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Energy Performance of a University Building for Different Air Conditioning (AC) Technologies: A Case Study

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Abstract: The study uses four AC technologies to assess the energy performance—this is a case study of an educational building in Barranquilla, Colombia. The building currently has split AC technology high-energy consumers. Therefore, it was necessary to assess a replacement with more efficient technology. Because of the non-seasonal climate in the building location, one month of monitoring of energy consumption was the reference for developing an energy model for the building using EnergyPlus and DesignBuilder software. The model was applied to forecast the building energy performance of our more efficient AC technologies available in the Colombian market, and valuable according to building specifications (Split, VRF, VAV, and Chiller). Results show a reduction in energy consumption of approximately 30% with the technology change and 15% savings in life cycle costs (LCCs), even though the building is already considered to have a low energy consumption according to national regulations. The findings of this study underscore the potential for widespread applicability across all types of buildings, regardless of their energy consumption profile, be it low, medium, or high. This extensive applicability not only highlights the adaptability and versatility of the technology but also underscores its significance in achieving substantial energy savings and cost reductions across the entire building industry, contributing to a more sustainable and economically efficient future.

Keywords: air conditioning systems; educational building; energy performance index (EnPI); energy simulation; life cycle cost (LCC); energy performance

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1. Introduction

Buildings consume approximately 30% of global final energy and produce 15% of CO_2 emissions. However, there is significant potential for improving energy efficiency (EE), which can significantly reduce these values [1]. One of the leading causes of this high energy consumption is the need to ensure comfort, which makes it necessary to condition indoor spaces independently of external climatic conditions [2]. In tropical areas, achieving comfortable conditions requires cooling indoor spaces through air conditioning systems. These are the largest electricity consumers in buildings [3,4]. Although air conditioning (AC) currently consumes approximately 57% of the electricity in buildings globally, a three-time increase is forecasted for the coming years [5,6]. However, with the implementation

of EE standards, improvements in building design, enhanced AC technologies, and better monitoring and proper energy management, it is estimated that it would be possible to improve the energy performance of air conditioning systems by approximately 50% by 2030 [7,8].

The classroom temperature is a crucial factor in the learning process, and prioritizing their improvement should be paramount [9]. Thus, AC use in school buildings has increased significantly in the last decades [10]. Educational buildings are around 17% of non-residential buildings [11]; they are among the fastest-growing category, significant according to the quantity of users, large building area, and high energy demand [12]. University buildings have particularities that make their energy consumption more challenging to fully comprehend than other non-residential buildings such as commercial establishments, offices, and schools [13]. Several research studies study the evaluation of the energy consumption of this type of building. An energy performance improvement between 7.19–9.59% from the ISO 50001 and ISO 50006 [14,15] implementations is reported in the Federal University of Itajubá, in Brazil [16]. A study in Brazil's Federal University of Roraima's buildings highlights the significance of university buildings' AC energy consumption (68% of total electricity consumption) in humid tropical climates [17]. A reduction of over 36% in the electricity consumption of buildings at Ain Shams University, Egypt, by the improvement of the energy efficiency of AC and measures to operate it was reported by Emil and Diab [18].

Since the mid-1990s, universities in Colombia have undergone a process of massification, reaching a coverage rate of 54% in 2022, accompanied by a significant increase in infrastructure [19]. Many are located in tropical regions and rely heavily on AC. Frequently, like many other developing countries [20], they have been built without consideration for climatic conditions or the occupants' comfort and energy consideration. Additionally, AC technology has been used since the construction of the building or subsequently adopted, but it is usually obsolete and has a low energy efficiency.

AC technologies with an increasingly higher energy efficiency have emerged in recent years. However, selecting the best is a complex decision-making problem requiring various factors [21]. In Colombia, the investment cost is primarily considered for choosing the AC system, leading to the development of a calculation method for the comprehensive selection of AC technology during the building design phase. However, replacing AC technologies with newer ones poses an even more significant challenge due to the rising geometric and construction restrictions. Selecting the best technology becomes even more complex, requiring, at least, estimates of the system's energy consumption over its life cycle to assess its economic feasibility.

Despite the reduction in global CO_2 and global building energy consumption being heavily affected by the energy conservation actions in existing buildings, there is an imbalance in the research on building energy efficiency between new constructions and existing buildings [22].

Existing buildings' energy-saving renovations are mainly aimed at reducing electricity consumption [23,24], and several options to reach it are available. These measures include renewable energy sources, structures' thermal performance improvement through energy efficiency materials use, the implementation of cogeneration systems, and the optimization of Heat Ventilation and Air Conditioning (HVAC) systems. Because their final energy signification is considered one of the main issues, updating AC technology is very important in order to enhance energy performance [25]. Nevertheless; the feasibility assessment is challenging because each building is unique, and several AC technologies should be assessed in order to select the best one [23]. Energy simulation methods, such as software simulations, are handy for determining the energy consumption in buildings and forecasting AC energy performance to a proper life cycle cost analysis to select the best technology for existing buildings' retrofit [26].

Since most university buildings in Colombia have been in operation for many years [27], in warm regions, they rely heavily on air conditioning (AC) with a high electricity con-

sumption [28], mainly due to the use of obsolete technology [2] for what is necessary to assess their replacement.

For this purpose, using tools to estimate potential AC technologies' energy performance is crucial.

