Enhancing indoor air quality and occupant well-being in Split Air-conditioned bedrooms through integrated ventilation

Nilabhra Mondal[1], Ajith Nair[1], Krithika Panicker[1], Prashant Anand[1]*, Ardeshir Mahdavi[2]
1: IIT Kharagpur, Kharagpur, India; 2: TU Graz, Graz, Austria
mondal.nilabhra@gmail.com

Abstract

Maintaining Indoor Air Quality (IAQ) and ensuring the well-being of individuals in split air-conditioned indoor spaces such as bedrooms can be challenging, primarily due to the increased risk of airborne infection transmission and high CO2 concentration. To address these issues, pertinent guidelines recommend ensuring adequate ventilation with fresh air, as it effectively mitigates the spread of indoor pollutants. However, split air-conditioned spaces often lack a continuous supply of fresh air. The resulting indoor air quality deterioration can cause occupants to resort to opening doors and windows. This, in turn, can result in an unnecessary increase in heating or cooling energy use. The objective of this study is to address the limitations of existing air cleaning and airconditioning systems, which may include insufficient ventilation, excessive recirculation of indoor air, limited effectiveness, and the inability to dynamically respond to indoor pollutants in an energy-efficient manner. It has been observed that occupant's open doors and windows for fresh air ventilation in response to a feeling of stuffiness for a considerable fraction of the total operational hours of a split AC in a bedroom. The present study suggests that by integrating ventilation and air-conditioning in a coordinated manner, IAQ and hence occupants' well-being in bedrooms can be enhanced in an energy-efficient manner.

Keywords - Bedroom Ventilation, CoVID-19, Split AC, Energy Efficiency, Occupant Behaviour, IAQ

1. Introduction

The demand for energy consumption in India has surged due to urbanization and population growth. Buildings are significant energy consumers, especially for lighting, heating, cooling, and appliances. Efficient energy use is crucial to curb consumption. The rapid growth of the building sector in India is anticipated to lead to a substantial increase in energy use [1]. Moreover, urban densification has posed challenges to the liveability and well-being of urban populations. The recent Covid-19 pandemic has underscored the critical nature of health outbreaks in densely populated indoor spaces such as bedrooms in residences, dormitories, hostels, and apartments. The virus can spread via aerosols or airborne infections, leading to rapid clusters of infection. Furthermore, poor indoor air quality has additional adverse impacts on human health [2-7].

To address this, a novel Fan Filter Unit (FFU) technology proposed in a previous study can be utilized, as this technology can mitigate Covid-19 transmission in crowded indoor spaces by enhancing ventilation with clean outdoor air [8]. However, the key energy efficiency operational concept of Split AC is the airtightness of indoor spaces, and bringing hot air from outdoors to indoors can lead to reduced energy efficiency, as more energy is required for cooling. Additionally, numerous studies in the past have tried to address efficiency within existing systems through demand-controlled ventilation to occupancy-based AC system control [2]. However, air conditioning has operational constraints such as ventilation issues prevalent in both residential and commercial spaces, influencing indoor air quality by modulating temperature, humidity, and CO_2 concentration. Thus, even modern buildings, designed with energy efficiency in mind, can limit outdoor air exchange, resulting in the accumulation of pollutants, discomfort, and respiratory issues. However, achieving the best possible energy efficiency without compromising indoor air quality is always challenging. Therefore, there is a need to investigate the trade-off between energy performance and indoor air quality to optimally operate building systems such as Split AC in an airtight bedroom [2]. It has been hypothesized that occupant's open doors and windows for fresh air ventilation in response to a feeling of stuffiness for a considerable fraction of the total operational hours of a split AC in a bedroom.

The objective of this study is to identify the occupants' energy usage behaviour by analysing window/door operations and AC usage, using indoor and outdoor environmental data such as CO2 concentration and Dry Bulb Temperature (DBT) data. A rule-based method is employed to understand the window/door operation behaviour using collected data and to identify instances of energy wastage. Through behaviour modification, the potential for energy savings is also assessed. The outcome of this study can prove valuable for bedrooms or similar air-tight spaces where split AC units operate without proper ventilation provisions, aiming to enhance indoor air quality for the occupants' health and well-being.

