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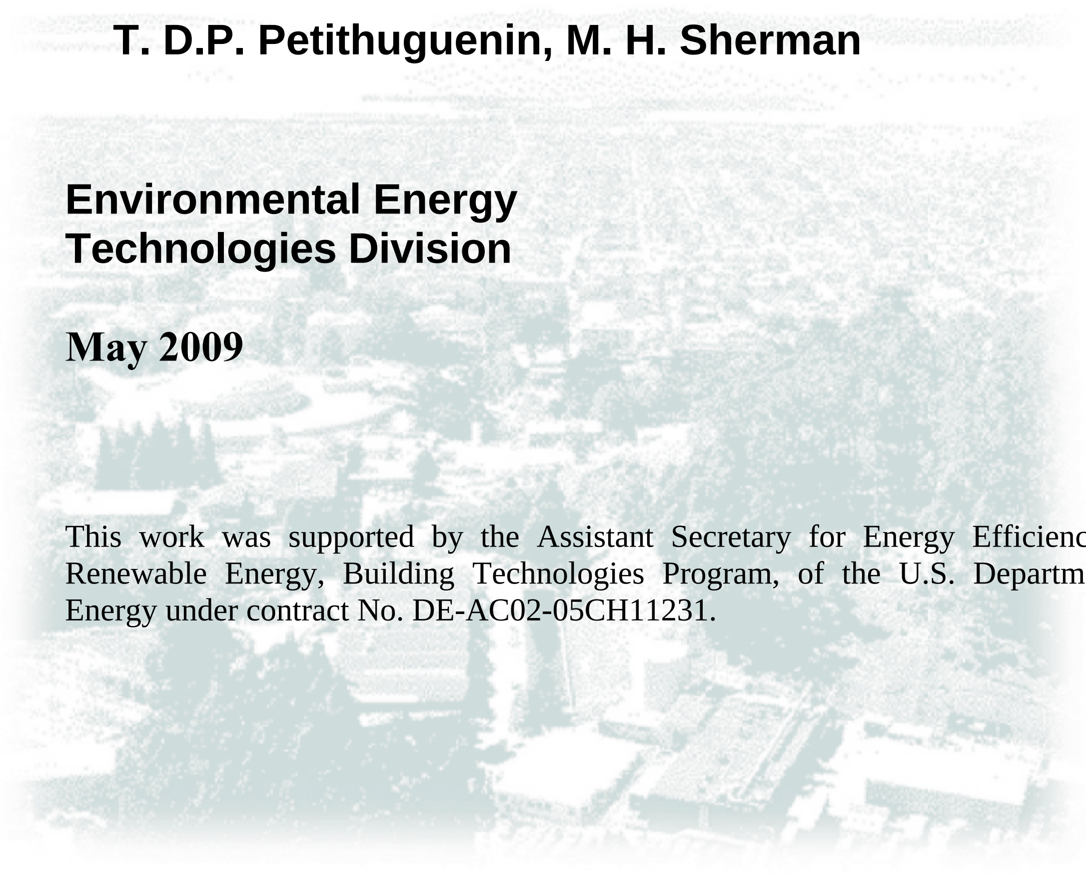
Air Distribution Effectiveness for Residential Mechanical Ventilation: Simulation and Comparison of Normalized Exposures



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May 2009

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Program, of the U.S. Department of Energy under contract No. DE-AC02-05CH11231.

Abstract

The purpose of ventilation is to dilute indoor contaminants that an occupant is exposed to. Even when providing the same nominal rate of outdoor air, different ventilation systems may distribute air in different ways, affecting occupants' exposure to household contaminants. Exposure ultimately depends on the home being considered, on source disposition and strength, on occupants' behavior, on the ventilation strategy, and on operation of forced air heating and cooling systems. In any multi-zone environment dilution rates and source strengths may be different in every zone and change in time, resulting in exposure being tied to occupancy patterns.

This paper will report on simulations that compare ventilation systems by assessing their impact on exposure by examining common house geometries, contaminant generation profiles, and occupancy scenarios. These simulations take into account the unsteady, occupancy-tied aspect of ventilation such as bathroom and kitchen exhaust fans. As most US homes have central HVAC systems, the simulation results will be used to make appropriate recommendations and adjustments for distribution and mixing to residential ventilation standards such as ASHRAE Standard 62.2.

This paper will report on work being done to model multizone airflow systems that are unsteady and elaborate the concept of distribution matrix. It will examine several metrics for evaluating the effect of air distribution on exposure to pollutants, based on previous work by Sherman et al. (2006).

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Tables

Nomenclature[1][2] [3]

$\underleftarrow{a}(t)$ Activity Vector (-)

$a_0(t)$ Indoor presence vector (-)

$A_0(t)$ Air change rate in perfect mixing (s^{-1})

$\underleftrightarrow{A}(t)$ Air change rate Matrix (s^{-1})

$C(t)$ Instantaneous contaminant concentration (g/m^3)

$\underrightarrow{C}(t)$ Instantaneous contaminant concentration vector (g/m^3)

$C_0(t)$ Instantaneous contaminant concentration in Perfect-mixing case (g/m^3)

C' Contaminant concentration in steady state (g/m^3)

$\underleftrightarrow{D}$ Distribution Matrix (-)

d Relative Dose (in zone i) (-)

$\underleftrightarrow{\varepsilon}(t)$ Non-steady turnover efficacy matrix (-)

$\varepsilon_0(t)$ Non-steady turnover efficacy in perfect mixing (-)

i, j, k Indices indicating zone (0,1 . . . N)

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[1] Symbols underlined with a single-headed arrow to the right are vertical vectors.

[2] Symbols underlined with a single-headed arrow to the left are horizontal vectors.

[3] Symbols underlined with a double headed arrow are square matrices.

N	Number of zones (-)
$Q(t)$	Air flow (m^3/s)
$Q_0(t)$	Total Air flow in or out of the building (m^3/s)
$\underset{\leftrightarrow}{Q}'$	Air flow matrix in steady state (m^3/s)
$\underset{\leftrightarrow}{Q}(t)$	Air flow matrix (m^3/s)
$\underset{\rightarrow}{R}(t)$	Instantaneous relative exposure vector (-).
$\underset{\rightarrow}{S}(t)$	Instantaneous source vector (g/s)
$\underset{\rightarrow}{S}'$	Source vector in steady state (g/s)
$\overline{\underset{\rightarrow}{S}}$	Normalized average source vector (g/s)
V_0	Zone volume in perfect mixing
$\underset{\leftrightarrow}{V}$	Zone volume matrix (m^3)
$\underset{\leftrightarrow}{\tau}$	Age of air matrix (equal to the inverse of the air change rate matrix) (s)
$\tau_0(t)$	Age of air in the perfect mixing case (equal to the inverse of the air change rate) (s)

Introduction

Ventilation and the transport of both contaminants and clean air is becoming an ever more important issue as we strive to both improve energy efficiency in buildings and the indoor air quality within those buildings. The following study pursues three objectives: the first, studies how occupants of a dwelling are affected by ventilation systems that distribute fresh outdoor air in different ways. The second focuses on the benefits of mixing indoor air and makes a recommendation on best mixing rates for optimizing Indoor Air Quality (IAQ). The third uses the multizone continuity equation to develop mathematical predictions of relative dose. Relative dose is the preferred variable for evaluating ventilation systems in this study as it compares exposures to what they are in a perfect mixing case. The main tool used is this study is the multizone modeling program CONTAM with which we will simulate ventilation patterns in homes.

Background

Ventilation standard and Indoor Air Quality

ASHRAE standard 62.2 for low rise residential buildings makes recommendations for mechanical ventilation in dwellings. In the standard, the amount of mechanical outdoor air ventilation is defined by the dwelling's floor area and its number of inhabitants, determined by the number of bedrooms. However, exposure levels within a house are strongly dependant on the ventilation system and assumptions about the pollutant source and occupant location (Sherman, 2008).

Unfortunately the standard does not indicate how to evenly distribute ventilation or other ways to ensure the provided outdoor air results in acceptable IAQ, despite the fact that past work has shown that residential ventilation systems do not provide equivalent performance even when providing the same nominal outside air flow rate. For example, Hendron (2007) found that an exhaust only system provides less uniform distribution when interior doors are closed. Because we are trying to investigate impacts of mechanical ventilation, we will minimize the effects of natural ventilation.

The measure of IAQ performance in this paper will be in accordance with ventilation standards (such as ASHRAE 62.2, 2007) where it is usually defined in terms of the total dose of some generic (i.e. not a specific chemical) pollutant over a long period of time. That is, ventilation rates are not set to protect against acute (or threshold) pollutants.

Modeling

In this study multizone modeling was used to evaluate different ventilation systems. Specifically, we want to derive metrics from the multizone continuity equation to calculate relative dose with the intent that these could be applied to any system of air distribution, evaluating the impact of air distribution on the occupants according to the various scenarios (contamination and occupancy profiles - mostly), without having to run simulations or make extensive measurements.

The multizone continuity equations from which metrics are derived have been well developed for applications to tracer gas measurements (Sherman (1990a) has reviewed the basic techniques). However, these applications, for example the concept of distribution matrix and relative dose metrics developed by Sherman and Walker (2008), were for constant flow systems. What this study proposes is to expand these concepts to unsteady flow systems.