Therefore, this paper aims to analyze a case study in an educational building in Barranquilla, Colombia. The research assesses the energy performance in the life cycle of four feasible AC technologies that, according to the characteristics of the building, can replace the one currently in use, and evaluates their life cycle feasibility through an energy simulation by Energy Plus (10) and DesignBuilder (V7) software.

2. Methodology and Case Study

The selection of the best air conditioning technology is crucial for improving the energy performance of the university building. This research methodology includes three main phases: data collection, simulation and analysis, and life cycle cost assessment. Firstly, measurements of the current energy consumption of the building with split AC technology are conducted, and climatic data from the region are gathered, considering its limited variability and non-seasonal climate.

The DesignBuilder software simulates the building's energy consumption and evaluates four air conditioning technologies (Split, VRF, VAV, and Chiller). In addition to calculating thermal loads and daily energy consumption, the life cycle cost of these technologies and long-term energy savings are analyzed. The results of this research highlight the importance of using simulation tools to predict energy consumption and assess different technologies.

2.1. Case Study Description

The study is conducted in a university building located in Barranquilla, (10°59′16″ N; 074°47′20″ W), in the Caribbean region of Colombia (Figure 1). The climate is Tropical Savanna (Aw) according to the Köppen and Geiger climate classification [29]. This location has a yearly average maximum temperature of 32 °C, and relative humidity higher than 70%.

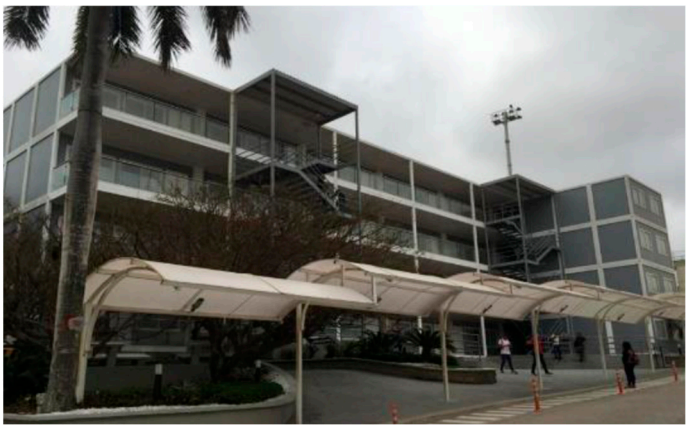


Figure 1. Studied building [30].

Figure 1 shows the case study building. It has four floors with a similar layout. Each floor has eight classrooms, each measuring 43.16 m^2, with a maximum capacity of 40 students.

The AC system in the building is split type one, with 36,000 BTU/h units in each classroom. The temperature is set at 20 °C, and they are kept running continuously from Monday to Saturday, during working hours, from 6:30 a.m. to 9:30 p.m. Figure 2 shows a picture of the classrooms with split units installed.



Figure 2. Classrooms air-conditioned using split units [30].

2.2. Measurement of Indoor and Outdoor Environment Parameters

Indoor air temperature (T_{a_in}), outdoor air temperature (T_{a_out}), outdoor relative humidity (RH_{out}), and indoor relative humidity (RH_{in}) were monitored and acquired in all classrooms. The data were collected in the building under study [4] during September. Measurements and surveys were applied to students in each occupied classroom in the daily academic programming (8:30 a.m.–4:00 p.m.), with an intervention time average of 3 h. The results were supplied to DesignBuilding V7 software to validate the building's computational modeling and establish differences between indoor and outdoor conditions in controlled operational conditions. The equipment used in the monitoring data are shown in Table 1.

Table 1. Instruments for measuring indoor and outdoor environmental parameters.

Equipment	Range	Accurancy
Digital Thermometer Lutron TM-949	−20 to 650 °C; (−4 to 1202 °F)	−20 to 400 °C: ±3%.
Testo Multifunction Meter 435-4 with probes 0632 1535 and 0636 9736	−50 to +150 °C; 0 to +100% RH; 0 to +20 m/s	±0.3 °C (−25 to +74.9 °C); ±2% RH; ±(0.03 m/s + 5% of m.v.)
Davis Weather Station Pro2 Plus 6162	−40 to +65 °C; 1 to 100%	±0.3 °C; ±2% RH

The average results by classroom are shown in Figure 3. The relative humidity variation between the indoor and outdoor environment is approximately 4.9% to 20%, respectively. From the measurements carried out in all classrooms, an average RH_in of 51% and a T_in of 25.3 °C were obtained for the entire building. Additionally, continuous measurements of these parameters were monitored simultaneously to electricity consumption measurements per floor. Monitored data have been used to calibrate the simulated model by DesignBuilder software and validate the predictions of electricity consumption.

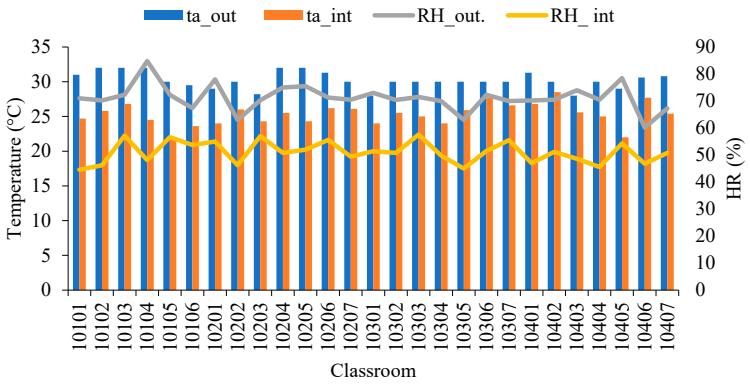


Figure 3. Outdoor and indoor measured climatic conditions [2].

