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Assessing the Air Change Rates Pre and Post Residential Energy Retrofit Using CO_2, Temperature, Relative Humidity and Motion Sensors

Sameeraa Soltanian-Zadeh
Student Member ASHRAE

Shayan Mirzabeigi
Student Member ASHRAE

Bess Krietemeyer, PhD

Jianshun Zhang
Fellow ASHRAE

ABSTRACT

Air Change Rate (ACR) is a key parameter influencing building energy performance and the indoor environment. An accurate estimate of ACR can inform building envelope retrofit decisions to improve airtightness and Indoor Air Quality (IAQ). However, windflow and interior-exterior temperature differences make the accurate measurement of the ACR challenging. Conventional testing approaches present certain drawbacks limiting their applicability in various buildings. We studied the advantages and disadvantages of various methods including a steady-state approach where the CO_2 level is relatively constant, a decay method, a transient CO_2 mass balance method, and air moisture balance method for estimating ACRs. These methods were compared with measurements in two single-family attached residential apartments in which indoor environmental data (CO_2, temperature, and humidity) and motion data were collected for pre- and post-retrofit conditions to assess the effectiveness of an integrated retrofit solution on the IAQ and energy performance. The study also compared ACRs in two bedrooms and the whole apartment unit, revealing significant spatial differences when the bedroom doors were closed. The results also revealed much higher ACRs during the occupied period compared to the unoccupied period for the pre-retrofit conditions where no mechanical ventilation was available due to opening of windows and doors by occupants as detected by motion sensors. For post-retrofit, more stable ventilation rates were achieved by the energy recovery ventilator. The findings for an end apartment unit and a middle apartment unit showed a 56% and 43% reduction in ACRs in the living room after the retrofit, respectively. This study contributes to a more accurate assessment of the post-retrofit condition relative to a baseline using the ACR metric, considering the important impact of the occupants and their preferences for prioritizing IAQ or thermal comfort.

INTRODUCTION

Sameeraa Soltanian-Zadeh is a PhD student in the Department of Mechanical & Aerospace Engineering, Syracuse University, Syracuse, NY. **Shayan Mirzabeigi** is an Assistant Professor in the Department of Sustainable Resources Management, State University of New York College of Environmental Science and Forestry, Syracuse, NY and a PhD student in the Department of Mechanical & Aerospace Engineering, Syracuse University, Syracuse, NY. **Bess Krietemeyer** is an Associate Professor at the School of Architecture at Syracuse University. **Jianshun Zhang** is a Professor in the Department of Mechanical & Aerospace Engineering, Syracuse University, Syracuse, NY.

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Ensuring optimal ventilation is critical for maintaining Indoor Air Quality (IAQ) and energy efficiency in residential buildings. A key metric in evaluating ventilation performance is the Air Change Rate (ACR), defined as the airflow rate of outdoor air supplied to the space devided by the space volume. Bringing in outdoor air serves to dilute and remove indoor pollutants and moisture, and maintaining adequate ACRs is essential to safeguard Indoor Environmental Quality (IEQ) and avoid negative outcomes such as health concerns, discomfort, reduced productivity, and increased absenteeism (Sundell et al. 2011).

As buildings are retrofitted to improve energy performance, understanding differences in air change rates is essential (Mirzabeigi et al. 2024). Retrofitting efforts that aim to reduce heat loss through improved insulation and air sealing often inadvertently affect ventilation performance. Therefore, quantification of ACR before and after the retrofit provides critical input for both the energy and environmental outcomes of such interventions. However, windflow and interior-exterior temperature differences often make the accurate measurement of the ACR challenging (Batterman 2017). Conventional methods for measuring ACR include blower door tests (ASTM 2010), and tracer gas techniques (Sherman 1990), which, while reliable, are often invasive, expensive, and limited to short-term assessments, limiting their applicability in various buildings.

