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Compartmentalization and Ventilation System Impacts on Air and Contaminant Transport for a Multifamily Building

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ABSTRACT

The proper provision of fresh air ventilation and avoidance of cross-contamination in multi-family apartment dwellings has never been more critical than during the global COVID-19 pandemic. The airtightness of interior partitions and the design of ventilation systems in multifamily buildings determines the flows across the exterior envelope and interior partitions. These flows change the total ventilation rate for the building and individual units, and also impact the mixing of air and contaminants between apartment units or with common spaces. These flow patterns can have important implications for HVAC energy use, indoor air quality (IAQ) and occupant health and comfort. This study examined the changes in air flow and contaminant transport in multifamily buildings using a combined CONTAM/EnergyPlus modeling approach. Key parameters were systematically varied, including weather, apartment airtightness, and type of mechanical ventilation system. Simulations were performed for a four-story, mid-rise building with an enclosed common corridor. Each case was simulated for a full year with three-minute time-steps that allowed for scheduling of occupancy-related contaminant releases and operation of ventilation systems. Contaminants simulated in the analysis were $PM_{2.5}$, formaldehyde and water vapor, together with CO_2 as an indicator of bioeffluents and other human-activity-related pollutants. The results of this work are intended to assist codes and standards bodies (e.g., ASHRAE 62.2) in setting appropriate air tightness limits and ventilation system design guidelines for multifamily buildings.

KEYWORDS

Multifamily, ventilation, compartmentalization, simulation, indoor air quality

INTRODUCTION

Multifamily buildings have internal air flows that transport air, contaminants and heat within the building, both from dwelling-to-dwelling and between dwellings, common and interstitial spaces. These air flows depend on the internal leakage paths and the pressures caused by wind, stack and mechanical systems. The ASHRAE Handbook of Fundamentals (Chapter 16) (ASHRAE, 2021) has illustrations and discussion of this phenomenon, and other studies (e.g., (Yoon et al., 2019)) have investigated stack-driven internal flows and their effects on air flows and heating loads.

Internal air leakage in multifamily buildings is usually referred to by the term “compartmentalization” (or compartmentation), indicating how well the internal spaces are isolated from each other. Ideally, internal and exterior leakage paths would be separately specified and measured. However, this has proven difficult to achieve in practice. Accordingly, the key metric used to assess compartmentalization (whole dwelling leakage at 50 Pa (0.2 in. water) (L/s_{50} or cfm_{50})) does not distinguish between internal and exterior leaks. Most commonly, this metric is normalized by dividing by the six-sided surface area of the dwelling to obtain an airflow per unit area ($L/s_{50}/m^2$ or cfm_{50}/ft^2). In order to limit internal flows, the ASHRAE 62.2 Standard (ANSI/ASHRAE, 2019) specifies a maximum value of 1 $L/s_{50}/m^2$ (0.2 cfm_{50}/ft^2). This value is based on over 2,000 test results in new buildings from the US EPA/DOE Energy Star Multifamily Highrise Program. One objective of the current study is to investigate how well this airtightness specification restricts internal air flows and if a different limit is justified. The different supply, exhaust and balanced ventilation systems in multifamily dwellings can create different air flow patterns, and a key question is how sensitive dwelling unit air flows are to changes in the ventilation system design. A second objective of this study is to simulate several different systems to determine this sensitivity.

A recent literature review (Lozinsky & Touchie, 2020) concluded that lack of interzonal airtightness paired with poor pressure control can lead to insufficient ventilation, additional contaminant transport and other energy and safety-related issues. Several previous field studies have shown that under some circumstances, dwelling units in multifamily dwellings can have a substantial fraction of their total airflow sourced from other units in the building, ranging from around 2 to 25% of total flow (Bohac et al., 2007; Francisco & Palmiter, 1994; Harrje et al., 1988; Peter Moffatt et al., 1998; Ricketts & Straube, 2014; Wilson et al., 2020; Wray, 2002). Markley et al. (2014) simulated ventilation in multifamily buildings, finding that increased compartmentalization indeed reduced flow from other units and saved energy. Others have simulated ventilation in multifamily buildings, but have not systematically assessed leakage or ventilation types.

The current simulation study builds on this previous work with a focus on the unit-to-unit flows in the building and on the associated transport of contaminants from a source unit to other dwelling units in the building. This study aims to answer two key questions:

- Can we recommend a level of compartmentalization that minimizes internal air flows to the point where there are diminishing returns for IAQ?
- At that level of compartmentalization, does it matter what ventilation system you have. Are different vent types more or less sensitive to compartmentalization?

