Building Simulation 2009

Eleventh International IBPSA Conference
Glasgow, Scotland
July 27-30, 2009

THE INFLUENCE OF DESIGN DECISIONS ON ENERGY CONSUMPTION AND THERMAL PERFORMANCE: THE CASE OF UFRN CAMPUS, BRAZIL

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ABSTRACT

This paper presents simulation results of three hypothetic models, which aims to represent different design decisions concerning administrative buildings at UFRN Campus, Brazil. Simulations were made with the DesignBuilder software. The analysis is intended to emphasize the influence of envelope architectural decisions on air conditioning energy consumption and the improvement of buildings thermal performance. The modelling process was supported by a field survey on 13 buildings at the Campus and by energy monitoring procedures. In general, the results of all three models were complementary to each other. The results indicates a major influence of thermal gains caused by the incidence of solar radiation.

INTRODUCTION

Envelope design is an effective way to reduce air conditioning energy consumption and to improve thermal performance of buildings (Pedrini 2003). 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 (Bay 2001). 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 architectural 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 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 – specially 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.

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.

MODELLING PROCESS

Even though the models proposed are not intended to represent a specific building at the Campus, some variables concerning occupancy schedules, envelope basic features and spatial organization must be representative in terms of what can be actually found at the Campus.

Therefore, the field survey in 13 administrative buildings and monitoring procedures at the Main Administration Building allowed the definition of relevant variables, such as representative envelope properties and occupancy variables, such as power density of equipments and lighting, schedules and set point temperatures.

Field Survey

In order to define representative settings of geometry and spatial organization, we carried out a field survey in 13 administrative buildings at the campus. The buildings selected are representative in terms of occupation and envelope settings. Altogether, four aspects were analyzed: shape and geometry, shading devices, fabric (walls and roofs) and internal layout.

According to the field survey, three types of shapes were identified: compact, lengthy and mixed shapes (usually formed by the grouping of compact and lengthy parts). Regarding building verticalization the significant majority of the buildings at the Campus have one or two storeys.

Shading devices are rarely adopted in the buildings surveyed. In fact, older buildings, not designed to use artificial conditioning, have much more shading devices than the recent ones. Two basic systems of shading devices were found: overhang and sidefins + overhang.

In terms of fabric properties (walls and roofs), only traditional low-tech construction systems were identified, such as 6-hole ceramic bricks on the walls and fibrocement tiles on the roofs.

The internal layout of administrative buildings usually consists of a group of cells (office rooms), which are connected to each other by circulation halls. Two types of internal layout were identified: central and lateral circulation halls.

Temperature Monitoring

In order to define a set point temperature to be adopted in the simulations, the temperature of seven office rooms at the Main Administration Building at the Campus was monitored during two weeks using HOBO data loggers. This building was chosen because it is quite representative in terms of administrative use at the Campus.

Despite the considerable differences between the rooms monitored, the results indicate that lower temperatures occur during occupied periods (when the air conditioning equipment is on).

The set point temperature was defined by an occurrence analysis during occupied periods. Results indicate that in 73% of occupied periods the temperature was between 24,5°C and 26°C (Figure 1). The average temperature of this chunk of data was adopted as the set point temperature of the models, which was 25°C.

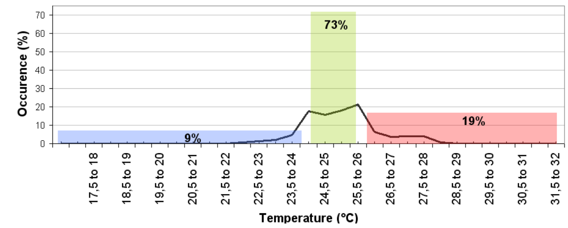

Figure 1 - Occurence of temperature intervals of monitored office rooms.

Energy Monitoring

For air conditioning consumption monitoring a SAGA 4000 analyzer was used during 11 weeks at the Main Administration Building.

The analysis of average work days of each week indicate slight variations of air conditioning consumption (Figure 2).

