THERMOENERGETIC PERFORMANCE ANALYSIS OF A HIGH THERMAL MASS HISTORIC BUILDING

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Abstract. *The present work analyses the thermoenergetic performance of a high thermal mass historic building. This building makes part of Rio Grande do Sul Federal University (UFRGS) historic buildings restoration program. It was inaugurated on June 8th of 1926 as a Chemical Industrial Institute and is located in the main University Campus, in Porto Alegre city, Rio Grande do Sul State, Brazil. The study developed in this work makes part of the restoration program, in which the building will be a University Cultural Center. The software used to analyze the building thermo energetic performance is EnergyPlus, version 2.2. The simulation is performed with fourteen design days and with Porto Alegre climate weather data. A total of 69 thermal zones form the building model, each one with all heat transfer surfaces, including, also, doors and windows in details. In the total, there are 39 conditioned thermal zones. The other 30 thermal zones are left without air-conditioning in order to analyze their thermal response regarding temperature evolution during the simulation. The air-conditioned system used in the simulation is Variable Refrigerant Flow (VRF). The air-conditioned system in the simulation takes into account the performance curves of VRF outdoor units and performance data of indoor units selected. The maximum values of refrigeration capacity obtained in the simulation are under the indoor and outdoor units refrigeration capacity selected, and keep the zone mean air temperature in the thermostat set point. Also, it's analyzed the thermal comfort parameters of simulated zones, as mean air temperature, mean radiant temperature, operative temperature, relative humidity and PMV during all the months of the year and in the design days, whose limits are defined using thermal comfort zones. The work concludes that the thermostat control by zone mean air temperature is not enough to keep the other thermal comfort parameters within thermal comfort zones envelope, meantime, for the most of zones analyzed with air-conditioned, the thermal comfort parameters are within the limits of the summer thermal comfort zone envelope. In the end, it's evaluated the monthly electrical power consumption and cost of the building with the air-conditioned VRF. It's shown that equipment, in which it's included the computers, is the greatest one in building electrical consumption, followed by lighting and cooling.*

***Keywords**: EnergyPlus, VRF, Thermal Comfort, High Thermal Mass Building*

1. INTRODUCTION

The study of thermoenergetic performance of buildings is an area of Energy that has been growing considerably in the last few years, propped strongly by the aid of sophisticated energy building softwares that have been affording the researchers a wide variety of resources of simulation that didn't exist a few decades ago. In the other hand, all these computational resources existing currently in these softwares, as seen in EnergyPlus, require a great experience of the researcher to adapt the real building to the software data model, since is not always possible to obtain all the parameters and data necessary to perform the simulation, due to the richness of details that these softwares take into consideration. As for instance, neither always the manufacturers provide to the users all the performance data of air-conditioning equipment in details, as cooling and heating capacity tables to obtain the performance curves coefficients, that are indispensable to the coupling of air-conditioning system to the building or zone simulated. With an increasing concern that all buildings have a good thermoenergetic performance, as is the case of green buildings, these softwares are important tools to the certification of these type of buildings, whose simulation would be complete if existed softwares contemplating the VRF air-conditioning system. The VRF manufacturers still don't have a software which contemplates a complete system of mathematical equations that represents the VRF and therefore there are few articles published in the world, that focus the VRF on the thermoenergetic performance of the buildings with energy simulation softwares [Zhou et al., 2006 and 2007] and [Pan et al., 2007]. Another pertinent concern that comes up with the sophisticated resources existing in EnergyPlus is the thermal comfort analysis of simulated zones according to ASHRAE [2004a]. There are articles that focus on the thermal comfort analysis presenting strategies to control zone mean air temperature to keep the operative temperature and PMV within thermal comfort zones [Corgnati et al., 2007] with good results. Within this context, the present work analyzes the thermoenergetic performance of a historic building with VRF system.

2. BUILDING SIMULATED

The building simulated has three floors and it is an old historic building of Rio Grande do Sul Federal University, located in Porto Alegre, Rio Grande do Sul State, Brazil, and it was inaugurated in june of 1926. In Figure 1, the picture shows the building south façade in winter season. In Figure 2, the picture shows the building north façade with external shading formed by neighbors buildings and by plane trees (south façade) in summer.

Figure 1. Building south façade

Figure 2. Building north façade

The building has a total floor area of 3572 m^2, 140 exterior windows with 3 mm thickness clear single pane glazing and with hard wooded frames and dividers, hard wooded doors in the most of building environments, high thickness walls (up to 76 cm) layered with massive bricks and a roof with constructed area of 1090 m^2 and red ceramic tiles. In the east façade, there is a shading formed by a neighbor building whose height is nearly 13 m. All the exterior surfaces has a low solar absorptance of 0,3 (yellow color). The window to wall area ratio of the building is 33 % and the building has a deficient external shading in the west façade of 2^{nd} and 3^{rd} floors, items that require a special attention in air-conditioning building design proposals. Around 45 % of all windows area is made of wooded dividers and frames.

3. SIMULATION MAIN TOPICS

The software used in this work is the EnergyPlus 2.2. and has its predecessors in other two softwares: BLAST (Building Loads Analysis and System Thermodynamics) and DOE 2.1E (Department of Energy). Both softwares were developed in the end of 70´s, as simulation tools of design thermal loads and energy consumption analysis. The BLAST and DOE were developed amid the concerns steered by energy world crisis in the beginning of 70´s and later the recognition that the energy consumption in buildings is the major component of the total energy consumption [EnergyPlus, 2008]. However, the most of computational codes that have been developed in 70´s could not follow the evolution of computational codes that lead with the zone energy balance equations in a sophisticated computational language, as EnergyPlus has envisioned. Therefore, the EnergyPlus developed by USA Department of Energy (DOE) combines the best features of softwares DOE and IBLAST (research version of BLAST).