METHODS

Simulation Framework

The buildings were simulated using EnergyPlus v9.1. The airflow calculations, and most transport estimates, were performed by CONTAM v3.4, using its Functional Mockup Unit (FMU) co-simulation capability. Moisture transport was simulated in EnergyPlus, in order to take advantage of its advanced models for surface interactions. During co-simulation, at each timestep EnergyPlus passes CONTAM the zone temperatures and humidity ratios, ventilation system airflows, weather data, generation rates for pollutant sources, and other model parameters. CONTAM returns the infiltration and zone-to-zone airflows, along with the concentrations of the pollutants of interest. A set of Python scripts generates the EnergyPlus input files and corresponding CONTAM FMUs, then runs the simulations. The input files differ according to the climate zone, ventilation system type, and so on, as described below. The FMUs differ mainly in the building leakage characteristics. The simulations are run at a 3-minute time-step, but outputs are written at only one-month intervals.

Prototype Building

The mid-rise common corridor (midr_cc) prototype building geometry corresponds roughly to the Pacific Northwest National Laboratory (PNNL) multi-family prototype models used in energy code analysis. The mid-rise common corridor prototype has four levels, with 8 apartment dwelling units on each level (32 units total), along with corridor, stairwell and elevator zones on each level. The prototypical floorplan layout is shown in Figure 1. Each dwelling unit has a floor area of 88.25 m^2 (950 ft^2), 3-bedrooms, 2-bathrooms and 4-occupants (two adults and two children). Occupancy is used to determine CO_2 and moisture emissions, as well as thermal loads from biological activity. These occupants are always home on fixed schedules. Each unit is modeled as a single zone, ignoring any interior partitions. Substantial changes were required to make the PNNL prototype models suitable for multi-family ventilation and compartmentalization analyses, including:

- Eliminating use of zone multipliers and instead explicitly modeling each dwelling unit and level independently.
- Addition of elevator and stairwell zones to the EnergyPlus models.
- Over-riding all existing zone ventilation objects.

The HVAC equipment specified in the PNNL prototype models were used: in each dwelling unit and corridor zone, a gas furnace with 80 AFUE was specified, along with a direct expansion (DX) cooling coil with a rated COP of 3.6. Heating and cooling thermostat set-points were: 21.1°C (70 F) for heating and 24.0°C (75.2 F) for cooling.

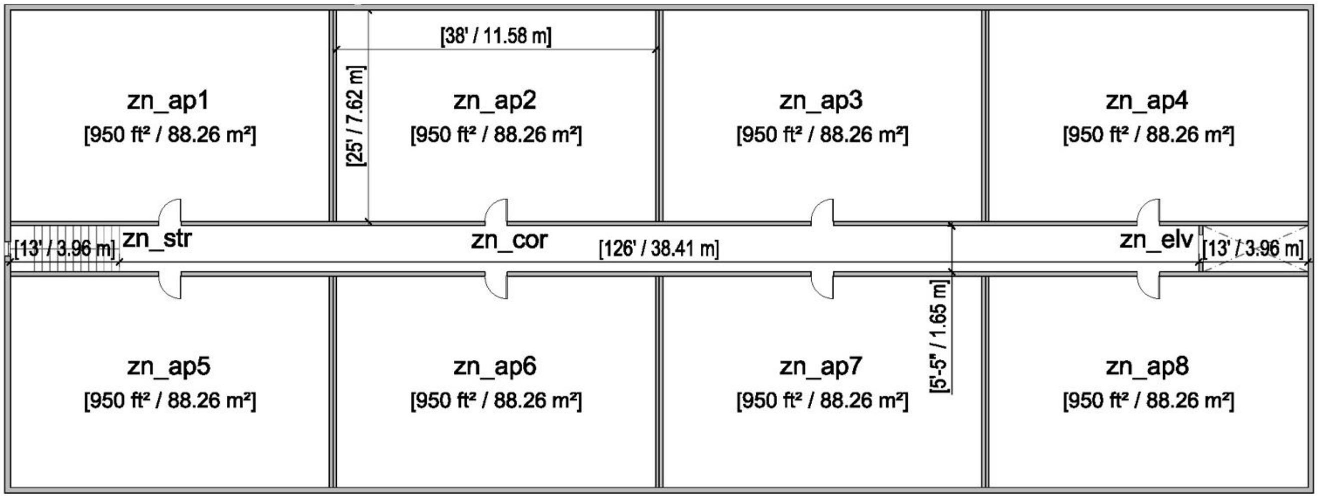

Figure 1 Multifamily building floor plan.

