# The Impact of Simplified Window and Exhaust Fan Assumptions on Model-Based Predictions of Inter-Zonal Air Flow and Contaminant Transport in Multifamily Buildings

Iain S. Walker[1], Brennan D. Less[1], Cara H. Lozinsky[1,2],
Núria Casquero-Modrego*[1], Michael D. Sohn[3]

| | |
|---|---|
| [1] *Residential Building Systems Group,*<br>*Lawrence Berkeley National Laboratory,*<br>*Berkeley, CA 94720, USA*<br>**corresponding author: nuriacm@lbl.gov* | [2] *Civil and Environmental Engineering Department, Carleton University, Ottawa, ON, Canada* |
| [3] *Energy Analysis and Environmental Impacts Division,*<br>*Lawrence Berkeley National Laboratory*<br>*Berkeley, CA 94720, USA* | |

## ABSTRACT

In residential buildings, the indoor air quality can be significantly affected by ventilation measures initiated by occupants, including the operation of windows and in-unit exhaust fans in kitchens and bathrooms. The outcome of these measures can be highly variable and difficult to accurately characterize in building simulation frameworks. Consequently, many simulations simplify these factors by disregarding window opening behaviours and using fixed schedules for exhaust fan operation across all residential units. To determine if these simplifications are reasonable and estimate the magnitude of changes in air flow and contaminant transport, this study used coupled CONTAM and EnergyPlus models to simulate airflow, contaminant transport, and controls in multifamily dwellings. The coupled models parametrically varied climate zone, building airtightness, and mechanical ventilation system types. The study focused on two key occupant behaviours: (1) operating kitchen and bathroom exhausts on different schedules in individual dwelling units, and (2) scheduling open windows on ground and top floors. The findings show that the simplified assumptions regarding uniform in-unit exhaust fan operation and window operation had a minimal impact on inter-unit air flow and contaminant transport simulations across a broad range of building airtightness and mechanical ventilation system types. Staggering exhaust fan operation schedules had close to zero effect on average inter-unit air flow with maximum changes of about 1 L/s (2 cfm). For contaminant transport, the changes in concentrations were typically much less than 1%, compared to baseline assumptions. These findings suggest that for buildings with tight construction it is reasonable for most modelling and simulation efforts to ignore the effects of non-uniform exhaust fan operation and window opening.

## KEYWORDS

Occupant behaviour; compartmentalization; multifamily buildings; CONTAM; EnergyPlus

## 1 INTRODUCTION

In multifamily residential buildings, occupants can supplement dwelling unit ventilation by opening windows and/or operating in-unit exhaust fans. Window operation increases the air change rate of the dwelling unit, diluting contaminants from indoor emission sources. In-unit exhaust fan operation also helps to improve indoor air quality (IAQ) by capturing contaminant emissions from indoor sources (e.g., humidity from showering/bathing and humidity and contaminants from cooking and heating) and exhausting them before they mix with the indoor air. While window and exhaust fan operation can be motivated by dissatisfaction with the IAQ, occupant behaviours are not easily predictable. Window operation behaviours can be influenced by indoor and/or outdoor climate, time of day, perceived air quality, building orientation/construction, adequacy of ventilation and/or space conditioning systems, occupant activities, and security, among others (Fabi et al., 2012; Andersen et al., 2013). Exhaust fan operation is also highly variable and does not always track perfectly with indoor emission events (Lozinsky et al., 2023). In simulation studies, it is common to make simplifying assumptions regarding occupant behaviours, either assuming no window and/or exhaust fan operation, or using fixed schedules. The impact of occupant behaviours in whole building energy simulations has been extensively studied (Fabi et al., 2012; D'Oca et al., 2014; Sorgato et al., 2016). These studies consistently show that variations in occupant behaviour profiles have significant effects on energy consumption. While field studies on single-family homes have demonstrated that window and exhaust fan operations can alter air flow patterns and air change rates (Howard-Reed et al., 2002; Wallace et al., 2002; Nazaroff, 2021), the impact of occupant behaviours in multi-zone air flow simulations remains less thoroughly documented.

This study presents a sensitivity analysis, to evaluate the impact of window and exhaust fan operation on air flow and contaminant transport in multifamily buildings using coupled CONTAM/EnergyPlus simulations. The study parametrically varied building type (mid-rise, high-rise), climate zone, dwelling unit air leakage rate, and mechanical ventilation system type.

## 2 METHODOLOGY

This analysis utilized a simulation framework previously developed in a project that assessed compartmentalization and ventilation system performance in multifamily buildings. The following provides an abridged description of the methodology. For more details, refer to (Walker et al., 2024).

