Orientation, Building Height and Sky View Factor as Energy Efficiency Design Parameters

Léa Cristina Lucas de Souza[1] and Marcio Luis Yamaguti[2]

[1] Department of Architecture, Urbanism and Landscape, Faculty of Architecture, Arts and Communication, São Paulo State University, Bauru, Brazil
[2] Graduate Student of the Faculty of Architecture, Arts and Communication, São Paulo State University, Bauru, Brazil

ABSTRACT: The energy efficiency of buildings should be a goal at the pre-design phase, though the importance of the design variables is often neglected even during the design process. Highlighting the relevance of these design variables, this research studies the relationships of building location variables with the electrical energy consumption of residential units. The following building design parameters are considered: orientation, story height and sky view factor (SVF). The consideration of the SVF as a location variable contributes to the originality of this research. Data of electrical energy consumption and users' profiles were collected and several variables were considered for the development of an Artificial Neural Network model. This model allows the determination of the relative importance of each variable. The results show that the apartments' orientation is the most important design variable for the energy consumption, although the story height and the sky view factor play a fundamental role in that consumption too. We pointed out that building heights above twenty-four meters do not optimize the energy efficiency of the apartments and also that an increasing SVF can influence the energy consumption of an apartment according to their orientation.

Keywords: urban environment, GIS, urban canyons, urban thermal comfort

1. INTRODUCTION

Human activities determine the energy performance of a building, being affected by the building design themselves. In this matter, building location variables play an essential role on reaching its energy efficiency. Essentially, the electrical energy consumption is related to: building types, the use of electrical appliances, and artificial lighting [1]. However, building orientation has a strong influence on this consumption, too [2].

This research represents an interface study of building design and urban geometry, seeking for a relationship between building location and electrical energy consumption.

The orientation, the height and the sky view factor (SVF) of residential units are the main elements adopted in this paper to establish building location. The consideration of the SVF as a location variable is one of the aspects making this research original. SVF is a dimensionless parameter that allows the estimation of the visible area of the sky from an observer viewpoint [3]. Its value ranges from 0 (no sky visibility) to 1 (100 % of sky visibility). The larger the visible area of the sky viewed from an internal point of a building, the higher the amount of natural daylight available. But on the other hand, it could also represent higher solar access, leading to higher thermal energy load. Thus, thermal and luminous factors should be jointly considered for the study of elements that influence the electrical energy consumption of buildings.

The complexity of the relationships of those variables suggests an analysis through the application of Artificial Neural Networks (ANN), which is a technique also applied by other authors [4]. The model developed for the present study applying this technique allows the identification of the relevance of the variables and their influence on the electrical energy consumption of multi-story buildings.

The following two topics describe the methodology and the results, respectively, leading to the analysis and discussion presented in section 4 and followed by the conclusions.

2. METHODOLOGY

Three residential buildings are studied and here named as A, B and C. They all present exactly the same design and colours, and are located in a row, as shown in Fig. 1. These are twelve-stories buildings with four symmetrically displayed apartments per story.

This display of apartments leads to different orientations per building column. The orientation of each column, height story and SVF were established for each apartment for the study. Each apartment occupies two different façades, one placed either on a main front or back façade and the other one on a secondary, side façade.

Regarding their orientation, the following designation was assigned per apartment:

- Units with their main façades oriented to NW and secondary façades oriented to NE were identified simply as NW-NE;
- Units with their main façades oriented to NW and secondary façades oriented to SW were identified simply as NW-SW;
- Units with their main façades oriented to SE an secondary façades oriented to SW were identified simply as SE-SW;
- Units with their main façades oriented to SE and secondary façades oriented to NE were identified simply as SE-NE.

Figure 1: Locations of buildings A, B and C on the urban tissue

Each story is three meters height, thus the highest story reaches the level of thirty-six meters from the ground.

The very first step of this methodology was to calculate the SVF by applying the 3DSkyView extension [5], which is an algorithm incorporated to a commercial GIS package (ArcView). The SVF values were calculated considering the medium point of the main and secondary façades of each apartment. The SVF values of these façades varied from 0.3 to 0.5.

Data recorded by the power supply company operating in the area, named CPFL - Companhia Paulista de Força e Luz, and a questionnaire applied to the buildings households were the basis for the electrical energy consumption values. Other apartments variables identified were: the location on buildings A, B or C, the number of households, the households' incomes, the shadowing situation, and the presence of appliances such as air-conditioning and freezers in the apartments. The season (summer or winter time) was another variable considered to identify the pattern of monthly consumption.

