Indoor Air Quality Assessment via Experimentally Calibrated Dynamic Simulation: A Case Study in an Office Building in Panama

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Abstract*– Air quality plays a decisive role in the performance of the occupants considering that people spend at least 70% of their life indoors. This research aimed to determine if an air split unit in a small public office provide appropriate air quality for its employees. The ventilation performance was evaluated in passive and mechanical mode; the dynamic interface DesignBuilder simulated three case studies: the first one was to validate the data obtained with a temperature sensor during 10 workdays, the following two compared exclusively mechanical ventilation and exclusively natural ventilation with all windows and doors opened. The indicators utilized were CO_2 concentration, indoor air renewal rates, and thermal comfort. The results showed that natural ventilation is insufficient to ensure high indoor air quality due to thermal discomfort, but acceptable CO_2 concentrations were registered. In contrast, mechanical ventilation improved thermal comfort levels, but the CO_2 concentration remained slightly outside the acceptable limits. These results demonstrated that the office is not designed to operate passively, restricting their functionality with mechanical ventilation.

***Keywords*—Environmental condition, dynamic simulation, indoor air quality, monitoring, temperature, thermal comfort.**

I. INTRODUCTION

Indoor air quality (IAQ) is an important factor that have considerable influence on occupant comfort. It is defined by ASHRAE [1] as “the air in which there are no know contaminants at harmful concentrations and with which a substantial majority (80% or more) of the people exposed, do not express dissatisfaction”. The acceptable concentration limits of contaminants are determined by local authorities depending on the region. Ensuring optimal indoor air quality, has become a concern because people spend about 70% to 90% of their lives indoors, from our homes, schools and work [2], [3]. The IAQ is biased by indoor and outdoor temperature, relative humidity, CO_2 concentration, wind speed, indoor light, and daylight levels and to achieve desired IAQ, control of environmental conditions must be considered. The first step to achieve acceptable IAQ is reducing pollutant levels: if the contaminant are particulate matters it can be removed by filtration and those in the form of gases or odors by an acceptable level of ventilation [4]. According to ASHRAE [1], the ventilation air is that portion of supply air that can be combined with recirculated air, which then has been treated for the purpose of maintaining acceptable IAQ; parametrically is defined as the air change rate (ACH) and can be natural (passive mode), mechanical (active mode) or hybrid. Natural ventilation is provided by temperature changes, wind flows or air diffusion trough intentional openings in buildings, moreover mechanical ventilation is provided by electromechanical equipment such as fans, splits units or central HVAC systems and lastly, hybrid ventilation operates with both types of ventilation. When it is not possible to ensure thermal comfort and high IAQ with natural ventilation, mechanical ventilation is used. Besides the air change rate, CO_2 concentration can be used as an IAQ indicator when assessing indoor spaces, considering that the main polluting source is the human metabolism[5]–[7]; according to ASHRAE [1] CO_2 levels must be below 1000 ppm in indoor spaces.

In 2016, Ben-David, Rackes & Waring [8], simulated the impacts of natural versus mechanical ventilation in different office buildings located across fourteen United States cities. The authors evaluated the IAQ in terms of air change rate and concentration levels of known contaminants. In both ventilation modes, passive and active, the ventilation rates were below 0.5 ACH and de CO_2 indoor/outdoor ratio above 1 meaning there was an interior concentration higher than the permitted limits. Indoor concentrations and I/O ratios were similar for both scenarios except for particulate matters which were reduced by filters employed in active mode.

Ventilation equipment can also influence Indoor Air Quality. Central heating, ventilation and conditioning systems, introduces outdoor air into indoor spaces but split units depends mainly on recirculated air that has gone through filters [6] and certainly, in spaces where split units are implemented, there is no mechanical ventilation system for air renovation [9]. Oliveira, Rupp & Ghisi, recommended implementing an air

Digital Object Identifier (DOI):
http://dx.doi.org/10.18687/LACCEI2022.1.1.440
ISBN: 978-628-95207-0-5 **ISSN:** 2414-6390

exchange device when using split air-conditioner devices, to provide suitable indoor ventilation and reduce pollutant concentration[10]. Due split units don't provide an air change rate, this may have an impact over IAQ, in other words, rising pollutant concentration. González et al [11] discovered by employing a survey analysis to know occupants' preferences that most participants in the study, selected split air units as their cooling systems, thus it's the most common and known mechanical ventilation system utilized. In contrast,[12] showed that occupants of buildings with centralized ventilations system were thermically unsatisfied compared to occupants who worked in spaces with split units, since with this type of ventilation, the user can control the interior temperature at his comfort.