### 2.1 Prototype Buildings and Simulation Framework

The building geometry, building envelope, heating, ventilation, and air conditioning (HVAC) equipment were modelled based on the Pacific Northwest National Laboratory (PNNL) mid-rise multifamily prototype model used in energy code analysis (Department of Energy (DOE), 2023). This prototype is a four-storey building, with eight dwelling units per floor, a common corridor, with a stairwell and elevator shafts on each end of the corridor (Figure 1). Additionally, a high-rise version of this building type was simulated, comprising twenty storeys, each with the floor plan shown in Figure 1. Each dwelling unit was modelled as a single zone, leaving out any interior partitions.

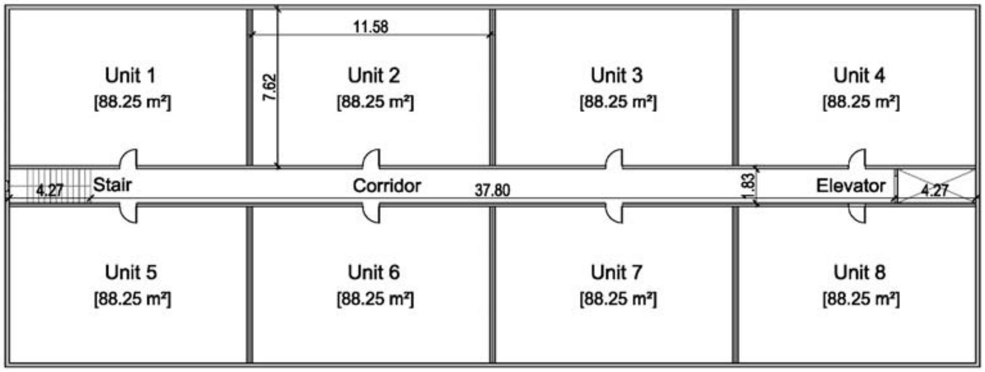


Figure 1: Layout of a prototypical building floor for the mid-rise and high-rise common corridor simulations.

During co-simulation, EnergyPlus provided CONTAM with zone temperatures, humidity ratios, ventilation system air flows, weather data, contaminant source generation rates, and other model parameters at each time step. CONTAM returned the infiltration and zone-to-zone air flows, along with the concentrations of the contaminants of interest. Simulations were run at a 3-minute time-step, although outputs were recorded at hourly intervals. The short time step was essential for adequate representation of short time-scale events such as cooking and intermittent exhaust fans operation and to minimize time step lag by co-simulation introduced between EnergyPlus and CONTAM. For a detailed description of the coupling process, refer to (Dols et al., 2016) and (Justo Alonso et al., 2022).

## 2.2 Climate Zone

We simulated three EnergyPlus climate zones (CZs) to cover the range of conditions across the continental United States: CZ 2A (Hot humid, Tampa, FL), CZ 4A (Mixed humid, New York, NY), and CZ 7 (Very Cold/International Falls, MN). The hourly Typical Meteorological Year 3 (TMY3) weather data were linearly interpolated by EnergyPlus within each hour to accommodate the 3-minute time steps used in the simulations.

## 2.3 Ventilation System Types

In this study we considered three whole dwelling ventilation system types (Table 1): (1) Unit Balanced HRV; (2) Unit Exhaust, Corridor Supply; and (3) Unit Supply. Dwelling unit mechanical fan flow rates met the minimum calculated requirement of 27.5 L/s (58 cfm) based on ASHRAE 62.2-2019 (ASHRAE, 2019b). For the Unit Balanced HRV and Unit Supply cases, the corridor on each floor was supplied with outdoor air at a minimum rate of 19.2 L/s (41 cfm), based on ASHRAE 62.1 requirements for common corridors (ASHRAE, 2019a). For the Unit Exhaust with Corridor Supply cases, the corridor supply air flow rate was 220 L/s (466 cfm), which includes the 19.2 L/s (41 cfm) for the corridor and 27.5 L/s/dwelling unit (58 cfm per dwelling unit). The Unit Balanced HRV cases included sensible heat recovery at 70%. For further details on in-unit exhaust operation schedules, refer to Section 2.6 and Table 3.

Table 1: Whole dwelling ventilation system air flow rates.

| Ventilation System Type | Dwelling Exhaust Flow L/s (cfm) | Dwelling Supply Flow L/s (cfm) | Corridor Supply Flow L/s (cfm) |
|---|---|---|---|
| Unit Balanced HRV | 27.5 (58) | 27.5 (58) | 19.2 (41) |
| Unit Exhaust, Corridor Supply | 27.5 (58) | 0 | 220 (466) |
| Unit Supply | 0 | 27.5 (58) | 19.2 (41) |