Perfect mixing case

Consider the reference case where there is perfect mixing within the entire space. The space is a single-well mixed zone, with equal instantaneous air densities and concentrations everywhere. The concentration is assumed to be uniform within the space, but not in time, since the indoor to outdoor air flows match those of the multizone case. The continuity equation for this single zone, non-steady state is as follows:

$$V_0 \cdot \dot{C}_0(t) + Q_0(t) \cdot C_0(t) = S_0(t)$$

Where V_0 is the sum of all volumes in the environment and $Q_0(t)$ is the total flow in and out of the building at time *t*. Note that the continuity equation is in fact a mass balance equation; however we consider air densities to be equal from zone to zone, and therefore volumetric terms apply. The solution to this equation is:

$$C_0(t) = \int_{-\infty}^{t} e^{\int_{t}^{t'} A_0(t'')dt''} \cdot V_0^{-1} \cdot S_0(t')dt'$$

Where

$$A_0(t) = V_0^{-1} \cdot Q_0(t)$$

If we assume the source strength can be presumed constant, the concentration can then be defined in terms of the instantaneous turn-over time (as from Sherman and Wilson 1986);

$$C_0(t) = \tau_0(t) \cdot V_0^{-1} \cdot S_0$$

Where:

$$\tau_0(t) = \int_{-\infty}^{t} e^{\int_{t}^{t'} A_0(t'')dt''} dt'$$

As opposed to the steady case where air change rate is equal to the inverse of the turn over time, in the unsteady case, we introduce an efficacy term to relate the two.

$$\varepsilon_0(t)^{-1} \cdot A^{-1}(t) = \tau_0(t)$$

Multizone continuity equation

We look at the problem a bit more generally. The space can be broken up into multiple interacting zones where each zone is assumed to be well mixed. We will look at the case where there are a finite number of internally well mixed, interacting zones filling the entire interior space. In such a case we can write the multizone continuity equation in matrix form:

$$\underleftrightarrow{V} \cdot \underrightarrow{\dot{C}} + \underleftrightarrow{Q} \cdot \underrightarrow{C} = \underrightarrow{S}$$

or if we consider a specific zone i:

$$V_i \cdot \dot{C}_i + \sum_j Q_{i,j} \cdot C_j = S_i$$

The diagonal elements of the air flow matrix, Q_{ii}, are the total flow into or out of that zone and the Q_{ij} elements represent the flow to zone "i" from zone "j". For the general case of multiple zones and unsteady flows, we can solve this equation the same way it was solved in the single-zone one, taking care to honor the matrix nature. Thus

$$\underleftarrow{\mathbf{C}}(t) = \int_{-\infty}^{t} e^{\int_t^{t'} \underleftrightarrow{\mathbf{A}}(t'')dt''} \cdot \underleftrightarrow{\mathbf{V}}^{-1} \cdot \underleftarrow{\mathbf{S}}(t')dt'$$

Where

$$\underleftrightarrow{\mathbf{A}}(t) = \underleftrightarrow{\mathbf{V}}^{-1} \cdot \underleftrightarrow{\mathbf{Q}(t)}$$

If we assume the source strengths can be presumed constant, the concentration matrix can be defined in terms of the age-of-air matrix (as from Sherman and Wilson 1986);

$$\underleftarrow{\mathbf{C}}(t) = \underleftrightarrow{\boldsymbol{\tau}}(t) \cdot \underleftrightarrow{\mathbf{V}}^{-1} \cdot \underleftarrow{\mathbf{S}}$$

Where

$$\underleftrightarrow{\boldsymbol{\tau}}(t) = \int_{-\infty}^{t} e^{\int_t^{t'} \underleftrightarrow{\mathbf{A}}(t'')dt''} dt'$$

We introduce an efficacy term to relate the air change matrix and the age-of-air matrix.

$$\underleftrightarrow{\boldsymbol{\varepsilon}}^{-1}(t) \cdot \underleftrightarrow{\mathbf{A}^{-1}}(t) = \underleftrightarrow{\boldsymbol{\tau}}\ (t)$$

Steady state: $\underleftarrow{C}' = \underleftrightarrow{Q}'^{-1} \cdot \underleftarrow{S'}$

Non-steady state: $\underleftarrow{C}(t) = \underleftrightarrow{\varepsilon}^{-1}(t) \cdot \underleftrightarrow{Q}^{-1}(t) \cdot \underleftarrow{S}$

Distribution matrix

Sherman and Walker (2009) have introduced the concept of the Distribution Matrix to characterize the ability of a ventilation system to distribute air between zones, compared to what it would be in perfect mixing. This matrix could be used to evaluate the value of relative dose.

The entries in the matrix are the concentration in the ith zone of a contaminant emitted in the jth zone divided by what that concentration would be if the entire space were perfectly mixed. If, for example, there was perfect mixing between all zones, each value of the distribution matrix would be unity and the relative dose would be unity regardless of the activity and source patterns. For any other distribution pattern, the relative dose will depend on the details of the activity and source distribution.

This distribution matrix contains all of the important information about how air distribution affects indoor air quality. Each element describes how emissions in one zone are coupled to exposures in any other zone. In the limiting case of non-interacting zones (i.e. no air distribution at all), the distribution matrix is diagonal; and if all zones are identical, then each diagonal element is equal to the reciprocal of the number of zones. In the other limiting case of perfect mixing, each and every element of the distribution matrix is equal to unity.

$$D_{ij}(t) = C_{ij}(t) / C_0(t)$$

Where, if we consider the sources to be of constant strength, concentrations can be defined in terms of the age-of-air matrices, as explained previous sections:

$$C_{ij}(t) = \tau_{ij}(t) \cdot S_j \;/ V_{j,j}$$

$$C_o(t) = \tau_0(t) \cdot S_j \;/ V_o$$

Hence the value of an individual element of the distribution matrix is:

$$D_{ij}(t) = \tau_{ij}(t) \cdot V_o \;/ (\tau_0(t) V_{jj})$$

Or in matrix notation:

$$\underset{\leftrightarrow}{D}(t) = \underset{\leftrightarrow}{\tau}(t) \cdot \underset{\leftrightarrow}{V}^{-1} V_o \;/ \tau_0(t)$$

Or by substituting in definitions, we can get the equivalent expression:

$$\underset{\leftrightarrow}{D}(t) = \varepsilon_0(t) \underset{\leftrightarrow}{\varepsilon}^{-1}(t) \cdot Q_o(t) \underset{\leftrightarrow}{Q}^{-1}(t)$$

The distribution matrix is a coupling between zones due to time varying air flows. If the flows change very slowly and thus the efficacy is high, it’s terms will go to unity and distribution matrix will be in the form used by Sherman (2008) and Sherman and Walker (2009): $\underset{\leftrightarrow}{D} = Q_o \underset{\leftrightarrow}{Q}^{-1}$.

The distribution matrix as defined above is time-dependant. However, we want to evaluate the air distribution over a period of time, typically one day, to calculate relative dose. Since relative dose derives from exposures (which are integrations of concentration over time), we will use entries in the overall time integrated distribution matrix as the integrated values of the concentrations over the appropriate period:

$$D_{ij}(\Delta t) \;=\; \frac{\int_{\Delta t} C_{ij}(t)\,dt}{\int_{\Delta t} C_0(t)\,dt}$$

With this matrix we can define relative dose, *d*, in terms of three time-invariant factors: a normalized activity vector where entries are the fraction of time spent in each room ($\underset{\leftarrow}{a}$), a normalized source vector ($\underset{\rightarrow}{S}$) where every entry is the fraction emitted in the zone, and the distribution matrix ($\underset{\leftrightarrow}{D}$).

$$d = \underset{\leftarrow}{a} \cdot \underset{\leftrightarrow}{D} \cdot \underset{\rightarrow}{S}$$

Dose metrics

Via the above formula the concept of relative dose allows us to define metrics with which to evaluate systems depending on activity and source patterns. We will compare these metrics to our simulation results and attempt to pinpoint those that reflect actual cases in the hope of applying them to any multizone flow system. Metrics can be developed to estimate relative dose from the distribution matrix, based on occupancy behavior and source distribution (changes in $\underleftarrow{a}$ and $\underrightarrow{S}$). That is, when there is poor air distribution one can construct scenarios in which the occupant's exposure is either significantly above or below the average depending on the choices of activity patterns and source distribution. We start by considering the seven metrics developed by Sherman and Walker (2008) for estimating relative dose.

Metrics 1 through 5 are based on specific source and activity patterns. Metrics 6 and 7 are not based directly on source and activity patterns, but rather are a measure of how far the actual distribution pattern is from an idealization. These last two metrics do not represent a dose for some simple combinations of activity and source patterns, but their value lies in being independent of that. Since relative dose is in itself a measure of how far the system is from an idealization (either perfect mixing or perfect isolation), it would be appropriate if metrics 6 and 7 coincided with our simulation results. Therefore we will use the simulation results to improve them.

Metric 1: Mean Exposure: For some houses, the sources will be reasonably evenly distributed thus each entry in the source vector will be *1/N*. Similarly, we assume the occupant remains in each zone for an equal amount of time and therefore each value of the activity vector will be *1/N*.

$$d_1 = \frac{1}{N^2} \sum_{i,j} D_{i,j}$$

d_1 is the average of the terms in D and is therefore the simplest (in the sense that it is a single value) metric we consider. This is the simplest possible measure of relative dose, but is not a very good measure of how good or bad a given spatially complex air flow pattern is at delivering IAQ because the terms in D will always average out to a value very close to 1. We now focus on alterations of activity and source patterns ($\underrightarrow{a}$ and $\underrightarrow{S}$) that better represent real-life situations.

Metric 2: Volume-weighted Sources: We consider a case where the sources are distributed in proportion to the volume of each space instead of being exactly the same (i.e. each source vector element is V_j/V_0). This is equivalent to the simulated case VOL in which the contaminant is continually emitted in each elemental volume within the home. We consider once more that all entries in the activity vector are *1/N*. We can expect this metric to always be very close to 1.

$$d_2 = \frac{1}{N} \sum_{i,j} D_{i,j} V_j \; / V_0$$

Metric 3: Volume-weighted Worst Case: Metric 2 assumes that the exposure is spread across all zones, but in some cases it might be necessary to assume that the occupant spends their time in a single zone (i.e. the activity pattern vector has unity in one zone and zeros elsewhere). We chose for this zone to be the worst and in this case the relative dose would be:

$$d_3 = Max(\sum_j D_{i,j} V_j \,/\, V_0)$$

Metric 4: Absolute Worst Case: The absolute worst case would be if all the sources were in the same zone as the occupant and that was the worst zone to be in because it had the least air exchange. This means the activity and source strength vectors here are unity for the worst zone and zero for the others. In such a case the relative dose is just the largest value in the distribution matrix, which must always be on the diagonal. Since we consider all zones, even the most isolated ones where an occupant would not spend all his time, we can expect d_4 to be unrealistically high.

$$d_4 = Max(D_{i,j})$$

Metric 5: Worst Cross Contamination: In the worst cross-contamination case, the source and occupancy are again both concentrated, but in different zones. In such a case the relative dose is just the largest off-diagonal value in the distribution matrix.

$$d_5 = Max(D_{i,j \neq i})$$

Metrics 6 and 7 compare the distribution matrix to an ideal case. These do not represent dose calculations as such, but we hope that through their gradual modification, we will find norms that illustrate the evolution of dose in comparison to those ideal cases.