2.3. Measurement of Electrical Consumption

The measurements of electrical consumption in the building have been monitored simultaneously with the indoor and outdoor environmental variables, aimed at validating the building model and the electric AC consumption predictions obtained from the computerized simulation by EnergyPlus, through all these environmental variables and the building characteristics of case study. The equipment used for these measurements and their installation in the building are shown in Table 2.

Table 2. Electrical measurements equipment.

Equipment	Magnitude	Range	Accurancy	Installed
Electrical Network Analyzer	Voltage (rms)	1 V a 1000 V Phase to Neutral	±0.1% of Nominal Voltage	
	Intensity (rms)	5 A a 6000 A	±0.5%	
	Frequency	51 Hz to 69 Hz	±0.01 Hz	
Ct Meter With RS485 Modbus	Four-channel three-phase, 480 V, open-core of 200 A, BMS ZENNIO software for data loading.			

The daily energy consumption values for AC obtained with the measurement equipment (Table 3) are compared with the values obtained from the simulation.

Table 3. Daily energy consumption values measured in the building.

Day	kWh/Day	Day	kWh/Day
1	781.4	16	780.4
2	619.5	17	710.4
3	879.5	18	760.5
4	811.7	19	730.8
5	790.7	20	560.2
6	814.6	21	810.2
7	716.7	22	760.2
8	475.6	23	801.5
9	735.9	24	760.2
10	677.9	25	730.2
11	699.8	26	510.5
12	704.4	27	780.3
13	713.2	28	745.2
14	539.6	29	673.4
15	779.2	30	480.2

2.4. Energy Consumption Buildings Forecast

The methods for forecasting energy consumption in buildings depend on how the data are acquired and the scope of the energy performance assessment to be applied [29]. The characteristics of the façade, the HVAC system, and occupancy are three fundamental factors that influence the energy performance of buildings [30]. In this research, the performance of the Building Energy Performance Assessment Report is assessed in a typical year of building operation, validated with actual measurements from September.

The energy simulation of the building is the most used tool for the energy performance assessment of buildings due to the use of EnergyPlus calculation engine and the Transfer Function (TF) [31–33] (Equation (1)):

$$Q_0 = v_0 \times q_0 + v_1 \times q_1 + v_2 \times q_2 - w_1 \times Q_1 - w_2 \times Q_2 \quad (1)$$

where Q is the cooled space load, q is the heat gain, and v_0, v_1, v_2, w_1, w_2 are the transfer function coefficients.

Considering the internal heat gains and weather data (temperature and relative humidity) for indoor and outdoor environments, energy consumptions (kWh/day) are analyzed for the building modelled and calibrated in the simulation software for 8760 h a year. Energy simulation is also helpful in comparing energy technologies' performance in buildings, as it forecasts energy consumption, allowing a comparison between their energy performance, using the indicator of electrical consumption per area (ENPI). For AC systems, ENPI is calculated next (Equation (2)):

$$\text{ENPI} = \frac{\text{Forecasted AC Energy consumption}}{\text{Cooled area}} \ [\text{kWh/m}^2] \quad (2)$$

Figure 4 shows how the energy consumption of the building has been determined. Input data such as climate and the characteristics of the educational building were taken into account to calculate the energy consumption for each AC system in the first stage. In the second stage, measurements were made in the real building, and the 3D model of the building was developed to carry out energy simulation. The results obtained from measurements and simulations are compared to validate the model. The third stage is developed with the validated building model, where the energy consumption values for each AC technology (Split, VRF, VAV, Chiller) are obtained.

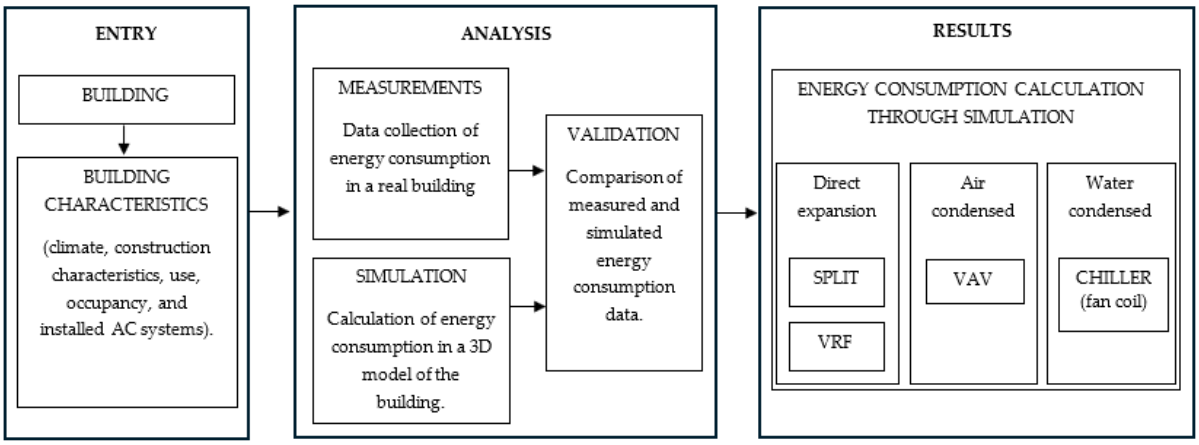


Figure 4. Method for determining the energy consumption for each AC technology in the building.