2. Methods

A three-step methodology has been adopted in this study. In the first step, time series environmental data of indoor and outdoor CO_2 concentrations and air temperature (DBT) were collected for 2 months (15/02/2023-15/04/2023). This included time series occupant behavioural data for window and door opening and closing, along with time series data of the Split AC's on and off status, all obtained from the bedroom of a 1BHK residential apartment. Moving to the second step, the rule mentioned in Table 1 was utilized to identify window or door opening and Split AC's on and off behaviour.

Data status	Occupancy Status	Window/Door Status	Split AC Status
Indoor CO_2 > Outdoor CO_2 + Threshold (150 ppm based on sensor accuracy)	Yes	Closed	NA
Indoor CO_2 = Outdoor CO_2 + Threshold (150 ppm based on sensor accuracy)	Yes/No	Open/Closed	NA
Indoor DBT < Outdoor T + Threshold (3°C)	Yes/No	NA	AC ON

Table 1: Rule-based predictions for window opening and closing

This was done by computing the differences between indoor and outdoor CO_2 concentrations as well as indoor and outdoor temperatures. Proceeding to the third step, a comparison was made between the actual occupant behaviour and the rule-based occupant behaviour for window/door opening/closing and AC on/off activities. For the collection of indoor and outdoor environmental data, Testo 160 IAQ sensors were employed.

3. Results

- Overview of data:

The outdoor concentration values were mostly found stable, ranging between 400-450 ppm. In contrast, indoor concentrations in the bedroom were found varying from 400 ppm to 2800 ppm, depending on the presence of indoor CO_2 generation sources. Further, the outdoor DBT during the study period ranged between 22°C and 33°C. However, the indoor DBT was found mostly higher and ranging from 26°C to 32°C. However, instances where the indoor DBT pattern deviated from the outdoor trend were primarily observed when the split AC was in operation.

- Identification of No occupancy and AC usage hours:

Based on on-the-ground truth, the time-series data for CO_2 concentration and temperature profiles in Figure 3 have been annotated to indicate periods of no occupancy and usage of the split AC.

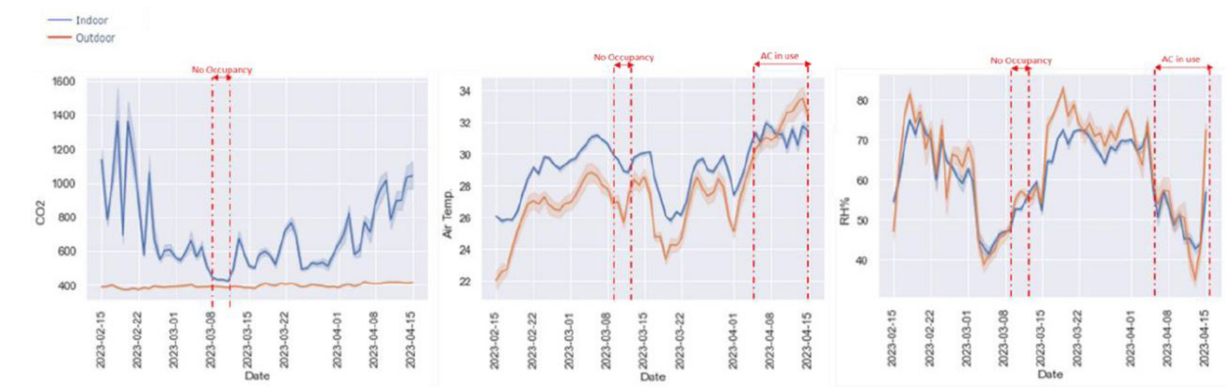

Figure 3: CO2 concentration and temperature profiles

- Identification of AC usage during no occupancy and window open hours:

Moving on to Figure 4 and 5, after excluding the ground truth data and relying solely on rule-based analysis, it was determined that out of the total instances occupancy status and window/door closed status was confirmed for 3391 instances, while for 2384 instances it was uncertain whether occupants were present or not and window/door was open or not. Furthermore, since the rate of CO_2 concentration decay is generally higher than the rate of generation [9], this method may estimate instances in a more conservative manner rather than leading to overestimation. The decrease in CO_2 concentration could be attributed to either the absence of occupants or the opening/closing of doors and windows. In both cases, whether occupants are absent or doors/windows are open, it is evident that energy is being wasted if the split AC is on. The main limitation with this method could be situations where occupants have left the room, but the delay in the decrease of concentration is solely due to the window/door being closed. However, based on ground truth, the likelihood of this scenario is negligible. To address this issue, a more detailed data assessment is needed. However, if this scenario exists, further assessment should involve analysing the slope of the time series difference between indoor and outdoor CO_2 concentration data to determine if there is occupancy or the status of windows/doors (open versus closed) is the key factor. If the slope of the difference between indoor and outdoor concentration is positive, it suggests that the window/door can be considered closed, indicating occupancy. Still, this interpretation depends on numerous factors, including the rate of infiltration/exfiltration and airtightness of the bedroom, which can be only confirmed through experiments such as the blower door test.