In recent years, there has been growing interest in using environmental sensor data to develop inverse models for estimating ACR (Xiong et al. 2021). These methods, leveraging data on CO_2 levels, temperature humidity, offer a non-invasive, continuous, and cost-effective alternative (Li, Hong, and Sofos 2019). Occupant-generated CO_2 has been widely used as a tracer gas for estimating the ACR. CO_2-based methods are convenient since CO_2 is inert, emission sources are present in all buildings and usually well dispersed throughout occupied spaces. CO_2-based methods are typically categorized based on occupancy stages or the pattern of concentration changes (Carrer et al. 2015; Batterman 2017). These categories include the build-up phase, steady-state, and decay methods. Additional methods involve pulse injections, hybrid approaches that integrate multiple occupancy phases, and transient mass balance models capable of capturing both varying occupancy phases and complex occupancy patterns. These methods have different assumptions, strengths, and limitations (Hänninen 2013). Water vapor generated by occupant activities can also serve as another opportunistic tracer gas. In a study, experiments using the decay of humidity ratio were performed in three different buildings to assess the feasibility of using water vapor for estimating ACRs, and the method was validated using the nitrous oxide (N_2O) (Giesbrecht, Curtis, and Viraraghavan 1999). The use of these methods is not without limitations. CO_2 can originate from various sources, and outdoor CO_2 concentrations fluctuate with time and location—affected by factors like traffic emissions and daily cycles, especially in urban areas (George et al. 2007). Furthermore, CO_2 generation indoors varies with occupant number and activity level and is typically estimated using demographic and activity-based models rather than direct measurement. Additionally, sensor accuracy also plays a role (Yasuda, Yonemura, and Tani 2012).

This paper focuses on studying various methods including a steady-state approach where the CO_2 level is relatively constant, a decay method following the leave of occupants from the space, a transient CO_2 mass balance method, and air moisture balance method for estimating ACRs, assisted with motion sensors for door and window openings. It presents a comparative evaluation of four ACR estimation methods using environmental and motion sensor data in two occupied, single-family attached apartments, assessing their effectiveness in real-world, dynamic occupancy conditions. The study assesses ACRs for pre- and post-retrofit conditions to assess the effectiveness of an integrated energy retrofit solution.

METHODOLOGY

This section provides an overview of the data used in this study and describes the data analysis. It presents a detailed explanation of the methodological framework developed for ACR estimation using indoor environmental and motion sensor data. Each method is outlined in terms of its assumptions, data inputs, and computational process.

Description of the Building and Retrofit Systems

This study was conducted in a single-family attached residential building located on Syracuse University's campus, where monitoring systems were installed in the building to assess the impact of a building retrofits on IAQ and energy performance. The building area is 608.42 m^2 with eight two-bedroom apartment units. It was originally constructed in 1972-1973. The exterior walls consist of pre-cast concrete walls and wood-framed walls. While the apartments have electric resistance baseboard as their heating systems, there is no cooling and mechanical verntilation system, and makeup air is provided by

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infiltration. The project's whole-building retrofit approach includes highly insulated prefabricated exterior building envelope panels for improved thermal performance and airtightness at the walls, roof, and foundation, and a high-efficiency integrated mechanical pod solution with real-time performance monitoring for heating, cooling, ventilation, and domestic hot water. The building envelope panels consist of a prefabricated, reinforced, insulated Expanded Polystyrene (EPS) foam exterior panel system with air-sealing at seams, and penetrations for mechanicals, windows, doors, foundation, and sealant and backer rod for continuous seal for air and moisture barrier. The mechanical system utilizes a hydropod with high-efficiency heating, cooling, hot water, using air-to-water heat pump and energy recovery ventilation. The heating and cooling provided by the mechanical pod systems are distributed to fan coil units at each bedroom and living room.

Data Collection

The monitoring period began twelve months prior to the planned retrofit and continued through the post-retrofit phase. The building was equipped with various sensors for both indoor and outdoor environmental monitoring, with a specific focus on two research units within the building. Various indoor and outdoor environmental parameters were continuously measured using advanced monitoring equipment and our established comprehensive monitoring framework (Mirzabeigi, Soltanian-Zadeh, et al. 2024). Indoor parameters included air temperature, relative humidity (RH), carbon dioxide (CO_2) concentrations, total volatile organic compounds (TVOC), and particulate matter (Figure 1). Additionally, motion sensors were deployed to monitor occupancy and activity, along with door/window status sensors to track window and door open and close activity. Outdoor parameters measured included temperature and RH, CO_2, solar radiation, wind intensity and direction, and particulate matter concentrations.