3.1. Design Days and Weather Data

The design days are used to design the air-conditioning system capacity and its methodology is defined in ASHRAE [2005c]. The information for the design days include values of dry bulb temperature, wet bulb temperature, dew point temperature, humidity ratio and wind speed with directions in several frequency of occurrences. The data for the Porto Alegre design days has a statistical analysis based on information carried out in the period from 1982 to 1993. In this study, 12 design days have been created for summer season (from december to march), four days for each psychometric property, as humidity ratio, and dry bulb and wet bulb temperatures, corresponding to 99,6% annual cumulative frequency of occurrence and 2 days for winter (june and july). The simulation with weather data of a city is used to predict the energy consumption of a building, including lighting, electric equipments and air-conditioning. The weather file contains geographic data of the city (latitude, longitude, elevation) and the hourly weather information (around 17 parameters) for 8760 hours of the year. It's has been used the EPW format (EnergyPlus Weather) for Porto Alegre.

3.2. Considerations about Air Infiltration and Thermal Comfort Evaluation

The air infiltration rates in building environments when air-conditioning is off (from 18:00 to 08:00) or for those environments without air-conditioning is 0,5 air change per hour (ACH) in winter and 1,0 ach in summer. These values were determined having as reference the values of air infiltration histogram for new residential constructions [ASHRAE, 2005b], since the building will have a heavy refurbishment on its construction, including all the windows, doors, walls, floors and ceilings materials and masonry. Meantime, the determination of air infiltration value in a building environment is fairly complicated and subject to a significant uncertainty, since the air infiltration is generally caused by opening and closure of exterior and interior doors, cracks in windows and leakage even in the several masonry elements of a building construction.

The thermal comfort analysis of the building environments is performed having as references the summer and winter comfort zones defined in ASHRAE [2004a]. As thermal comfort is defined "that condition of mind that expresses satisfaction with the thermal environment" [ASHRAE, 2005a], design an air-conditioning system that contemplate all thermal comfort parameters defined in thermal comfort zones in ASHRAE [2004a] is a great challenge to engineering and architecture. The thermal environment is defined by environmental parameters that are subdivided in two groups: those that can be measured directly and those that are calculated from other measures. Seven of parameters frequently used to describe the thermal environment are psychometrics and other two parameters are calculated: the mean radiant temperature and operative temperature. The mean radiant temperature can be calculated by a mean value of the surroundings surface temperatures, weighted by the respective view factors between person and the surroundings surfaces. The operative temperature can be calculated by a mean of mean temperature radiant and mean air temperature values weighted by the respective convection and radiant heat transfer coefficients, being the most representative environmental parameter of thermal comfort analysis.

3.3. Variable Refrigerant Flow (VRF) Air Conditioning System

The air conditioning system used in the building simulation is Variable Refrigerant Flow (VRF) with the aid of air conditioning engineering manuals data provided by the manufacturer [Daikin, 2005]. The decision to use the VRF system for the building has been taken due to the space limitation required by the restoration project to install the air-conditioning units, since the VRF system is compact and, therefore, just only one outdoor unit placed in outside building can serve the entire building. Different with conventional types of air-conditioning system, the VRF system can be regarded as a larger version of the split-type air-conditioning unit, in which a compact air-cooled condensing unit located outdoor and be linked to several dozens of indoor fan coil units. To represent the VRF system performance in the simulation, biquadratic performance curves coefficients have been obtained for each outdoor unit selected from manufacturer cooling and heating capacity tables with the rated air mass flow rate of each indoor unit. The single DX (direct expansion) cooling acts here as the indoor units of the VRF system operating at partial loads with constant refrigerant mass flow rate, since the existing cooling coil module in the software is not able to deal with the multi-evaporator working along with a single condenser unit.

4. BUILDING MODELING

4.1. Thermal Zoning

The thermal zones are defined in EnergyPlus as an air volume in uniform temperature [EnergyPlus, 2008] with the boundaries formed by heat transfer surfaces, as walls, floors, ceilings, doors and windows. The building was modeled in EnergyPlus with 69 thermal zones, summing 1193 heat transfer surfaces, where 760 surfaces are floors, ceilings and walls, and other 433 are doors and windows. In conference halls, are installed interior shading devices, as curtains made out of white opac fiberglass fabric with double sided pvc-backing . The other zones are simulated with white pvc-coated fiberglass fabric curtains with a visible light transmittance of 19,2%. The Figure 3 shows the views in perspective of west and south façades, and the Fig. 4 shows the north and east façades of all exterior thermal zones modeled in 3D.

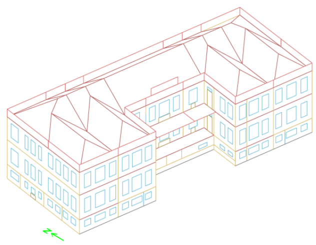

Figure 3. West and south façades model 3-D

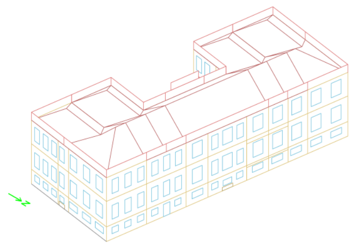

Figure 4. North and east façades model 3-D

The total building height with thermal zones from the ground of 1st floor to the highest part of the roof is 17 m. The building total dimensions are 49,6 m length and 20,6 m width. The height of 1st, 2nd and 3rd floors are 2,95 m, 5,1 m and 4,8 m respectively.

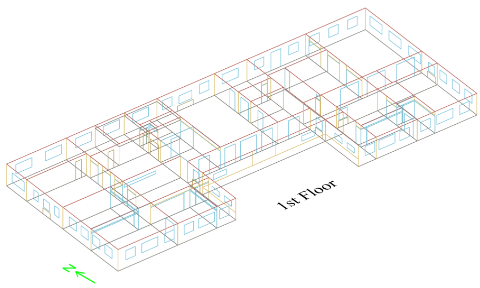

Figure 5. 1st floor 3-D thermal zones

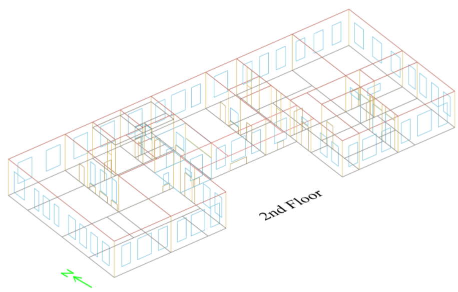

Figure 6. 2nd floor 3-D thermal zones

The Figures 5 and 6 shows the views in perspective of all building 1st and 2nd floors thermal zones, as the detailing of the interior and exterior surfaces zones construction, as doors, windows, walls and ceilings. The first and second floors have 30 and 20 thermal zones respectively. The third floor has 18 thermal zones, as shown in Fig. 7.