Simulation Parameters

In total, five simulation parameters were systematically varied in the work, including climate zone (n=5), ventilation system type (n=11), envelope leakage (n=5), ambient particles (n=2) and filtration (n=2). In total, 1,100 simulations were executed using the values for each parameter described in detail below.

Climate zone. Simulations use standard EnergyPlus climate files for the representative climate zones: 2A (Hot humid, Tampa, FL), 2B (Hot dry, Tucson, AZ), 3C (Warm marine, San Diego, CA), 4A (Mixed humid, New York, NY) and 7 (Very Cold/International Falls, MN).

Ventilation system type. 11 distinct ventilation system types were evaluated in this work. Each system type is characterized in Table 1. The dwelling unit mechanical fan flow rates were sized according to ASHRAE 62.2-2019 calculations. The trickle vent cases (sizing described below) are notable for having small, medium, and large fan flow rates, representing code minimum, 50%- and 100%-above code minimum, respectively. The corridor is typically supplied with outside air at a minimum rate of 19.2 L/s (41 cfm) (based on ASHRAE 62.1 requirements of 0.3 L/s/m^2 (0.06 cfm/ft^2) of floor area), except in the Unit Exhaust with Corridor Supply case, where outside air is intentionally delivered to each unit by pressurizing the corridor based on the sum of the supply ventilation flows for each dwelling unit (27.5 * 8 = 220 L/s (466 cfm)). The Balanced HRV and Balanced ERV cases include sensible (70%) and latent (60%) heat recovery.

Each dwelling unit is also equipped with kitchen (50 L/s (106 cfm)) and bathroom (25 L/s (53 cfm)) exhaust fans, along with a laundry exhaust of 37.5 L/s (79 cfm). Local exhaust fans in all dwelling units are controlled on an identical, fixed daily schedule (see Table 2) in concert with contaminant emissions from cooking and bathing.

Table 1 Ventilation system types.

Ventilation Type	Shorthand Name	Dwelling Exhaust Flow, L/s (cfm)	Dwelling Supply Flow, L/s (cfm)	Corridor Supply Flow, L/s (cfm)
Unit Balanced HRV	balHrv	27.5 (58)	27.5 (58)	19.2 (41)
Unit Balanced ERV	balErv	27.5 (58)	27.5 (58)	19.2 (41)
Unit Exhaust with Corridor Supply	exDoorMua	27.5 (58)	0	220 (466)
Unit Exhaust with 5pa Trickle Vent, Small	ex5VentSmall	27.5 (58)	0	19.2 (41)
Unit Exhaust with 5pa Trickle Vent, Medium	ex5VentMed	41.25 (87)	0	19.2 (41)
Unit Exhaust with 5pa Trickle Vent, Large	ex5VentLarge	55.0 (116)	0	19.2 (41)
Unit Exhaust with 10pa Trickle Vent, Small	ex10VentSmall	27.5 (58)	0	19.2 (41)
Unit Exhaust with 10pa Trickle Vent, Medium	ex10VentMed	41.25 (87)	0	19.2 (41)
Unit Exhaust with 10pa Trickle Vent, Large	ex10VentLarge	55.0 (116)	0	19.2 (41)
Unit Supply	supply	0	27.5 (58)	19.2 (41)
None	noVent	0	0	0

Table 2 Schedule of activities and local exhaust fan operation.

Time		Activities	Kitchen Fan, L/s (cfm)	Bathroom Fan, L/s (cfm)	Laundry Fan, L/s (cfm)
Start	End				
7:00	7:30	Showering	0	25 (53)	0
7:30	8:00	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
21:00	21:30	Dishwasher	0	0	0
21:30	22:00	Laundry and Dishwasher	0	0	37.5 (79)

