Envelope Design, Energy Consumption and Thermal Performance:
A case study at UFRN Campus, Brazil

RAONI VENANCIO[1], ALDOMAR PEDRINI[1]

[1]Universidade Federal do Rio Grande do Norte, Natal, Brazil

ABSTRACT: This paper aims to quantify the influence of envelope design decisions in administrative buildings at UFRN Campus and propose low budget design guidelines considering the context of research. The results presented here are based on computer simulation procedures using the DesignBuilder software. In order to quantify the influence of different design decisions, the simulation procedures were divided in three separate models. The first model represents early design decisions, permuting different types of geometry with three settings of envelope properties. The second model aims to quantify the thermal balance of conditioned rooms and unconditioned circulation halls – central or lateral. The third model approaches some middle-design and detailing envelope decisions. In this model, different alternatives for shading devices, walls, roofs properties and external colours were simulated. In general, the results of all three models were complementary to each other. The analysis indicates a major influence of thermal gains provoked by the incidence of solar radiation.

Keywords: Envelope design; energy consumption; thermal performance.

INTRODUCTION

Envelope design is an effective way to reduce air conditioning energy consumption and to improve thermal performance of buildings. However, such design parameters are often neglected by architects due to the lack of reference to support design decisions.

Architects decisions are usually supported by precedent knowledge, such as previous examples or design guidelines [2]. We assume that the first step to provide design support to improve thermal performance is to understand the influence of architectural design decisions in a specific context.

In order to support local architects, this paper aims to quantify the influence of envelope design decisions for air conditioned administrative buildings at UFRN Campus, combining field survey and simulation procedures using the DesignBuilder software. This type of building was chosen due to the feasibility of field survey and energy monitoring procedures.

The Universidade Federal do Rio Grande do Norte (Federal University of Rio Grande do Norte) Campus is located in the city of Natal, Brazil, which coordinates are 5°45'S and 32°12'W. The climate is hot and humid, with low temperature variation (daily and seasonal), high humidity levels and intense solar radiation. The Campus was built in 1970 and none of the buildings were seriously designed considering the potential of passive strategies to reduce energy consumption.

RESEARCH BACKGROUND

This paper approaches envelope design decisions, such as geometry, fabric and the use of shading devices. These strategies could be easily implemented in the Campus.

The modelling and simulation procedures were supported by the following procedures:

1. Field survey on 13 buildings: this procedure allowed the identification of typical envelope variables used in representative buildings at the Campus. Even though the models proposed are not intended to represent a specific building at the Campus, some variables concerning envelope basic features and spatial organization must be representative in terms of what can be actually found at the Campus.
2. Building monitoring at the Main Administrative Building: internal temperature, energy monitoring and equipment/lighting checklist were important to characterize building occupation schedules (air conditioning, lighting and equipments), set point temperatures and internal power densities of equipments and lighting.

SCOPE OF THE MODELS

Simulation procedures are usually based on a single model, in which some variables are modified. Since the final purpose of this research is to provide data to support different design stages, the simulation results should reflect the most common envelope design decisions. Therefore, three hypothetic models were proposed to represent specific design decisions related to envelope properties, like geometry, fabric or shading.

The DesignBuilder software was chosen because it combines a robust algorithm (which is based on EnergyPlus) with a friendly user interface. However, the process of simulating several alternatives can be very time consuming – especially concerning complex models. Therefore the models proposed had to be simplified in order to reduce the complexity of the models and the number of alternatives.

All three models proposed intend to represent some features of administrative buildings at the Campus. In order to adopt in the model representative occupation variables, the occupation schedules and system settings were both derived from monitoring procedures.

Aside from these variables, some envelope properties were also assumed to be constant to emphasize some variables considered most relevant to the research purpose. Therefore, all models represent ground floor buildings (which are more exposed to heat gains through the roof) and have a single 4mm glazing system (widely used at the Campus due to cost constraints). Vertical buildings were not simulated because it was not considered representative in terms of building configuration at the Campus. In fact, most buildings at the Campus have one or two pavements.

Even though many of the variables simulated might also affect lighting consumption (shading devices, building shape, etc), daylight calculations were not carried out because it extrapolates the research goals.

MODEL 1: GEOMETRY X ENVELOPE

Some classical bioclimatic guidelines suggest compact shapes for cold climates – in order to minimize heat loss through external surfaces – and lengthy shapes specifically orientated for hot-humid climates, to maximize heat loss by natural ventilation and reduce solar thermal gains [3]. However, the influence of shape and geometry on thermal performance is strongly related to envelope properties.