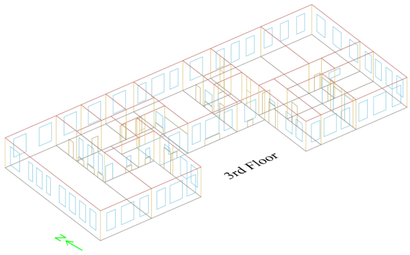

Figure 7. 3rd floor 3-D thermal zones

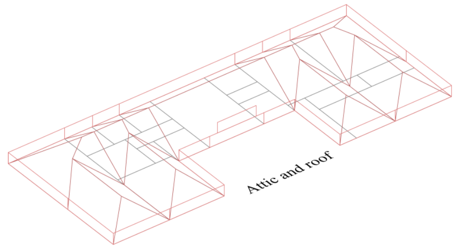

Figure 8. Attic and roof in 3-D

The Figure 8 shows also the building attic. The attic is a single zone and there are no internal divisions. All the small masonry walls (1,5 m height) along the roofing perimeter have been informed in the simulation in order to the software calculate the effects of the shading of these elements in the building simulation thermal load.

4.2. Building Construction Elements Materials and Internal Gains

The building construction elements materials of walls, floors, ceilings, internal divisions, doors, windows and the roof were obtained from data available in building plain drawings and from the measures taken in the building place. The materials thermophysics properties follow basically the information available in ABNT [2003]. The circulation zones, restrooms and bars floors are composed by an inner layer of granite (indoor side). The offices and conference halls floors are composed by an inner layer of hard wood. The only main difference in the offices floor layers composition between the three stories is that the second and third stories the floor inner layers of hard wood are attached on a steel structure and the first story floor inner layers are on a mortar/cement. The walls layers are composed by solid bricks (one large single internal layer) with cement/sand plaster in both outer and inner layers. The wall thickness in the 1st floor is up to 76 cm, decreasing in a half in the 3rd floor. All the exterior walls are painted with yellow color (α: visible and solar absorptance of 0,3). All interior walls are painted with white color (α=0,2). All the exterior windows structure (frame and dividers) and doors are made out of hard wood painted with white color (α=0,2). All the materials used in the building has a thermal absorptance of 0,9, except the polished granite (α= 0,45). On the ceiling outer layer of the 3rd floor rooms was installed a glass wool insulation blanket of 5 cm thick and α= 0,5. The ceramic tiles are 1,4 cm thick and α= 0,75.

Not all the influence for energy consumption in the building is due to envelope and ambient conditions, but also the participation of internal gains that comprehend the heat transferred by people, various electric equipment types, lighting and air infiltration to its building thermal zone. These internal gains have an important role in the zone energy balance equation. The zone total internal gains are composed by portions of convection heat, of radiation heat (short and long waves) and of latent heat. The people metabolic heat generation used in air-conditioning zones is from 60 - 70 W/m^2 (seated - standing) with 0,5 clo (cloth insulation) in summer and 1,0 clo in winter. The fluorescent lighting density level is 20 - 60 W/m^2 and the electric equipment density level is 15 - 35 W/m^2, where in the computer offices reaches 50 - 90 W/m^2. The internal gains are scheduled to be used from monday to friday, and from 08:00 to 18:00 h during all year.

4.3. External Shading

The building external shading is formed by neighbors buildings and a wide variety of trees. All other elements that don't make part of the building construction or that are not attached to the building, are not considered as external shading, although they have an important role in building shading, as for instance the overhang structures. In the simulation, the neighbors buildings have been considered opac to the radiation solar transmission. Otherwise, all the trees have its transmittance modified according to the year seasons, since a lot of them have it leafs fallen in winter, mainly the plane trees located in south façade (as shown in Fig. 1). The solar transmittance of these trees have been defined at 0,5 in summer and 0,9 in winter according to leafs fall characteristics of each tree. The Figure 9 shows the views in perspective of south and west façade building external shading with plane trees of 13 m height in south façade. The Figure 10 shows east and north façades external shading with neighbors buildings between 10 and 13 m height.

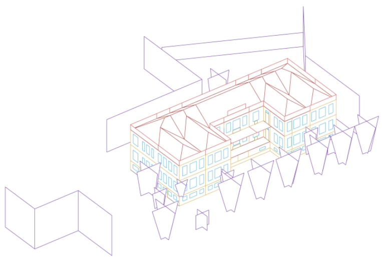

Figure 9. South and west façades external shading in 3-D

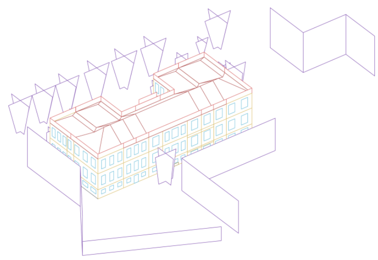

Figure 10. East and north façades external shading in 3-D

5. VRF SYSTEM AIR CONDITIONING COOLING CAPACITY DESIGN STRATEGY

The simulation strategy applied to design the air-conditioning cooling capacity of VRF system of indoor and outdoor units make use of the powerful simulation resources available in the software EnergyPlus to take into consideration the influence of all adjacent thermal zones without air-conditioning and also those zones with air-conditioned turned off during the simulation. That it is the reason why all the thermal zones were modeled in details in EnergyPlus, dispensing the use of other side coefficient function in the program. During air-conditioning schedule occupancy (08:00 - 18:00 h), there is no air infiltration rate into the zones, even when the dual air temperature set point (22 and 24,5 ^{o}C) with dead band turns off the air-conditioning. The outside air ventilation is 0,0047 m^3/s per person.