## 2.4 Air Leakage Pathways

The analysis included three dwelling unit air leakage rates: (1) “Leaky”: 5.1 $L/s_{50}/m^2$ (1.0 $cfm_{50}/ft^2$); (2) “Typical Practice”: 1.0 $L/s_{50}/m^2$ (0.20 $cfm_{50}/ft^2$); and (3) “Tight”: 0.25 $L/s_{50}/m^2$ (0.05 $cfm_{50}/ft^2$). Leakage areas were distributed to the different dwelling unit surfaces based on field studies that measured partition-level air leakage rates in low- and high-rise multifamily buildings (Bohac et al., 2007, 2020; Ricketts, 2014; Lozinsky & Touchie, 2023): 2.5% to each party wall, 10% to each floor or ceiling surface, 45% to the corridor wall and 30% to exterior wall surfaces. Each element of the building envelope's leakage was treated using the power law formulation in CONTAM, with a discharge coefficient ($C_d$) of 1.0, flow exponent (n) of 0.67, and a reference pressure of 4 Pa. Interior door leakage paths were treated as orifices using the power law formulation in CONTAM ($C_d = 0.60$ and $n = 0.50$ at 4 Pa). The elevator and stairwell doors had leakage areas of 300 $cm^2$ (46.5 $in^2$) and 200 $cm^2$ (31.0 $in^2$), respectively. Dwelling unit entry door undercuts for Unit Balanced HRV and Unit Supply cases were assumed to be 13 $cm^2$ (2.0 $in^2$) (Tian et al., 2020), while the Unit Exhaust, Corridor Supply had door undercuts of 210 $cm^2$ (32.6 $in^2$) (Peter Moffatt et al., 1998).

## 2.5 Contaminant Emission

The models included three types of contaminants: carbon dioxide ($CO_2$), formaldehyde ($CH_2O$), and particulate matter with a diameter less than 2.5 microns ($PM_{2.5}$). Details regarding indoor emission rates/sources and outdoor concentrations are listed in Table 2.

Table 2: Dwelling units Indoor emission rates and outdoor concentrations.

| Contaminant | Indoor Dwelling Unit Emission Rates | Outdoor Concentration |
|---|---|---|
| $CO_2$* | Sleeping: 6.5 mg/s (adult), 4 mg/s (child)<br>Awake: 10 mg/s (adult), 6.5 mg/s (child)<br>(Emmerich et al., 2005) | 400 ppm |
| $CH_2O$ | Calculated based on zone air temperature, relative humidity and ventilation rate (Zhao et al., 2022). | 2 ppb |
| $PM_{2.5}$ | Cooking: 0.0416 mg/s**<br>Occupant-generated emissions: 0.00007 mg/s<br>(Chan et al., 2020) | Hourly, diurnal concentrations calculated from U.S.E.P.A. monitoring station for Sussex, DE (Site 1002)*** |
| *$CO_2$ generation assumes each dwelling is occupied 24 hours of the day with two adults and two children (occupants spent 16 h awake and 8 h sleeping)<br>**Cooking emission rates were reduced by 50% in the models, to account for exhaust fan capture efficiency<br>***Mean concentration = 8.1 $\mu g/m^3$. This site was selected as a typical outdoor $PM_{2.5}$ profile. | | |

The models assumed no particle filtration in the mechanical ventilation systems. Interior and exterior leakage pathways were modelled with a 50% removal efficiency for $PM_{2.5}$, to account for penetration losses, while the particulate deposition rate was modelled at 0.6/h. We simulated two types of indoor contaminants: (1) global contaminants; and (2) shadow contaminants. Both contaminant types followed the identical emission rates and schedules described previously. Global contaminants were uniformly emitted in every dwelling unit to characterize indoor contaminant concentrations from typical occupant activities. These contaminants were not specific to individual units, meaning that we did not track their origin or movement. In contrast, shadow contaminants were emitted in Unit 2 (Figure 1) on three levels in each building type: levels 1, 3 and 4 in the mid-rise building; and levels 1, 11 and 20 in the high-rise building. These contaminants were labelled with a unique identifier to facilitate independent tracking from the global contaminants. This classification allowed us to characterize the impact of compartmentalization on inter-unit contaminant transport.

## 2.6 Exhaust Fan and Window Operation Schedules (Sensitivity Analysis)

The baseline simulation scenarios assumed the default exhaust fan operation schedule (Table 3) across all dwelling units. The variable exhaust fan schedule scenarios used three different profiles as follows: Profile 1 used the default exhaust fan operation schedule, while Profile 2 shifted all exhaust fan operation events forward by 30 minutes. Profile 3 rescheduled the showering event to 19:00 – 19:30 and increased the bathroom fan flow rate to 50 L/s (106 cfm), omitted the morning cooking event, shifted the mid-day cooking event forward by 60 minutes to 12:45 – 13:15, moved the evening cooking activity forward by 30 minutes and extended its duration by 30 minutes (18:30 – 19:00), and used the same scheduling and fan flow rate for the laundry event as Profile 1. The total fan air flow was the same for all three profiles. The profiles were assigned to dwelling units in a continuous rotation (e.g., Profile 1 was assigned to units 1ap1, 1ap4, 1ap7, etc; Profile 2 to units 1ap2, 1ap5, 1ap8, etc; and Profile 3 to units 1ap3, 1ap6; 2ap1, etc) to ensure both horizontal and vertical variability. Consistent with the baseline model assumptions, both the default and variable exhaust fan simulation cases assumed no window operation.