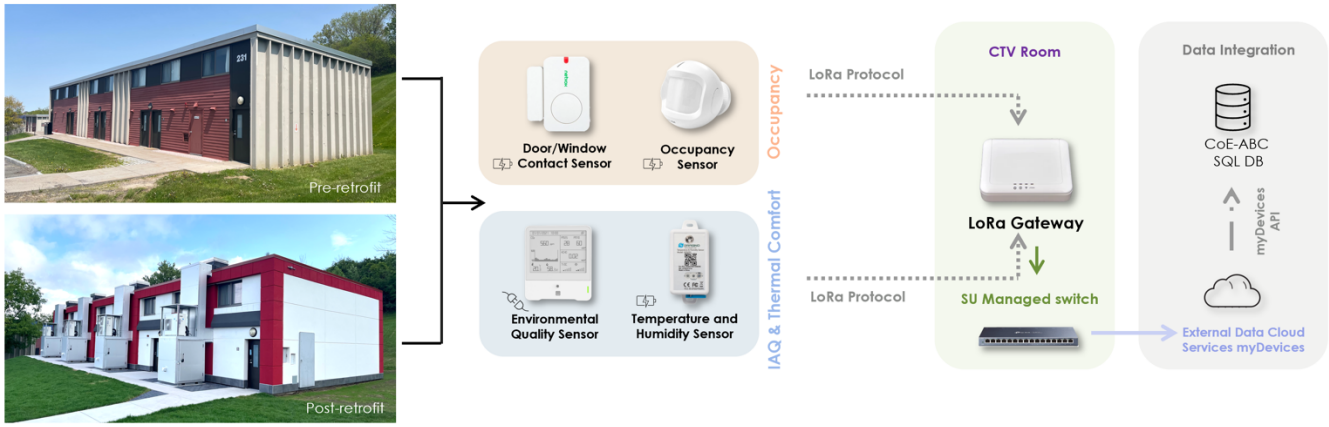

Figure 1. Real-time performance monitoring diagram.

Air Change Rate Estimation Methods

Raw sensor data, particularly from window/door contact sensors, were processed to generate time series data for further analysis. This allowed for the assessment of the relationship between window/door status activity and changes in indoor environmental conditions, such as CO_2 concentrations. CO_2 levels were chosen as a key indicator of ventilation, allowing for the evaluation of ACR dynamics. The study aims to focus on estimating air change rates by extracting the naturally occurring indoor CO_2, humidty, and motion data in residences for comparison of pre- and post-retrofit conditions. Methods using CO_2 as a tracer gas are based on a mass balance model assuming perfect mixing in the space.

$$V\frac{dC}{dt} = E + QC_R - QC \quad (1)$$

where V = room volume (m^3); C = indoor CO_2 concentration ($mg \cdot m^{-3}$); C_R = outdoor CO_2 concentration ($mg \cdot m^{-3}$); Q = flow rate of outdoor air ($m^3 \cdot h^{-1}$), and E = CO_2 emission rate of indoor sources ($mg \cdot h^{-1}$). Generally, E is calculated as n GP, where n = number of persons in the room, and GP = CO_2 generation rate per person ($L \cdot h^{-1}$). The air change rate, ACR (h^{-1}), is Q/V. Several methods were employed to estimate the ACR in the monitored units. The transient CO_2 mass balance method is the

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dynamic method (time-resolved occupancy) that accounts for fluctuating CO_2 levels and air exchange (numerical solution), allowing for a more precise estimate of the ACR over time.

For the steady-state approach, it assumes that CO_2 concentrations remain relatively constant over compution time, providing an estimate of the ACR based on steady ventilation conditions. In this case, setting the left side of Equation (1) to zero, we have:

$$ACR_s = Q/V = E/[V(C_s - C_R)] \quad (2)$$

where subscript "s" is used to represent "steady-state" condition.

Decay method can be used when a space is vacated after occupancy, and the wind is stable. The decay air change rate for a zone can be estimated using two CO_2 measurements (Batterman 2017).

$$ACR_d = 1/\Delta t \ln[(C_1 - C_R)/(C_0 - C_R)] \quad (3)$$

where Δt = duration of measurements (h); C_0 and C_1 = measured CO2 concentrations over the decay period (ppm); and C_R = outdoor CO_2 concentration (ppm). The reliability of the 2-point estimate can be evaluated by calculating an upper bound for the ACR, using the highest and lowest concentrations observed within a defined window around the target times, such as within ±1 hour of the nominal points.