Envelope Leakage. Five whole dwelling unit leakage scenarios were simulated: Typical (5 $L/s_{50}/m^2$ ($1 cfm_{50}/ft^2$)), Current practice (1.5 $L/s_{50}/m^2$ (0.3 cfm_{50}/ft^2)), Moderate target for better performance (1 $L/s_{50}/m^2$ (0.2 cfm_{50}/ft^2)), Tight (0.5 $L/s_{50}/m^2$ (0.1 cfm_{50}/ft^2)) and Super tight (0.25 $L/s_{50}/m^2$ (0.05 cfm_{50}/ft^2)). The leakage is distributed based on David Bohac et al. (2020): 2.5% to each party wall, 10% to each floor or ceiling surface, 45% to the corridor wall and 30% to exterior wall surfaces. The split between interior and exterior leakage is broadly similar to results of other studies summarized in (Lozinsky & Touchie, 2020). Slight modifications are applied to ground-floor units, top-floor units and corner units. In corner units, one of the party walls becomes an exterior wall, and the 2.5% leakage is added to the typical 30% exterior wall leakage. For all top-floor apartments, the ceiling surface still has 10% of total dwelling leakage, but the leakage is to outside. For ground-floor apartments, the building is assumed to have a slab-on-grade foundation, and therefore all floor leaks are eliminated. The model also included discrete flow paths: elevator door leakage (1000 cm^2 (1.1 ft^2)), stairwell door leakage (200 cm^2 (0.22 ft^2)), and dwelling unit entry door undercuts (13 cm^2 (0.0013 ft^2)) (Tian et al., 2020) or 210 cm^2 (0.23 ft^2) for Unit Exhaust with Corridor Supply cases only (Peter Moffatt et al., 1998)). Trickle vent system types include in each dwelling unit an exterior wall leak at 1m above floor height acting as make-up air for exhaust fans. Trickle vents are sized based on guidance from European manufacturers to have 5 or 10 Pa (0.02 or 0.04 in. water) design pressures at the dwelling exhaust fan flow.

Filtration. Two particle filtration scenarios were included, no $PM_{2.5}$ filtration and best current practice (MERV 13 with 90% $PM_{2.5}$ removal efficiency). Filter elements were included on dwelling unit supply ventilation air flows, corridor supply ventilation air flows, and dwelling unit recirculated air flows from the heating and cooling system. Particles were also removed as they passed through interior and exterior envelope leakage elements, as described below.

Ambient Particles. Two different scenarios were simulated for ambient fine particle pollution ($PM_{2.5}$), representing typical and worst case situations around the United States. For each of 665 US EPA monitoring sites across the US, we calculated annual statistics covering 2013-2018, and based on mean concentrations over the 5-year period, we selected specific locations representing the 50th (Sussex, Delaware, Site #1002, mean of 8.1 $\mu g/m^3$ (5×10^{-10} lb/ft^3) and the 99th percentile (Los Angeles, California, Site #4008, mean value of 14.8 $\mu g/m^3$ (9×10^{-10} lb/ft^3)). For each of these sites, we calculated typical diurnal hourly patterns for weekdays and weekends for each month of the year (24 diurnal patterns in total). These typical diurnal patterns were then used to assemble an entire year of hourly ambient particle data for each site.

Contaminant Emissions and Modeling

Four contaminants were modeled (water vapor, carbon dioxide, formaldehyde and fine particles ($PM_{2.5}$)), including outdoor sources as well as emissions from occupant activities (e.g., cooking, bathing, breathing). In addition, we created shadow contaminants for each contaminant species that are emitted from specific dwelling units in the building, with emission rates that exactly match those of the global contaminant in the apartment dwelling unit of interest. The shadow contaminant emissions occurred in apartment number two (a middle unit, see Figure 1) on levels one, three and four. Using distinct shadow contaminants, as opposed to generic tracers, allows us to determine the fraction of each contaminant in every zone of the building that came from the shadow source zone.

Formaldehyde. The formaldehyde emission rate was calculated from the zone's air temperature, relative humidity, and ventilation rate, based on a model fitted to measured field data from the LBNL HENGH study in occupied single family homes, as described in Zhao et al (2022). Formaldehyde emission rates in common corridors, stairwells, and elevator shafts are assumed to be zero. Outdoor formaldehyde concentration is fixed at 2 ppb.

Fine Particles. The generation of $PM_{2.5}$ in each dwelling unit is driven by both cooking and occupant activities. We estimated generation of particulate matter as $PM_{2.5}$ equivalents using data derived from the HENGH field study conducted by LBNL (Wanyu R. Chan et al., 2020). We used an average emission rate of 0.0416 mg/s (329×10^{-6} lb/hour) for cooking and 0.00007 mg/s (0.55×10^{-6} lb/hour) per occupant for other background emissions generated by the occupant when present and not sleeping in the dwelling. A range hood capture efficiency of 50% was assumed, which reduces the cooking emissions from 0.0416 (329×10^{-6} lb/hour) to 0.0208 mg/s (165×10^{-6} lb/hour). Removal mechanisms for particles were: removal when passing through envelope leaks (50% removal for both interior and exterior leak sites in all cases), through media filters (0 or 90% removal) and due to indoor deposition.