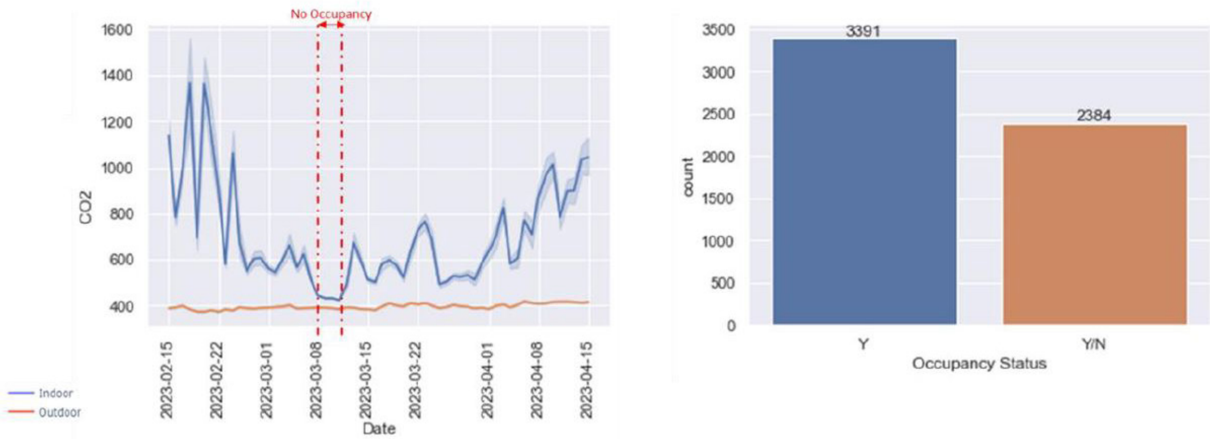

Figure 4: Occupancy presence/status identification

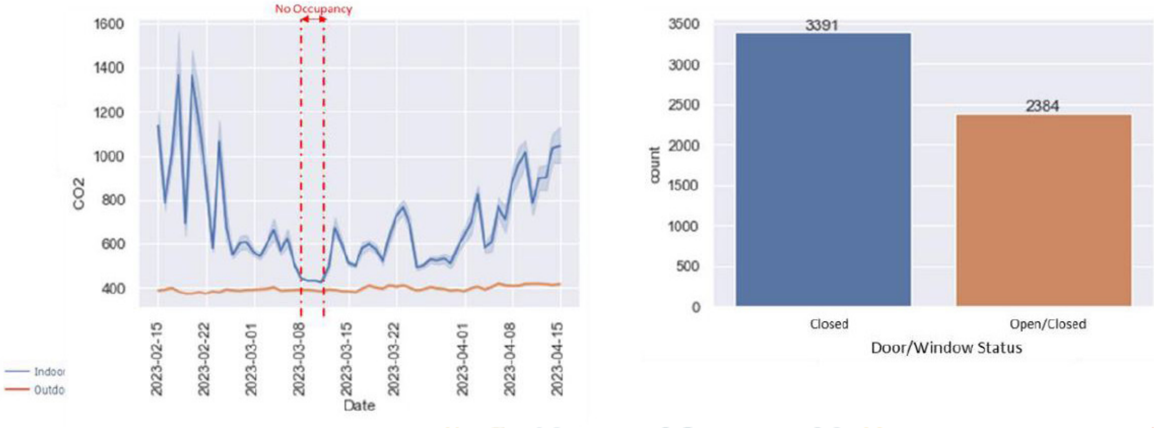

Figure 5: Window/Door Open/Close status identification

Furthermore, utilizing a rule-based approach to AC usage based on DBT, the on and off status of the AC is plotted against the air temperature profile in Figure 6. It was assumed that if the indoor temperature is consistently 3°C or lower than the outdoor temperature, the air conditioner (AC) is operational. This assumption is based on past observations, indicating that even when the AC is not running, the room maintains, primarily due to its thermal mass, a temperature that, as compared to outdoor temperature, is up to 3 K lower during summer and up to 3 K higher during winter. Among the total 227 instances when the AC was found to be on, in 64 instances, either doors or windows were open, or there was no evidence of occupancy. This indicates a potential for energy savings if the operation of doors and windows could be synchronized with the usage of the split AC.

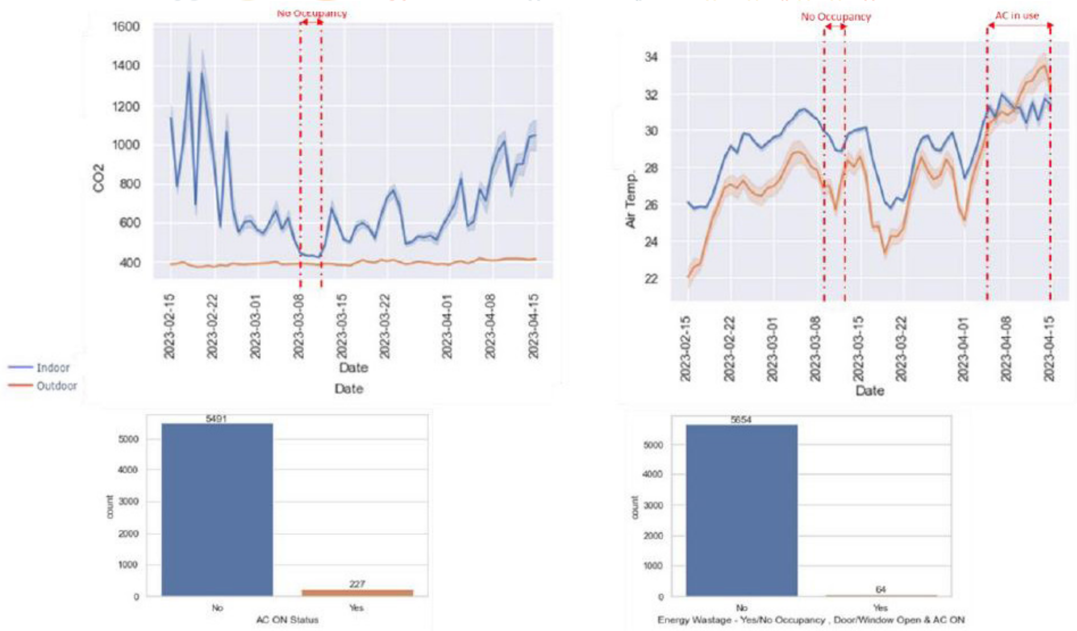

Figure 6: AC usage and corresponding window/door opening/closing behaviour

However, due to limitations in the collected data, accurately identifying energy wastage scenarios is challenging. For example, instances where windows and doors are open may be due to demand for fresh air ventilation as occupants might feel the space is stuffy. Therefore, a comprehensive investigation is needed to understand the reasons behind occupants' door/window opening and closing behaviour. Another limitation of this rule-based study is the consideration of CO2 concentration without accounting for time lags. There could be cases where occupants have left the room, but the delay in concentration decay is solely due to the room's door/window being closed. To address this issue, a more detailed data assessment is necessary. This should include the analysis of the slope of the time series difference between indoor and outdoor CO2 concentration data to infer the presence/absence of occupancy or the open/close status of windows/doors. Thereby, if the slope of the difference between indoor and outdoor concentration is positive, the window/door can be considered to be closed and occupants can be assumed to be present.