Crosby & Rysanek [13], studied the correlations between thermal comfort and non-thermal conditions (IAQ) in offices, applying Bayesian logistic regression. The results suggested that there was evidence supporting that indoor CO_2 concentrations were correlated with the thermal satisfaction of the employees. With a concentration near 500 ppm, the employees were thermally satisfied compared to occupants experiencing indoor conditions near 900 ppm. Additionally, [14] in 2021 presented a numerical study related to the performance evaluation of ventilation systems in the Technological University of Panama. The purpose was to determinate if the students were getting high indoor air quality with natural ventilation and mechanical ventilation, considering air renewals, CO_2 concentrations and thermal comfort. After an academic year simulated with DesignBuilder software, the authors concluded that natural ventilation was not enough to ensure appropriate indoor air quality. The ventilation system of the buildings, are not designed to operate passively, restricting their operation exclusively in mechanical mode.

Indoor air quality is an important factor that have considerable influence on occupant productivity [15]–[17]. In 2020, Wargocki et al[15], applied an experimental study to identify the relationship between classroom air quality and children performance in a school with mechanical ventilation; indoor air quality was characterized by CO_2 concentration and air change rates. The results showed that CO_2 levels below 900 ppm and increasing the ventilation rates from 2.0 L/s*person to 10 L/s*person, increased the productivity of students up to 12%.

Previous experimental research had shown the use of data in situ to maintain IAQ. S. Pan et al. [18]. employed indoor temperature sensors, motion sensors and windows position detectors (through infrared wavelengths transmitted by human body), to record under which environmental conditions, occupants opened windows. The outcomes presented, showed that there was a correlation between opening windows with indoor and outdoor environmental conditions; also, sensor recorded data can be employed to take to do thermal and environmental predictions. This is the case of C. Thilker et al. [19] who developed an indoor temperature prediction modeling through air condition monitoring and S. Ryu and Y. Chen [20] who performed an occupancy prediction with the data obtained via motion sensors.

Since IAQ can affect occupant's productivity and thermal comfort, this article is aimed to evaluate the indoor air quality of an office building via dynamic simulation using DesignBuilder software, in terms of air change rate per hour (ACH) and Carbon dioxide concentration levels (CO_2). For this, experimental data was used to calibrate the 3D model of the office studied.

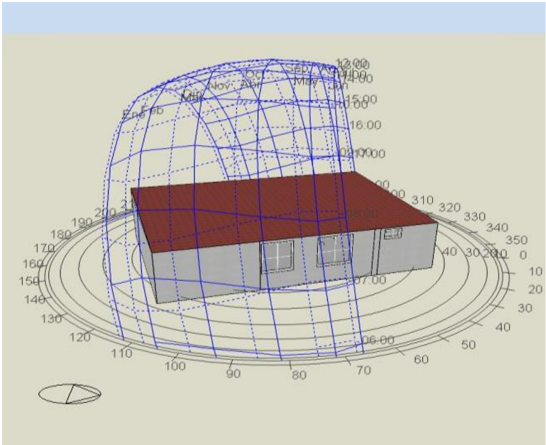
II. METHODOLOGY

This section presents the methodology employed to evaluate the air quality in the case study, giving structural and energy use details, 3D modeling in DesignBuilder, instrumentation, as well as other considerations.

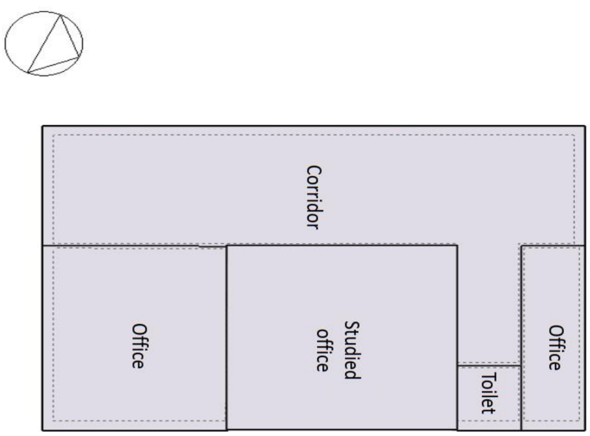
A. Description of the case study

The case study consists of a two-occupant office inside an office building located in the Technological University of Panama, Panama City, (Latitude 9°1'11.69" N and longitude 79°31´57.56"O), as shown in Fig. 1 (a), where the end of the arrow indicates the northern side of the structure; the location is under Tropical savanna climate Awi, according to the classification of Köppen-Geiger. The meteorological data employed in the simulations, for Panama location, is provided by ASHRAE, which considers January to March and July to September as summer and winter season, respectively; the remaining months are periods of transitioning weather changes. It should be noted that the meteorological data indicates that the minimum outdoor temperature is recorded in November, around 26.3°C and the maximum is in March with 28.24°C in average. However, with a daily comparison, March can reach up to 30.4°C.