Since there is no specific module to simulate VRF system in EnergyPlus until the simulation is conducted, unitary air-to-air heat pump system with DX (direct expansion) coil is used to replace it, due to the similarity of the two systems. The indoor and outdoor units cooling capacity are obtained in the simulation from the results requested for variable DX Coil Total Cooling Rate for each thermal zone simulated. On the whole, there are 11 thermal zones configurations, included different floors, to obtain the indoor unit cooling capacity, and 6 thermal zones blocks to obtain the outdoor unit cooling capacity, comprehending 39 thermal zones with air-conditioning in the total. The simulation of each thermal zone with air-conditioning is performed in separated, which means that all adjacent zones with air-conditioning are turned-off, configurating the worst situation to air-conditioning design. Those thermal zones that don't participate of air-conditioning simulation load or the air-conditioning are turned off, there are no internal gains from people, electric equipment and lighting, and just the air infiltration rate is kept. The selection of indoor and outdoor units cooling capacities is done by the result of the maximum hourly cooling capacity (or cooling capacity peak) of the block or thermal zone between the design days and the weather data, according to the configuration simulated.

6. RESULTS AND ANALYSIS

In this item, will be commented the routine of simulation performed to the VRF system cooling capacity design. Initially, step one, it's performed the simulation for each thermal zone in separated with indoor units data in autosize format in EnergyPlus, that is, all the indoor units performance data, as rated air mass flow rate, cooling and heating capacities are designed by EnergyPlus, which are necessary to select the indoor unit from manufacturer catalogue. It's used in the program the design factor 1,25 to the indoor unit cooling capacity, as recommended by ASHRAE [2004b], when the indoor unit cooling capacity calculated by EnergyPlus is not sufficient to serve the zone demand. The selection of indoor unit cooling capacity, based on the maximum hourly DX Coil Total Cooling Rate between the design days and weather data, and on the rated air mass flow rate calculated by EnergyPlus, are used as reference to the selection of the indoor unit performance data. After determined the maximum hourly indoor unit cooling capacity between the design days and weather file for each zone, the indoor units are selected from the manufacturer catalogue.

In the sequence, step two, it's performed the simulation of all blocks thermal zones in separated, that is, each block is simulated alone, meanwhile other blocks have all air-conditioning and internal gains turned off. The maximum hourly cooling capacity between the design days and weather data for each block is determined by summing the all the zones DX Coil Total Cooling Rate corresponding to the hourly block peak load. The outdoor units are selected from manufacturer catalogue, obtained under standard rated cooling conditions with inside wet bulb temperature (T_{wb}):19 and outside dry bulb temperature (T_{db}):35 ^{o}C [ARI Standard 210/240].

For the outdoor units selected, step three, the refrigerant piping length correction factor is applied for the cooling capacity, according to manufacturer recommendation. The correction factor takes into consideration the equivalent piping length and the level difference between the indoor and outdoor units position, and the factor depends on the outdoor unit model installed as well. The outdoor units heating capacity correction factor was not applied, because all the refrigerant piping lengths are below the minimum necessary to apply the factor. All the outdoor units performance data in refrigeration and heating cycles were informed in simulation, as the coefficients of performance in refrigeration (COP_{refr}) and heating (COP_{heat}) cycles, the compressor and fan electric power. The three biquadratic performance curves (function of temperature) that describe the change in total cooling capacity and efficiency at part-load conditions for the cooling DX coil were informed: total cooling capacity modifier curve, energy input ratio (EIR) modifier curve and part load fraction correlation (function of part load ratio). Generally, the indoor units of VRF system are assumed to run at constant air flow rate, and therefore the two quadratic or cubic performance curves related to air flow rate are neglected in this study. The performance curves coefficients were obtained by the least squares regression method with the aid of capacity tables. The performance curves coefficients values in refrigeration cycle don't change with the application of the piping length correction factor. All the indoor units performance data in refrigeration and heating cycles were informed in simulation, as cooling and heating capacities, rated air mass flow rate and supply fan pressure rise and efficiencies. Before the next step, the design factor passes to 1,0 for all the following simulations.

With all indoor and outdoor units selected, step four, it's performed the simulation of each thermal zone and block. It's verified if the maximum zone DX Coil Total Cooling Rate calculated by the program with all performance data informed is served by the indoor cooling capacity selected for each zone and if the zone mean air temperature is under thermostat control set point in 24,5 ^{o}C during all the period of air-conditioning operation. In the same way, it's checked if the block DX Coil Total Cooling Rate peak is served by the outdoor cooling capacity selected. If all these items of step four were satisfied, the simulation routine is finished.

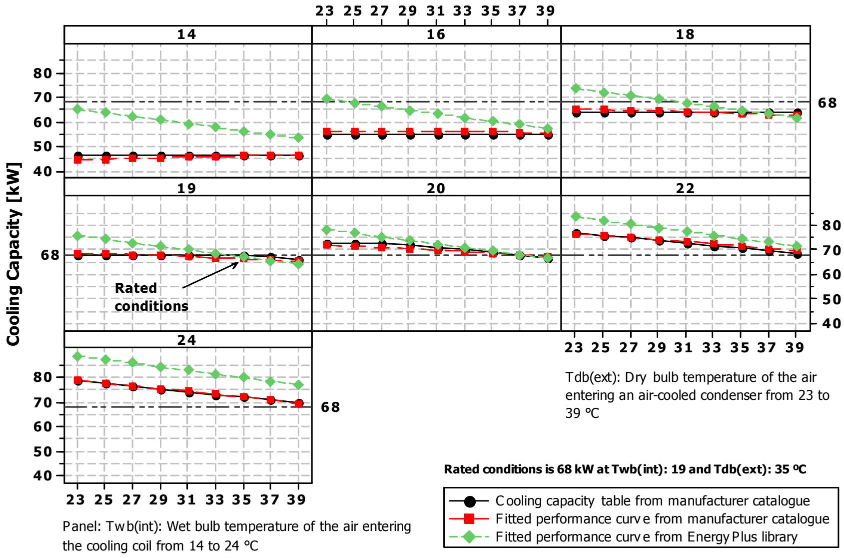

Figure 11. Outdoor unit model RXYQ24MAY cooling capacity variation

For each building block was selected an outdoor unit model (step two of simulation) and the model RXYQ24MAY is the most used in the building, the reason why it is analyzed. The Figure 11 depicts the cooling capacity performance variation in function of Twb_{int} and Tdb_{ext} comparing the performance values from manufacturer catalogue with the fitted performance curve used in EnergyPlus library and with the curve obtained in the present work by least squares regression. The cooling capacity values obtained from the EnergyPlus performance curve are near the cooling capacity values of manufacturer catalogue in Twb_{int}:19 and 20 ^{o}C. The maximum cooling capacity value obtained by EnergyPlus performance curve is 89 kW in Twb_{int}:24 and Tdb_{ext}:23 ^{o}C, comparing with 78,8 and 78,7 kW obtained from manufacturer catalogue and from the performance curve fitted in the work respectively. Therefore, 89 kW has a difference of more than 13 % in relation to manufacturer catalogue table value. The cooling capacity values obtained with the performance curve fitted in the work are coincident with manufacturer catalogue values along the Twb_{int} and Tdb_{ext} variation. This analysis shows the importance of using the fitted performance curves for each outdoor unit model.

