

Continuous, Scalable Building Envelope Monitoring Using Low-cost Gas Sensor Networks

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Summary:

Air exchange in buildings affects energy consumption, indoor air quality, and occupant health, and varies dynamically. Continuous monitoring of the air exchange rate (AER) is therefore important to understand real ventilation conditions and detect changes in building performance. Conventional methods only allow for short snapshots and cannot capture this variability during normal operation. Here continuous monitoring combined with automated mass-balance analysis is shown to yield scalable comparison of air exchange rates across rooms and building sections for real-time analysis of ventilation behavior.

Keywords: air exchange, sensor network, building envelope, long-term monitoring, digital twin

Introduction

Buildings exhibit complex temporal and spatial dynamics that influence ventilation, energy performance, and indoor air quality. In educational buildings, ventilation conditions directly affect both energy consumption and occupant health and performance. The air tightness and the associated air exchange rate (AER) are therefore key parameters for understanding the interaction between the building envelope, occupant behavior, and environmental conditions.

Conventional methods for determining air tightness and AER, such as blower door or artificial tracer gas tests, provide accurate results but are limited to short-term measurements under controlled conditions. As a result, they cannot capture the temporal variability and spatial heterogeneity of ventilation processes during normal building operation. With increasing building sensorization, distributed networks of low-cost sensors now continuously monitor parameters such as temperature, humidity, and carbon dioxide (CO₂) [1]. Occupant-generated CO₂ can be used as a natural tracer gas, and its temporal evolution reflects the balance between generation and removal through ventilation [2].

Recent research highlights significant spatial and temporal variability of indoor CO₂, motivating spatio-temporal sensor network analysis to capture heterogeneous concentration distributions and airflow dynamics [3]. However, large-scale, long-term applications of such approaches for assessing air exchange behavior in

naturally ventilated school buildings remain limited.

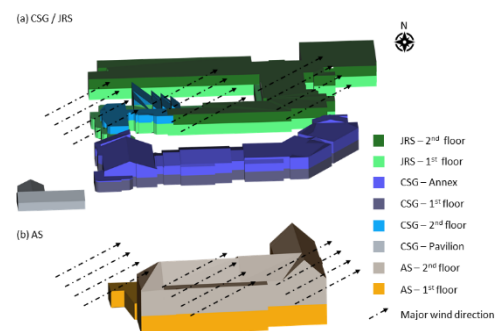


Fig 1: Digital twins of the three schools with building parts marked in color and the predominant wind direction indicated with arrows.

Here a tracer-gas modeling is combining with multi-sensor time-series analysis to determine ventilation behavior and air exchange processes under real operating conditions.

Experimental

Three schools in Holzwickede, Germany were instrumented to monitor indoor environmental conditions. The buildings, constructed between 1927 and 1994, each have two floors and are predominantly naturally ventilated, with a small number of laboratory classrooms equipped with mechanical ventilation. A total of 134 classrooms across the schools were equipped with sensor nodes measuring CO₂ concentration, temperature, and humidity. Each node records CO₂ every 30 s and transmits the data via a Wi-Fi

mesh network (ESP32-based) to an InfluxDB time-series database for continuous monitoring.

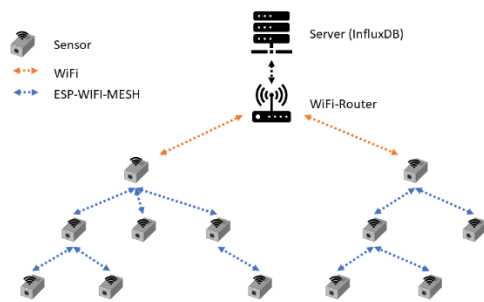


Fig 2: Schematic representation of the sensor network setup consisting of a central server, Wi-Fi access points for internet connection, and sensor nodes interconnected by ESP-WIFI-MESH protocol.

Indoor CO₂ concentration in a classroom is described using a mass-balance model that relates concentration changes to room volume, outdoor CO₂, ventilation airflow, and indoor CO₂ generation by occupants. During classes, metabolic CO₂ production causes a roughly linear increase in concentration, while after occupancy ends the concentration decays exponentially toward the outdoor level. This decay behavior enables estimation of the air exchange rate (AER) by fitting the measured CO₂ decrease to an exponential model. To automate the analysis, sensor data are smoothed and filtered for quality, and only days with sufficient CO₂ buildup and decay are used for the nonlinear fit used to determine AER.

Results

Continuous CO₂ measurements enable analysis of both occupancy patterns and ventilation behavior by examining concentration increases during occupancy and decay periods caused by ventilation or vacancy.

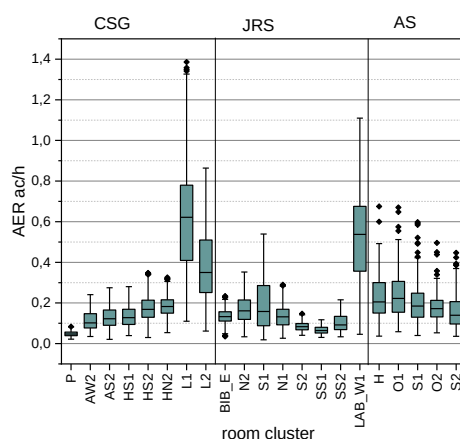


Fig 3: AER distribution for room clusters allow for identifying weak spots or abnormal user behaviour.

The final CO₂ decay after school hours provides an estimate of the undisturbed natural AER, while earlier decays during the school day

indicate higher AER due to window opening or temporary vacancy. Analysis of the decay-derived AER shows that window-opening behavior depends on outdoor temperature, with windows more frequently left open at higher temperatures, and that AER varies with environmental drivers such as wind speed and temperature. Spatial differences in AER between rooms and building sections further allow the identification of potential weaknesses in the building envelope, while mechanically ventilated laboratories exhibit significantly higher AER values than naturally ventilated classrooms.

Conclusion

Estimating the natural air exchange rate from CO₂ decay using a non-linear mass-balance analysis provides a robust method for long-term monitoring. The approach is largely independent of absolute sensor calibration and does not require an external measurement of ambient CO₂.

The results show that after-hours CO₂ decay can be used to compare relative air tightness across naturally ventilated classrooms and provide building-level insights into the envelope. However, weather conditions influence the measured AER, with observable dependencies on outdoor temperature and wind speed, which should be considered when comparing results.

Reliable application requires adequate CO₂ buildup before the decay period and well-mixed indoor air, which makes school building ideal for this approach. Despite potential influences such as interzonal air exchange, the method provides a scalable and non-invasive way to analyze air tightness and ventilation behavior using large sensor datasets.

References

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