Referring to the office description, the floor area is 23.2 m^2 and it is a typical Panamanian construction that has the following structural parameters described in Table I. This office has only one external wall with two windows. The other walls are internal partitions adjoining with other offices and corridor (Fig. 1b). The occupancy profile consists of two persons (one woman and one man) following a standard office schedule from 8:00 a.m. to 4:00 p.m. (schedules adjusted after Covid19 pandemic). The studied office was at 24°C setpoint temperature, the other offices and corridors were air conditioned at the same temperature. The windows area is 2.26 m^2 and 1.96 m^2 and their status is always closed, but window shading is specified as blind with high reflectivity slats. The cooling system design day was determined for March 15th, because it is considered the day with highest temperature. The office was equipped with two desktop computers that were employed during working hours and two printers that were used only when necessary.



(a)



(b)

Fig. 1 3D Model of the Office building studied: (a) Axonometric view and (b) Plant view.

TABLE I
CONSTRUCTION MATERIALS

Section	Material	Thickness (m)	U-value (W/m^{2}K)
External walls	Cast concrete Mortar-cement	0.1 0.01	2.7
Partitions	Gypsum	0.07	2.8
Glazing	Dbl grey	$3 \cdot 10^{-3} / 6 \cdot 10^{-3}$ air	3.1
Ceiling	Ceiling Tiles	$20 \cdot 10^{-3}$	1.3
Roof	Clay tile	$15 \cdot 10^{-3}$	2.9
Floor	Cast concrete	$20 \cdot 10^{-2}$	2.5

B. Data acquisition system design and installation

The temperature sensor used, was the DS18B20 digital thermometer. This device is integrated with Arduino One to register the indoor temperatures. Measures temperature from -55 °C to 125 °C and has an accuracy of ±0.5 °C. The temperature sensor was located near the external wall, between windows at a 1.6 m height.

C. Dynamic simulation: indoor air quality evaluation

Indoor Air Quality was evaluated using dynamic simulations that were performed using DesignBuilder software v.6.1.6.11 (from Energy plus). This program takes as input the whole building parameters, such as: construction materials for roof, floor, glazing, partition, and external walls; schedules for occupancy, cooling system and lighting operation; cooling setpoint temperature; shading factors; and are introduced in the model data base (activity, construction, openings, lighting, and HVAC). Moreover, location and meteorological data were needed. This software allows to predict hourly air temperatures, passive and active ventilation results in terms of air change rates, CO_2 concentrations indoors in ppm and thermal comfort.

With the aim of developing a dynamic model to be validated with experimental data, an office building was performed. To fill out the fields required, the parameters exposed in section A were investigated through survey and following Panamanian designs for buildings construction. Furthermore, the surrounding areas were considered because the shading factor is affected by one residential building adjoining the office building. Then, the experimental results were compared with the building modeling program outcomes, in this case, ten-day indoor air temperature monitoring, defined as First scenario, which considers 2-day office labor and the remaining days as holidays, and just the occupied days were mechanical ventilated, and all windows always closed. This scenario was simulated from December 14 to 24.

Once the experimental model is calibrated and validated, it is proposed to continue the development of the following scenarios:

1) First scenario: 2-day office labor with mechanical ventilation (active mode), 8-day holiday (lighting, and cooling systems switched off),
2) Second scenario: Ten-day office labor, with mechanical ventilation (active mode). This scenario was simulated from December 14 to 24.
3) Third scenario: Ten-day office labor, with natural ventilation (passive mode). All windows and doors opened. This scenario was simulated from December 14 to 24.

The selected indicators to evaluate indoor air quality, are described in accordance with ventilation type and thermal comfort.

Mechanical ventilation (first scenario) was evaluated using the following indicators: air change rate per hour (ACH) and indoor CO_2 concentration. Furthermore, thermal comfort selected indicators were indoor air temperature and predicted mean vote (PMV). As stated by ASHRAE [21], PMV is an index that predicts the mean value of thermal sensation votes, expressed from -3 to +3, corresponding to the categories of "cold", "cool", "slightly cool", "neutral", "slightly warm", "warm" and "hot". Equivalently, natural ventilation (scenario 2) was assessed with the same IAQ indicators of active mode but adding the adaptive model with 80% of thermal acceptability. In the adaptive model, ASHRAE states: "environmental measurements are linked to satisfaction through an empirical model in which the prevailing mean air outdoor temperature determines the position of percent satisfied contours bordering the comfort zone [22].” It should be noted that the adaptive model 80% acceptability only is applied in spaces where the occupants are free to adapt their clothing to indoor or outdoor conditions (0.5 to 1.0 clo), there is no conditioning system in the space and the people’s metabolic rates are between 1.0-1.5 met (light work or office work); also, the outdoor temperatures cannot exceed 33.5 °C. If one of the four conditions is not met, the adaptive model is not applicable. This parameter is evaluated with values from 1 to -1, where a “1” value indicates that the interior temperature is within the established limits of thermal comfort of 80% of the people thermically satisfied, a “0” value indicates that the interior temperature is outside the limits and a “-1” reflects that the model cannot be applied because any of the conditions explained is not met [23].