Carbon Dioxide. We based emission rates on the analysis provided by the National Institute of Standards and Technology (NISTIR-7212, 2005) with average CO_2 generation rates for adults of 10 mg/s (79×10^{-3} lb/hour) when awake (6.5 mg/s (51×10^{-3} lb/hour) asleep) and for children of 6.5 mg/s (51×10^{-3} lb/hour) when awake (4 mg/s (31×10^{-3} lb/hour) asleep). We assumed 8 hours of sleeping and 16 hours awake. We assumed no CO_2 from cooking. The outdoor CO_2 concentration is fixed at 400 ppm.

Water Vapor. Total moisture generation rates for each dwelling unit were designed to roughly align with assumptions for moisture generation from ASHRAE Standard 160. Event- and occupancy-based water vapor generation rates are similar to those reported in NISTIR-7212 (Emmerich et al., 2005) and NISTIR-6162 (Andrew K. Persily, 1998). We assumed water vapor emissions from cooking (280 mg/s (2.2 lb/h)), showering (660 mg/s (52 lb/h)) and dishwashing (130 mg/s (1.0 lb/h)), as well as emissions from occupant respiration of 15 mg/s (0.1 lb/h) (awake) / 9 mg/s (0.06 lb/h) (asleep) for adults and 10 mg/s (0.07 lb/h) (awake) / 6 mg/s (0.04 lb/h) (asleep) for children. See activity schedules in Table 2. We assumed that local exhaust ventilation captured half of the moisture released during the activity. Lastly, we estimated background moisture generation to be 20 mg/s throughout the house (ASHRAE 160-2016). We use the EnergyPlus Effective Moisture Penetration Depth (EMPD) model to estimate moisture transport and storage in the simulations. We used values for EMPD model coefficients from the example file that comes with the EnergyPlus distribution (MoistureMaterials.idf).

RESULTS

Values reported in this work represent annual average values within individual dwelling units. We then calculate representative values (e.g., maximum) across the 32-units in the building. Finally, the building values for each simulation are summarized according to the key simulation parameters, namely leakage, climate zone and ventilation system type. We focus solely on airflows directly from adjacent dwellings and on shadow concentrations of $PM_{2.5}$, CO_2 and formaldehyde.

Flow from adjacent units. We show an example heat map of each zone in the mid-rise building in Figure 2, with the values and colors representing the flow directly from one unit to another unit in the building (this does not include flows from a unit to the corridor and subsequently into another unit), as well as the flow fraction. We selected worst-case results for illustrative purposes, so the flows from other units are substantial (around 15-19 L/s (32-40 cfm) annually, representing 20-

22% of total unit flows). On average across all cases and all dwelling units the flows are much lower: around 3 L/s (6 cfm) or 5%. For each simulation case, we identify and record the zone with the highest annual mean flow directly from other adjacent units. In this example, it is one of the middle apartments (# 6 and 7) on the top level of the building. Inter-zonal flows tended to move vertically in the building, and as a result, the ground floor units have almost zero flow from other adjacent units. The corridor, stairwell and elevator shafts clearly play important roles in distributing flows from dwelling units throughout the building.

We used a multivariate linear regression to estimate the sensitivity to each simulation parameter. Figure 3 shows the results based on the worst case dwelling unit for each of the 1100 cases. The results show that air tightness dominates the transport of air between dwelling units in multifamily buildings. Relative to the tightest scenario we assessed, the current limit in ASHRAE 62.2 adds roughly 2 L/s (3% of total flow) of airflow directly from adjacent dwelling units annually in the worst-case zone. At leakage rates five times the maximum allowed in the standard (5 L/s/m^2 (1cfm/ft^2)), typical worst-case annual inter-unit air transfer increases substantially; around 11 L/s (23 cfm), representing 14% of the total flow entering the unit from all sources. In the worst-case dwelling unit across all 1,100 simulations, this value reached 19 L/s (40 cfm) (39% of total flow). Colder ambient conditions drive increased stack pressures and air exchange vertically in the building. Relative to climate zone 2A, the coldest location simulation (CZ 7) on average increased annual worst-case inter-unit airflow by only 4 L/s (8 cfm) annually (5%). This climate effect becomes much more important in buildings with leakier envelopes. The ventilation system type appears to play only a marginal role in determining interzone transport, with impacts in either direction of less than 1 L/s (2 cfm) (2%) annually. Comparing typical unit results to these worst-case results showed about 20-50% less sensitivity to all these parameters. While the ventilation system type had minimal impact on airflow from other units, whole dwelling airflows were substantially lower in the no ventilation case and higher in the exhaust fan trickle vent cases sized at 50% and 100% greater than code minimum. The dwelling unit supply ventilation case was slightly less sensitive to envelope leakage in terms of whole dwelling airflow, but again the transfer between units is the same as other ventilation types.