In baseline simulations we did not assume window operation. For window operation cases we assumed all dwelling units on the ground and top floors had their windows open. In both scenarios, the open windows had an opening area of 0.38 $m^2$ (4.04 $ft^2$) in each unit. The two cases of no window opening and all window at the top and and bottom of the buildings represent the operational extremes providing an expected range of performance. Both the baseline and "top/bottom open" window operation simulations assumed the default exhaust fan operation schedule.

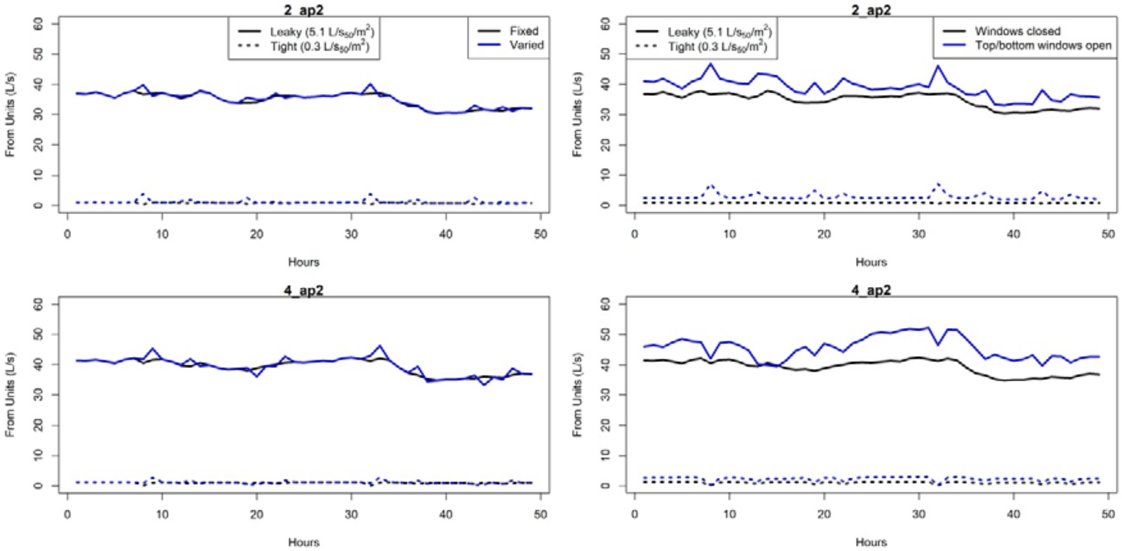
Table 3: Default exhaust fan operation schedule.

| Start and End Times | Activities | Kitchen Fan L/s (cfm) | Bathroom Fan L/s (cfm) | Laundry Fan L/s (cfm) |
|---|---|---|---|---|
| 07:00 – 07:30 | Showering | 0 | 25 (53) | 0 |
| 07:30 – 08:00 | Cooking and Showering | 50 (106) | 25 (53) | 0 |
| 11:45 – 12:15 | Cooking | 50 (106) | 0 | 0 |
| 18:00 – 18:30 | Cooking | 50 (106) | 0 | 0 |
| 21:30 – 22:00 | Laundry | 0 | 0 | 37.5 (79) |

# 3 RESULTS

## 3.1 Direct Air Flow from Adjacent Units

Air flow between dwelling units is a necessary precursor to the transport of contaminants between dwelling units. This study assessed the air flow directly from adjacent dwelling units throughout multifamily buildings (for mid- and high-rise buildings). Previous research has established that "From Unit" air flows (air flows from units that are adjacent to each other) are generally dominated by vertical air flows and are uniform throughout the building. The exception is for the ground floor, which has no units below and therefore negligible inflow from other units (Walker et al., 2024).



(a) Variable exhaust fan schedule

(b) Window operation

Figure 2: Occupant activity schedule and window operation impacts from adjacent units for the mid-rise common corridor prototype.

Figure 2a and Figure 2b show hourly mean "From Unit" air flows for Unit 2 on Floors 2 and 4, over a 48-hour period in January (winter) for the variable exhaust fan schedules and window operation cases, respectively. The example results are for Corridor Supply, Unit Exhaust ventilation in CZ7 for the mid-rise common corridor prototype. "Leaky" and "Tight" dwelling cases are compared with solid and dashed lines respectively. Baseline cases (i.e., fixed occupant activity schedules and closed windows) are compared with varied occupant activity schedules in adjacent units and open windows on the top and bottom floors by line colour (i.e., black and blue lines, respectively).

The variations in variable exhaust fan schedules and window operation showed relatively minor impacts on air flow from other units. Variable exhaust fan schedules had  minimal changes in air flow from adjacent units in both the "Leaky" and "Tight" dwellings, with maximum "From Unit" air flow changes coincident with changed fan operation of about 5 L/s (11 cfm)for the Leaky case and 2.5 L/s (5 cfm) for the tight case, with similar effects observed on the 2nd and 4th floors. Typical changes are close to zero. Window operation caused a consistent increase in air flow from other units with a greater absolute increase in air flow observed in the "Leaky" buildings (about 5 L/s (11 cfm) compared to 1-2 L/s (0.5-1 cfm) for tight construction).