D. Model validation

The model validation was carried out in accordance with experimental data and dynamic simulations outcomes comparison.

As shown in Fig. 2 the indoor air temperature taken from dynamic simulation tools had a similar behavior with the data obtained from temperature sensor, however, there was a mismatching in both results. The first two days reflected an oscillation within 22.8°C and 25.4°C from experimental data, on the other hand, the simulation showed a constant value at 24°C. For that reason, a statistical analysis was performed by calculating the difference between measured and simulated values. According to this, the major differences was recorded during the last day from 5:00 a.m. until 3:00 p.m., about 1.9 °C to 3.4°C. Nevertheless, there were three other days with errors above 1.7°C, ranging between 1:00 p.m. to 6:00 p.m. those periods reflected a rise in temperature and then a slowly declining, this phenomenon happened in [24] but no more than 1°C.

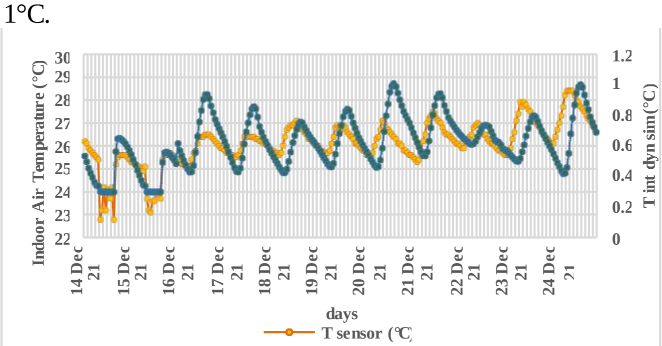


Fig. 2 Comparison between measured data from temperature sensor and DesignBuilder result

To know the error of the implemented model, the average error within the ten days was calculated (Fig. 3), this is 0.7°C and with a standard deviation of 0.62°C. Additionally, it was considered important to include the instruments margin error, in this case 0.5°C, this allowed a better fit between both indoor air temperatures. Therefore, it was assumed that the simulation model could be used.

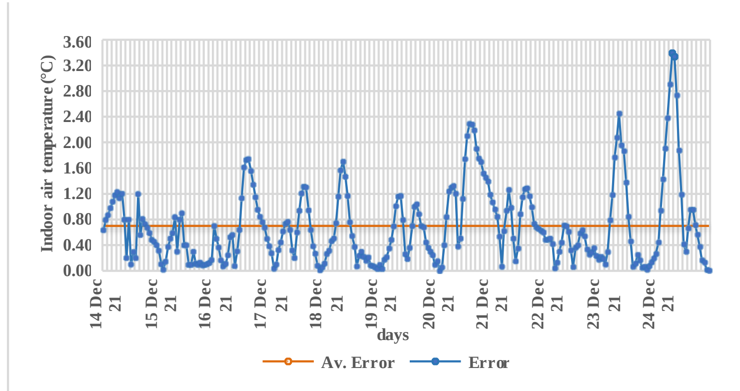


Fig. 3 Error between measured data from temperature sensor and DesignBuilder result.

III. Results Analysis and Discussion

First scenario

As a first analysis, indoor air renewal rates and indoor temperature were compared in Fig.4. One of the points of interest in this study was to identify how having a split unit to condition a space, can affect the air quality of the occupants. As observed in the study by Rasli et al. [6] and Oliviera et al. [10], while the split unit is operating inside the office, there was no air exchange registered, as shown in Fig.4. The split unit was turned on while the employees were working in the office (December 14-15). In the graph, it is also observed that while the office was occupied, the interior temperature was 24 °C and after being unoccupied, the temperature varied from 26 °C to 29 °C.

It should be noted that the workers were not present the rest of the days, so the mechanical ventilation was not turned on. This explains the temperatures recorded above the comfort temperature of the occupants after December 16. Next, the renewal rates are compared with the interior temperature on the days that there was natural ventilation and without occupation. Although in this period, the windows and doors were always closed, the infiltration of the office favored the air change rates, with 0.69 ACH being the lowest rate and 0.71 the highest rate. This analysis does not demonstrate a clear relationship between indoor temperature and air exchange rates.