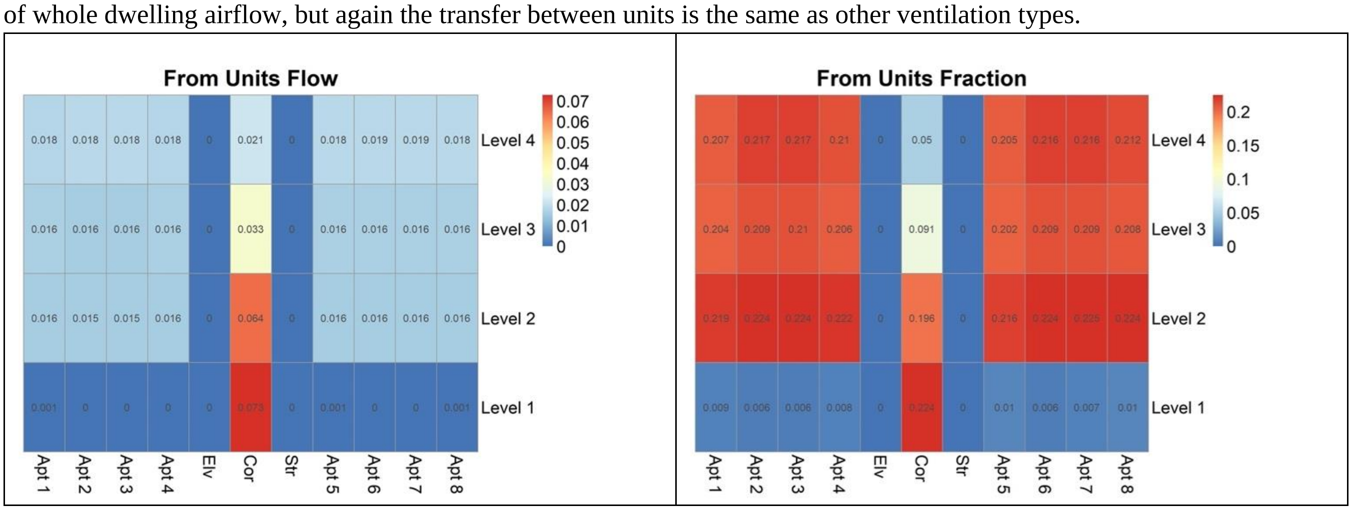

Figure 2 Heat maps showing the annual mean flow (L/s) from other units (left) and flow fraction (right). Case: Leakage 1.0, In-unit Exhaust with corridor supply, CZ7.

Shadow Contaminants. We show an example heat map of each zone in the mid-rise building in Figure 4, with the values and colors representing the concentration and concentration fraction of shadow CO_2 emitted from a source zone on the ground floor (red zone, Apt 2, Level 1). Of all CO_2 in the source zone, 280 ppm (39%) of it was emitted in that same zone. For each simulation case, we identified and recorded the non-source zone with the highest annual mean concentration of the shadow contaminant. In almost all cases, it is the apartment directly above the source (Apt 2, Level 2), with 54 ppm (7%) of CO_2 from the source zone. Shadow contaminants tended to move vertically in the building, with the stack of units directly above the source zone commonly having the greatest concentrations, due to overall vertical airflow in the building. In addition to vertical transport, a source zone also appears to contribute more contaminants to other dwellings on the same level of the building (2-4 ppm on level 1 vs. 1-1.5 ppm on other levels in Figure 4), likely through the common corridor connection. If we look at all units in the building, a source on the ground floor is distributed most widely throughout the remaining units in the building and at higher concentrations. A source on the 2nd level contributes additional contaminant to other 2nd level units and a consistently lower amount to all other units higher in the building, and almost nothing to units below. This trend continues on each level of the building. Based on these trends, we expect the top-level apartments to have the most contaminants contributed from other dwellings in the building.