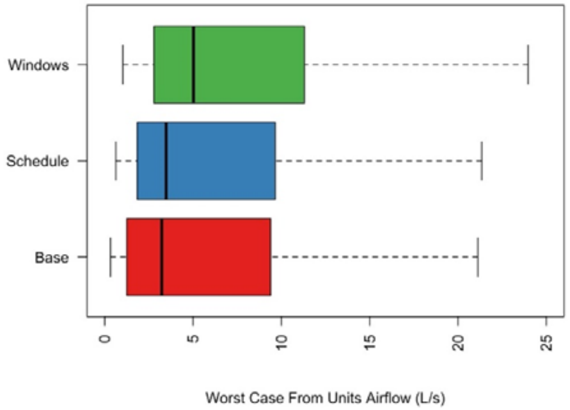
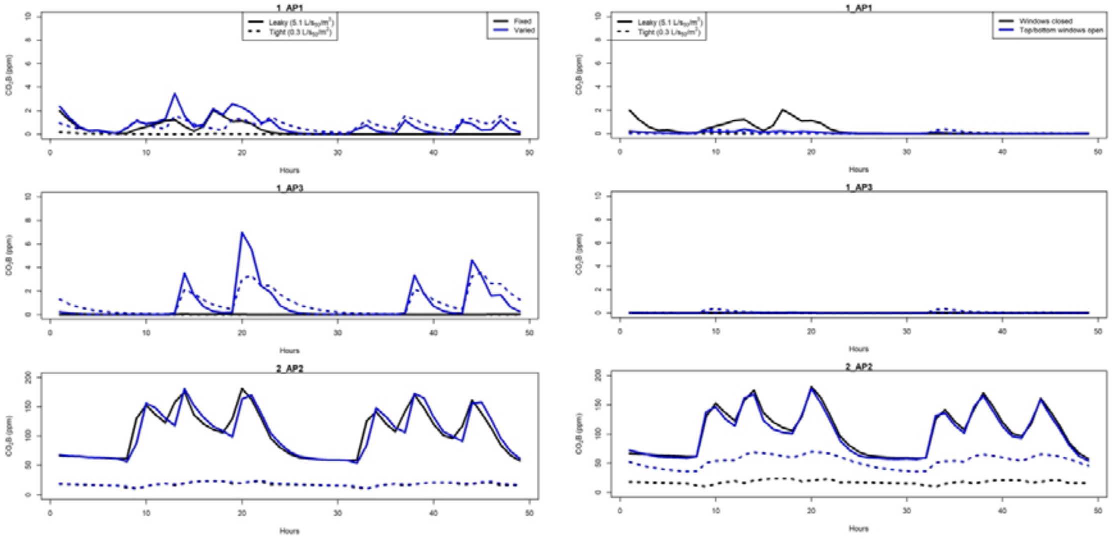


Figure 3: Annual mean "From Unit" air flows in worst-case dwellings from every simulation case. Boxplots are coloured according to the simulation case—baseline, variable exhaust fan schedules and window operation. Distributions show the annual average values for the worst-case dwelling unit in each building.

As shown by the time-series results from select buildings and dwellings, building operation assumptions have minimal impacts on hourly mean air flow directly from adjacent dwelling units. For the annual impacts on a whole building level, Figure 3 shows the distribution across all simulated buildings of the worst-case "From Unit" air flows for any given dwelling unit. These distributions are compared for the baseline (red colour), variable exhaust fan schedule (blue colour) and window operation (green colour) cases across all simulated climate zones, building types, leakage levels, and ventilation system types. Overall, both open windows and varied exhaust fan schedules increase the "From Unit" air flow, with windows having a somewhat greater impact (~2 L/s (~4 cfm)) compared with the variable exhaust fan schedules (<1 L/s (<2 cfm)). These are small fractions of the dwelling unit air flows of 27.5 L/s (58 cfm). The building prototype (i.e., mid- and high-rise) had minimal impacts on the results. These worst case air flow changes are a small percentage of the whole dwelling mechanical system flow of 27.5 L/s (58 cfm), with typical changes being even smaller. Other ventilation system results are very similar.

## 3.2 Contaminant Transport

The study evaluated the impacts of building operation on inter-dwelling contaminant transport using the shadow contaminant analysis described in the methodology. Figure 4 shows the bottom shadow $CO_2$ concentration (i.e., shadow $CO_2$ released in Unit 2 on the 1st floor) in the three directly adjacent units (i.e., Units 1 and 3 on the 1st floor, and Unit 2 on the 2nd floor) for two days in January.  These example results are for the case of Corridor Supply, Unit Exhaust ventilation in CZ7 for the mid-rise common corridor prototype. "Leaky" and "Tight" building cases are compared with solid and dashed lines, while fixed and variable exhaust fan schedules are indicated by blue and black line colouring. Note the differing y-axis scales in the bottom plot panes for the dwelling unit directly above the source dwelling unit (2_ap2). For comparison, the peak $CO_2$ in the source dwelling unit was about 700 ppm at times corresponding to the peak concentrations in Figure 4.