For the air moisture balance method, the specific humidity is calculated based on dry bulb tmperature and RH. The air mass flow rate is calculated using the following equation and assuming a constant internal vapor generation rate and negligible sorption by materials in the space (Vivian et al. 2023).

$$G_a = \frac{G_v}{x_i - x_e} \quad (4)$$

where G_a = air mass flow rate (kg/h); G_v = internal vapor geenration (kg/h); x_i = indoor air specific humidity (kg_v/kg_a); and x_e = external air specific humidity (kg_v/kg_a). The air mass flow rate was then converted into air change rate by normalizing the data with respect to the building volume.

$$ACR = \frac{G_a}{\rho_a V} \quad (5)$$

where V = room volume (m^3); and ρ_a = air density ($kg \cdot m^{-3}$).

Data analysis was conducted using the Python programming environment, with packages such as NumPy and scikit-learn employed for the analysis. The correlation between indoor environmental parameters, such as CO_2 concentrations, and window/door status activity was assessed to understand how occupant behavior influenced air change rates.

RESULTS AND DISCUSSION

Air Change Rates Before and After Retrofit Using Various Methods

The results presented in this section are based on the application of four estimation techniques across various scenarios inclusing pre- and post-retrofit. This section is only limited to the analysis in one of the research units (A-8) to keep this paper short. Figure 2 shows example of analysis from the West and East bedroom of the unit A-8 (end partment unit) for the pre-retrofit. Figure 3 demonstrates the analysis from the same spaces for the post-retrofit condition. This gives the opportunity to compare the special variability across two bedrooms for pre-and post-retrofit condition. Examples of data usage for computing various methods have been highlighted in gray (unoccuplied - decay method), orange (steady-state method), and blue (example transient mass balance method). For each compution, those highlighte have been selected based on the status of occupancy and window and door status in that bedroom (and that of the other bedroom).

Table 1 summarizes the ACR values for the west bedroom in Unit 8, estimated using four different methods. The average ACR during unoccupied periods using the decay method dropped from 0.2426 h^{-1} pre-retrofit to 0.2059 h^{-1} post-retrofit. During occupied periods, both the transient mass balance and steady-state methods showed increased ACR values for the post-retrofit condition, reflecting more stable and enhanced ventilation provided by the ERV system. Specifically, ACR invreased from 0.5997 h^{-1} to 0.8251 h^{-1} using the mass balance method, and from 0.4841 h^{-1} to 0.9940 h^{-1} using the steady-state method. In agreement with the two previous methods, the moisture balance method also indicated an increase in post-retrofit ACR (from 0.4701 h^{-1} to 0.6410 h^{-1}), though with a larger variability, influenced by occupant activities such as cooking or showering.