Overall, the unit-to-unit air transfer is low, resulting in generally low concentrations of shadow contaminants in non-source zones. As with airflow directly from other units, variability in the maximum shadow concentration in non-source zones was driven by envelope leakage, followed by climate zone and ventilation type. The impact of leakage was least for shadow formaldehyde, due to the increased emissions with increasing ventilation. Figure 5 shows the maximum concentration of each shadow contaminant in a non-source zone, aggregated by envelope leakage (the dominant simulation parameter) and by the level of source zone in the building (bottom, middle and top). Maximum concentrations in non-source zones are highest when the source is on the bottom or middle level of the building (depending on leakage), and they are least when the source zone is at the top of the building, because the source does not tend to move downward in the building. Even in the worst case scenarios of the leakiest dwellings with a source on the ground floor, the typical shadow concentrations are low: around 1 $\mu g/m^3$ (6×10^{-11} lb/ft^3) or less for shadow formaldehyde and $PM_{2.5}$, and 40 ppm or less for shadow CO_2. Across all dwelling units in the 1,100 simulations, maximum shadow concentrations in non-source zones from a single other source zone reached as high as 9.5 $\mu g/m^3$ (6×10^{-10} lb/ft^3) (formaldehyde), 212 ppm (CO_2) and 1.0 $\mu g/m^3$ (6×10^{-11} lb/ft^3) ($PM_{2.5}$) annually. Fine particles were the most sensitive to the location of the shadow source, and in general for all contaminants, the location of the source was less important for the most airtight scenarios. In each zone, we also calculated the fraction of each contaminant that came from each shadow source zone. In looking at the maximum fraction in non-source zones, fine particles were least likely to have come from other zones in the building (shadow $PM_{2.5}$ making up typically 0.3 to 1.3% of total zone $PM_{2.5}$, and up to 7.5%), likely due to substantial deposition and penetration losses on their path between dwellings. Maximum non-source zone fractions that came from other dwellings in the building were highest for formaldehyde (typically 1-4%, and up to 20%), and somewhat less for carbon dioxide (typically 0.7-3.3%, and up to 15%).

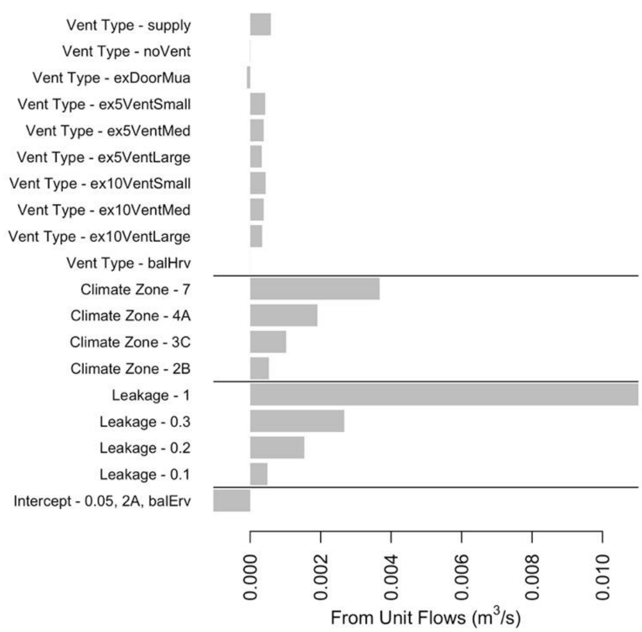

Figure 3 Worst-case annual mean airflow directly from other dwelling units, regressed on all relevant simulation parameters.