The Figure 12 depicts the histograms for twelve months of DX Coil Total Cooling Rate and the maximum value of the design day (step four of simulation) of the conference hall with 171 m^2 floor area and capacity of 160 persons, located in the 3rd floor of the building west façade. The mean and standard deviation of each monthly cooling capacity histogram were calculated by a standard normal distribution with the monthly frequency in hourly basis, regarding the total hours of air-conditioning is turned-on.

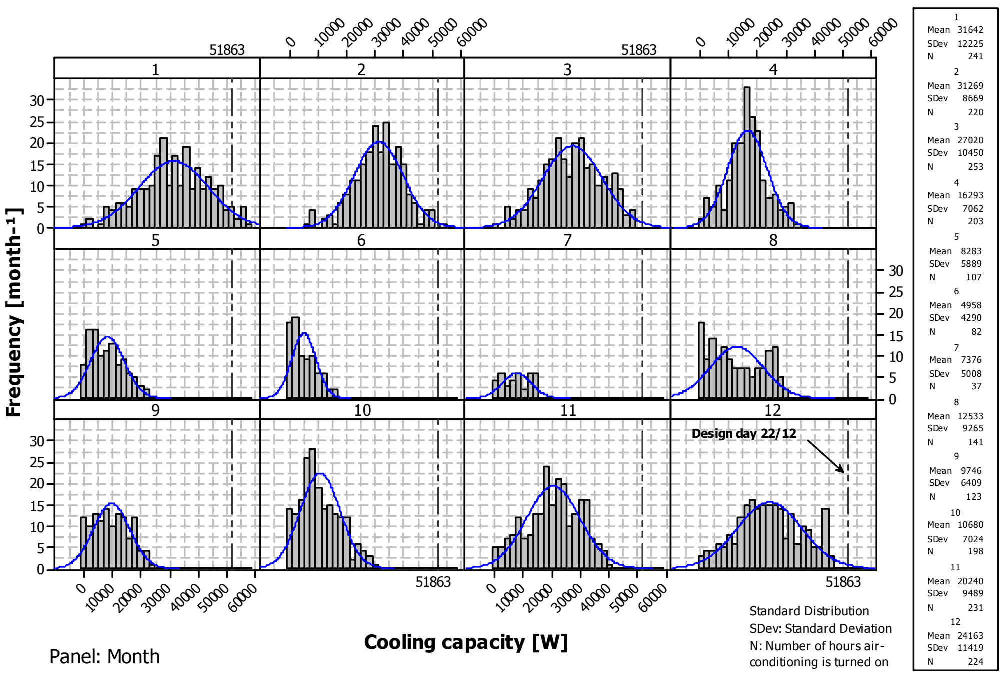

Figure 12. Histograms for 12 months of DX Coil Total Cooling and maximum value of the design day of conference hall

The maximum zone DX Coil Total Cooling Rate is 57373 W with weather data simulation in 24/01, at 16:00 h. The maximum DX Coil Total Cooling Rate between the twelve summer design days is 51863 W in 22/12 (in wet bulb temperature), at 16:00 h. According to the january histogram, the total monthly frequency of occurrences of DX Total Cooling Rate values greater than the maximum of the design day value is 11 hours. Based on this analysis, 5 indoor units of 14000 W cooling capacity each one were selected to serve the thermal zone peak cooling demand.

6.1. Maximum Dx Coil Total Cooling Rate of a Representative Building Block (3rd Floor East Block)

The Figure 13 depicts the Dx Coil Total Cooling Rate profile load of each thermal zone in the day of the maximum block peak load between the design days and weather data simulation results of building east block located in 3rd floor. The sum (blue line) of all Dx Coil Total Cooling Rate of each zone describes the profile load of VRF outdoor unit. In this graph, the peak load is 62131 W and occurs in 25/01, at 13:00 h. Based on this analysis, the outdoor unit model RXYQ24MAY with 65280 W maximum cooling capacity (corrected by piping length) serves to the block cooling peak load demand. The block comprehend two conference halls (north sided) with 87 m^2 of floor area and with capacity of 48 persons each one, two exhibition halls (south sided) with 100 m^2 of floor area and other small offices.

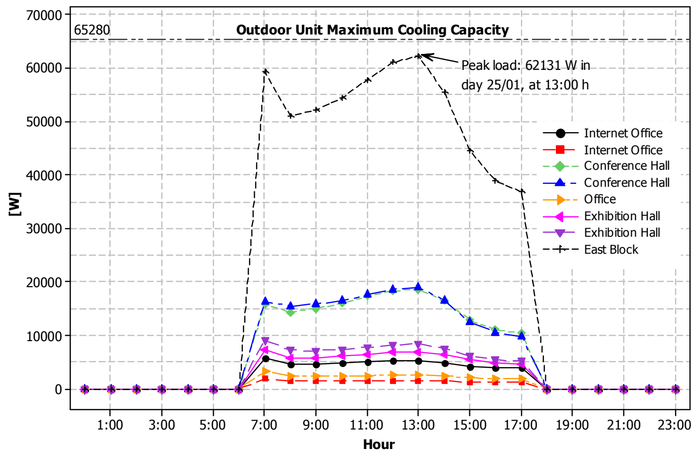

Figure 13. Maximum Dx Coil Total Cooling Rate of the 3rd floor building east block

6.2. Thermal Comfort Evaluation in a Representative Building Thermal Zone (Conference Hall)

The Figure 14 depicts the histograms for 12 months of operative temperature with its limits of the conference hall.