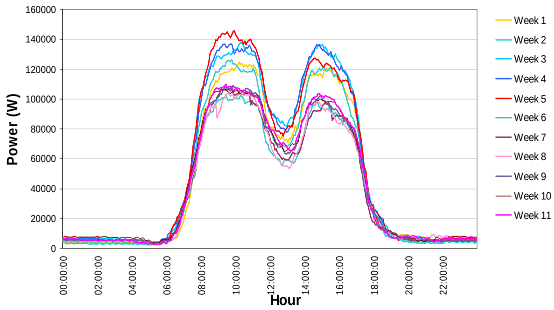

Figure 2 – Average work days of 11 weeks of monitoring.

The results analysis allowed the definition of air conditioning schedules (Figure 3), which defines the hours the equipments are turned on (minimum 80% consumption) and off (maximum 20% consumption).

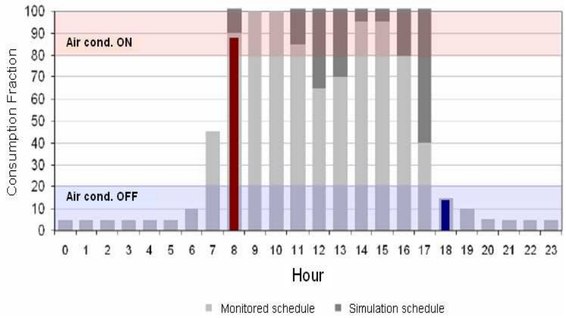

Figure 3 – Air conditioning schedules: hours when equipments are turned on and off.

During preparation of the monitoring process we intended to do the same procedure to define lighting and equipment schedules. However, it was detected that the electrical circuits concerning lighting and equipment consumption could not be identified separately in the same way that air conditioning circuits could.

Therefore, a much more simplified procedure was adopted using the total consumption – which was monitored during 2 weeks -, and the data regarding air conditioning consumption. Lighting and equipment schedules were derived from the subtraction of these average results (Figure 4).

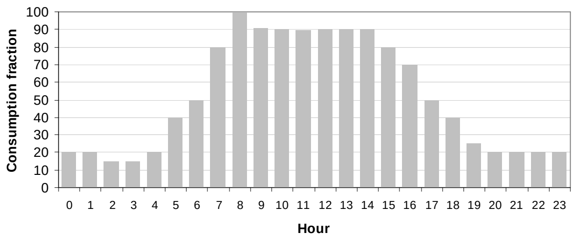

Figure 4 – Lighting/Equipment schedule.

In order to identify equipments and lighting power densities (Table 1), we made a checklist of all equipments and lamps installed in the building.

Table 1 - Power densities of equipments, computers and lighting

EQUIPMENTS	COMPUTERS	LIGHTING
8W/m²	5W/m²	17W/m²

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 (Olgyay 1963). However, the influence of shape and geometry on thermal performance is strongly related to envelope properties.

In order to quantify the influence of early design decisions, the first model intends to combine different types of geometry – G1, G2 and G3 -, with three levels of envelope performance – E1, E2, and E3 (Figure 5).

Concerning geometry settings, 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.

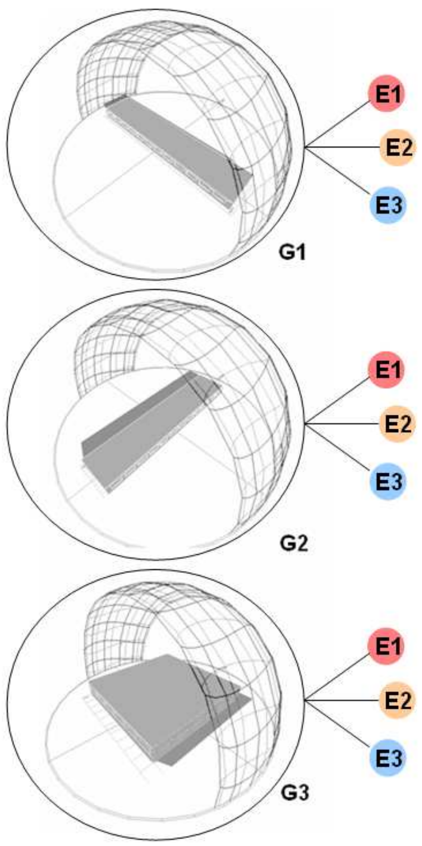

Figure 5 – Model 1: simulated alternatives.