Therefore, simulations procedures were made to combine three basic types of geometry – G1, G2 and G3 (Figure 1) with three levels of envelope performance – E1 (low performance), E2 (intermediate performance) and E3 (high performance) (Table 1).

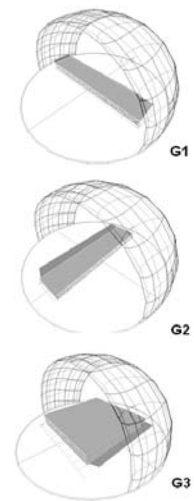

Figure 1: Geometry types simulated.

Table 1: Envelope variables.

E1 (low performance)
- No shading devices - Brick wall (α = 70% e U = 3,70 W/(m^2.K)) - Fiber-cement roofing + air gap 5mm + Concrete slab 10cm (U = 3,00 W/(m^2.K))
E2 (intermediate performance)
- Partial shading device (0,5m overhang) - 6-hole brick wall (α = 50% e U = 2,47 W/(m^2.K)) - Fiber-cement roofing + air gap 200mm + Concrete slab 10cm (2,2 W/(m^2.K))
E3 (high performance)
- Complete shading device (louvres + overhang + sidefins) - Lightweight Concrete Blocks TECLEVE (α = 30% e U = 1,66 W/(m^2.K)) - EPS sandwich panel (aluminum sheets) + aig gap 200mm + Concrete slab 10cm (U = 0,5 W/(m^2.K))

The distribution of glazing surfaces in compact and lengthy shapes is usually different due to specific layout possibilities of each geometry type. According to the field survey, in compact geometries, glazing is usually distributed in all façades, while in lengthy geometries, is distributed only in larger façades.

Simulation results indicate a major influence of envelope properties on total energy consumption (including equipments and lighting consumption). The results of low-performance envelopes (E1) show that geometry has an influence of 6% on energy consumption. The influence of geometry on energy consumption of high performance envelopes (E3) is only 2%. For the same geometry, the envelope performance has a maximum influence of 22% (Table 2). The range of energy consumption results is divided in five levels, from one to five stars (from worst to best performance).

Table 2 : Energy consumption of simulated cases.

Geometry	Envelope	KWh/m²	Performance
G1	E1	215,42	★★
	E2	201,58	★★★
	E3	178,44	★★★★★
G2	E1	228,68	★
	E2	209,18	★★
	E3	179,09	★★★★★
G3	E1	221,69	★
	E2	200,47	★★★
	E3	174,46	★★★★★

Thermal analysis shows a difference of 76% between the thermal gains of extreme cases G2_E1 (worst performance) and G3_E3 (better performance). According to simulation results, the following aspects can be highlighted (Figure 2):

1. Design decisions concerning building orientation, especially in terms of glazing exposure to solar radiation are the most influent.
2. Walls insulation has little impact on the global thermal performance of the simulated cases.
3. The influence of geometry on thermal performance can vary considerably according to envelopes' properties.

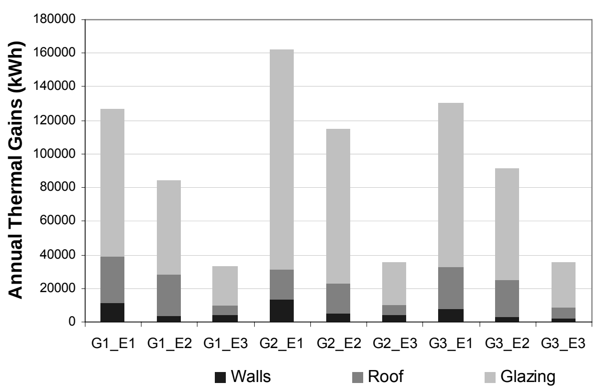

Figure 2 :Annual thermal gains of simulated cases..

MODEL 2: INTERNAL LAYOUT

The internal layout of administrative buildings at the Campus consists in groups of separate conditioned office rooms (cells), which are connected to each other by unconditioned circulation halls. Regarding the position of circulation halls, two layout types were identified: central and lateral circulation halls.