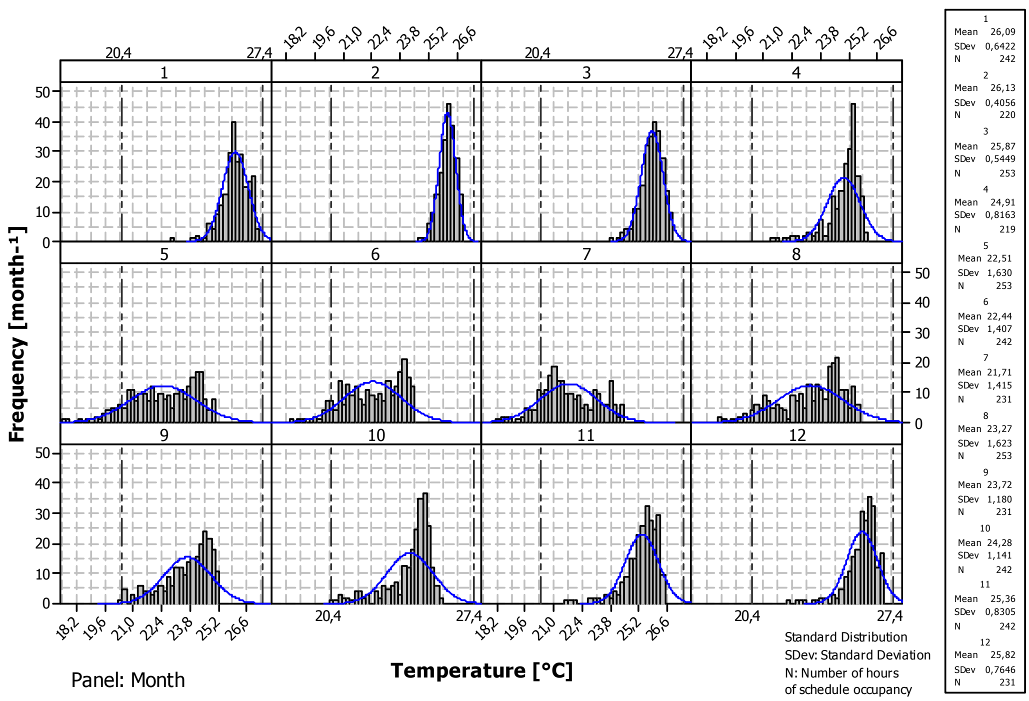

Figure 14. Histograms for twelve months of operative temperature with its limits of the conference hall

The operative temperatures are evaluated within the mean values taken in the boundaries of thermal comfort zones of summer and winter envelope according to ASHRAE [2004a], where the PMV is +0,5 in the summer and the PMV is -0,5 in the winter zone. The maximum temperature used is 27,4 °C, which corresponds to the mean of 26,8 and 27,9 °C temperatures in summer zone. The minimum temperature used is 20,4 °C, which corresponds to the mean of 19,6 and 21,2 °C temperatures in winter zone. The monthly histograms of zone operative temperature show values within the limit of 27,4 °C, but in may and august months, there are occurrences of operative temperature values less than 20,4 °C. The maximum zone operative temperature between the design days is 27,4 °C in 21/12 (dry bulb temperature), at 16:00 h. The most of the greater mean values of operative temperature occur from december to march, due to the increase of mean radiant temperature thermal zone interior surfaces, resulting in greater demands of air-conditioning system to cooling the zone. The zone maximum operative temperature in the weather data is 27,2 °C in 25/01, at 13:00 h. The annual frequency of occurrences of zone operative temperature less than 20,4 °C is 107 hours. The zone minimum temperature value with the weather data simulation is 17,6 °C in 22/05, at 08:00 h. The minimum temperature between the winter design days is 8,1 °C in 21/07 (dry bulb temperature), at 08:00 h. Based on these outcomes, the subject zone located in the 3rd floor west façade gain as much heat as lose, due to the influence of the radiation heat transferred from the roof and window glazing, and from the internal gains too. The inside shading devices with high solar reflectance and opac, and the glass wool insulation of 5 cm thick installed on the roof had a considerably effect in reducing the zone operative temperatures in summer, otherwise the operative temperature would be beyond 27,4 °C. An alternative to the zone operative temperature reduction is to alter the zone mean air temperature set point from 24,5 to 22 °C in summer, which it would implicate energy consumption increase [Corgnati et al., 2007] and it would also result in a thermal discomfort during the periods of low mean radiant temperature, since the air-conditioning equipment thermostat doesn't control the operative temperature. Therefore, this alternative was not taken into consideration in the present work.

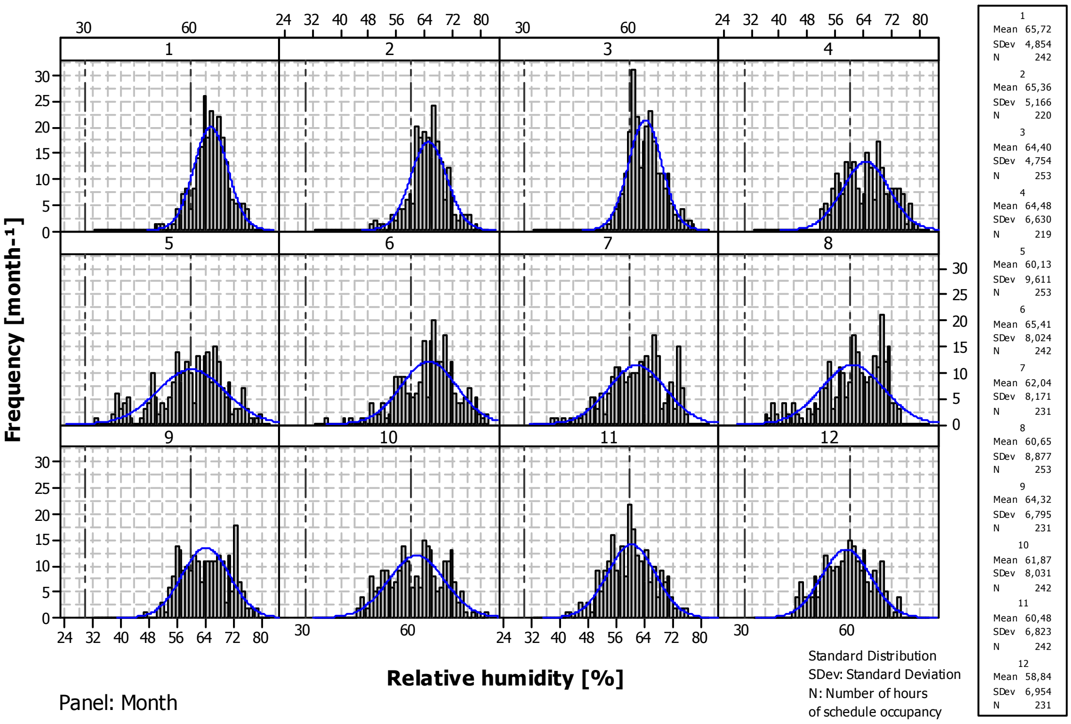

Figure 15. Histograms for twelve months of relative humidity with its limits of conference hall