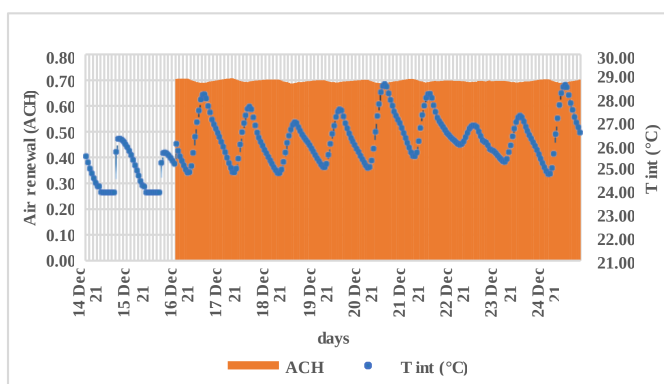


Fig. 4 Comparison between air renewal and indoor air temperature

In Fig. 5, the CO_2 concentration was compared with the indoor temperature. On the two days of occupation, the temperature remained at 24 °C and the CO_2 concentration with the two occupants inside, ranged from 553 ppm to 997 ppm on December 15, while on December 16, 554 ppm to 1015 ppm. This was the only day that the limit allowed by ASHRAE 62.1-2019[1] was exceeded. Despite being a few hours close to the allowed limit and even exceeding it and also, not having mechanical equipment that provides adequate air renewal, the office of the Technological University of Panama provides a safe air quality for the performance of their collaborators.

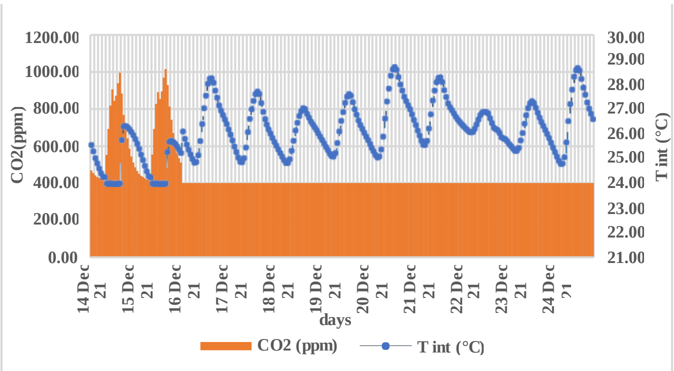


Fig. 5 Comparison between CO_2 concentration and indoor air temperature

Next, in Fig. 6, indoor air renewal rates were compared with CO_2 concentration. In this case, as explained above, there were no indoor air renewal records on occupied days, so with split-type units it is not possible to analyse any type of relationship between CO_2 concentrations and air renewal rates. Regarding the concentration of CO_2, the levels remained close to the exterior CO_2 concentration, registered at about 400 ppm, from December 16 to December 24. This is because in this period recorded the office was not occupied.

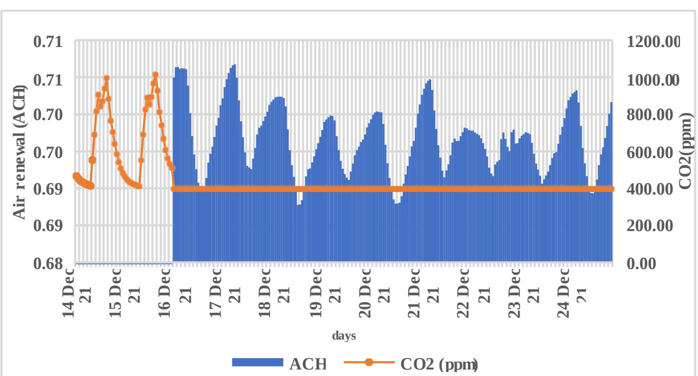


Fig. 6 Comparison between air renewal and CO_2 concentration

In Fig.7, the PMV registered is indicated for the occupants. During workdays, the occupants did not show thermal discomfort when performing their duties. The registered values varied between -1 to 1, approximately but staying close to the neutral thermal sensation.

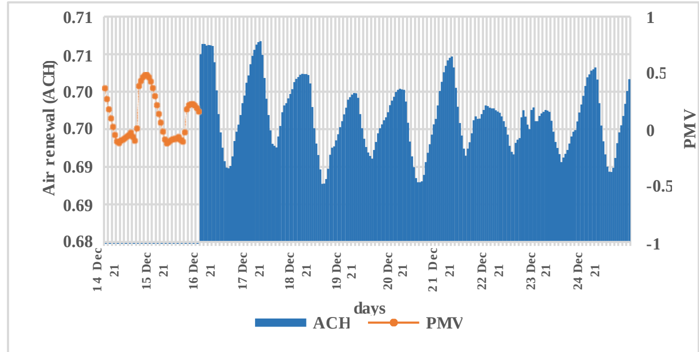


Fig. 7 Comparison between air renewal and PMV

Second Scenario: simulation considering mechanical ventilation and full occupancy in selected days

After comparing the simulation with the data recorded during the days of occupation, two more scenarios were proposed to analyze indoor air quality and thermal comfort considering a total occupation on the days studied.

As observed in scenario 1, there was no record of air renewal rates, so the graph comparing indoor temperature and ACH was not considered for this scenario.