Firstly, *Metric 6* compares D to what it would be under perfect mixing circumstances. i.e., every entry of the matrix is equal to 1. This suggests that the metric is the difference between the actual distribution matrix and the perfect mixing matrix. In matrix notation this becomes:

$$d_6 = 1 + \frac{1}{N}\left\| \underleftrightarrow{D}, \underleftrightarrow{1} \right\|_2 = 1 + \frac{1}{N}\sqrt{\sum_{i,j} (D_{i,j} - 1)^2}$$

Secondly, *Metric 7*: Compares D to what it would be if each zone was perfectly isolated and ventilated independently: In such a case all the off-diagonal elements should be zero and the relative dose metric is a measure of how far the distribution matrix is from having zero off-diagonal elements:

$$d_7 = 1 + \frac{1}{N}\left\| \underleftrightarrow{D}, \underleftrightarrow{D_{diag}} \right\| = 1 + \frac{1}{N}\sqrt{\sum_{i,j \neq i} D_{i,j}^2}$$

New dose metrics

Many more metrics were considered, but we specifically wanted to aim those that might coincide with the contamination profiles we simulated, therefore certain metrics do not appear in the following table (such as d_{10}).

metric	*formula*	*Description*
d_8	$\left[\min(\sum_i D_{i,j})\right]\frac{1}{N}$	*Metrics 8, 9 and 11* mimic B&K. Metric 8 considers that all sources are situated in the zone that communicates the least with other zones. Typically this would be the bathroom or any of the wet rooms equipped with exhaust fans. We take a normalized activity vector (equal time spent in each zone) which yields a division by N. *Metric 9* is similar to metric 8 but considers the most communicating room. This is generally a room equipped with a return duct for the AHS.
d_9	$\left[Max(\sum_i D_{i,j})\right]\frac{1}{N}$	
d_{11}	$\left[\min_1(\sum_i D_{i,j})+\min_2(\sum_i D_{i,j})\right]\frac{1}{2N}$	*Metric 11* takes the two least communicating zones and places the sources half in one and half in the other. This should be good a good representation of the B&K case.
d_{12}	$\left[\sum_i D_{ii}\right]\frac{1}{N}$	*Metric 12* is an attempt to reproduce OCC. We consider an occupant that goes from zone to zone, in which the zone he is presently in is affected by a source vector equal to unity.
d_{13}	$1+\frac{1}{N}\sqrt{\sum_{i\neq j}(D_{i,j}-1)^2}$	*Metric 13* is a modification of d_6, where we remove the diagonal elements of D in the norm to make values lower and converge slower.
d_{14}	$d_7-1=\frac{1}{N}\sqrt{\sum_{i,j\neq i}D_{i,j}^2}$	*Metric 14* is an attempt to correct metric 7. Metric 7 evolves in a similar way to the B&K curves but converges to 2 instead of 1, so very simply: d_7 -1.
d_{15}	$\|\underleftrightarrow{D}\|_2 = \frac{1}{N}\sqrt{\sum_{i,j}D_{i,j}{}^2}$	*Metric 15* is imply the norm-2 of D.
d_{16}	$(d_{11}+d_{14})\frac{1}{2}$	These three metrics are proposed combinations to lean toward results of relative dose obtained with the simulations (i.e. complex behavior and contamination patterns).
d_{17}	$\sqrt{d_3\times d_9}$	
d_{18}	$\sqrt{d_3\times d_6}$	

Calculation Approach

Relative exposure and relative dose

In this investigation, impacts of exposure patterns that are uniform in neither space nor time are compared to what they would be in the perfectly-mixed ventilation case. In this reference the space is a single-well mixed zone, with an equal concentration everywhere (contaminants and outdoor air are evenly distributed in the space). The reference $C_0(t)$ is the instantaneous concentration of the generic contaminant in the perfectly-mixed case, which varies over time with ventilation and source patterns. This evaluation method was developed by Sherman (2007), and later used in the field by Sherman & Walker (2007, 2008).

Relative exposure:

The relative exposure is defined as the instantaneous contaminant exposure divided by the contaminant concentration that would have resulted from the reference case:

$$\underleftarrow{R}(t) = \underleftarrow{C}(t) / C_0(t)$$

Relative dose:

The relative exposure values are an instantaneous and local measure of how contaminated a zone is compared to the perfectly-mixed reference. We are not overly concerned with instantaneous exposures because we want to evaluate the exposure of inhabitants over a period of time, so our measure of comparison is either total integrated exposure or relative dose.

This allows us to define ventilation effectiveness as a ratio of an occupant's exposure to what it would have been under perfect mixing. The relative dose is the integrated concentration that an occupant is exposed to divided by what they would have been exposed to in the perfectly-mixed case. Whatever the activity patterns, source distribution, or air distribution, the relative dose, *d*, is a measure of how good or bad the IAQ is compared to the case of perfect mixing. A larger relative dose means that the occupant's exposure to contaminants is higher than if the space were perfectly mixed.

Relative dose: $$d(\Delta t) = \frac{\int_{\Delta t} a'(t) \cdot \underleftarrow{C}(t)dt}{\int_{\Delta t} a_0(t)C_0(t)dt}$$

Where:

$a'(t)$ is the activity vector, a horizontal vector that identifies the zones occupied by an occupant at *t* (1 in the occupied zone and 0 elsewhere, 0 everywhere when the occupant is outdoors), it denotes when and for how long the occupant is in each zone.

$a_0(t)$ is a scalar equal to 1 when the occupant is indoors and 0 when outdoors.

The formula for relative dose shows a direct dependence on the activity vector and the concentration. Indirectly though, the variables that come into play are: Ventilation, Distribution and strength of contaminants, the activity patterns of the people in building, the building geometry, and the central forced air heating and cooling system mixing rate. Our simulations will concentrate on identifying the effects of these parameters.

Simulation tool

We use a multizone modeling technique for the computer simulation of airflows and contaminant transport in buildings. Multizone airflow and pollutant transport modeling takes a macroscopic view of IAQ by evaluating average pollutant concentrations in the different zones of a building as contaminants are transported through the building. The multizone approach is implemented to identify the impact on an entire house, by constructing a building model as a network of elements describing the flow paths (HVAC ducts, doors, windows, cracks, etc.) between the zones of a building. The network zones are modeled at a uniform pressure, temperature, and pollutant concentration. After calculating the airflow between zones and the outdoors, zone pollutant concentrations are calculated by applying mass balance equations to the zones, which may contain pollutant sources and/or sinks.

House characteristics

The multizone airflow modeling program used in this study was CONTAM (Walton 2005, Dols 2001), in which the three model houses were represented. These model homes were chosen to represent a reasonable cross-section of a database of most common US dwellings (Persily A.K., Musser A., Leber D., 2006). The dwelling is the first variable in this study. Different volumes, number of rooms, geometries, will lead to different concentrations because of house-specific nominal outdoor air rates (given the ASHRAE std 62.2 formula) and air distribution patterns. Three different houses were chosen to represent a reasonable cross-section of U.S. homes: a small single story detached home, a large two-story detached home, and an attached town house with a half underground basement and a tuck-under garage. Refer to appendix 1 for the floor plans and room areas of the houses.

To characterize the airflow between zones and the outdoors, CONTAM uses different types of flow elements. A summary of the flow elements used in this model is provided in Appendix 2. As shown in Appendix 4, the model flow elements combine leakage area and orifice area data from the literature for different types of openings (essentially interior walls and doors), plus leakage elements that are calculated to suit the requirements of these simulations (indoor to outdoor openings).

A simple recirculation air handling system (AHS) was added to each model, with a supply in each room and a central return on each floor. There is no contaminant removal in the AHS, as well as no sinks in the home, as we wish to study the effects of ventilation alone on contaminant-removal. Furthermore, we assume that the system ductwork has no leakage and that the supply and return systems are fully balanced.

Occupancy

In addition to occupancy patterns determining exposure, we included the effects of occupancy on intermittent mechanical ventilation systems. Kitchens and Bathrooms are equipped with intermittent fans that are occupant-activated. Since the occupants' behavior drives ventilation (via occupant-activated intermittent fans) and contaminant generation (through their activities), we chose to model their presence in the space as realistically as possible, and run multiple scenarios. We did not want to caricature worst or best case scenarios. In this way the mean will be an appropriate value and one could estimate a worst or best case value with standard deviance analysis.

Occupancy details can be found at Appendix 3. In short, the profiles considered were:

i) A family with two working parents: 4 occupants in the small home, 5 in the larger ones.
ii) A family with an at home parent: 4 occupants in the small home, 5 in the larger ones.
iii) A retired couple who spend most of their time at home.
iv) A single occupant who spends less time at home relative to the other occupancy patterns.

Ventilation systems

The prime purpose of this study is to quantify how differences in air distribution resulting from different ventilation systems affect IAQ. We simulated the two most common systems that are used and proposed for mechanically ventilating homes. In both cases the outdoor air rate is that determined by ASHRAE Standard 62.2 (2007), which accounts for floor area and occupancy. We also decided to have intermittent fans in the wet rooms that are activated by the presence of the occupants. As previously mentioned, this means that the daily flow pattern depends on the houses' occupancy.

Following ASHRAE 62.2 (2007), the mechanical ventilation air flow rates are:

i) Outdoor Air (cfm): 0.01*floor area (ft^2) + 7.5*(number of bedrooms+1).
   or Outdoor Air (L/s): 0.05*floor area (m^2) + 3.5*(number of bedrooms+1).
ii) Intermittent Kitchen fan: 100 cfm (0.0472 m^3/s).
iii) Intermittent Bathroom fan: 50 cfm (0.0236 m^3/s)

The ventilation systems considered are:

i) Central Fan Integrated Supply (CFIS): Outdoor air is periodically drawn into the return duct of the central forced air system. Every room is equipped with a supply vent and the central room of each floor is equipped with a return. Supply and return are balanced and there is no duct leakage. In this scenario, the air handler operated for 30 minutes per hour, 20 minutes of which has outdoor air supply.

ii) Exhaust with air handler (EXH + AHS): The exhaust fan in the master bathroom operates constantly. The house is equipped with the same air handler as for CFIS, which mixes air in the house one sixth of the time.

iii) Exhaust only: This is the exhaust case with no air handler operation.