5. Conclusion

Maintaining good indoor air quality in split air-conditioned spaces such as bedrooms is crucial for people's health. However, these spaces often lack sufficient fresh air ventilation, leading to a decline in indoor air quality. Consequently, people frequently resort to opening doors and windows to introduce fresh outdoor air into the environment. This practice inadvertently results in the split air conditioner consuming more energy to maintain the room's cooling. Upon evaluating indoor and outdoor CO_2 levels, along with temperature data, it can be shown that individuals commonly open doors and windows while the split AC is operational. Although accurately quantifying the energy wastage is challenging due to data limitations, it is evident that significant energy savings can be achieved by influencing occupants' behaviour with regard to building systems operation. Nevertheless, this shift may potentially compromise indoor air quality (IAQ). This underscores the necessity for a smart ventilation system that collaborates with the split AC, automatically detecting deteriorating IAQ and supplying the minimal necessary ventilation to uphold occupants' health and well-being while optimizing energy usage. This insight thus suggests that orchestrating a coordinated relationship between the operation of the air conditioner and the provision of fresh air can not only improve indoor air quality in bedrooms and enhance occupants' well-being, but also reduce energy consumption.

6. Acknowledgements

The resources utilized for this study are supported through the Sponsored Research and Industrial Consultancy (SRIC) grant No: IIT/SRIC/AR/MWS/2021-2022/057, the Department of Science and Technology grant No. DST/IC/Austria/P-15/2021, OeAD - International Cooperation in Higher Education/ MPC /Programme WTZ (Project: IN 06/2022), and the SERB grant No. IPA/2021/000081.

7. References

[1] Balaji Kalluri, Jay Dhariwal, Pandarasamy Arjunan, Prashant Anand, and Chirag Deb. 2022. The Way Forward for Building Energy Benchmarking in India. In The 9th ACM International Conference on Systems for Energy-Efficient Buildings, Cities, and Transportation (BuildSys '22), November 9–10, 2022, Boston, MA, USA. ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/3563357.3566141

[2] Anand, P., Cheong, D., Sekhar, C., 2022. Science of the Total Environment A review of occupancy-based building energy and
IEQ controls and its future post-COVID. Science of Total Environment 804, 150249 https://doi.org/10.1016/j.scitotenv.2021.150249

[3] A.N. Nair, P. Anand, A. George, N. Mondal, A review of strategies and their effectiveness in reducing indoor airborne transmission and improving indoor air quality, Environ Res. 213 (2022), https://doi.org/10.1016/j.envres.2022.113579.

[4] Megahed, N.A., Ghoneim, E.M., 2021. Indoor Air Quality: rethinking rules of building design strategies in post-pandemic architecture. Environ. Res. 193, 110471 https://doi.org/10.1016/j.envres.2020.110471.

[5] Melikov, A.K., 2020. COVID-19: reduction of airborne transmission needs paradigm shift in ventilation. Build. Environ. 186, 19– 21. https://doi.org/10.1016/j.buildenv.2020.107336.

[6] Melikov, A.K., Ai, Z.T., Markov, D.G., 2020. Intermittent occupancy combined with ventilation: an efficient strategy for the reduction of airborne transmission indoors.Sci. Total Environ. 744 https://doi.org/10.1016/j.scitotenv.2020.140908.

[7] Miller, S.L., Nazaroff, W.W., Jimenez, J.L., Boerstra, A., Buonanno, G., Dancer, S.J., Kurnitski, J., Marr, L.C., Morawska, L., Noakes, C., 2021. Transmission of SARS-CoV-2 by inhalation of respiratory aerosol in the Skagit Valley Chorale superspreading event. Indoor Air 31, 314–323. https://doi.org/10.1111/ina.12751.

[8] K.W. Tham, G.K. Parshetti, P. Anand, D.K.W. Cheong, C. Sekhar Performance characteristics of a fan filter unit (FFU) in mitigating particulate matter levels in a naturally ventilated classroom during haze conditions Indoor Air, 31 (3) (2021), pp. 795806, 10.1111/ina.12771.

[9] A. Kabirikopaei, J. Lau, Uncertainty analysis of various CO2-Based tracer-gas methods for estimating seasonal ventilation rates in classrooms with different mechanical systems, Build. Environ., 179 (2020), Article 107003