The energy demanded by each AC technology is calculated by integrating their load function, and the energy consumed is calculated by dividing the building's thermal load function by the stational efficiency of the thermal installation according to the following equation, Equation (3) [33]:

$$E_{cons}^{sist} = \int_{to}^{tf} P(t)_{cons}^{sist} dt = \int_{to}^{tf} \frac{P(t)_{demand}^{build}}{\eta(t)_{global}^{sist}} \quad (3)$$

where:

E_{cons}^{sist}: energy consumption of AC system;
$P(t)_{cons}^{sist}$: AC technology load function;
$P(t)_{demand}^{build}$: building's thermal load function;
$\eta(t)_{global}^{sist}$: stational thermal efficiency of AC system;
to, tf: initial and final time.

2.5. Life Cycle Cost (LCC) of AC System

Comparing the different alternatives' long-term financial performance is valuable for assessing the economic viability of AC technology replacement. The net present value (NPV) method determines the life cycle cost (LCC), considering the operating, maintenance, and investment costs. The investment and maintenance costs are estimated based on cost references obtained from HVAC companies.

For the LCA analysis, the thermal load of the building in the cooled areas is calculated to determine the AC capacity, which, together with the AC technology selected, allows investment cost estimation. The expected lifespan of each AC technology alternative can evaluate the operating and maintenance costs for each analyzed system. The energy consumption obtained from the simulated building is also necessary in order to calculate the operating and maintenance costs. Usually, the lifespan of AC systems' design is over 20 years, and total NPV is calculated using Equation (4) [34]:

$$NPV_{cv} = \sum_{i=0}^{20} \frac{\Delta C_n}{(1+d)^n} \quad (4)$$

where:

VPN_{cv}—sum of yearly VPN_n for 20 years, including the investment cost in year 0;
ΔC_n—difference between the annual energy cost of the AC system and the energy cost of the alternatives for replacement in year n, with a discount rate d.

2.6. AC Technologies Assesed

In this study, four AC technologies have been included. The split technology and three possible technologies for replacing it are simulated in the building (Table 4).

Table 4. AC technologies assessed in the building.

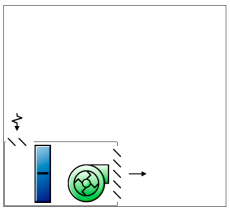
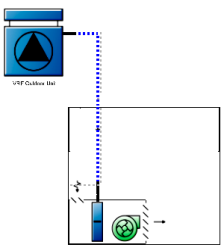
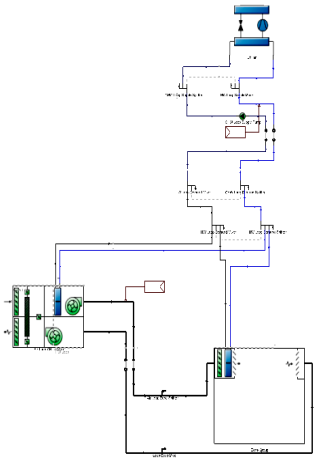
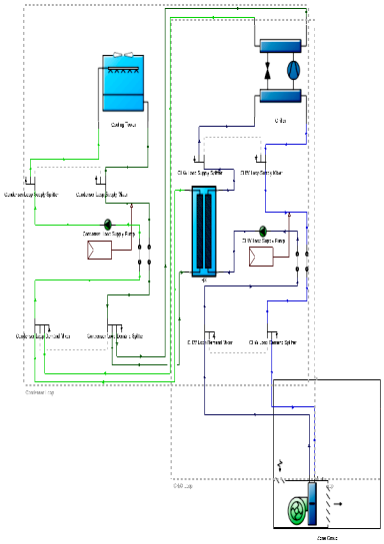
AC Technology		Characteristics	Diagrams
Direct expansion	Split	Direct expansion system of type Split. Fan coil floor ceiling of 4TR 1PH-220V-60HZ per zone.	
	VRF	Direct expansion system with variable refrigerant flow (VRF). 130 TR 3PH-440V-60Hz.	

Table 4. *Cont.*

AC Technology		Characteristics	Diagrams
Air-condensed	VAV	Air-cooled system with screw compressor type Chiller. Variable air volume distribution system (VAV). 130 TR, 3PH-440V-60Hz.	
Water-condensed	Chiller (Fan Coil)	Water-condensed system and a screw-type compressor chiller. Fan Coil terminal units. Cold water temperature was set at 7 °C and water returned the temperature to 12 °C. 120TR, 3PH-440V-60 Hz	

3. Building's Model

Figure 5 shows a screenshot of the building modelled by the DesignBuilder V7 software.

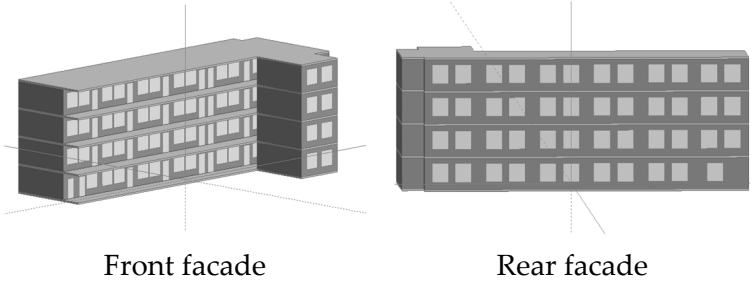


Figure 5. Building modelled by DesignBuilder v. 7 software.

