations that would be necessary to define the thermal properties parameters, increasing the analysis speed.

This proposal is now being discussed by the local population of Salvador. Architects, engineers, builders and local authorities are involved in negotiations to analyze and to approve the thermal properties recommendations for the envelope presented in this paper.

The national energy efficiency regulation is being initially studied by the federal committee responsible to develop regulations for buildings and related equipment. Similar parameters for the rest of the existing Brazilian climate zones can be developed to be directly prescribed or can be used in the calculation of an energy cost budget for the national standard. Some adjustments must be made for the other climate zones, such as including in the analysis the energy consumption for heating for climates with low mean temperatures. After developing a national standard, the inclusion of energy efficiency parameters in the building codes of other cities can be encouraged by the federal government.

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NOMENCLATURE

a_{roof}= roof absorptance

A_{roof}= Area of roof

A_{total}= Total area on plan

$A_{façade}$= Area of façade

BC= Building Code

C= Annual energy consumption

ILD= internal load density

PF= projection factor

SC= shading coefficient

SHGC= solar heat gain coefficient

Std 90.1= Standard 90.1.

U_{roof}= roof thermal transmittance

WWR= Window to Wall Ratio