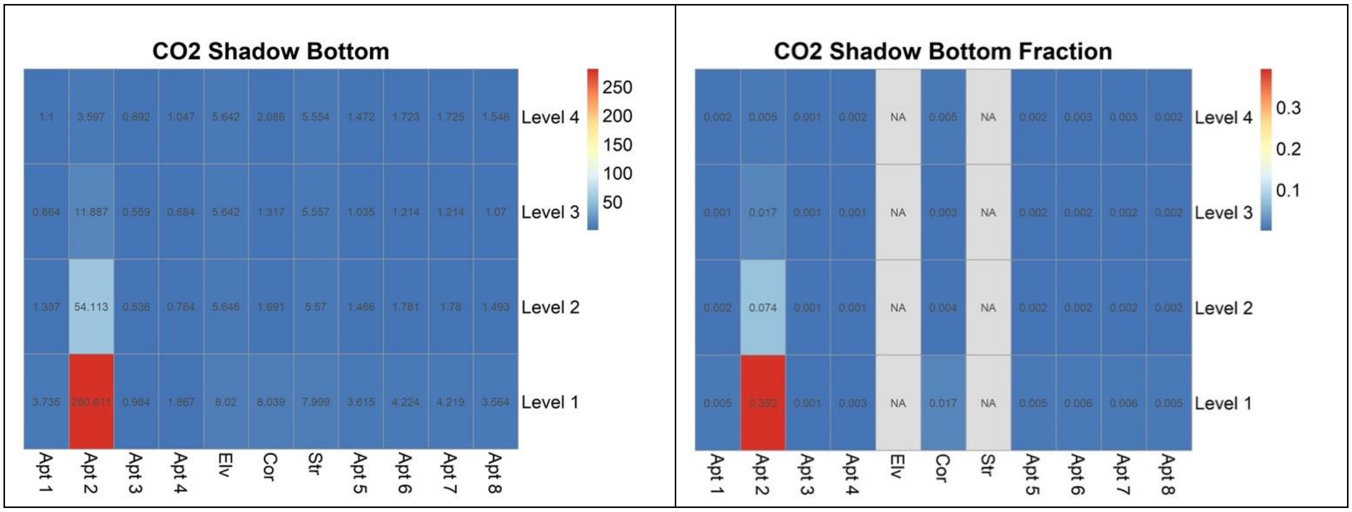

Figure 4 Heat maps showing the annual mean shadow CO_2 concentration ppm (left) and concentration fraction (right) sourced from Apartment 2 on Level 1 of the building. Case: Leakage 1.0, exhDoorMUA, CZ7.

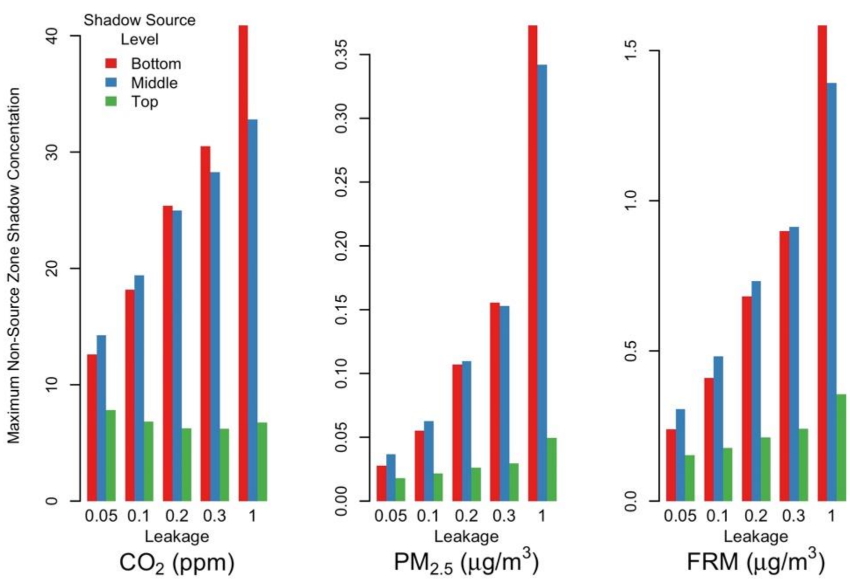

Figure 5 Worst-case annual concentration of shadow contaminants found in non-source zone, aggregated by leakage (in $L/s_{50}/m^2$) and level of source zone in the building.

CONCLUSION

This study found the current compartmentalization leakage requirement in the ASHRAE 62.2 ventilation standard already leads to very low air and contaminant transport between units in the building. Cross contamination increased with poorer compartmentalization (i.e., more leakage in each unit), as well as with increasingly cold climate conditions, due to increased stack effect pressures. The type of ventilation system had only very marginal impacts on cross-contamination in the building.

Air and contaminant transport in the building was largely vertical, with some transport between units on the same level of the building, due to corridor connections. Future work will include investigation into the effects of window operation and varying activity schedules from unit-to-unit, along with other prototypical building types, including a mid-rise walk up and high-rise. The current results are based on long-term average flows and concentrations, and future work will also investigate more transient effects at the time-step level.

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