Artificial Neural Networks (ANN) were applied to establish the role each variable plays on the electrical energy consumption. The software EasyNN, developed by Stephen Wolstenholme, was applied for that purpose [6].

This kind of modeling approach simulates the behavior of human brain neurons, based on real input and real output data. These data are used in a training procedure, what allows the learning of relationship patterns among input and output variables, the growth of a network and the development a model. Once the patterns are learned, the network model is able to simulate new output values when looking at different input values. It is though important to highlight that these new values should fit within the range (minimum and maximum values) of data that generated the model. Actually, this limitation is also found in many other modeling techniques, which allow the simulation, but not the extrapolation.

In the case here studied the output variable is the monthly average consumption of electrical energy, while the input is represented by the other variables determined for the apartments. The proposal of the application of the ANN was to enable evaluation of the influence of variables on the electrical energy consumption. This research was not interested in identifying a mathematical representation of the model itself.

For each model, three sets of data were prepared for learning, validating and testing the network, respectively. In the preparation of each data set, the real data were divided randomly in three groups: 50 % of data for the phase of training (when the network "learns" the patterns), 25 % for the phase of validation (when the variables weights are evaluated and adjusted iteratively) and 25 % for the phase of test (when the model simulates new values for comparison with actual values that have never been "seen" by the network). The comparison of the values simulated with the real values is needed for the model evaluation. The model performance can be analysed by looking at, for example, the determination coefficient (r^2) and the relative errors of the validation and test phases.

After the selection of the best model and identification of the relative importance of its input variables, an analysis allowed the determination of the influence of the location variables on the electrical energy consumption.

3. RESULTS AND ANALYSES

The model selected presented a determination coefficient of 0.72 and a relative error of about 15 %. The relative importance of the variables in this model is presented in table 1.

As one can observe, the orientation is one of the main variables of location in the model. For a detailed evaluation of the influence of the location variables in the monthly energy consumption of the apartments, the model was submitted to simulation tests. While one input variable was forced to a variation of values that fitted between minimum and maximum values, the other variables were kept on its average values. The results of this evaluation are presented in the following topics.

Table 1: Relative importance of the input variables in the selected model

Input variables	Relative Importance in the model (%)
Orientation	15
Summer or winter time	13
Number of households	13
Building A, B or C	12
Floor height	10
Shadowing situation	9
Air-conditioning	8
Households income	8
Freezer	7
SVF	7

3.1 Influence of buildings A, B, C and their orientation

Varying the apartments building among building A, B and C and also their façade orientation, the first test for summer time brought up the results shown in Fig. 2. In this simulation the shadowing conditions of each building was kept as they individually are, instead of applying an average value.

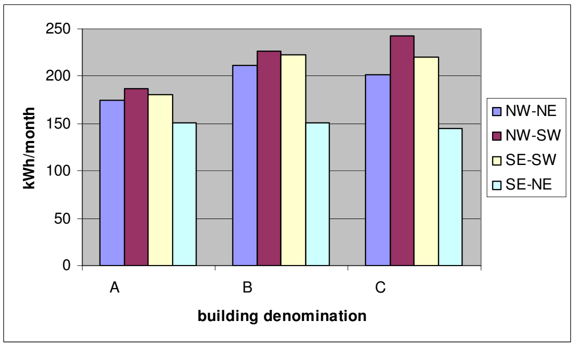

Figure 2: Summer electrical consumption for each orientation for buildings A, B and C.

The same evaluation applied for winter time reveals the results of Figure 3.

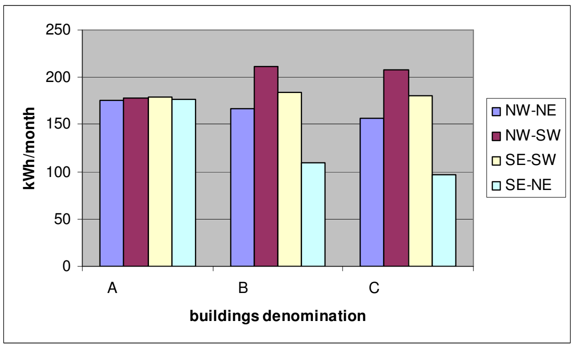

Figure 3: Winter electrical energy consumption for each orientation for buildings A, B or C.

While building A presented similar values for any orientation, buildings B and C demonstrated a decrease in winter consumption in relation to summer time. The average consumption of the apartments was 150 kWh/month.

The NW-SW apartments tended to be the highest consumers, followed by those oriented to SE-SW. The apartments with the lowest consumption were the SE-NE ones, showing in summer very similar values among them.