Envelope properties chosen should fit in the Campus context in terms of fabric and shading devices. Even though most envelope variables simulated consists of low-tech solutions, these variables are most likely to be actually adopted at the Campus (Table 2).

Table 2 – Model 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))

Simulation results indicate a major influence of envelope properties on energy 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 3). The range of energy consumption results is divided in five levels, from one to five stars (from worst to best performance).

Table 3 – Energy consumption of simulated cases.

Geometry	Envelope	KWh/m²	Performance
G1	E1	215,4	★★
	E2	201,5	★★★
	E3	178,4	★★★★★
G2	E1	228,6	★
	E2	209,1	★★
	E3	179,0	★★★★★
G3	E1	221,6	★
	E2	200,4	★★★
	E3	174,4	★★★★★

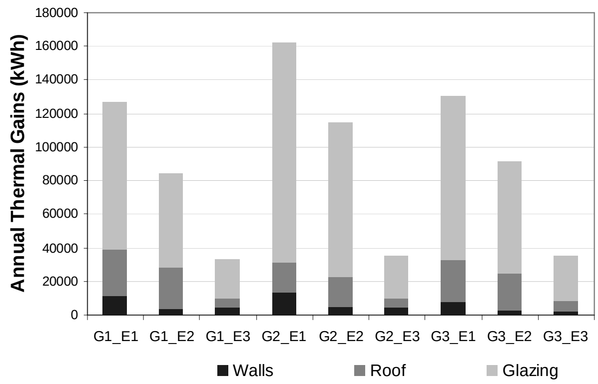

Figure 6 – Model 1: Annual thermal gains of simulated cases.

Thermal analysis shows a difference of 76% between the thermal gains of extreme cases. According to simulation results, the following aspects can be highlighted (Figure 5):

1. Design decisions concerning building orientation, especially in terms of glazing exposure to solar radiation are the most influent (66,9% to 80,9%).
2. The influence of roof thermal gains is intermediate (10,6% to 28,7%).
3. In simulated cases, wall properties (insulation and external absorptance) has little impact on the global thermal performance of simulated cases (3,1% to

12,0%). This limited influence also reflects geometric characteristics of the model. Certainly the impact of wall properties would be higher in multi-storey buildings.

4. The influence of geometry on thermal performance can vary considerably according to envelopes' properties (up to 85% in thermal gains and 21% in energy consumption).

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 naturally ventilated circulation halls. Regarding the position of circulation halls, two layout types were found: central and lateral circulation halls.

Central circulation cases vary only according to its orientation (N-S and E-W) (Figure 7) 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.

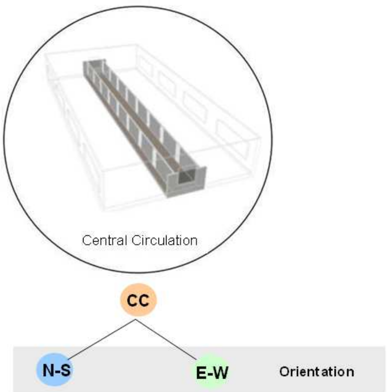

Figure 7 – Model 2: Central Circulation cases.

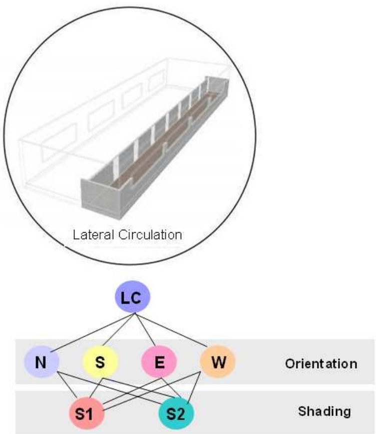

Figure 8 – Model 2: Lateral Circulation cases.

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 (cases S2). The cases S1 consists of circulations without any shading device.

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.

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).

Some relevant aspects in terms of heat changes can be pointed out (Figure 9):

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 natural ventilation on heat dissipation.
3. Solar incidence by openings is the most influential aspect in circulation thermal gains.