CO_2 and indoor temperature are compared in Fig. 8. During the occupancy period from 8:00. to 16:00, from December 14 to December 24, the interior temperature remained at 24 °C, the thermal comfort temperature of the occupants. During this period, the CO_2 levels had a similar behavior: the lowest concentration was recorded at the time of entry, approximately 550 ppm. As the working hours passed, the concentration decreased during the lunch hour and then increased, reaching the maximum at the time of leaving, approximately between 16:00 and 17:00. The maximum recorded was 1030 ppm on December 18. After the workers finished their work hours, the concentration of CO_2 decreased until it approached the concentration outside of 400 ppm and once occupied again, it increased. This behavior was repeated on the days analyzed. Regarding CO_2 levels, [25] stated in his study that split units are related to high CO_2 levels. Rasli et al [6] states that to lower CO_2 levels in spaces where split air is installed, at least one fresh air intake must be ensured in the office.

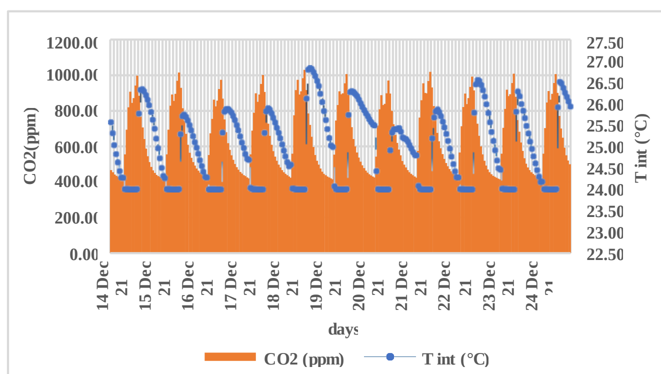


Fig. 8 Comparison CO_2 concentration and indoor air temperature

In Fig. 9, the air renewal rates are compared with the CO_2 concentration in the office. Again, there was no record of air rates, so an analysis was not established for this comparison of indicators.

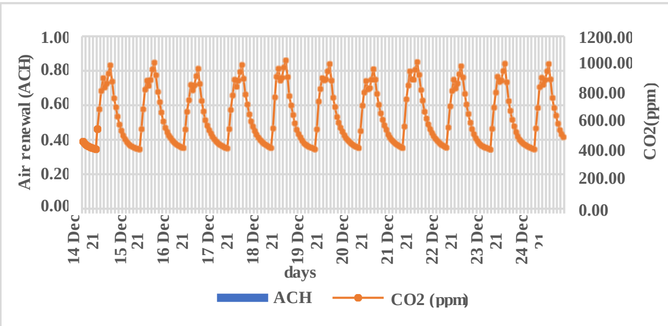


Fig. 9 Comparison between air renewal and CO_2 concentration

In Fig. 10, the PMV that interprets the thermal comfort of the employees is observed. This figure reflects that the occupants during their working hours maintained a "neutral" thermal sensation, with a slightly negative tendency towards a "slightly cool" thermal sensation. Therefore, during the 10 days, the employees were always thermally satisfied.

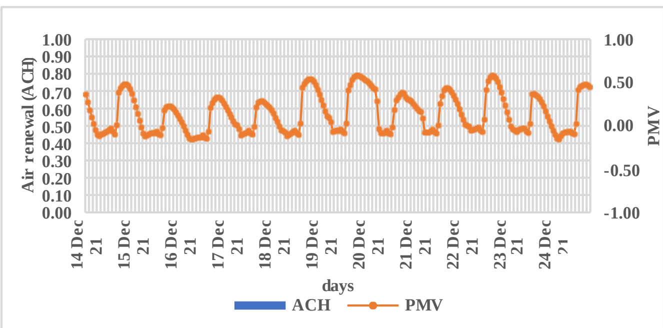


Fig. 10 Comparison between air renewal and PMV

Third scenario: simulation considering exclusive natural ventilation and full occupancy in selected days

The natural ventilation provided to the Technological University of Panama office was also evaluated to assess whether it is possible to provide sufficient air quality to the workers. This scenario, like the previous one, was simulated considering a total occupation on the days selected for the study. In Fig. 11 air renewal rates are compared with the temperature inside the office. Air changes rates, ranged from 0.69 ACH to 0.71 ACH, similarly to the first scenario with closed doors and windows. The temperature, on the other hand, was maintained between 25 °C and 29 °C approximately. Throughout days 14, 15, 16, 17 the temperature increased in the office if the ACH also increased. The rest of the days, there was no characteristic pattern, so no relationship was established between the ACH and the interior temperature. It should also be noted that the temperature inside the office, increased from the time the workers began their workday until they finished their job schedule. After being unoccupied, the temperature dropped to around 25°C every day. This indicated that the interior temperature could increase due to the heat generated by the people who occupied the space.