Central circulation cases vary only according to its orientation (N-S and E-W) (Table 3) because central halls are less exposed to solar radiation. In order to analyze ventilation heat loss, two openings were proposed in both ends of each circulation hall, each one with 50% WWR (window/wall ratio – the ratio of window area to the gross exterior wall area).

Table 3 : Central circulation cases.

Orientation 1 (N-S)	Orientation 2 (E-W)
CC_N-S	CC_E-W

Due to its higher exposure to solar heat gains, lateral circulation cases have one alternative for a partial shading device for each orientation, which consists of an overhang. Lateral circulations at the Campus are usually opened to allow heat loss. Accordingly, the model has an opening in the main external wall with 50% WWR.

Table 4: Lateral circulation cases.

	N	S	E	W
No shading (S1)	LC_N_S1	LC_S_S1	LC_E_S1	LC_W_S1
Overhang shading (S2)	LC_N_S1	LC_S_S1	LC_E_S1	LC_W_S1

Simulation results show that the layout of the circulation hall can have an influence up to 18% on office room thermal gains (case LC_W_P1). On the other hand, office rooms can also have a significant impact on circulation heat gains, specially in central circulation cases (CC_E-W and CC_N-S).

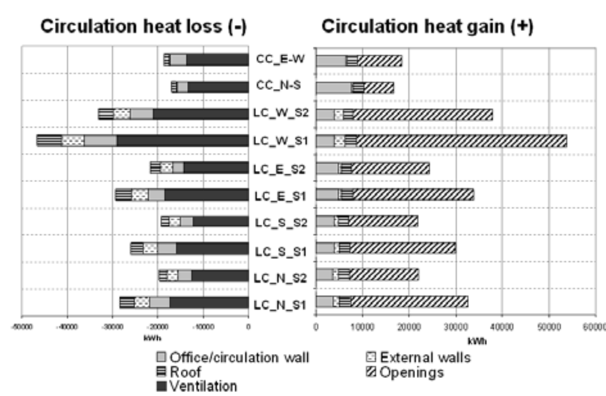

Figure 3: Circulation heat gains and losses.

Some relevant aspects in terms of heat changes can be pointed out (Figure 3):

1. West oriented circulation transmits more heat to office rooms (up to 18%). On the contrary, central

circulation halls have little impact on office rooms' thermal gains.

2. Central circulation cases have thermal losses slightly higher than thermal gains. However, this result is due to a major influence of crossed ventilation on heat dissipation.
3. Solar incidence by openings is the most influential aspect in circulation thermal gains.

Results suggest that the use of crossed ventilation and exhaust openings in the circulation hall can be quite effective to dissipate stored heat. The central circulation model with office rooms oriented to North and South gains 17% less heat than the other case, which office rooms are oriented to East and West. However, the amount of heat gains caused by solar radiation incidence is 10% higher due to the orientation of openings on both ends of the circulation hall (East and West). In this case, the partial shading of openings located at both ends is strongly recommended, as long as the air flow through circulation hall remains unaffected.

The use of an overhang on opposite openings of the circulation hall minimizes thermal gains caused by solar radiation without affecting the air flow in the circulation hall (Figure 4).

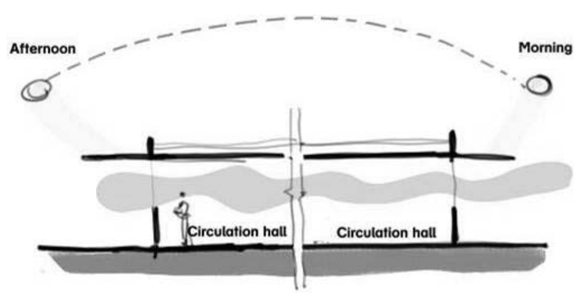

Figure 4: Partial shading of central circulation openings.

Lateral circulation halls do not have a major influence on the thermal performance of rooms. However, in West oriented rooms the use of a shading device is recommended to minimize office heat gains from the circulation hall and to improve comfort conditions (Figure 5).

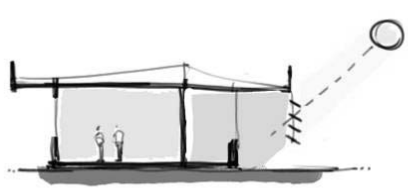

Figure 5: Shading device of a West oriented circulation hall.