The Figure 15 depicts the histograms for twelve months of zone relative humidity values with its limits of the conference hall, evaluated during the zone occupancy (from 08:00 to 18:00 h). According to ASHRAE [2005a], the relative humidity values between 30 and 60 % comprehend the thermal comfort zones in summer and winter. The annual frequency of occurrences of zone relative humidity values greater than 60 % is 1980 hours. The maximum value of relative humidity is 82 % in 09/10, at 09:00 h with weather data simulation. There are no occurrences of relative humidity values lower than 30 % in the year. The main reason why of the relative humidity values are greater than 60 % during the year is due to latent heat transferred by 160 persons to the zone and also to the air infiltration latent heat during the night time (0,5 ach in all seasons). Regarding the PMV values, most of monthly frequency of occurrences of PMV values in summer and winter seasons are between neutral scale (-0,5 to +0,5) of thermal comfort zones.

6.3. Evaluation of Energy Consumption with Air-Conditioning System

The EnergyPlus classifies the total energy consumption in main three groups: Total Energy Consumption = Building + Air-Conditioning (HVAC); Building = Lighting + Equipment; Air-Conditioning = Cooling + Heating + Ventilation.

The Figure 16 depicts a graph with the monthly energy consumption classified with its major groups. The ventilation energy consumption is almost constant in all months of the year, consuming between 555 and 640 kW.h per month. The air conditioning energy consumption in the heating is below the ventilation energy consumption, reaching 600 kW.h during the winter months, since all the building internal gains are scheduled with its maximum level, heating the thermal zones and dispensing the air-conditioning heating cycle in the most of hours in winter.

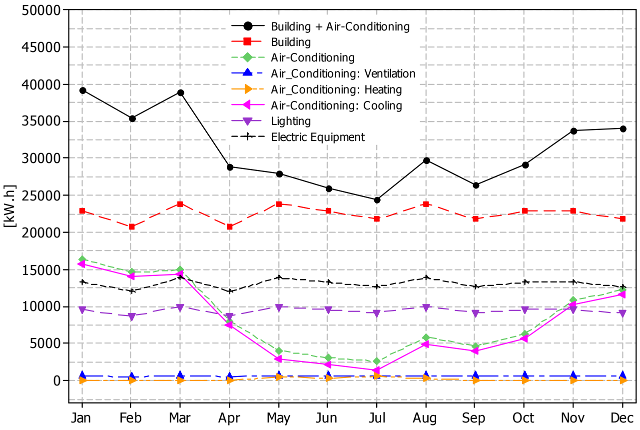

Figure 16. Monthly energy consumption

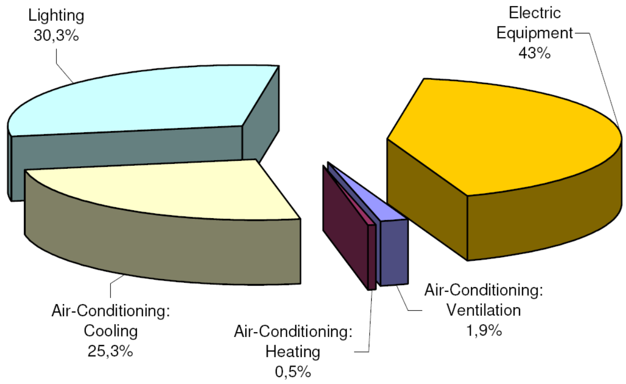

Figure 17. Total annual energy consumption breakdown

The air-conditioning energy consumption in the cooling cycle has 40 % (15713 kW.h) of participation in the january total energy consumption. During the winter months, the air-conditioning energy consumption in the cooling cycle has 10,6 % (2605 kW.h) of participation in july total energy consumption. The Figure 17 depicts the participation of all components in the annual total energy consumption, that it is 373470 kW.h. The greatest participation in the annual total energy consumption is the electric equipment, followed by lighting and air-conditioning in cooling cycle. According to Pan et al. [2007], the equipment is the greatest one in the annual total energy consumption of building + air-conditioning. This information is also confirmed in the current study and corresponds to 43 % of annual total energy consumption. The air-conditioning in the heating and the ventilation cycles are the lowest in participation of annual total energy consumption. In Zhou et al [2006], the VRF system has a 42 % of annual total energy consumption of building + air-conditioning with outdoor units operating above cooling capacity rated conditions and variable COP.

The main factors that contribute with the low air-conditioning energy consumption (maximum 27,7 %) are the external shading in the building, the internal shading devices with high solar reflectance, building with high thickness walls, efficient air-conditioning, around 45 % of window to structures area ratio are dividers and frames, and the window to wall area ratio of the building is 33 %. The Figure 18 depicts the monthly total energy consumption cost, considering a tariff of 0,30598 R$/kW.h applicable to all public buildings. The maximum monthly total energy consumption cost is R$ 11984 and occurs in january with 40 % of participation of air-conditioning in refrigeration cycle. The minimum monthly total energy consumption is R$ 7667 and occurs in july with the participation of air-conditioning in cooling and heating cycles with the lowest values of the year.