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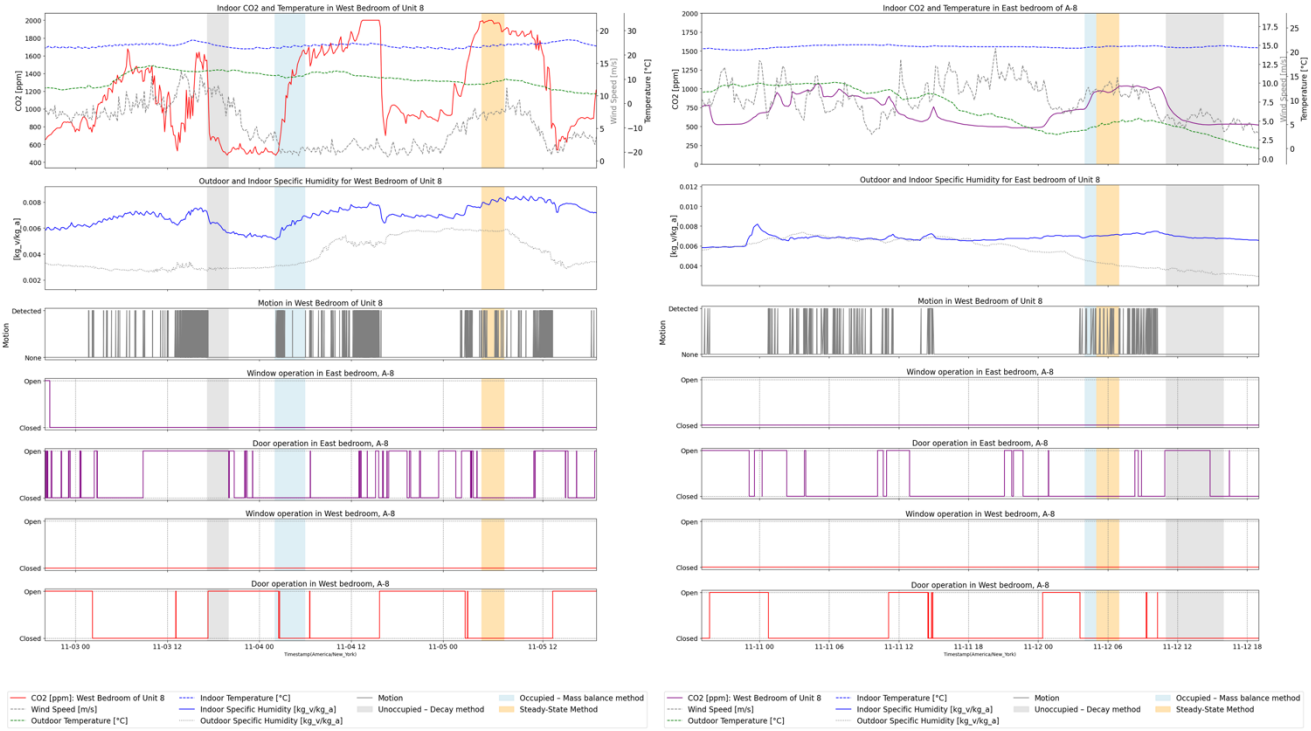

Figure 2. Example of analysis from the West and East bedroom of the unit A-8 for the pre-retrofit.