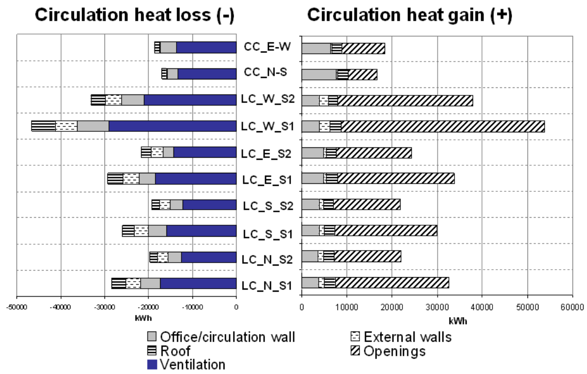

Figure 9 – Model 2: circulations heat gains and losses.

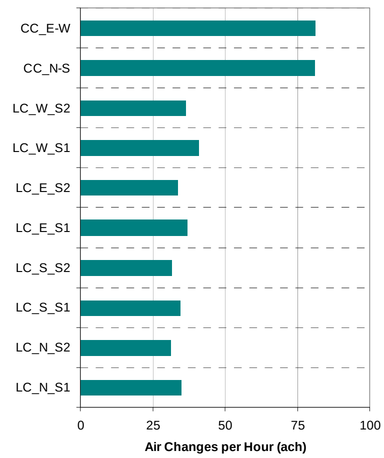

Figure 10 – Model 2: Air changes per hour

In order to get some quick insight in terms of airflow behaviour, air changes calculations were carried on

Design Builder software, which uses AirNet algorithm. The air changes per hour is considerably higher in central circulations in comparison with lateral circulations. Even though the opening area of lateral circulation halls is larger, the location of openings in central circulation allows crossed ventilation (Figure 10). However, natural ventilation may vary according to specific features of each site or context, which highlights the relevance of CFD studies in real design situations.

Thermal analysis indicate 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 would reduce thermal gains caused by solar radiation without affecting the air flow in the circulation hall (Figure 11)

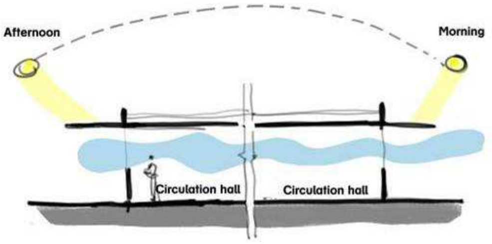

Figure 11 – Partial shading of both openings.

Since the office/circulation walls are shaded for most of the time, lateral circulation halls do not have a major influence on the thermal performance of rooms. However, in West oriented circulation halls the use of a shading device is recommended to minimize office heat gains from the circulation hall and certainly to improve comfort conditions in the corridor (Figure 12).

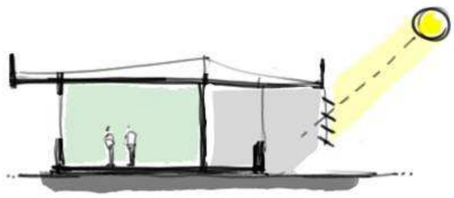

Figure 12 – Shading device for a West oriented circulation hall.

MODEL 3: INFLUENCE ANALYSIS

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. As well as on previous models, 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 and three internal partitions separating different zones. The fourth partition – or the corridor wall – is represented by an adiabatic surface. Apart from the elimination of the circulation variables – simulated in the previous 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 13).

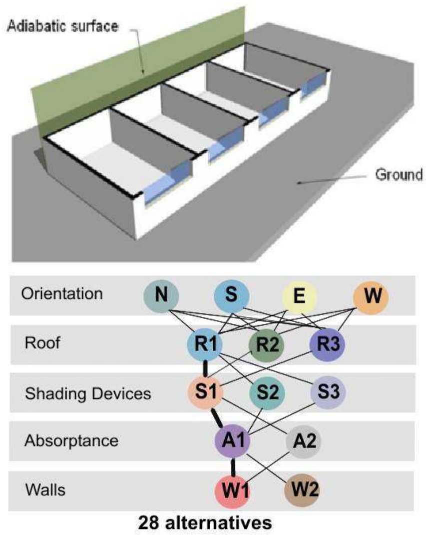

Figure 13 – Model 3: generation of alternatives.