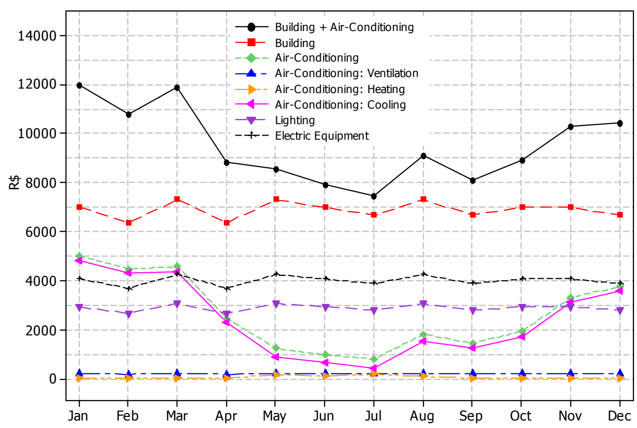

Figure 18. Monthly energy consumption cost

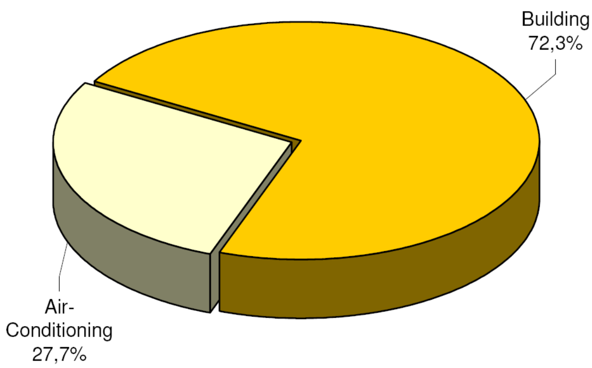

Figure 19. Annual energy consumption total cost breakdown

The annual total energy consumption cost of building and air-conditioning is R$ 114275. The greatest one participation in annual total energy consumption is the building (72,3 %) and the air-conditioning corresponds to 27,7 %

of this total, as depicted in Fig. 19. This low value of the air-conditioning, already commented, shows the great advantage of a building with high thickness walls and high thermal mass.

7. CONCLUSIONS

The indoor units cooling capacity selected with its performance data from manufacturer simulated in the program keep the zone mean air temperature under the thermostat set point control for each zone during the schedule operation of air-conditioning that is one of the main objectives achieved in the study to perform a reasonable thermal comfort evaluation. The results of the maximum value of DX Coil Total Cooling Rate calculated by EnergyPlus are under the indoor unit capacity selected, as depicted in Fig. 12 for a building representative zone used for this analysis. The results of maximum DX Coil Total Cooling Rate calculated by EnergyPlus for each block are under the outdoor unit cooling capacity selected and corrected by the refrigeration piping length factor, serving the block hourly peak load, as depicted in Fig. 13 for a representative block as well. The mathematical equations of performance curves fitted for each outdoor unit selected from manufacturer represent the performance of a real air-conditioning unit tracking the variation of inside and outside environment thermodynamics states, as depicted in Fig. 11 for an outdoor unit model in the cooling cycle.

The monthly and annual energy consumption is evaluated with the air-conditioning system VRF, considering all the internal gains scheduled to be used with its maximum level. It's verified that the greatest one component in energy consumption are the equipments, followed by lighting and air-conditioning. The air-conditioning outcome has a great influence of building envelope, as the construction elements, window glazed area, and internal and external shadings.

The thermal comfort parameters in the most of zones evaluated with air-conditioning are within the limits defined in summer thermal comfort zone envelope, except those thermal zones with great number of persons, as the conference hall in the 3rd floor west façade, due to the great values of relative humidity in summer and low operative temperature values in winter months, as depicted in Fig. 15 for a building representative zone. These results showed that to keep the operative temperature and relative humidity within the thermal comfort zones limits by zone mean air temperature set point control is a great challenge from a dynamic building energy simulation perspective for all designers.

The EnergyPlus software proved to be a very efficient and useful tool to a building thermoenergetic performance analysis for air-conditioning thermal zones. The adjustment of performance curves for a real air-conditioning unit installed in buildings is a prominent area in the building thermoenergetic analysis coupled with air-conditioning systems. The detailing of the building parameters offset the work by the improvements in quality of the outcomes.

8. REFERENCES

ABNT, 2003. "Desempenho Termoenergético de Edificações Parte 2 – Projeto 02:135.07-001/3", Associação Brasileira de Normas Técnicas, Rio de Janeiro, Brasil.

ARI STANDARD 210/240-2006, Performance Rating of Unitary Air-Conditioning and Air-Source Heat Pump Equipment, Air-Conditioning and Refrigeration Institute.

ASHRAE, 2004a. "Thermal Environmental Conditions for Human Occupancy", ANSI/ASRHAE Standard 55-2004, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, USA.

ASHRAE, 2004b. "Energy Standard for Building Except Low-Rise Residential Buildings", ANSI/ASRHAE/IESNA Standard 90.1-2004, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., USA.

ASHRAE, 2005a. "Chapter 8 - Thermal Comfort", ASHRAE Fundamentals Handbook, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, USA.

ASHRAE, 2005b. "Chapter 27 - Ventilation and Infiltration", ASHRAE Fundamentals Handbook, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, USA.

ASHRAE, 2005c. "Chapter 28- Climatic Design Information", ASHRAE Fundamentals Handbook, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, USA.

Corgnati, P.C., Fabrizio, E., Filippi, M., 2007. "The impact of indoor thermal conditions, system controls and building types on the building energy demand", Energy and Buildings 40 (2008) 637-636.

Daikin, 2005. "Engineering Data VRV-II, Heat Pump and Cooling", ED39-428B, Daikin Industries, Japan.

EnergyPlus, 2008. "EnergyPlus Input and Output Reference – The Encyclopedic Reference to EnergyPlus Input and Output", Version 2.2., Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, USA.

Pan, Y., Yin, R., Huang, Z., 2007. "Energy modeling of two office buildings with data center for green building design", Energy an Buildings 40 (2008) 1145-1152.

Zhou, Y.P., Wu, J.Y,. Wang, R.Z., Shiochi, S., 2006. "Energy simulation in the variable refrigerant flow air-conditioning system under cooling conditions", Energy and Buildings 39 (2007) 212-220.

Zhou, Y.P., Wu, J.Y,. Wang, R.Z., Shiochi, S., Li, Y.M., 2007. "Simulation and experimental validation of the variable-refrigerant-volume (VRV) air-conditioning system in EnergyPlus", Energy and Buildings 40 (2008) 1041-1047

9. RESPONSIBILITY NOTICE

The authors Adriano Roberto Carotenuto and Paulo Otto Beyer are the only responsible for the printed material included in this paper.