Contaminant generation

To evaluate and compare different ventilation systems, we use a generic contaminant generated in three different ways. Generation of household contaminants will generally be combinations of these cases:

i) OCC: Occupant-generated contaminants. This represents emission of contaminants via respiration and perspiration. It does not include contaminant generation in an individual's vicinity due to activities such as using household cleaning products. Further assumptions are as follows:
   (a) In accordance with previous studies (SJ Emmerich, NISTIR-7212) the generation of an individual during sleep is 60% that when he or she is awake. This also helps give more weight to the occupants' daytime activity in the final result.
   (b) We wanted to take into account different magnitudes of emission between occupants. Therefore occupants were attributed body weights and their generation rate per unit body weight is the same.

ii) B&K: Half bath, half kitchen. Continuous and equal generation split between the kitchen and bathroom(s). This limit represents continuous emission of household contaminants kept in storage in these rooms. As opposed to OCC, this case is not related to activity-based emissions, even though these are common in wet rooms (via showering, cooking, dishwashing, etc.).

iii) CTM3: half occupant-generated, half volume-weighted sources. After initial simulations this profile was abandoned as dose results were very close to the arithmetic means of OCC and VOL.

iv) VOL: Volume-weighted sources. Contaminants are emitted with equal intensity per unit of floor space everywhere in the house. This limit represents continuous emissions from building materials such as paint, carpets, walls, etc.

Doors

When open, doors are modeled as large two-way flow air paths which induce very large amounts of air flow between adjacent zones with just slight temperature differences between them (for example, a 1°C difference would create an exchange of 50 cfm (0.0236 m^3/s) both ways). When doors are closed the air flow from the room to the rest of the house is modeled as if there were an undercut or transfer grille, i.e., one-way flow. Both approaches were studies, with most effort and analysis for the closed door cases.

Weather Independence and Simulation Period

Weather conditions greatly affect natural ventilation, but the present focus is on the air distribution effects due to mechanical ventilation alone. Hence, as opposed to previous studies that have arranged simulations in many climates on year-round periods to test the response of the system and house to each climate, we choose to minimize the weather dependence of our results. We did this by selecting a very tight building envelope, zero wind speed and an indoor-outdoor temperature difference of 5 °C (9 °F). . The simulations were run for 24 hour periods with these fixed weather conditions. We assumed a normalized leakage of NL=0.03 for all the houses, which is very low for US houses (approximately 0.6 ACH_{50}). In comparison, according to 253 measurements (Sherman & Dickerhoff, 1998), the average normalized leakage in the state of California is 0.73 (or approximately 14.6 ACH_{50}). The effective leakage (*ELA*) area of the dwelling was calculated via the following formula:

$$NL = 1000 \frac{ELA}{A_{floor}} \left(\frac{H}{2.5m} \right)^{0.3}$$

Where: *H* is the height of the building, and *ELA* the effective leakage area. The *ELA* is then split between the walls, ceiling, or floor. For each house, we chose to distribute the *ELA* between the different facades according to the following percentages.

- One story home: 50% ceiling, 15% floor level and 35% in the walls.
- Two story home: 35% ceiling, 15 % floor level and 50% in the walls.
- Three story attached home: 35% floor level, 30% walls, and 35% ceiling.

Flow

In all simulations we compare exposures to that of the perfectly mixed case. Mixing is therefore an important factor in determining the relative dose. It is expected that as we increase mixing; the closer relative dose values will get to 1, and as we reduce mixing, we expect these to diverge away from 1. Observing how quickly dose values converge towards 1 while increasing mechanical mixing will allow us to determine how much an air handler should run for exposure to be reasonably close to perfect mixing. The initial set of simulations was run with the air handler flow rate in cfm equal to the floor area in square feet. This is a little higher than typical, since, if we assume an approximate cooling load of 1 ton for 500 ft^2 of conditioned space, and following California's title 24 residential building energy efficiency standards compliance manual of 2008, which states that the central forced air system fans must maintain airflow greater than 350 cfm per nominal ton of cooling capacity, we would have a minimum flow of 0.7 cfm per ft^2 of conditioned space (for heating the flows would be even lower, for example, Title 24 default is 0.5 cfm per ft^2).

Parametrics

At first, the smallest time interval in schedules was that of air handling in the exhaust case, which runs 5 minutes of every half hour. Other schedules (occupancy, exhaust flows, contaminant generation) had fixed 15 minute intervals. With these parameters, a one minute time step and 5 minute output time was chosen for the simulations.

However, with 15 minutes as a minimum occupation interval for a zone, too many zones were left out (hall ways, stairwells…) and served only to dilute the contaminants emitted in other rooms since occupants weren't exposed to them. To remedy this problem and make the simulations more realistic, we chose to apply a 30 second duration to transit in rooms traversed by an occupant. This new schedule, associated with a 30 second calculation step and a one minute output interval, resulted sometimes in relative dose results as much as 15% different from their previous simulations. Since this was viewed as a more realistic approach to occupant behavior and exposure indoors, these shorter time steps were kept for all simulations.

Calculation of C_0

To model the reference case, simulation files were built without indoor flow elements. As such, the space is a single well-mixed zone that retains the exact same outdoor/indoor air exchange properties as its multizone counterpart. All other occupancy and source properties are kept identical.

RESULTS

First Runs: Fixed Air Handler Capacity

Analysis of results

A total of 108 combinations of occupancy, contamination, mechanical ventilation system, and building type were simulated. With our step-by-step discrete values, and considering a one day cycle, the calculation of relative dose becomes:

$$d(\Delta t) = \frac{\int_{\Delta t} a'(t)\cdot \underset{\leftarrow}{C}(t)dt}{\int_{\Delta t} a_0(t)C_0(t)dt} = \frac{\sum_{day} C_{occ}(t)}{\sum_{day} C_0(t)}$$

$\sum_{day} C_{occ}(t)$ is what we refer to as the “daily exposure” of an occupant.

$\sum_{day} C_0(t)$ is the daily exposure of an occupant in the case of perfect mixing (or “sum of C_0”).

We calculate the values of exposure, exposure in perfect mixing, and relative dose for every possible occupant. Ultimately, we want to focus on relative dose, but we first look at all three values to make sense of them.

We looked at each particular occupant’s results to observe general trends common to all cases. We then take into account all the occupants and houses in a statistical analysis. We will isolate variables in the calculation of means and standard deviations which allow us to identify the most influential variables, quantify their influence, estimate extreme values, establish means and evaluate their variability. In short, it will allow thorough comparison of the ventilation systems and all other variables that affect exposure.

Examples of results and general trends

The following graph (Figure 1) shows an example of the exposure of each inhabitant in the family with an at home parent, OCC case, with exhaust ventilation and no mixing.

Figure 1: Occupant exposures for 1 day: family with at home parent, OCC, exhaust only

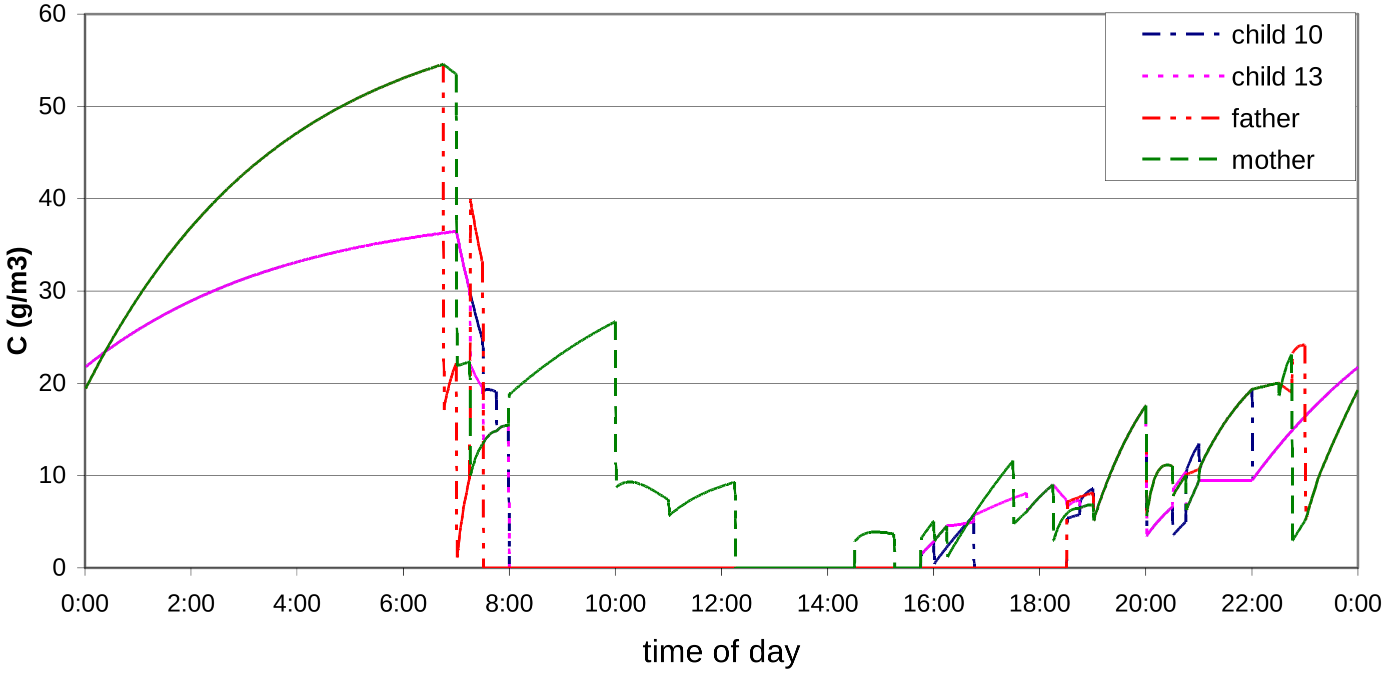


Figure 1 gives an idea of when and where occupants suffer the highest exposure, for example during the night, when occupants are constantly in the same room and exposed to increasingly higher concentrations of contaminants that they emit. During the day, peaks of exposure occur when occupants are all in the same room or in a small room. We also observe the exposure of the at home parent during the hours of the day when most of the family is away (at school or at work).

We now look at total exposure values and at relative dose. The example we chose to look at is the single occupant case. The trends should be easier to observe in this case since this occupant is alone and therefore his/her exposure is not tied to other occupants. Furthermore, our results indicate that this is the case where variations between ventilation systems and contamination profiles are greater. The following table (Table 1) shows this occupant's results for the one-story house, which is the simplest flow network with only five zones of living space.