3.2 Influence of story heights

The results of simulation for height variation were presented per building and per season. Fig. 4 and 5 exemplify some typical results for summer and winter. The height was varied from three meters (the first floor) to thirty-six meters above ground level (the highest floor).

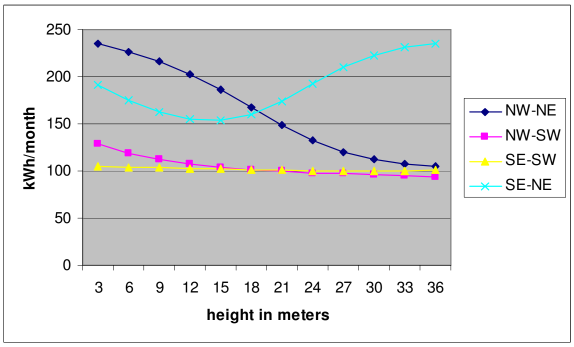

Figure 4: Summer consumption of building A, for each orientation as a function of apartment height.

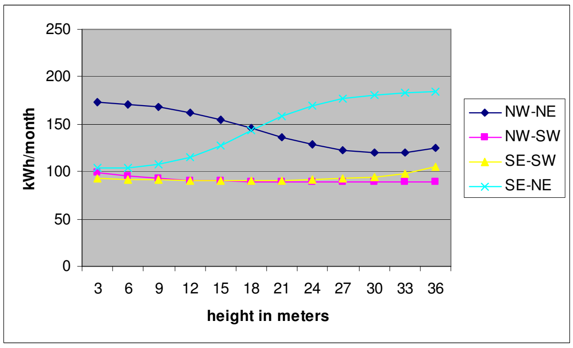

Figure 5: Winter consumption of building B, for each orientation as a function of apartment height.

The influence of height tended to be similar for the three buildings studied. The increment of height for NW-NE apartments represented a decrease of electrical energy consumption. Furthermore, when reaching eighteen meters above the ground level, the consumption of the apartments assumed values below the average of 150 kWh/month. This decrease, though, tends to present a stable behavior when reaching twenty-four meters high.

The opposite performance could be verified for SE-NE apartments. In this case, the electrical energy consumption tended to increase together with the increment of story height. In some cases, this increase occurred for apartments located higher than eighteen meters above ground level.

In general, NW-SW and SE-SW apartments presented similar consumption values below the average of 150 kWh/month.

3.3 Influence of SVF

The values of SVF are different for each building façade, according to their real position in the urban context. There was also a different performance for each façade.

The NW-NE apartments presented a slight increment of consumption due the SVF increment, mainly if one consider the winter time and building B (see Fig. 6 and 7). The NW-SW façades did not reveal any significant difference of consumption due to SVF variation. For many times, though, the increment of SVF for the SE-SW orientation generated a slight reduction of the consumption. Finally, the SE-NE orientation showed a tendency of higher consumption due to increments in the SVF values.

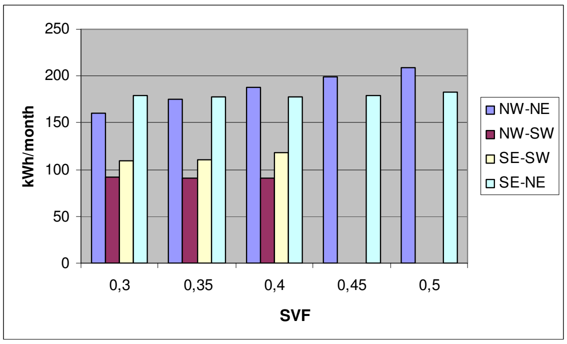

Figure 6: Summer consumption of building B, for each orientation and as a function of SVF values.

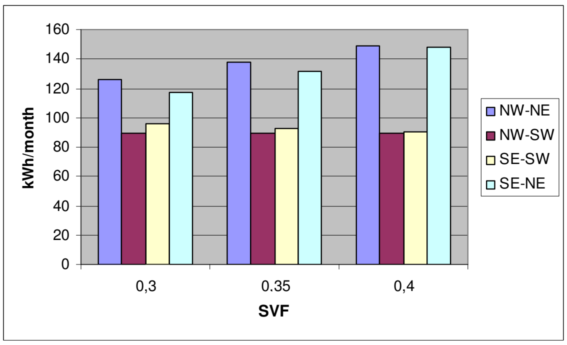

Figure 7: Winter consumption of building B, for each orientation and as a function of SVF values.