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 14).

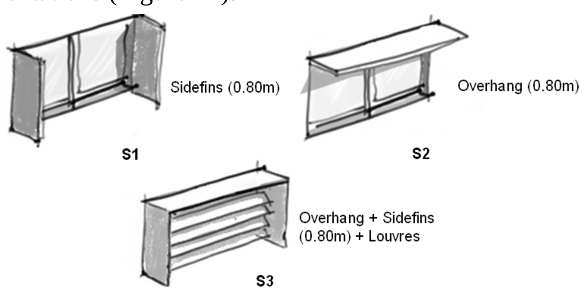

Figure 14 – Simulated shading devices.

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 4).

Table 4 – 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 similar shading devices. However, the results indicate that thermal gains of West oriented surfaces are 43% higher than East oriented surfaces. This dramatic difference is caused by the overheat of West external surfaces during daytime. On the contrary, East surfaces are exposed to direct solar radiation when external temperatures are lower (early morning).

In terms of shading design, a partial horizontal shading device can be adopted in East oriented openings, since it would be exposed during early morning hours. This 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 5). The wall W1 is the most widely adopted at the Campus, while the W2 represents a possible improvement, with lower transmittance.

Table 5 – 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. The limited influence of wall insulation is due to the following aspects:

1. Geometry: smaller amount of vertical surfaces (walls) area in comparison to horizontal surfaces (roofs).
2. Radiation gains: the incidence of direct radiation in vertical surfaces depends strongly on the sun path, which means that heat incidence in non-exposed walls is considerably lower.
3. Limited temperature difference: the difference between external and internal temperatures is limited in hot-humid climates, which minimizes heat transfer due to temperature differences.

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 6).

Table 6 – 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 happens because the rooms are not conditioned during weekends and at nighttimes, which maximizes the stored heat in the rooms. On the contrary, when solar gains are blocked, the room tends to gain more heat by the roof.

Results also indicate a high contribution of heat loss from office rooms by roofs, especially at nighttimes. Indeed, the room is still gaining heat when the air conditioning is turned off (6pm). For that reason, white painted fibrocement roof had a better performance for all orientations (Table 7). In this case, the white surface absorbs less solar radiation heat and still allows considerable heat loss at night.

In comparison with roof R2, the insulated roof R3 had a slightly lower performance for all orientations. Even though the roof R3 has a good performance in blocking heat loads during daytime, the high insulation properties also blocks heat losses at night. The stored heat is dissipated by air conditioning systems during early morning.

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 7).

Table 7 – 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%**	★★

The selection of wall colours is also made in detailing stages of design. 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 8). The influence of walls external colours on consumption is higher than walls thermal transmittance properties. In fact, as temperature differences between external and internal environments are quite low, the incidence of solar radiation on external surfaces is more significant on thermal performance.

Table 8 – 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 simulation and field studies and monitoring procedures, design guidelines were proposed in order to contribute to further designs at the Campus. The DesignBuilder software was used to simulate three models, which were proposed to represent different design stages. The use of multiple models allowed the quantification of different design decisions and improved the analysis process.

Feasibility aspects were considered to constraint the scope of the models. Therefore, only suitable low-tech and cost-effective solutions were proposed or simulated.

In general, results indicate a major influence of thermal gains motivated by the incidence of solar radiation. Envelope design had a considerable influence on energy consumption. The following results can be highlighted:

1. Early design decisions have a reduction potential of 27,4% on energy consumption. About 22% of this potential is due to envelope performance, while 6% concerns geometry types.
2. The performance of central circulation halls relies on office rooms thermal gains and on the heat exhaustion by ventilation.
3. Internal layout of West side circulation hall have an influence of 18% on thermal gains of East oriented office rooms.
4. Shading design had an influence up to 15% on energy consumption.
5. Glazing orientation had an influence up to 12,4% with lower performance shading.
6. Walls external colors had an influence up to 6,1%.
7. Roof properties had an influence up to 5,4%.

Despite the specific research scope, the results presented here can contribute to further development of design guidelines to be used as suitable design tools for architects.

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