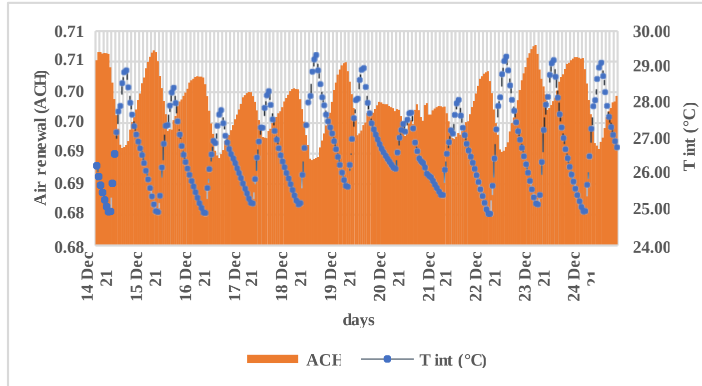


Fig. 11 Comparison between air renewal and indoor air temperature

In Fig. 12, the CO_2 concentration is compared with the indoor temperature. In periods where the office has no occupants, the CO_2 concentration remains around the 400-ppm recorded from outside air. Once the workday begins, the concentration of CO_2 increases gradually, reaching its maximum until the end of the working day. This pattern is repeated the 10 days analysed. It is noteworthy from this analysis the proportional relationship between the CO_2 concentration and the interior temperature. At the time of entry, the interior temperature increases as well as the carbon dioxide levels. Also, after the time of exit, the concentration of carbon dioxide decreases as interior temperature does. A similar result was presented in the study by [7]. Their results indicated that a higher CO_2 emission rate was registered at the higher temperature, at which the subjects were warm, and a lower emission rate in all conditions in which the background CO_2 concentration increased.

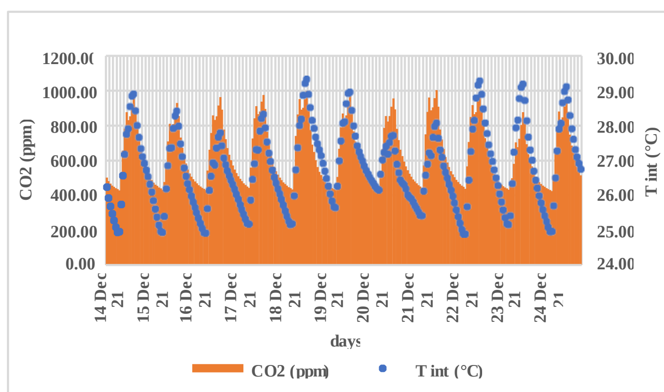


Fig. 12 Comparison between CO_2 concentration and indoor air temperature

The comparison between the indoor air renewal rates and the CO_2 concentration is shown in Fig. 13. The air renewal rates range from 0.70 to 0.71 ACH in the hours when the office was not occupied. Once the staff starts their work, the air renewal rates decrease inside the office and the concentration of carbon dioxide increases considerably. This inversely proportional behaviour occurs during the 10 days of study. This indicates that the air exchange rate produced by natural ventilation, are not enough to reduce the concentration of carbon dioxide in the office, however, none of the days did the concentration exceed

acceptable air quality.

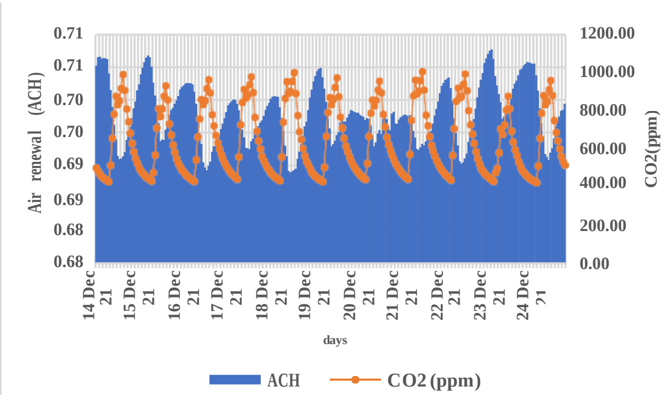


Fig. 13 Comparison air renewal and CO_2 concentrations

Next, thermal comfort was compared with indoor air renewal rates in Fig 14. In this scenario, the occupants are obviously dissatisfied with the thermal conditions. During the morning hours, their thermal comfort was recorded as "neutral" but as the hours of the day progressed, the thermal comfort was recorded as slightly warm until the end of the working day. This pattern was also repeated the 10 days, which indicates that, comparing to Fig. 11, at temperatures between 25 °C and 27 °C, the employees will be able to work thermally comfortable, but when exceeding this range, it is possible that they may reflect thermal unconformity.