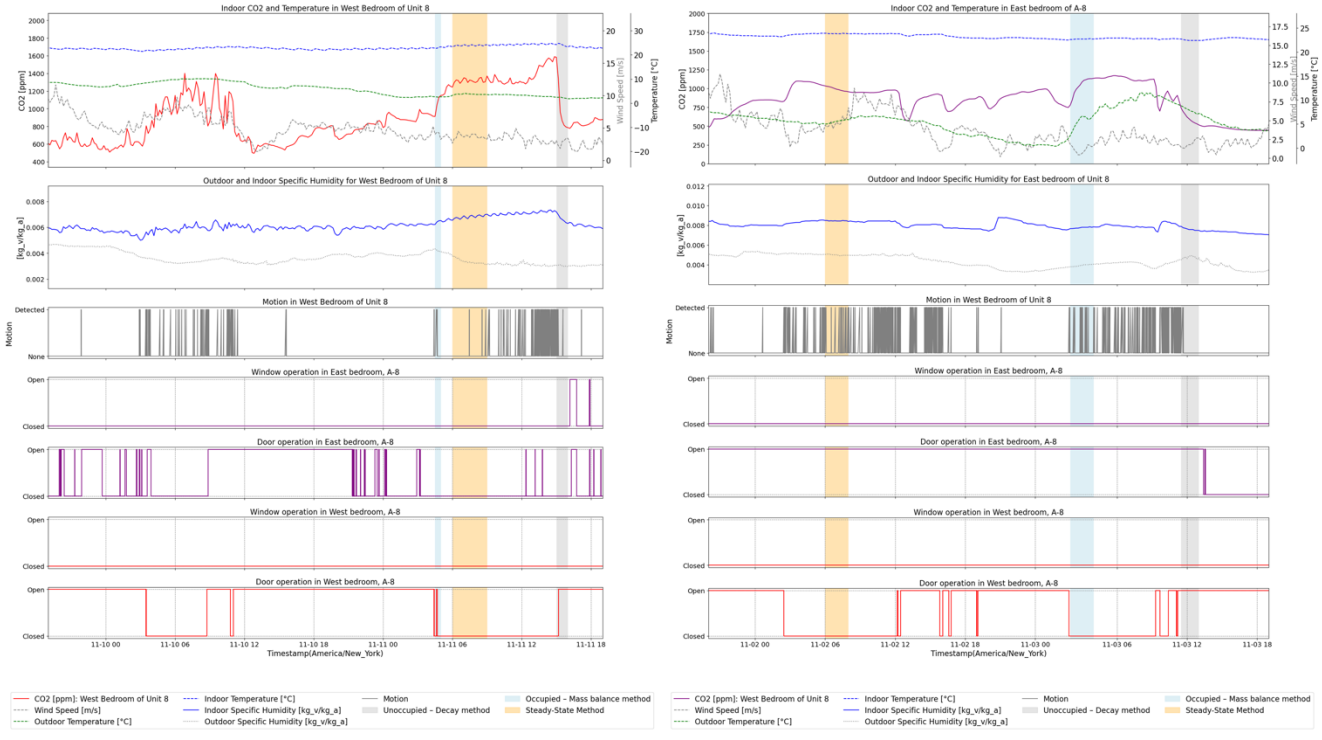

Figure 3. Example of analysis from the West and East bedroom of the unit A-8 for the post-retrofit.

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Table 1. Summary of ACR values in West Bedroom of Unit 8.

Estimated air change rates (1/h)	Unit 8 – West Bedroom – Pre	Unit 8 – West Bedroom – Pre	Unit 8 – West Bedroom – Post	Unit 8 – West Bedroom – Post
Method/Metric	**Mean**	**Std**	**Mean**	**Std**
Decay method (unoccupied)	0.2426	0.0722	0.2059	0.0501
Transient mass balance (occupied)	0.5997	0.1650	0.8251	0.1551
Steady-state (occupied)	0.4841	0.0353	0.9940	0.0136
Air moisture balance (occupied)	0.4701	0.0110	0.6410	0.0505

The transient mass balance method provided the most adaptable estimates under changing conditions and captured the dynamic behavior of indoor environments. The steady-state method worked effectively during stable periods but was sensitive to assumptions mentioned in the Methodology section. The decay method was straightforward but limited to clearly defined unoccupied periods with minimal airflow disturbances, in agreement with the literature, it underestimate the ACRs. The air moisture balance method showed promise but had higher sensitivity to variable internal humidity loads, and it is predicated value is also dependent on the assumption of constant internal vapor generation rate, that may change with different occupancy and activity. The analsysis showed a consistency in trend across all methods. However, there is a need to develop a hybrid ACR estimation framework considering occupied and unoccupied conditions for long-term evaluation of building performance.

Then, we looked at spatial variability in another research unit (A-7). Figure 4 shows example of CO_2 concentrations across various spaces with examples of motion (East bedroom and living room) for correlation (pre-retrofit). Examples of data usage have been highlighted in gray (unoccuplied - decay method), and blue (example transient mass balance method).

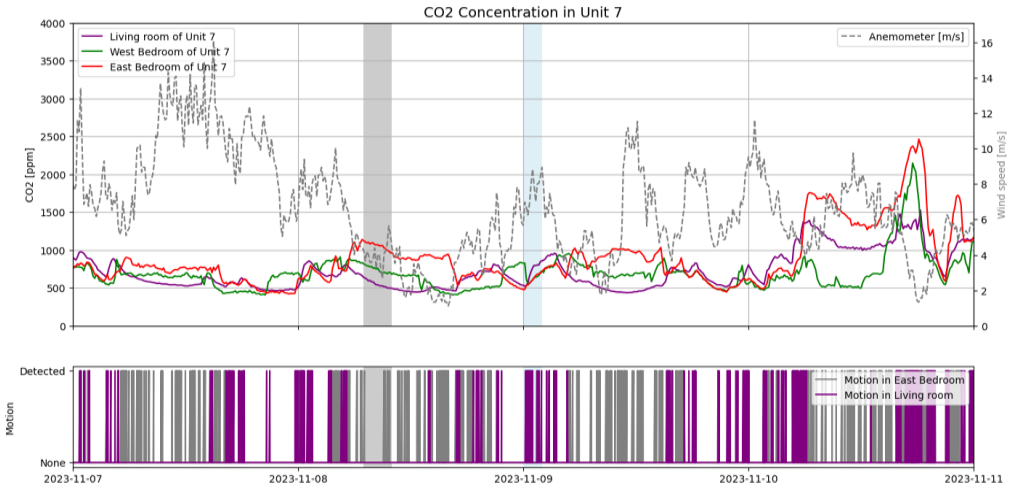

Figure 4. CO_2 concentrations across various spaces with examples of motion (East bedroom and living room).