(a) Variable exhaust fan schedule impacts on shadow contaminant concentrations of $CO_2$.

(b) Window operation impacts on shadow contaminant concentrations of $CO_2$.

Figure 4: Shadow contaminant concentrations of $CO_2$ in zones directly adjacent to the shadow contaminant source zone (1_ap2)

Horizontal and vertical transport of shadow $CO_2$ increased between the baseline and varied building operation schedule cases during emission events (e.g., cooking). For horizontally attached dwelling units, the increases were not significant: at most, ~3 ppm for the “Tight” case and 5-6 ppm for the “Leaky” case, and far less than this on average. This was typically less than 1% change in the total $CO_2$ concentration in these units. For the dwelling unit above the source zone (i.e., 2_ap2, bottom plot pane) there was $CO_2$ transport for the “Leaky” case, where $CO_2$ peaks were evident from cooking events in the dwelling unit below. The typical increase in total $CO_2$ due to shadow $CO_2$ was about 5-10%, assuming baseline conditions. The effect of window opening and variable fan schedules are hard to discern, particularly for the fan schedule changes where sometimes $CO_2$ transport increased and at other times decreased. For the “Tight” case in this dwelling unit (2_ap2), the variable fan schedules did not show any change in $CO_2$ concentrations, but window opening consistently increased shadow $CO_2$ concentrations by 20-50 ppm. For other dwelling units in the building *not directly attached* to a dwelling unit emitting a shadow contaminant, the increases in concentration of shadow contaminant were negligible at much less than 1% for the peak events shown in Figure 4, and even smaller when averaged over a year.

Inter-unit air flow (and contaminant transport) is predominantly driven by stack effect in these building simulations (Walker et al., 2024), particularly for the examples shown here for the coldest climate zone. These generally insignificant changes in air flows and concentrations are because the inter-unit pressure differences induced by the variable exhaust fan and window operations tend to be smaller than the background stack effect driving the inter-unit air flow. Similar results were observed for the units directly adjacent to the middle and top shadow source zones and were unaffected by the building prototype (i.e., mid-rise vs. high-rise).

While the example time series data are useful for observing trends and allow us to observe how air flows and concentrations change with different time-scheduled events, it is important to look at results for the full dataset covering all weather, different ventilation systems and both building prototypes. While the time-series results generally showed small effects on average, it can be instructive to examine the peak short-term results. To examine short-term effects and to better observe any differences, we searched the results for the occurrences where differences in concentrations caused by the fan schedules and window openings were the greatest: i.e., the worst-case results. Figure 5 shows the annual worst-case *non-source zone* $CO_2$ concentrations from each simulation case, for each shadow contaminant source location (i.e., how much of the shadow contaminant accumulates in adjacent zones). The variable exhaust fan schedules did not have a meaningful effect for shadow contaminants released near the bottom or middle of the building, but roughly doubled the transport of shadow contaminants released at the top of the building, with a median increase of 5 to 10 ppm above baseline cases. Open windows led to higher shadow $CO_2$ concentrations in zones adjacent to the source zone on bottom and top floors, but not near the middle of the building (~10 ppm increase in median, compared to baseline). This is likely driven by our model assumptions, which assumed open windows on the bottom and top floors. This would greatly increase infiltration/exfiltration rates near the top and bottom of the building, but would have minimal impact on the middle of the building. Evenly distributing the window openings across the full height of the building would likely have tempered this effect. For both the variable exhaust fan schedule and window operation cases, the increased inter-unit contaminant transport was typically less than 15 ppm (<3% of the total dwelling unit $CO_2$ concentrations).

## 4 SUMMARY AND CONCLUSIONS

This study explored the impacts of varied exhaust fan schedules and window operation on predictions of air flow and contaminant transport between dwelling units in multifamily buildings. We performed parametric, annual simulations for mid- and high-rise multifamily buildings with three types of envelope leakages ("Leaky", "Typical Practice" and "Tight"), three climate zones, three ventilation system types, and two building heights using a co-simulation framework that combined EnergyPlus and CONTAM. The air flow results showed close to zero change in average "From Unit" flow for changing fan schedules, with worst case changes less than 1 L/s (2 cfm). Open windows had consistent increases in "From Unit" flow of about 2 L/s (4 cfm) with tight construction being lower in the range of 1-2 L/s (2-4 cfm). These air flow changes are a small percentage of the whole dwelling mechanical system flow of 27.5 L/s (58 cfm). For contaminant transport, the changes in concentrations were typically much less than 1%. The exception is for the "Tight" case in the dwelling unit directly above the source unit, where window opening consistently increased shadow $CO_2$ concentrations by 20-50 ppm. Window operation had a larger impact on air flow and contaminant transport, compared to varied exhaust fan schedules; however, there was a height-based effect, induced by window opening locations. Different window operation assumptions may produce slightly different results. This analysis provides support for the use of static and simplified approaches to scheduling activities and window operation in simulation assessments of airflow and air quality in multi-zone buildings.