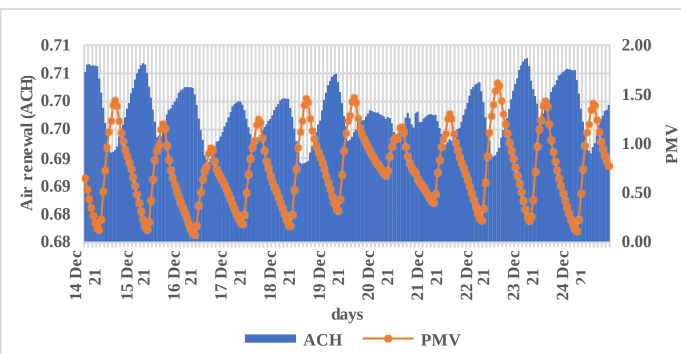


Fig. 14 Comparison between air renewal and PMV

Finally, the indoor air renewal rates were compared with the adaptive model at 80% acceptability in Fig 15. For this analysis, a repetitive pattern was determined on the days that were studied: during the hours of occupation, the model obtained values of "1", which indicated that at all workhours the employees were thermally satisfied. The points where values of "-1" were recorded, were the hours in which the office had no registered occupancy, including lunch hour.
Although indoor air renewal rates remained relatively low, this model reflects thermal comfort.

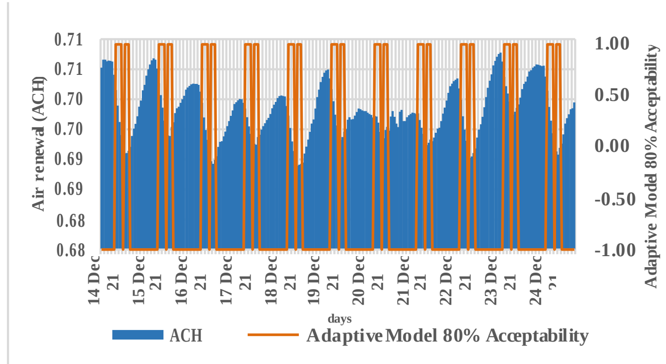


Fig. 15: Comparison between air renewal and adaptive model 80% acceptability

IV. Conclusions

The effect of the indoor environment on people's life is an actual concern since we spend at least 70% in indoor spaces and indoor air quality can impact health, performance and even learning outcomes as widely documented by many studies. On issues related to work or job performance, office employees usually spend at least eight hours a day in closed spaces. This study aimed to evaluate the performance of ventilation in an office with mechanical ventilation using a split air unit to ensure optimal air quality. The evaluation was carried out considering the air renewal rates and thermal comfort indicators.

The results showed that, with the use of mechanical ventilation, the quality of the indoor air was considerably acceptable, as well as the thermal comfort, since on all the days analyzed, the thermal comfort remained "neutral". An advantage of the split units is that the occupant could control the temperature to his preference so that most of the time, they remained thermally comfortable. However, since the split units do not have air renewal mechanisms, but rather are based on recirculating 100% of the air, no indoor air change rates were recorded in the office. For this reason, there were periods when CO_2 exceeded the established limit of 1000 ppm, so it is recommended to have air exchange devices in spaces where there are no fresh air inlets or opening windows to ensure airflow inside the closed space; time of fresh inlets and percentage of the windows opened must be studied to ensure safety and efficiency of air conditioning equipment. With this, it can be possible to guarantee the movement of air within the space and thus reduce CO_2 concentrations. Regarding natural ventilation, the results indicated that it is possible to maintain a high quality of indoor air with only the total opening of doors and windows, however, the use of natural ventilation does not provide more hours where people can feel thermically satisfied, therefore, the exclusive use of mechanical ventilation is recommended to ensure air quality and longer periods of thermal comfort.

Assessing indoor air quality considering thermal comfort ensures positive responses from the occupants who will remain in the spaces evaluated. To achieve desired ventilation and indoor air quality, on-site monitoring using sensors should be considered important to reduce contaminant levels. In addition to temperature sensors, for more precise controls the use of CO_2 sensors is recommended.

The use of software that use computational fluid dynamics (CFD) made possible to address the complexity of natural ventilation, predict mechanical ventilation and even the response of people inside buildings with thermal comfort indicators. However, many parameters must be considered when evaluating ventilation performance with this type of programming. It is recommended to start with characterizing the specific environmental conditions of the building to be evaluated, including the geographical location, solar incidence through the year, wind direction, the size of the spaces, building materials and the type of activity that people carry out in the place of study. Considering the above-mentioned parameters will allow more precise results when evaluating the performance of ventilation in buildings.

This study remains as evidence of the relevance of indoor air quality in the midst of a global health crisis such as COVID-19, where it is essential to ensure safe and, above all, healthy spaces for people who work in any type of facility (including those of health services): from offices, schools, universities and any type of building in the service or commercial area.

ACKNOWLEDGMENT

The authors would like to thank the Faculty of Mechanical Engineering within the Technological University of Panama for their collaboration. Part of this publication has received funding from the National Secretariat of Science, Technology, and Innovation (SENACYT) under the project code FID18-056, and the National Research System (SNI).

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