Table 1: Simulation results, single occupant in house 1

	Single Occupant								
	CFIS			EXH + AHS			EXHAUST ONLY		
HOUSE 1	OCC	B&K	VOL	OCC	B&K	VOL	OCC	B&K	VOL
sum of C	2.402	1.084	1.047	3.277	0.708	1.323	6.594	0.249	1.276
sum of C_0	1.680	1.172	1.172	1.861	1.340	1.340	1.861	1.340	1.340
d	1.430	0.925	0.893	1.761	0.529	0.988	3.543	0.186	0.952

<u>Observations:</u>

- The sum of C_0 is slightly lower in the CFIS case. This is because this system has slightly more total ventilation due to the added contribution of occupant-activated bathroom fans (as opposed to the exhaust cases where the bathroom fan is a constant exhaust).
- VOL relative dose values are very close to 1. We can expect this to always be the case and for the standard deviation of this contamination profile to always be very small because evenly distributed contaminants within a house will be little changed by mixing. Therefore the concentrations in the case we simulate are very close to their "perfect mixing" counterparts.
- For a given AHS capacity the CFIS profile involves more mixing, hence more dilution of contaminants, and a daily exposure closer to perfect mixing than with the exhaust profile. The relative dose value is therefore closer to 1.
- For a generation case where the sources are isolated and close to an exhaust vent (B&K), mixing is rarely beneficial since it spreads contaminants through the house which would otherwise be exhausted.

The following table (Table 2) shows the relative dose (our primary metric) of the single occupant profile for all three houses.

Table 2: Relative dose for all three houses, single occupant

d	Single Occupant								
	CFIS			EXH + AHS			EXH ONLY		
	OCC	B&K	VOL	OCC	B&K	VOL	OCC	B&K	VOL
House 1	1.430	0.925	0.893	1.761	0.529	0.988	3.543	0.186	0.952
House 2	1.505	1.034	1.016	1.462	0.839	1.021	1.583	0.852	1.047
House 3	2.014	1.024	1.018	1.454	0.814	1.019	1.467	0.822	1.034

Observations:

- House layout can change results by up to a factor of 2, but typically less than the difference incurred by the choice of ventilation system.
- EXH + AHS and EXH ONLY are very different for house 1, but much less so for house 2, this illustrates the importance of evaluating multiple houses to deduce generalizations.
- Variation of results is greater in the exhaust only profile, since it is a low or zero mixing rate profile and mixing theoretically brings all relative doses closer to 1.
- CFIS has greater house-to-house variability than EXH+AHS.

Table 3 shows the other occupant patterns relative dose results. It is an illustration of the fact that different real-life occupancy patterns can potentially lead to very different exposures, indicating that part of the solution to IAQ is tied to the behavior of the inhabitants.

Table 3: Relative dose, comparison of occupancy profiles

d	Family With Home Parent: At Home Parent						Retired Couple: Man					
	CFIS			EXH + AHS			CFIS			EXH + AHS		
	OCC	B&K	VOL	OCC	B&K	VOL	OCC	B&K	VOL	OCC	B&K	VOL
house 1	1.349	0.878	0.998	1.469	0.730	0.990	1.183	0.902	0.999	1.314	0.625	0.992
house 2	1.217	0.985	1.000	1.207	0.798	1.026	1.319	0.948	1.002	1.360	0.729	1.030
house 3	1.179	0.907	1.015	1.388	0.643	1.048	1.581	0.940	0.965	1.662	0.733	1.030

Observations:

- If we want to make generalizations suitable for standards, we need to take into account a range of occupancies.
- EXH + AHS is always better than CFIS for K&B generation and a little worse for OCC generation

General Analysis:

We used the simulation results to study the influence of each variable on relative dose. We assume that the distribution of results is geometric and analyzed the influence of variables two at a time. The following tables combine ventilation with contamination profiles for all three houses and occupancies. The other variables (occupancy and house) are averaged in the mean and their variability is captured in the standard deviation. As the distribution is geometric, the standard deviance is a multiplier to the mean. Table 4 shows the mean with the upper and lower limit of the standard deviance interval, table 5 gives the values of the geometric standard deviations.

Table 4: Geometric means for different ventilation and contamination profiles

GEOMETRIC MEANS				
	OCC	B&K	VOL	mean
CFIS	1.24 + 0.17 - 0.15	0.96 + 0.0 - 0.0	0.99 + 0.03 - 0.03	1.06 + 0.1 - 0.1
EXH + AHS	1.31 + 0.17 - 0.15	0.67 + 0.1 - 0.1	1.01 + 0.04 - 0.03	0.96 + 0.3 - 0.2
EXH ONLY	1.67 + 0.58 - 0.19	0.25 + 0.2 - 0.0	1.01 + 0.10 - 0.04	0.76 + 1.1 - 0.2
mean	1.40 + 0.38 - 0.36	0.55 + 0.5 - 0.2	1.01 + 0.06 - 0.09	0.92 + 0.7 - 0.5

Table 5: Geometric standard deviation for different ventilation and contamination profiles

GEOMETRIC STANDARD DEVIANCE				
	OCC	B&K	VOL	mean
CFIS	1.139	1.094	1.026	1.158
EXH + AHS	1.130	1.169	1.035	1.347
EXH ONLY	1.344	2.142	1.095	2.530
mean	1.269	2.056	1.060	1.798

Observations:

- EXH ONLY has the lowest dose, but is dominated by the K&B scenario results.
- EX+AHS is gives better results than the other mixing scenario (CFIS) because the exhaust removes contaminants at higher concentrations.
- EXH ONLY has the biggest variability so recommendations are less certain for an individual case. Also, using extreme values (such as those represented by adding +/- one standard deviation) leads to misleading results that are very far from the geometric mean.
- Increasing mixing reduces variability, therefore taking into account the worst case scenario to comment on a ventilation system would be very misleading and in contradiction with conclusions drawn from the means of the occupancies. Looking at the mean value for OCC, B&K and VOL, worst relative dose for EXH ONLY is 0.87, 1.26 for EXH + AHS, and 1.16 for CFIS.
- These tables show that B&K yields lower relative doses and greater deviances and that an exhaust system is much more efficient in this case and mixing only prevents pollutants from being exhausted.
- OCC yields higher relative doses; it is diluted better with CFIS and mixing.
- VOL results are all close to 1 and don't depend much on any of the variables

Table 6 compares the two other variables: the house and the occupancy patterns. Ventilation systems and contaminant profiles are averaged in the geometric mean. There are four occupancy profiles: two five person families, a retired couple, and a single occupant, which bring the total number of occupants to 13.

Table 6: House and Occupants, means and standard deviation of relative dose

GEOMETRIC MEANS				
	house 1	house 2	house 3	All houses
occ1	+ 0.84 0.79 - 0.41	+ 0.37 1.00 - 0.27	+ 0.59 0.83 - 0.35	+ 0.65 0.87 - 0.37
occ2	+ 0.70 0.84 - 0.38	+ 0.32 1.04 - 0.25	+ 1.02 0.89 - 0.48	+ 0.74 0.92 - 0.41
occ3	+ 0.97 0.70 - 0.41	+ 0.37 0.87 - 0.26	+ 0.36 1.00 - 0.27	+ 0.68 0.85 - 0.38
occ4	+ 0.82 0.74 - 0.39	+ 1.02 0.96 - 0.49	+ 0.29 1.04 - 0.23	+ 0.80 0.90 - 0.42
occ5		+ 1.05 1.01 - 0.52	+ 0.84 0.76 - 0.40	+ 0.97 0.88 - 0.46
occ6	+ 0.99 0.87 - 0.46	+ 0.33 0.97 - 0.25	+ 0.62 0.83 - 0.35	+ 0.69 0.89 - 0.39
occ7	+ 0.79 0.93 - 0.43	+ 0.24 1.01 - 0.20	+ 1.04 0.89 - 0.48	+ 0.75 0.94 - 0.42
occ8	+ 1.17 0.77 - 0.46	+ 0.34 0.83 - 0.24	+ 0.38 1.01 - 0.27	+ 0.72 0.87 - 0.39
occ9	+ 1.00 0.80 - 0.44	+ 0.70 0.83 - 0.38	+ 0.25 1.07 - 0.20	+ 0.75 0.89 - 0.41
occ10		+ 0.72 0.84 - 0.39	+ 0.86 0.76 - 0.40	+ 0.80 0.80 - 0.40
occ11	+ 0.74 0.89 - 0.40	+ 0.47 1.00 - 0.32	+ 0.56 1.10 - 0.37	+ 0.62 0.99 - 0.38
occ12	+ 0.73 0.92 - 0.41	+ 0.28 1.06 - 0.22	+ 0.43 1.09 - 0.31	+ 0.53 1.02 - 0.35
occ13	+ 1.23 1.00 - 0.55	+ 0.29 1.12 - 0.23	+ 0.37 1.14 - 0.28	+ 0.72 1.08 - 0.43
All occ	+ 0.93 0.84 - 0.44	+ 0.56 0.96 - 0.35	+ 0.68 0.94 - 0.40	+ 0.73 0.92 - 0.41

GEOMETRIC STANDARD DEVIANCES				
	house 1	house 2	house 3	all houses
occ1	2.064	1.372	1.72	1.755
occ2	1.83	1.31	2.147	1.805
occ3	2.372	1.429	1.363	1.797
occ4	2.115	2.071	1.277	1.889
occ5		2.041	2.104	2.102
occ6	2.136	1.346	1.747	1.775
occ7	1.852	1.241	2.174	1.801
occ8	2.513	1.407	1.373	1.834
occ9	2.253	1.834	1.23	1.842
occ10		1.859	2.127	1.999
occ11	1.827	1.473	1.51	1.624
occ12	1.798	1.261	1.393	1.52
occ13	2.223	1.256	1.325	1.665
All occ	2.109	1.58	1.719	1.8

<u>Observations:</u>

- In Table 5, the standard deviations are generally higher than in Tables 4 and 5. This means that ventilation and contamination profiles generally have more influence on relative dose than the choice of occupancy or house, even though as observed in Table 3, in specific cases relative dose can potentially depend as much upon the occupancy pattern as on the other variables.
- The above observation is true except for the exhaust and no mixing profile, where mixing rates are close to zero and variables other than the ventilation system have more weight. Furthermore, Means in Table 6 are generally closer to each other than in Tables 4 and 5; therefore occupancy patterns and choice of house have less influence on relative dose than the two other variables. This is an important result because we want to average over these parameters and study the response of a given ventilation system to a given contamination profile.

For the next step of this study we concentrate on the most important variables: ventilation system, mixing, and contamination profile. We will average over the occupants and the houses only to better understand the behavior of the more influential variables.