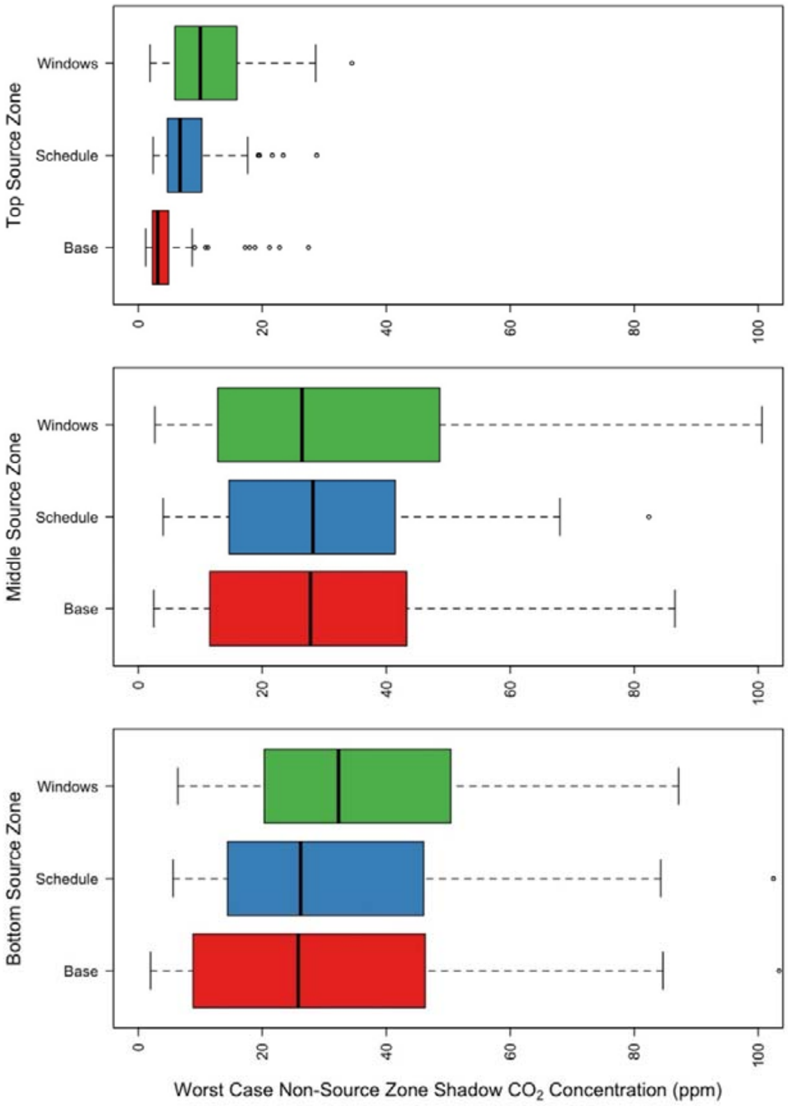


Figure 5: Annual worst-case non-source zone shadow $CO_2$ concentration. Boxplots are coloured according to the simulation case—baseline, varied activity schedules and window operation. Distributions show the annual average values for the worst-case dwelling unit in each building.

## 5 ACKNOWLEDGEMENTS

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Office, of the U.S. Department of Energy under Contract No. DE-AC0205CH11231.

## 6 REFERENCES

Andersen, R., Fabi, V., Toftum, J., Corgnati, S. P., & Olesen, B. W. (2013). Window opening behaviour modelled from measurements in Danish dwellings. *Building and Environment*, *69*, 101–113. https://doi.org/10.1016/j.buildenv.2013.07.005

ASHRAE. (2019a). *ANSI/ASHRAE Standard 62.1: Ventilation for Acceptable Indoor Air Quality*. https://doi.org/10.1201/9780849338960.ch6

ASHRAE. (2019b). *ANSI/ASHRAE Standard 62.2: Ventilation and Acceptable Indoor Air Quality in Residential Buildings*.

Bohac, D. L., Hewett, M. J., Fitzgerald, J. E., & Grimsrud, D. (2007). Measured Change in Multifamily Unit Air Leakage and Airflow Due to Air Sealing and Ventilation Treatments. *Buildings X: Thermal Performance of the Exterior Envelopes of Whole Buildings.*, 14.