The building is a multi-modular kind with flat-pack units for walls and floors. The walls are the sandwich type, made of stainless steel with glass wool insulation, a polyurethane roof, and PVC flooring, while, because of the hard sun intensity in the site, the windows are made of vacuum insulating glazing using internal blackout curtains. The characteristics and

properties of this type of construction and their material are obtained from an international manufacturer [35]. The features and transconductance of the envelope are shown in Table 5.

Table 5. Façade characteristics [30,31].

Façade Characteristics	Thermal Transmittance (U)
Wall Panel: Exterior cladding, galvanized-steel-coated, 0.5 mm thickness, 60 mm insulation, and 9 mm interior lining of agglomerated wood particle board, covered with galvanized and coated steel sheet of 0.5 mm.	0.527 $W/m^2 \cdot K$
Floors: Structure-welded and cold-rolled steel profiles 3 mm thick, fiber cement floor 18 mm thick, density of 1.26 kg/m^3, and water-resistant.	0.330 $W/m^2 \cdot K$
Roof: Welded and cold-rolled steel profiles with 4 mm frame, covered with galvanized sheet, 0.5 mm, of roof tiles double-folded in the middle of the top; internally coated by 9 mm agglomerated wood particle boards and a 50 mm steel sandwich panel that is isolated.	0.370 $W/m^2 \cdot K$
Windows: PVC frame with vacuum insulating glazing; double glazing of 6 mm/13 mm of air, sliding mechanism; size: 800 × 1100 mm.	2.708 $W/m^2 \cdot K$

4. Results and Discussion

4.1. Weather Data in the Simulation

In the building's hot and humid climatic zone, outdoor temperatures and relative humidity are high, with slight seasonal fluctuations. Figure 3 shows the results of the measurement campaign of outdoor and indoor climatic variables for the building zones, which were used to validate the simulation results. The indoor Relative Humidity (RH) is 51%, and the operative temperature is 25.3 °C.

Figure 6 shows the performance of the indoor temperatures of the building and indoor relative humidity obtained from the simulation. The average indoor relative humidity (RH) stands at 53.76%, with an operative temperature of 24.79 °C. The operative temperature of the building is obtained from the arithmetic mean between the air temperature (23.89 °C) and the average radiant temperature (25.69 °C). However, in the measurements, the difference between the surface temperature of the walls and the air temperature was minimal. Consequently, a variance of approximately 0.51 °C exists between the measurements and the simulation for the operative average temperature, and roughly 2.8% for the average relative humidity. These findings offer a deeper insight into how climatic conditions impact the internal environment of the building, which is crucial for its design and energy efficiency.

These results underscore the importance of accurately modeling and predicting indoor climate variables to optimize building performance and occupant comfort. This iterative process contributes to the advancement of sustainable building design and operation practices, ultimately leading to enhanced energy efficiency and indoor environmental quality.

Due to the low seasonal weather variability and the consistently high temperature and relative humidity conditions, one of the most critical functions of the HVAC system is the continuous dehumidification to reduce RH, rather than solely focusing on lowering the indoor temperature. This emphasizes the necessity of effective moisture control strategies in maintaining thermal comfort within the building environment. By prioritizing dehumidification, the HVAC system can better regulate indoor humidity levels, thereby enhancing occupant comfort and overall indoor air quality.

This proactive approach not only ensures occupant comfort but also contributes to the preservation of building materials and indoor air quality. Consequently, integrating robust dehumidification strategies into HVAC system design and operation becomes paramount for effectively managing indoor environmental conditions and optimizing the overall performance of the building.