MODEL 3: MIDDLE-DESIGN AND DETAILING

The simulations of the third model aim to quantify the influence of some variables associated with middle-design and detailing decisions. The influence analysis concerns shading devices, walls, roofs properties and external colours. Simulated alternatives must fit in the context of the Campus in order to be easily adopted in real projects.

The model geometry consists of a combination of 4 office rooms, which dimensions were based on structural modules currently used in the Campus. To avoid distortions on the results, the group of office rooms has only three external walls. The fourth wall – or the corridor wall – is represented by an adiabatic surface. Apart from the elimination of the circulation variables – simulated in the precious model -, this procedure aims to simplify the model.

Due to the great amount of possible alternatives, a Case Base was defined for each orientation to characterize the worst case possible. In the third model, only one variable is altered to generate new alternatives, which avoids combinatorial explosion and also allows effective influence analysis of each variable altered in comparison to the Case Base (Figure 6).

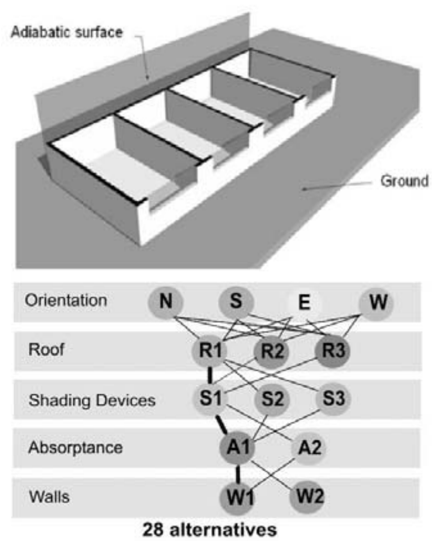

Figure 6: Generation of alternatives.

Shading devices and walls properties are usually defined in a middle-design stage, in which the whole architectural object and its parts are being defined. Shading design can be an effective way to reduce thermal gains in office rooms. Three basic types of shading devices were simulated in order to quantify the performance of each type for different orientations (Figure 7).

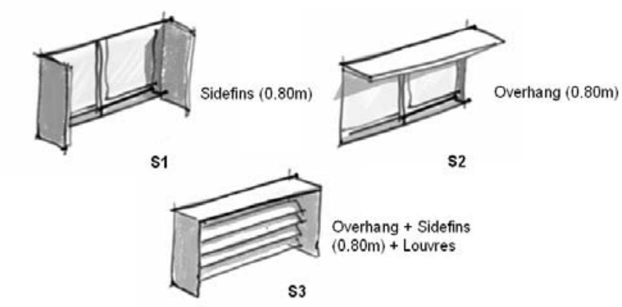

Figure 7: Simulated shading devices.

The use of overhangs, in comparison with sidefins, caused a consumption reduction between 2,7% and 5,8% The combination of overhang, sidefins and louvers had an influence between 6,5% and 15%. The influence of glazing orientation is up to 12,4% with lower performance shading (Table 5).

Table 5: Influence of shading devices on energy consumption.

Shading	Orientation	Consumption	Perf.
S1	N	Lower performance	★
	S		★
	E		★
	W		★
S2	N	- 3,6%	★★★
	S	-2,7%	★★★
	E	-4,1%	★★★
	W	-5,8%	★★
S3	N	-7,9%	★★★★★
	S	- 6,5%	★★★★★
	E	-9,4%	★★★★★
	W	-15%	★★★★★

In the city of Natal, North and South oriented openings have almost the same requirements for shading design. Simulation results and sun path studies suggest the combination of overhangs and sidefins as an effective way to block solar radiation in these cases.

East and West oriented openings also require shading devices design. However, the results indicate that thermal gains of West oriented surfaces are 43% higher than East oriented surfaces. Therefore, while partial shading design can be adopted in East oriented openings, the same criterion must not be used to shade West oriented windows.

The definition of walls constructive systems usually occurs at this stage of design. Two constructive systems were simulated in order to identify the influence of different walls on energy consumption (Table 6). The wall W1 is the most widely adopted at the Campus, while the W2 represents a possible improvement, with lower transmittance.

Table 6: Description of simulated walls.

Wall	Description
W1	Plaster + 6-hole ceramic brick + Plaster (U = 2,57 W/m²K)
W2	Concrete block with EPS aggregate (U = 1,66 W/m²K)

Simulation results indicate a limited influence of walls on energy consumption. In fact, the change of walls caused a maximum reduction of only 1% on energy consumption. However, in vertical buildings, with larger surface area, the influence of the walls would be certainly higher.