Bohac, D. L., Sweeney, L., Davis, R., Olson, C., & Nelson, G. (2020). *Energy Code Field Studies: Low-Rise Multifamily Air Leakage Testing*. US DOE. https://www.mncee.org/sites/default/files/report-files/LRMF_AirLeakageTesting_FinalReport_2020-07-06.pdf

Chan, W. R., Kim, Y.-S., Less, B., Singer, B., & Walker, I. (2020). *Ventilation and Indoor Air Quality in New California Homes with Gas Appliances and Mechanical Ventilation* (2001200R1). LBNL. https://doi.org/10.20357/B7QC7X

Department of Energy (DOE). (2023). *Prototype Building Models*. Building Energy Codes Program. https://www.energycodes.gov/prototype-building-models

D'Oca, S., Fabi, V., Corgnati, S. P., & Andersen, R. K. (2014). Effect of thermostat and window opening occupant behavior models on energy use in homes. *Building Simulation*, *7*(6), 683–694. https://doi.org/10.1007/s12273-014-0191-6

Dols, W. S., Emmerich, S. J., & Polidoro, B. J. (2016). Coupling the multizone airflow and contaminant transport software CONTAM with EnergyPlus using co-simulation. *Building Simulation*, *9*(4), 469–479. https://doi.org/10.1007/s12273-016-0279-2

Emmerich, S. J., Howard-Reed, C., & Gupte, A. (2005). *Modeling the IAQ impact of HHI interventions in inner-city housing* (NIST IR 7212; p. NIST IR 7212). National Institute of Standards and Technology. https://doi.org/10.6028/NIST.IR.7212

Fabi, V., Andersen, R. V., Corgnati, S., & Olesen, B. W. (2012). Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and models. *Building and Environment*, *58*, 188–198. https://doi.org/10.1016/j.buildenv.2012.07.009

Howard-Reed, C., Wallace, L. A., & Ott, W. R. (2002). The Effect of Opening Windows on Air Change Rates in Two Homes. *Journal of the Air & Waste Management Association*, *52*(2), 147–159. https://doi.org/10.1080/10473289.2002.10470775

Justo Alonso, M., Dols, W. S., & Mathisen, H. M. (2022). Using Co-simulation between EnergyPlus and CONTAM to evaluate recirculation-based, demand-controlled ventilation strategies in an office building. *Building and Environment*, *211*, 108737. https://doi.org/10.1016/j.buildenv.2021.108737

Lozinsky, C. H., Stopps, H., & Touchie, M. F. (2023). In-situ performance of a pressurized corridor ventilation system: A long-term study in a high-rise multi-unit residential building. *Journal of Building Engineering*, *70*, 106320. https://doi.org/10.1016/j.jobe.2023.106320

Lozinsky, C. H., & Touchie, M. F. (2023). Quantifying suite-level airtightness in newly constructed multi-unit residential buildings using guarded suite-level air leakage testing. *Building and Environment*, *236*, 110273. https://doi.org/10.1016/j.buildenv.2023.110273

Nazaroff, W. W. (2021). Residential air□change rates: A critical review. *Indoor Air*, *31*(2), 282–313. https://doi.org/10.1111/ina.12785

Peter Moffatt, Ian Theaker, & Craig Wray. (1998). *Field Testing to Characterize Suite Ventilation in Recently Constructed Mid- and High Rise Residential Buildings* [Research Report]. Canada Mortgage and Housing Corporation. https://publications.gc.ca/collections/collection_2011/schl-cmhc/nh18-1/NH18-1-177-1998-eng.pdf

Ricketts, L. (2014). *A Field Study of Airflow in a High-Rise Multi-Unit Residential Building* [M.A.Sc. Thesis]. University of Waterloo.

Sorgato, M. J., Melo, A. P., & Lamberts, R. (2016). The effect of window opening ventilation control on residential building energy consumption. *Energy and Buildings*, *133*, 1–13. https://doi.org/10.1016/j.enbuild.2016.09.059

Tian, X., Fine, J., & Touchie, M. (2020). The Impact of Sweeps and Weather Stripping on Suite Door Air Tightness. *ASHRAE Transactions*, *126*(1).

Walker, I. S., Less, B. D., Lozinsky, C. H., Lorenzetti, D., Casquero-Modrego, N., & Sohn, M. D. (2024). Compartmentalization and ventilation system impacts on air and contaminant transport for multifamily buildings. *International Journal of Ventilation*, 1–28. https://doi.org/10.1080/14733315.2024.2333669

Wallace, L. A., Emmerich, S. J., & Howard-Reed, C. (2002). Continuous measurements of air change rates in an occupied house for 1 year: The effect of temperature, wind, fans, and windows. *Journal of Exposure Science & Environmental Epidemiology*, *12*(4), 296–306. https://doi.org/10.1038/sj.jea.7500229

Zhao, H., Walker, I. S., Sohn, M. D., & Less, B. (2022). A Time-Varying Model for Predicting Formaldehyde Emission Rates in Homes. *International Journal of Environmental Research and Public Health*, *19*(11), 6603. https://doi.org/10.3390/ijerph19116603