Influence of Mixing

To examine the mixing effects of the central forced air system and to determine if there is an optimum operating schedule (i.e., an amount of mixing beyond which there is little change in results), we ran simulations with different Air handler flows that scaled with floor area. These were 0.13, 0.5, 1.0, 1.33, and 10.0 cfm/ft^2. We then had one more run for CFIS with no additional mixing to the supply of outdoor air; which corresponds to slightly different mechanical mixing air changes per hour depending on the house, but on average, approximately 0.22 ACH.

Figures 2 and 3, illustrate the trends in dose with changing mixing. The means combine the multiple homes and occupancies and the standard deviations (indicating the variability between simulations) are shown as bars around the mean.. The mechanical mixing provided by the air handler is expressed in building air changes per hour (ACH), (i.e., airflow through the air handler divided by the house volume).

Figure 2: Dependence of relative dose on mixing with EXH

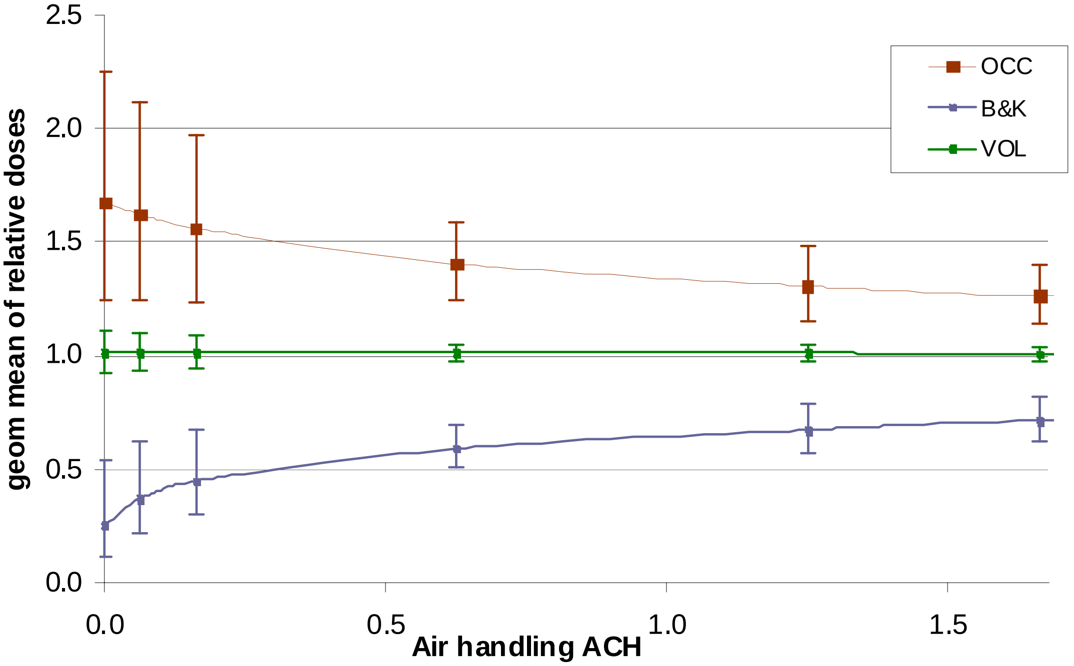
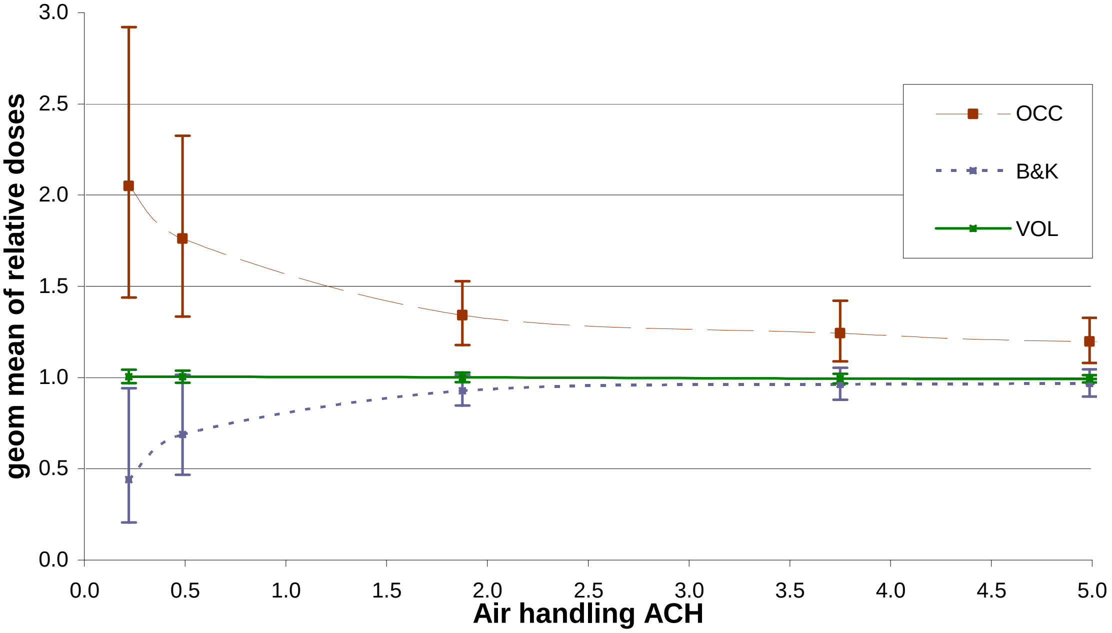


Figure 3: Dependence of relative dose on mixing with CFIS



<u>Observations:</u>

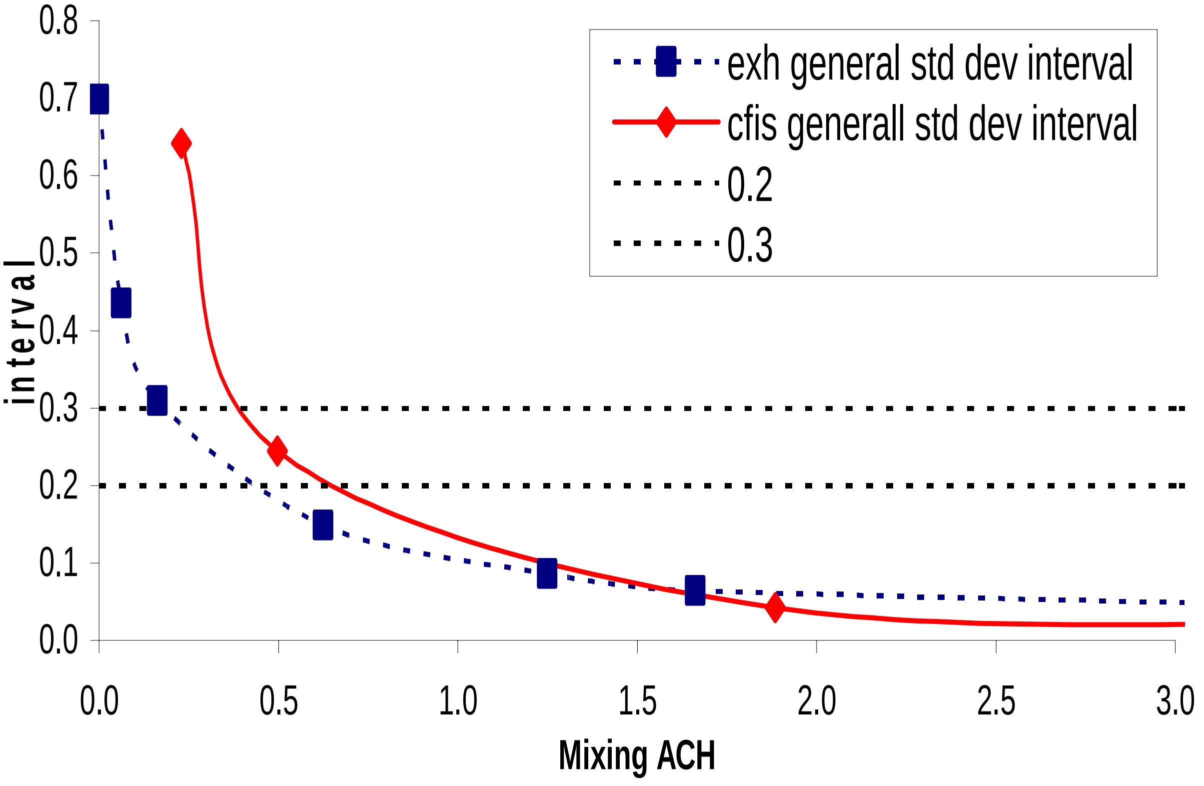
- Figures 2 and 3 show that increased mixing reduces the difference between means and the variability about the mean.
- The results show that increasing mixing above a certain rate has little effect on the results. Selection of this "cutoff" rate is fairly arbitrary, but about 0.7 ACH looks reasonable.

Reducing variability

In any typical house, contamination will occur in a household as a combination of OCC, B&K and VOL, as pollutants will be generated by occupants and their activities, by-products kept in the household in specific locations, and by materials on a surface-weighted basis throughout the home. For this reason, the above graphs that show how ventilation systems respond to specific contamination profiles do not help us define how much mixing should be provided by the air handler to obtain ideal living conditions. Figures 2 and 3 show that at low mixing rates, exposure can be very high, very low, or close to perfect mixing. To ensure that the worst case does not occur, it is important to focus on the other effect of mixing: reducing variability. If we provide enough mixing so that relative dose does not vary much from one occupancy profile to another, then we will ensure that no high exposure levels occur.

For each AHS rate, we calculated the overall standard deviation per ventilation system. Figure 4 summarizes these calculations.

Figure 4: Reduction in dose variability with increasing mixing



Observations:

- By changing the origin of the exhaust curve to that of the CFIS curve, we find that the curves coincide. This shift of 0.22 ACH between the two curves is constant, and the curves are otherwise identical. This shows that in an exhaust case, the forced air infiltration throughout the envelope, which travels throughout the house to the exhaust fan, creates a certain amount of mixing. This effect of the exhaust system can be given a certain mixing credit, apparently, at a rate of 0.22 air changes per hour.
- The influence of mixing on the trends is identical in both systems; the curves trend toward 0 in the same way.

We can attempt to make a recommendation for mechanical mixing rates on the basis of reducing risks of high exposure. A certain deviation interval has to be chosen to define the best possible mixing rate. Unfortunately, this is possible only subjectively. Moreover, with the choice of mixing rate comes a degree of responsibility from the occupants – the less they choose to mix the indoor air, the more their behavior can affect their exposure.