Table 2 summarizes the mean ACR values of occupied condition for the various spaces in two units for the pre- and post-rerofit condition, calculated using the transient mass balance method. The findings for the end apartment unit (A-8) and the middle apartment (A-7) unit showed a 56% and 43% reduction in ACRs in the living rooms after the retrofit, respectively. On the other hand, the ACR in the bedrooms has increased, and the percentage change is provided in Table 2.

Table 2. Summary of ACR values for Pre- and Post-retrofit.

Table 2. Summary of ACR values for Pre- and Post-retrofit.

Estimated air change rates (1/h)	A-7 East Bedroom	A-7 West Bedroom	A-7 Living Room	A-8 East Bedroom	A-8 West Bedroom	A-8 Living Room
Pre-retrofit	0.42	0.45	1.48	0.41	0.59	1.63
Post-retrofit	0.70	0.68	0.84	0.62	0.83	0.72
Percentage of Change	67%	51%	-43%	51%	41%	-56%

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Occupant Behavior Impact

A key observation was that ACRs were notably higher during occupancy—approximately more than two times compared to unoccupied periods in pre-retrofit conditions, demonstrating the influence of occupant behavior on natural ventilation. However, post-retrofit, ACRs became more consistent, with less pronounced fluctuation due to the continuous operation of the ERV, and less occupant interaction with windows. Figure 5 shows a sample analysis for correlating CO_2, temperature and specific humidty with occupant presence (motion) and window and door operation status. The example of ACR calculation period is highlighted in gray, and the distribution of calculated ACR for the East bedroom of unit 8 is shown in Figure 6.