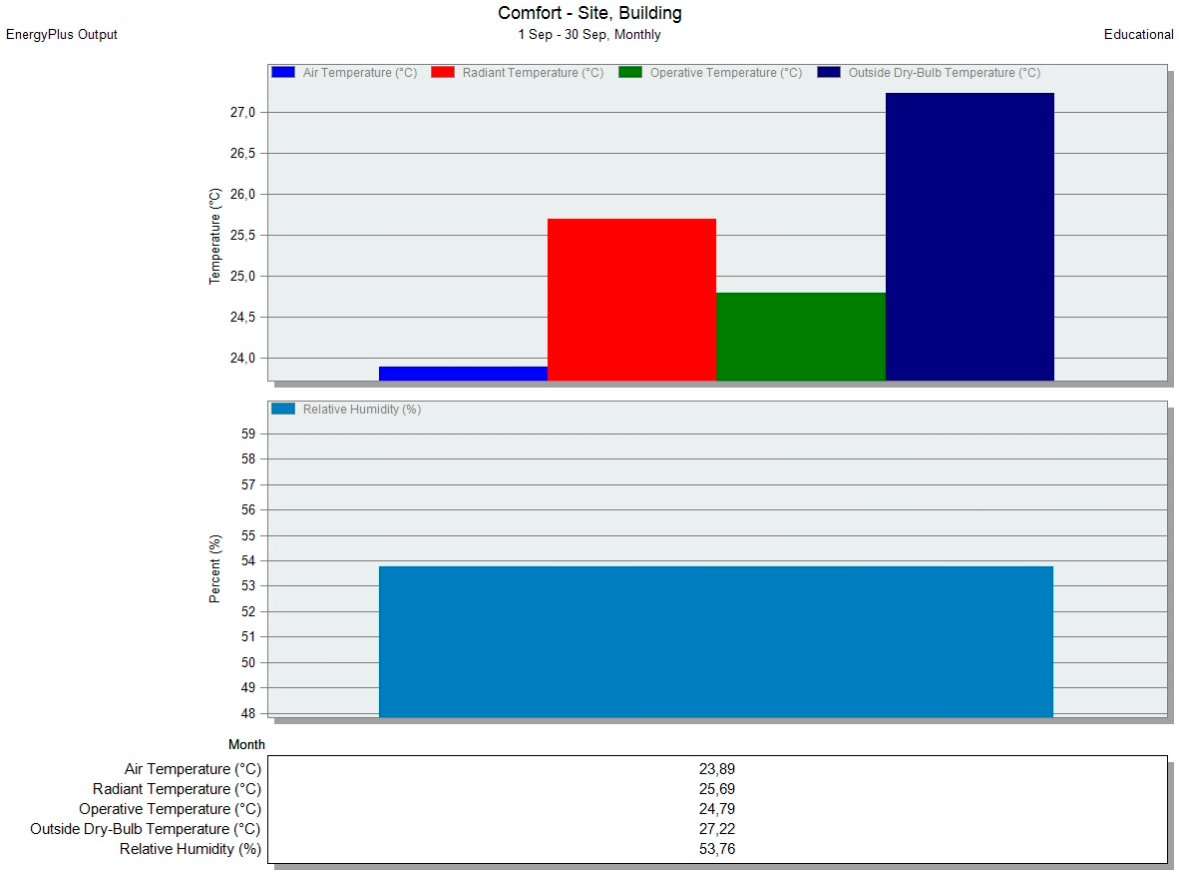


Figure 6. Simulation of the building climatic conditions by DesignBuilder software (screenshot).

4.2. Energy Consumption of the Building

The validation of the reference model of the building was carried out throughout an AC workday daily energy consumption measurement, which was compared with that calculated by simulation via DesignBuilder software, with the split technology used in the building. Figure 7 shows the scatterplot between the measured and calculated values.

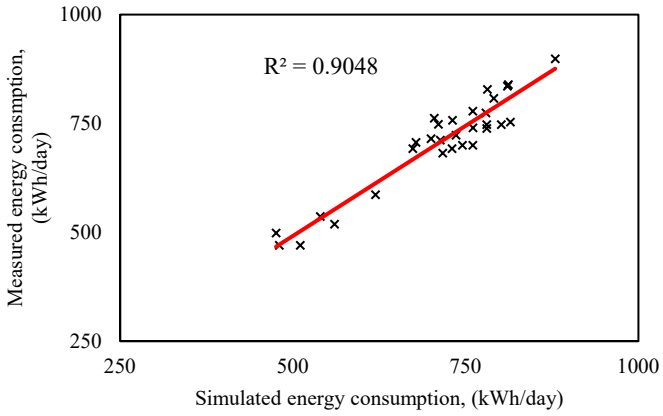


Figure 7. Scatterplot between measured and simulated values of energy consumption [30].

Since the coefficient of determination is 0.98 for the correlation between the values for the mean line on the scatterplot, comparing values through the least significant difference test indicates that, with a 95% confidence, there are no differences between the means of both variables. The standard deviation of the residual error between the measured and simulated values is only 39.7, and the mean absolute error is 31.8697. Additionally,

the Durbin–Watson statistic excludes serial autocorrelation in the residuals; with a 95.0% confidence level, the base model for the building energy simulation is validated.

4.3. Internal Building Heat Gains for the Building

The energy consumption also depends on the internal gains generated within the building. The thermal load of the simulated building was calculated using DesignBuilder software through the EnergyPlus simulation engine, which used the transfer function method validated by ASHRAE. These simulations consider heat gains (kW) from glazing, walls, floors, roofs, ventilation, electrical equipment, lighting, occupants, and solar radiation [31]. The maximum cooling load in each building's zone is multiplied by a safety factor 1.3, resulting in the AC design cooling capacity.

Therefore, using the reference model of the building, the behavior of the cooling thermal load obtained from the simulation for a typical day in September, from 6:30 a.m. to 9:30 p.m., is analyzed. The results of the hourly heat gains simulation for a typical day and the energy balance with building occupancy are shown in Figure 8.