The standard deviation observed here is affected by mechanical mixing from the air handler alone, which has to be replaced in our hypothesis of one-way air flows through doors. The numbers observed here would be altered by the added mixing from two-way flows through doors: there would be more natural mixing, hence less mechanical mixing needed. The following numbers are therefore higher than what they would be in real situations. In addition, the lower mean for the exhaust case allows for a higher standard deviation for the same maximum dose. So these values could be further reduced for exhaust systems if this maximum dose metric were considered.

Using a threshold deviance interval of 0.2, the appropriate mixing rates are:
For CFIS: 0.65 air changes per hour
For exhaust: 0.43 air changes per hour

Now for a less conservative deviance interval of 0.3, the appropriate mixing rates are:
For CFIS: 0.4 air changes per hour
For exhaust: 0.18 air changes per hour

Comparing Supply and Exhaust systems

The chosen ventilation systems yield very different results for a given air handler capacity. This is mainly because the air handler runs at unequal periods. We chose to compare the effectiveness of either system by comparing their response to a given contamination profile as a function of the mixing air changes provided by the Air Handling System.

Figure 5: Dependence of relative dose on mixing for OCC

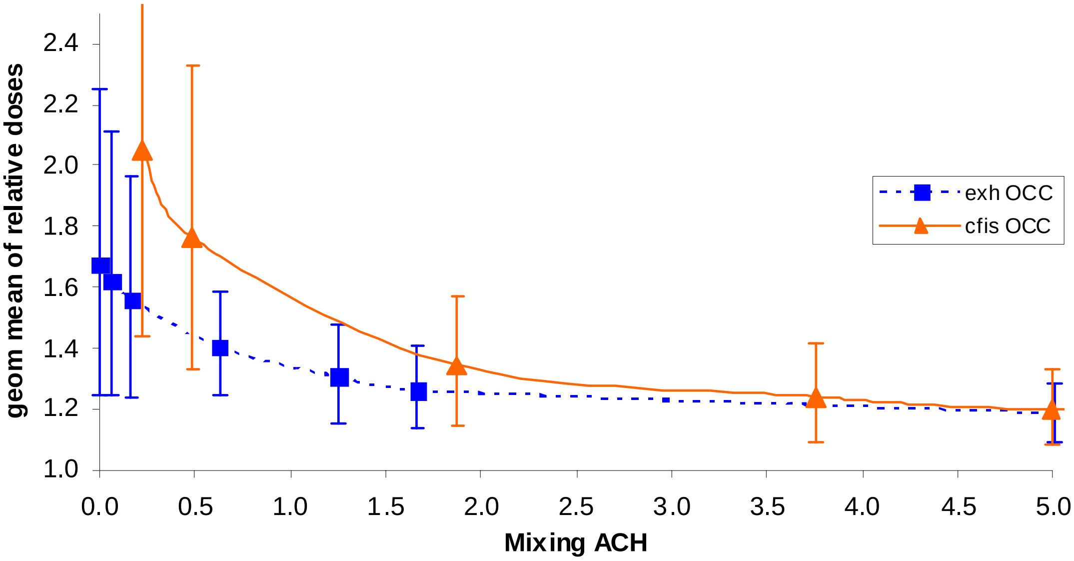


Figure 6: Dependence of relative dose on mixing for B&K

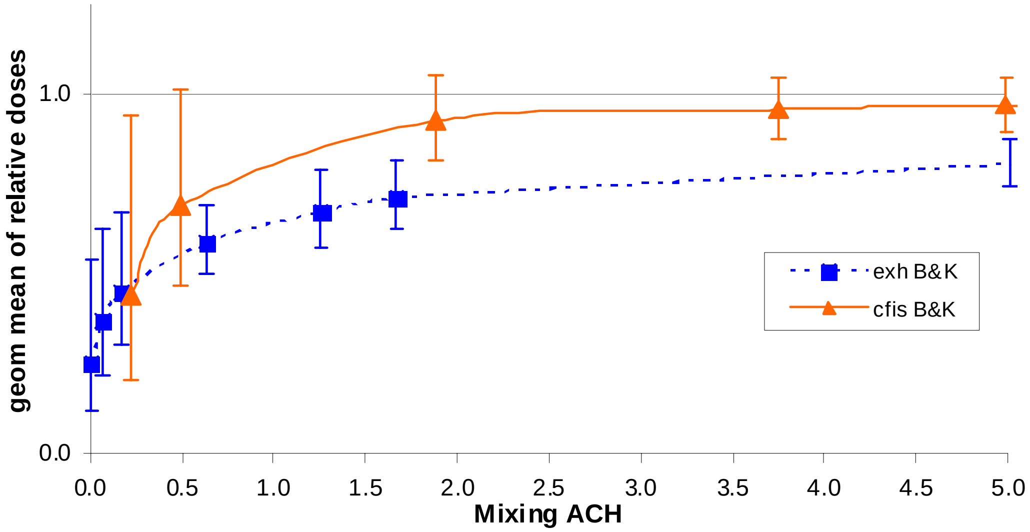
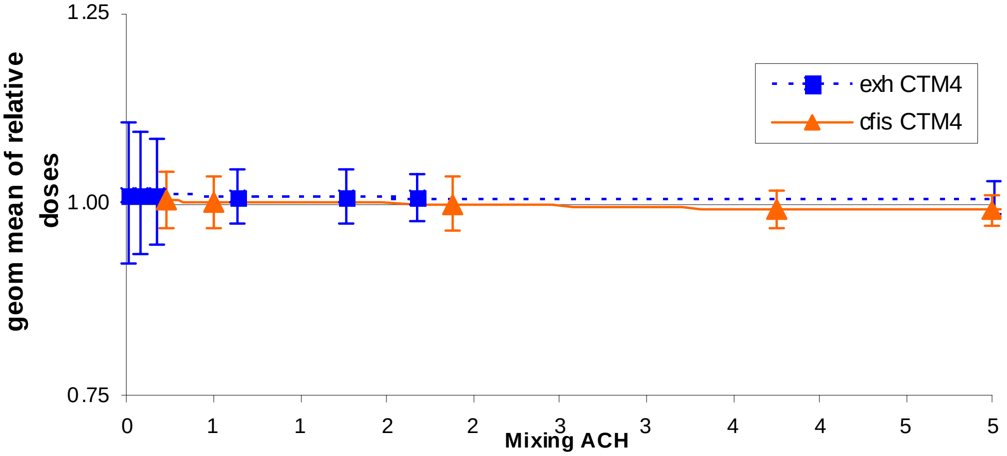


Figure 7: Dependence of relative dose on mixing for VOL



<u>Observations:</u>

- Relative dose in the VOL case, shown in Figure 7, is always very close to 1 regardless of the ventilation system because sources are well distributed in the space. Variability depends on where fresh air is distributed and where the occupants are.
- In OCC and B&K cases, for a given quantity of mixing, the relative dose obtained from an exhaust system is lower, as well as its variability. This shows beneficial aspects of the exhaust system: it tends to remove pollutants before they are mixed and outdoor air infiltration throughout the envelope and contributes to the mixing effect.
- To minimize relative dose, exhaust systems should exhaust from the zones of highest contaminant concentration and supply systems would provide air to where there was current occupancy. If there is not enough mixing to homogenize the concentration of contaminants then location of exhaust fans is important.

The observations made on the means and on the standard deviation intervals indicate that the EXH+AHS system is a better choice than CFIS. At equal mixing provided by the air handler, relative dose means are lower, as are standard deviations, meaning lower risks of extreme exposure. We attribute this benefit to the fact that central a central exhaust provides mixing in the house without the additional use of an air handler, and encourage future studies to compare distributed and central system.

DISCUSSION

Doors

An assumption that greatly affects results is whether doors are open with two way flow or closed with one-way flow (through an undercut or transfer grille. To quantify the importance of this assumption, we ran the simulations again using the assumption that doors are two-way flow openings (which we will refer to as “open doors”). Temperature differences of 1°C between the rooms were used to create the air exchange through open doors. This creates natural mixing when the air handler is off, and more mixing when it is on.

This additional mixing can easily be observed, as shown in the following Figures. Figure 8 shows relative doses for all contamination profiles in both closed and open doors scenario for the exhaust profile. For the exhaust system again, Figure 9 is a comparison of how the standard deviance of the results evolves with open and closed doors when increasing air handler capacity. Figures 10 and 11 show the same trends for the CFIS system.

Figure 8: Comparing mean relative dose for open and closed doors in EXH + AHS

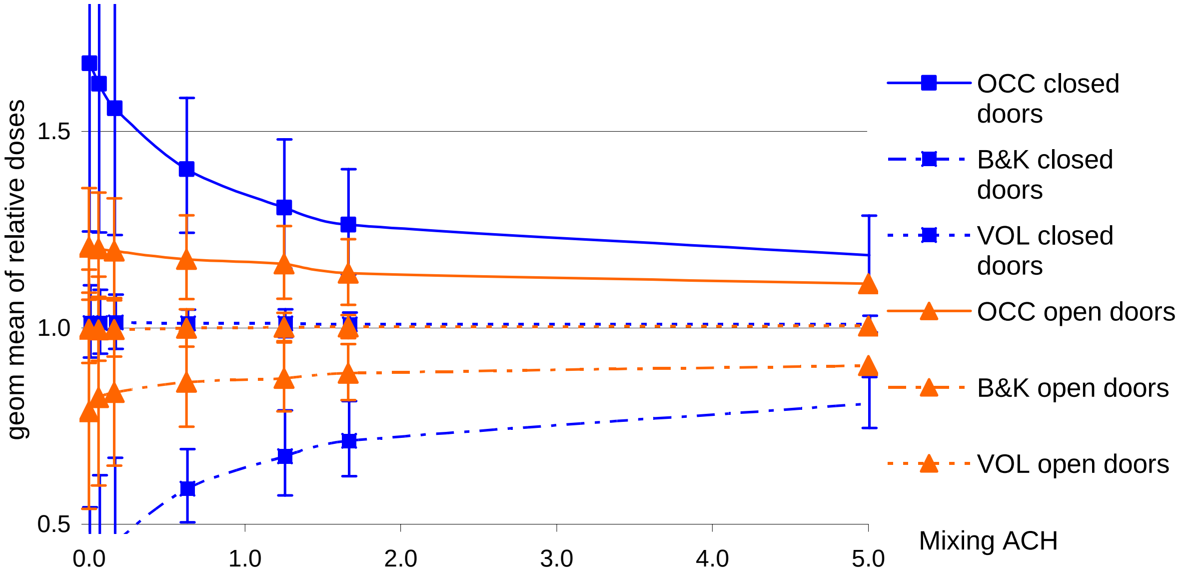


Figure 9: Comparing variability relative dose for open and closed doors in EXH + AHS