The selection of roof properties can be considered a detailing design decision. Designing a high performance roof is commonly associated with its insulation, although surface properties related to the external colours can also have quite an influence on thermal performance.

Fiber-cement tiles are widely used at the Campus due to the low cost and easy maintenance, while high insulated roofs are refused due to the relative high cost. Altogether, three roofs systems were simulated for each room orientation in order to quantify the influence of roofs external colours and transmittance (Table 7).

Table 7: Description of simulated roof systems.

Roofs	Description	U (W/m²K)
R1	Grey-colored fibrocement tiles + air gap (0.2m) + concrete slab (0.1m)	2,30
R2	White-colored fibrocement tiles + air gap (0.2m) + concrete slab (0.1m)	2,30
R3	Double aluminium tile with EPS filling + air gap (0.2m) + concrete slab (0.1m)	0,50

The results have shown a considerable influence of glazing orientation on thermal flows by roofs. An office room with high exposure to solar gains (with West oriented windows) tends to gain less heat by roofs. This is probably because the rooms are not conditioned during weekends, which maximizes the stored heat in the room.

Table 8: Influence of roofs on energy consumption.

Roofs	Orientation	Consumption	Perf.
R1	N	Lower performance	★
	S		★
	E		★
	W		★
R2	N	- 5,3%	★★★★★
	S	- 5,4%	★★★★★
	E	- 5,0%	★★★★★
	W	- 4,2%	★★★★★
R3	N	- 3,1%	★★★
	S	- 2,7%	★★★
	E	- 2,9%	★★★
	W	- 0,9%	★★

Results also indicate a high contribution of heat loss from office rooms by roofs, especially at nighttimes. For that reason, white painted fibrocement roof had a better performance for all orientations (Table 8). In this case, the white surface absorbs less solar radiation heat. Aside from that, a lightweight roof allows heat loss at night.

In comparison with roof R2, the insulated roof R3 had a lower performance for all orientations. Even though the roof R3 does not transfer heat to office rooms during daytime, the roof does not allow heat loss at night. Actually, high insulated roofs transmit a little amount of heat at nighttimes, which is dissipated by air conditioning systems during morning time.

In comparison with lower performance roof (R1), white painted roof caused a consumption reduction between 4,2% and 5,3%. This reduction was lower in high insulated roofs, between 0,9% and 3,1% (Table 8).

The selection of wall colours can be also considered a detailing stage decision. Two levels of absorptance were simulated, representing dark and light colour walls. Light painted walls caused an energy consumption reduction between 5% and 6,1% (Table 9). The influence of walls external colors on consumption is higher than walls thermal transmittance properties.

Table 9: Influence of walls external colours on energy consumption.

Color	Orientation	Consumption
C1	N	Lower performance
	S	
	E	
	W	
C2	N	- 6,1%
	S	- 5,0%
	E	- 5,1%
	W	- 5,6%

CONCLUSION

The main purpose of this research was to identify the influence of architectural design decisions on energy consumption and thermal performance of administrative buildings at UFRN Campus, Natal.

Supported by field survey and monitoring procedures, the DesignBuilder software was used to quantify the influence of architectural design decisions and contribute to further designs at the Campus.

In general, results indicate a major influence of solar gains. Envelope design had a considerable influence on energy consumption. Simulation results reinforce the influence of architectural decisions on energy efficiency. The following design guidelines can be highlighted:

1. Geometry: North and South façades are most favourable for glazed surfaces. East and especially West glazing require specific shading design.
2. Internal Layout: Central circulation performance relies on office rooms thermal gains and natural ventilation heat loss. West oriented Lateral circulation requires a shading device to minimize thermal gains.
3. Walls: Constructive systems have limited impact on thermal performance. However, the use of high performance walls is recommended for vertical buildings.
4. Shading devices: North and South openings can be fully shaded with the combination of sidefins and overhangs. East openings can have a good performance with the partial shading of an overhang, which allows solar incidence during the earlier hours of the morning. However, this same strategy must not be applied to West oriented openings. In this case, fully shaded openings are recommended.
5. Roofs: an insulated roof causes thermal gains reduction but also affects heat loss at nighttimes. The use of a white painted lightweight roof is recommended in order to dissipate stored heat.
6. External color: the use of light colors has quite an influence on thermal performance. Its use is strongly recommended for West walls.

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