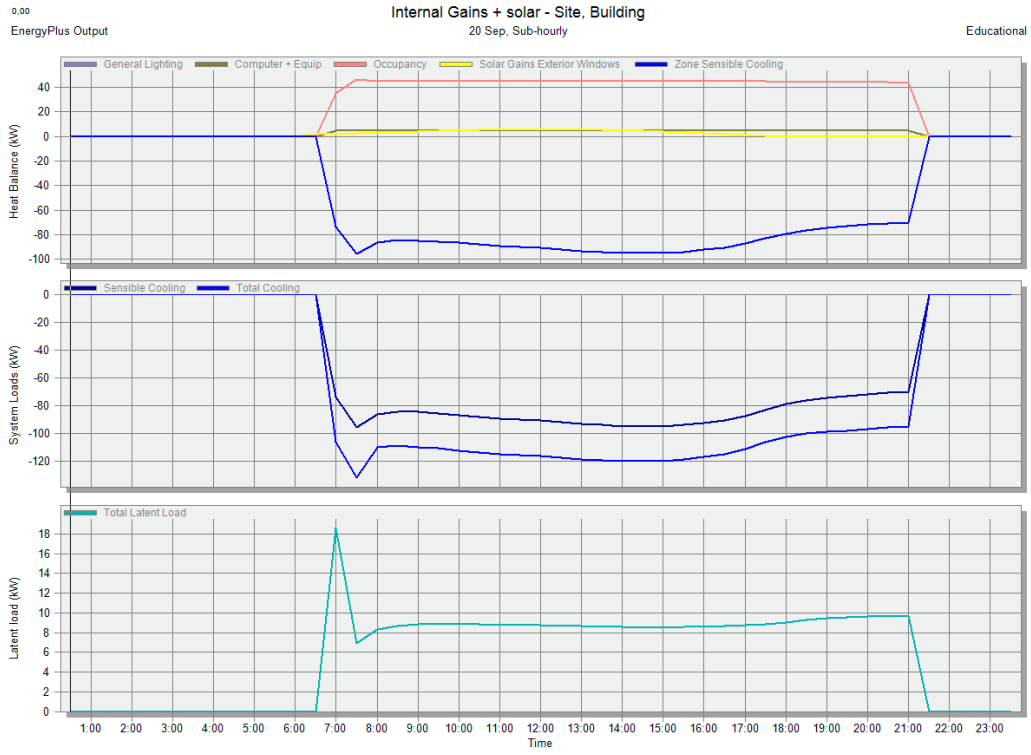


Figure 8. Performance of the internal gains in the building simulated by DesignBuilder software (screenshot).

The building occupancy was 40% to 50%. From the simulation, it is determined that heat gains due to occupancy have a significant impact on the energy balance, with an average performance of 44.7 kW. Lighting and equipment contribute an average of 4.81 kW to the heat gains. The average sensible internal gains for the conditioned areas were −88.1 kW, and the total cooling load for the building was −112.8 kW. Thus, occupancy significantly influences the HVAC system, and its impact on the energy balance of the building is evidenced. The total latent load of 8.85 kW showed a difference of 9.96 kW in the first 30 min, a characteristic pattern in a humid climate, remaining relatively unchanged in the subsequent hours due to the continuous operation of the HVAC systems.

The AC system design data have a cooling capacity requirement of 181 kW (51.5 tons of refrigeration) for the building, with an average cooling capacity of 7 kW (2 tons of refrigeration) per zone. The typical design cooling load per floor area is 139.3 W/m^2 (0.04 tons of refrigeration per square meter). In scenarios with a 100% building occupancy, which establish the conditions for AC system design, the necessary cooling capacity increases to 230 kW (65.5 tons of refrigeration) for the entire building, with an average of 8.5 kW (2.5 to 3 tons of refrigeration) of cooling capacity per zone. The average design cooling load per floor area rises to 175.4 W/m^2 (0.05 tons of refrigeration per square meter).

4.4. Building Energy Consumption According to AC Technology

One of the main challenges in installing AC in regions with this climate has been the lack of well-founded evaluations for selecting the best performance technologies from an energy perspective for each solution. An approach with the lowest initial investment, rather than an LCC approach, predominates [36].

The relationship between the building's thermal load and the energy performance of AC defines the energy consumption. The operation of the building was simulated to estimate the monthly electricity consumption for the four AC technologies. Since the climate in the region is non-seasonal, simulations were carried out daily with the actual occupancy in a typical month, September. The results for the four AC technologies under study are shown in Figure 9.

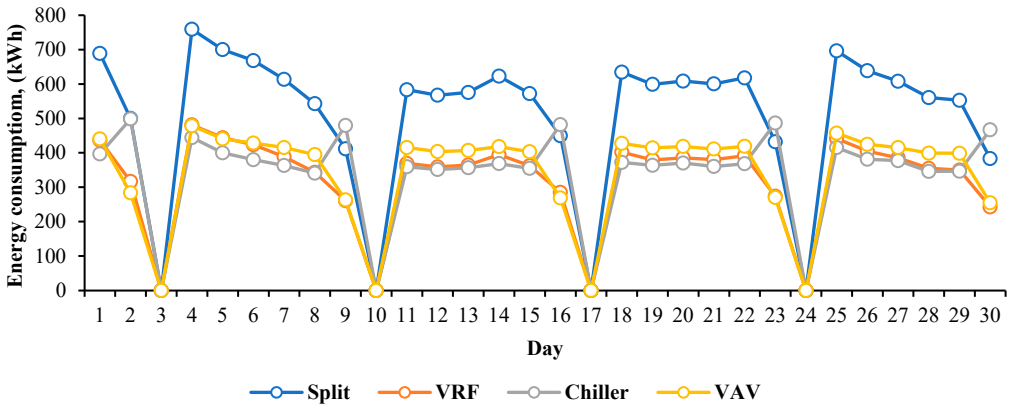


Figure 9. Energy consumption (kWh) in the building with split AC systems.

The total building energy consumption for the current split AC is 18,549.6 kWh/month, 15,187.6 kWh/month (80%) in AC, and 3362.0 kWh/month (20%) in lighting and auxiliary electrical equipment. For the VRF technology, the energy consumption is 9626.9 kWh/month, 10,173.4 kWh/month for VAV, and 10,225.4 for Chiller. This evidences that the system in use has the highest energy consumption, and, indeed, in its selection, the investment cost was the main criterion considered.

The building under study with the current split AC has an energy performance index of 15.02 kWh/m^2·month, and, thus, can be considered a low-energy-consumption building [37], and, according to Colombian Standards, it is within the established baseline range [32]. However, its energy performance can improve significantly with the other AC technologies, as shown in Figure 10.