4. DISCUSSION

Given the high number of variables involved in electrical energy consumption, this analysis would not be carried out easily only by means of real data comparison. This stresses the relevance of ANN, because it is as a tool that allows the assessment of the relative importance of the variables.

The orientation was the most important location variable affecting consumption, but the weights of the variables are very similar. All weights in the model developed varied its importance in a range from 7 to 15%. This fact suggests that none of the variables could be eliminated in the model.

Building A is the one located in the Eastern extreme, while building C is in the Western extreme, and building B is positioned between them. Considering these locations and the sun access, buildings A and B should present lower energy consumption than the other, because most of the façades of building C receive west solar access.

In relation to the story heights, the NW-NE apartments are the most susceptible to that kind of variation. There was a reduction of consumption due to height up to the value of twenty-four meters above ground. After reaching this height, the consumption values remain in the same magnitude. This means that the energy efficiency due to heights increment for NW-NE façade has a limit of optimization. This limit takes place in the eighth-story, if one considers a three meters height per story.

Apartments oriented to NW-SW façades are the highest consumers. For this orientation, neither the increment of height, nor the SVF increment, represents significant changes in the consumption patterns. Probably the solar access is the main cause of this fact, indicating that the thermal human requirements guide the consumption of those apartments.

For SE-SW apartments, the SVF increment could represent a consumption reduction. As those apartments present solar access restricted to sunrise and sunset times, the higher SVF represents larger natural light availability. So the artificial lighting use is reduced, minimizing the electrical energy consumption. There is, thus, a strong influence of artificial lighting demand in those apartments.

The SE-NE apartments are the lowest consumers. For them the increments of height and SVF values result in the increment of electrical energy consumption. Those are apartments with the best solar access. This fact could probably indicate that the thermal conditions are again the priority demand for electrical energy consumption.

So, this study brought up some tendencies generated by the location variables, if the average consumption of 150 kWh/month is considered. Highlighting these tendencies tables 2 to 5 summarize the discussion above, considering each orientation.

The following legend is used from table 2 to 5:

⇩ reduction of consumption in relation to 150 kWh/month, due to a variable increment;

⇧ increase of consumption, in relation to 150 kWh/month, due to a variable increment;

⇔ neutral behavior, which means it keeps the average of 150 kWh/month, due to a variable increment

Table 2: NW-NE apartment tendencies

Variable	Behaviour
General consumption	⇔
Height increment	⇩ lower than 24 m ⇔ higher than 24m
SVF increment	⇧
Probable priority of human requirements that demand electrical energy consumption	thermal and lighting

Table 3: NW-SW apartment tendencies

Variable	Behaviour
General consumption	⇧
Height increment	⇔
SVF increment	⇔
Probable priority of human requirements that demand electrical energy consumption	thermal

Table 4: SE-SW apartment tendencies

Variable	Behaviour
General consumption	⇧
Height increment	⇔
SVF increment	⇩
Probable priority of human requirements that demand electrical energy consumption	lighting

Table 5: SE-NE apartment tendencies

Variable	Behaviour
General consumption	⇩
Height increment	⇔lower than 18m ⇧ higher than 18m
SVF increment	⇧
Probable priority of human requirements that demand electrical energy consumption	thermal

5. CONCLUSIONS

The ANN helped on extracting information from the data about electrical energy consumption. The results showed that orientation, height and SVF play a fundamental role on the electrical consumption patterns. Therefore, these parameters should not be neglected during the building design process.

Among the orientations studied, the highest consumers are the NW-SW apartments. So, the presence of windows in these façades represents the lowering of energy efficiency. The lowest consumers are SE-NE apartments, which present solar access restricted to sunrise and sunset.

In relation to the height, the NW-NE and SE-NE results indicate that there is no benefit on energy efficiency for heights above twenty-four meters. So, a limitation of buildings height to eight-story building could be a guide for future buildings constructed in this area.

In relation to SVF, its increment or reduction influence is dependent on the façade considered. If a SVF increment varying from 0.3 to 0.5 causes larger solar access for façades already presenting high sun incidence, then this could represent higher energy consumption. On the other hand, if the façades have restricted solar access, its SVF increment could reduce electric energy consumption. For this reasons, we suggest that SVF should be kept around 0.3. In addition, for SE-SW orientation, there could be an additional building element allowing its enhancement on winter time.

A further extension of the present research could be the study of window-to-wall ratio of these buildings, allowing suggestions for buildings guidelines. This would strongly complement the height and sky view factors guides here established.

ACKNOWLEDGEMENT

The authors would like to thank the Brazilian agencies FUNDUNESP, FAPESP, CNPq, and CAPES for their financial support in many phases of this research.

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