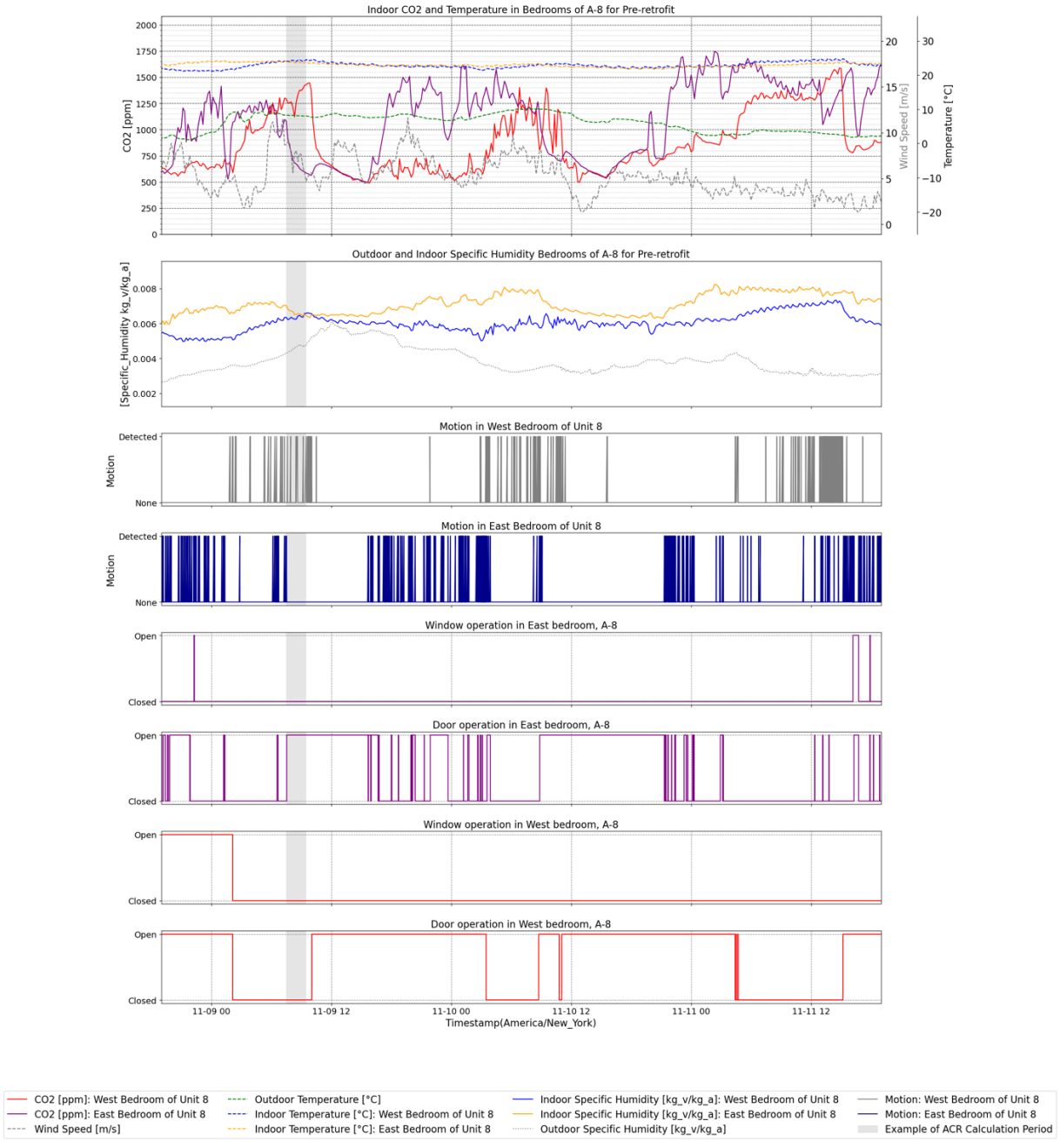

Figure 5. Sample plot for correlating CO_2, temperature and specific humidty with occupant presence (motion) and window and door operation status.

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Window status played a significant role in ACR variability. Data analysis revealed significantly higher ACRs when windows were open, especially pre-retrofit. For the post-retrofit, the data reported is only for the heating seson, and that is the reason that only closed window data was shown. For this period, even when windows remained closed, the ERV system ensured sufficient air exchange, reducing the need for occupant-mediated ventilation.

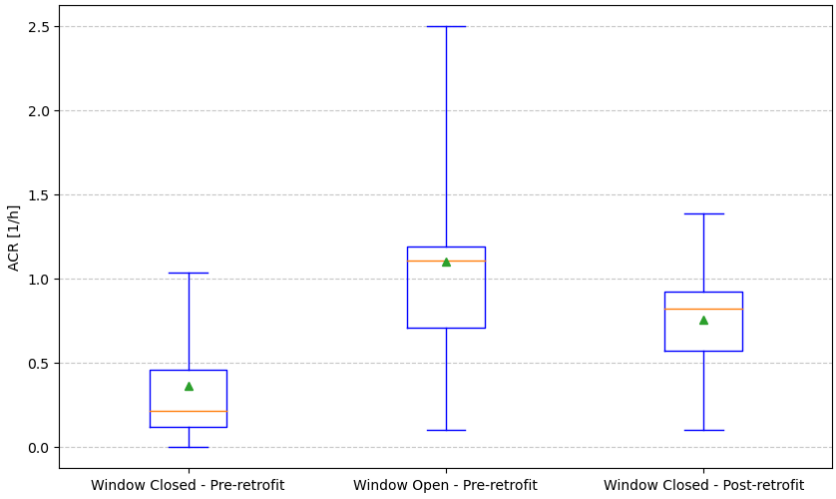

Figure 6. Distribution of ACRs for the open and closed window status in East bedroom of unit 8.

CONCLUSION

This study investigated the estimation of air change rates in residential settings using environmental and motion sensor data, comparing four methods: steady-state, decay, transient CO_2 mass balance, and air moisture balance. Results across two test apartments demonstrated the impact of an integrated retrofit strategy that included envelope improvement and mechanical ventilation on ACRs. ACRs pre-retrofit were highly variable and closely linked to occupant behavior and window operation, where no mechanical ventilation was available. For the post-retrofit condition, ERV systems reduced this variability and ensured consistent ventilation, even in the absence of occupant interaction. The decay method showed lower average estimations ACR values compared to other methods that had a better agreement, specifically for the pre-retrofit. Spatial differences within apartments, especially between closed bedrooms and open spaces, and occupant behavior consideration, highlight the need for zonal evaluation.

The findings reinforce the effectiveness of real-time sensor-based methods in estimating ACR and provide a foundation for evaluating and validating retrofit performance. Additionally, these assemsnents support the studies of energy performance improvement, IAQ, thermal comfort for the energy retrofit project with the quantification of an important performance variable of ACR. These techniques enable a more occupant-centric and data-informed approach to retrofit design and assessment.

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