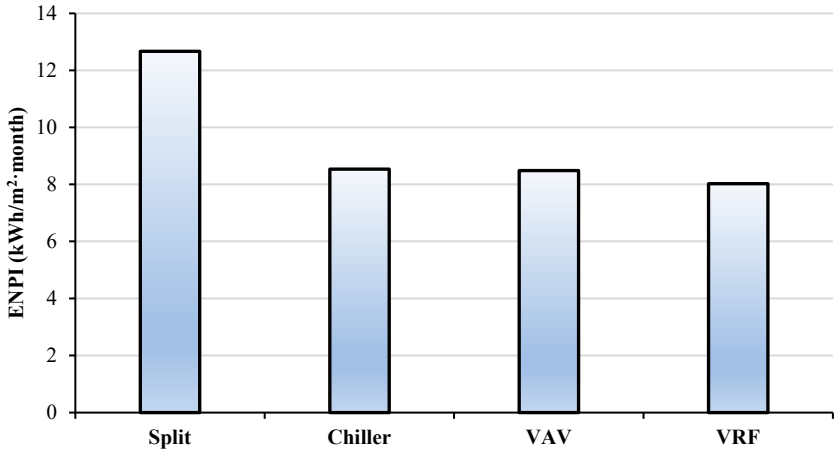


Figure 10. Energy performance index by AC technology.

The VRF system at 8.03 kWh/m^2·month decreased by 36.6% compared to the Split system at 12.67 kWh/m^2·month. The VAV and Chiller systems also demonstrate an energy performance improvement, 8.48 kWh/m^2·month and 8.53 kWh/m^2·month, respectively. However, they also result in a higher electricity consumption than the VRF system, by approximately 5 to 6%.

4.5. Life Cycle Cost (LCC) by AC Technology

The cost analysis is based on the market prices. The investment cost (InvC), and operation and maintenance cost (OMC) of each AC system alternative installed in the reference building have been considered according to the cooling capacity and under the same operating and functioning conditions. Operating costs are calculated according to the annual energy consumption for an average price for the commercial sector in Colombia (0.18 USD per kWh in 2022) and from actual commercial quotes for maintenance operations. Table 6 shows the results.

Table 6. Life cycle costs by AC technology.

Cost (USD)	Split	VRF	VAV	Chiller (Fan Coil)
CInv	75,082.00	149,622.90	298,247.76	333,358.28
COpM	49,506.74	32,920.32	36,476.34	37,170.83
LCC	1,444,051.53	1,193,318.85	1,213,713.18	1,261,470.41

According to the LCC analysis, the NPV associated with energy consumption is compared for the four AC technologies for the 20-year lifespan scenario for those with water-cooled and air-cooled chillers. A 10-year lifespan is considered for direct expansion systems, followed by a new investment for another ten years. The average annual growth rate is 5.6%, based on the economic performance from 2020 to 2021 [38]. The discount rate (n) established in the building project is 3.5% [39,40].

The lower NPV for the 20-year lifespan of the AC systems is the VRF, which also has the smallest LCC. For the Split system, the savings by switching to the VRF system are approximately 20%, even when the investment cost for both systems has been doubled for the analysis period. LCC values for the VAV and Chiller are also positive, representing savings of 16% and 13%, respectively. These options are more cost-effective in the long run compared to the Split system.

5. Conclusions

The results demonstrate that the current practice in regions with this climate, prioritizing the investment cost in AC technology, needs to be revised and should not be the sole factor in the choice of AC technology for buildings. The building studied with the current

split technology has an energy performance indicator of 12.07 kWh/m^2·y, which, according to Colombian standards, is classified as a low-consumption building. This could be an additional barrier to implementing an LCA perspective in selecting the AC technology for a specific project, as it provides a wrong idea of efficiency and may prevent the consideration of other options with a better energy performance, as demonstrated by the results. This study conclusively demonstrates that the application of split technology results in a significant energy overconsumption, ranging from 30% to 35% compared to alternative technologies evaluated through simulations. Furthermore, a substantial potential for cost savings in the LCC of installations is identified, varying between 13% and 20%, depending on the type of technology selected.

The methodology employed in this study yields essential findings that can be extrapolated to various climatic conditions, with the primary aim of enhancing the energy efficiency in buildings of low, medium, and high consumption. This approach perfectly aligns with the global imperative of decarbonizing and optimizing the building stock in accordance with worldwide energy efficiency goals.

The results of this study underscore the need to reassess the common practice in regions with similar climatic conditions. In these areas, the tendency to prioritize the upfront cost of air conditioning technology as the determining factor in the choice of HVAC systems for buildings is clearly unsustainable. It is revealed that the widely-used split air conditioning technology is not energy-efficient and, in accordance with some standards, it is inadequately classified as a low-efficiency option in the life cycle analysis of HVAC technology.

This study has proposed to consider alternative HVAC solutions that not only reduce long-term operating costs but also contribute to sustainability and climate change mitigation. The results obtained in this case study show that a correct selection of air conditioning technologies offers a much more efficient and environmentally friendly technology in a wide range of climates.

The methodology employed in this study provides valuable insights that can be extrapolated to various climatic conditions, offering a pathway towards enhanced energy efficiency and environmental sustainability in buildings worldwide. By making informed decisions regarding HVAC technology selection, stakeholders can contribute to a more sustainable and energy-efficient future, aligning with global efforts to decarbonize and optimize the building stock in accordance with international energy efficiency goals.

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