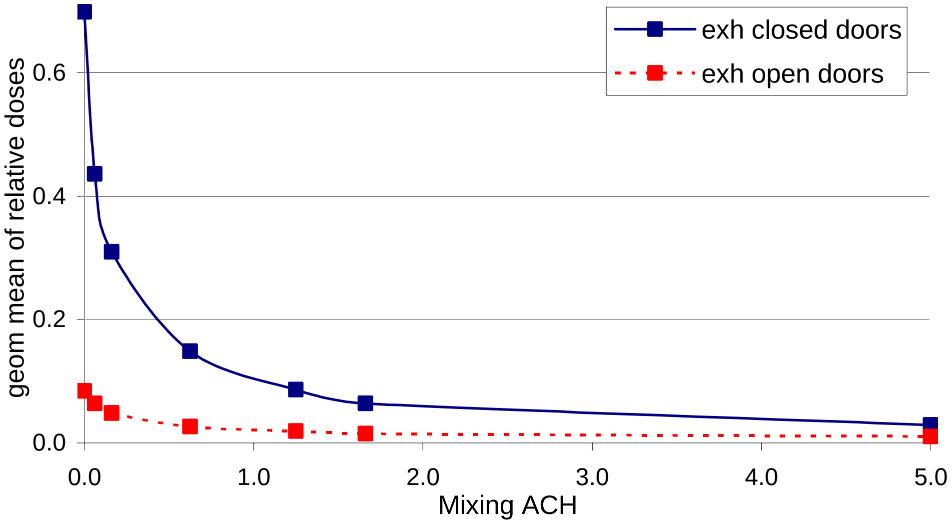


Figure 10: Comparing mean relative dose for open and closed doors in CFIS

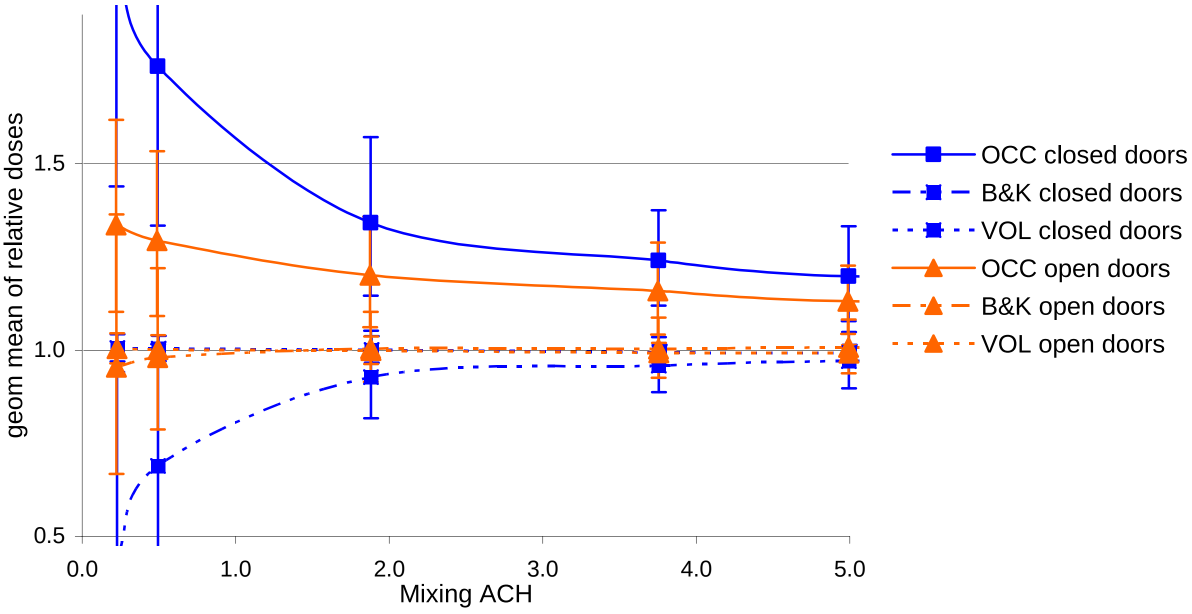
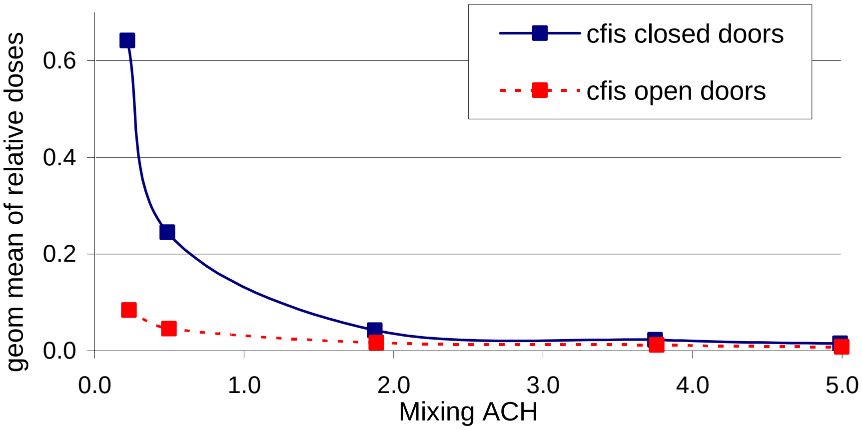


Figure 11: Comparing variability relative dose for open and closed doors in CFIS



<u>Observations:</u>

- In the exhaust profile (Figure 8), natural mixing occurs through doors five sixths of the time (one sixth has the air handler running), resulting in additional mixing that shifts the curves by approximately four air changes per hour.
- In the CFIS profile (Figure10), natural mixing occurs through doors half the time (the other half has the air handler running), resulting in additional mixing that shifts the curves by approximately two air changes per hour.
- The additional mixing provided naturally by open two-way flow doorways with small temperature differences can also be observed in the variability of relative dose results. As seen in the standard deviance interval curves (Figure 9 for exhaust and Figure 11 for CFIS), the shift in both cases is approximately one air change per hour.

Most importantly, these curves show that natural mixing occurring through doors can have a noticeable effect on IAQ, and that this is a variable that should not be overlooked.

Results for seven original metrics

The first step, before calculating the metrics, was obtaining the distribution matrix for every ventilation case. In our case where ventilation is tied to the occupancy schedules - we ultimately have 24 (four occupancy groups, three houses, two systems) matrices to calculate. There are then just as many values of every dose metric.

The calculation method for the distribution method is a simulation of the full multi-source, multizone measurement approach described by Sherman et al. (1990c), where there is a distinct source in every zone (S_i) which is tracked in all zones. We use CONTAM with the same models previously used, and place a distinct source with a constant emission in each zone. Post-processing tools were quite flexible and allowed to make certain zones implicit (such as the supply and return systems, which are unoccupied zones).

Each of the seven metrics was calculated for all 24 distribution matrices at a given AHS rate. The value of a metric which we look at for a given ventilation system is the geometric mean of 12 results (3 houses and 4 occupancy groups). These calculations were repeated for all the air handler rates. The results can be observed in Figures 12 and 13:

Figure 12: Dependence of mean dose on selected metrics for EXH

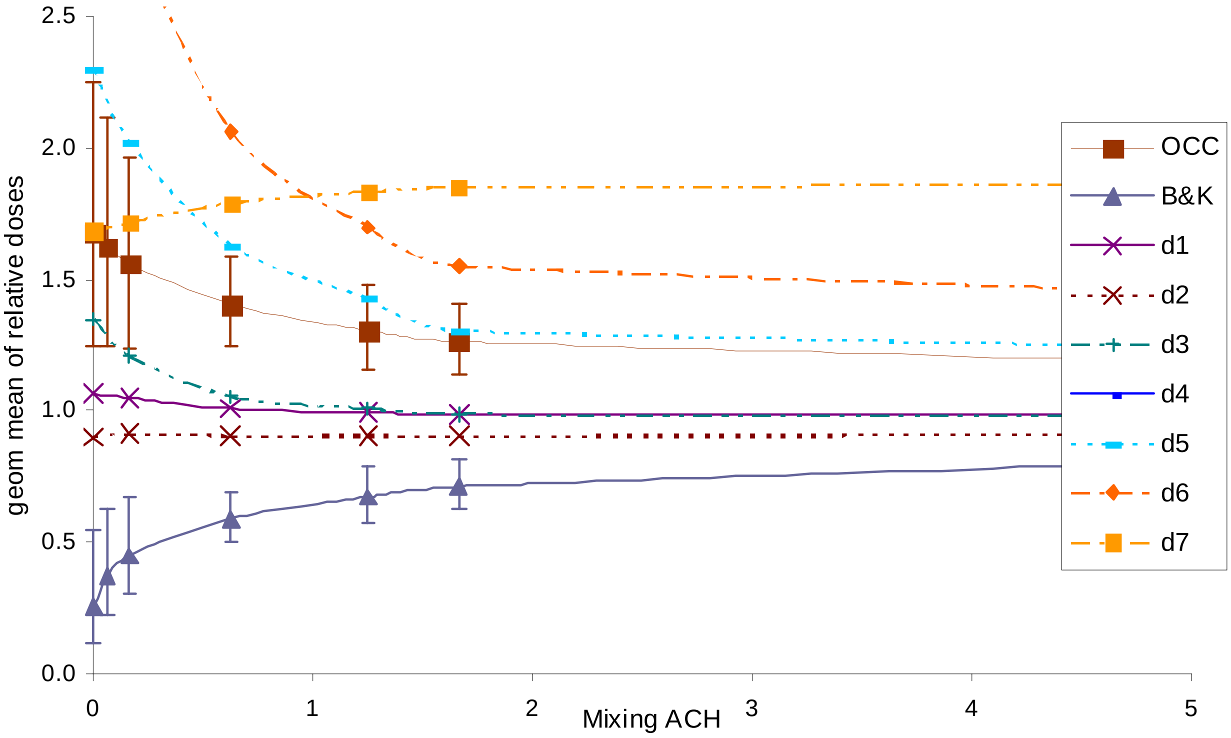
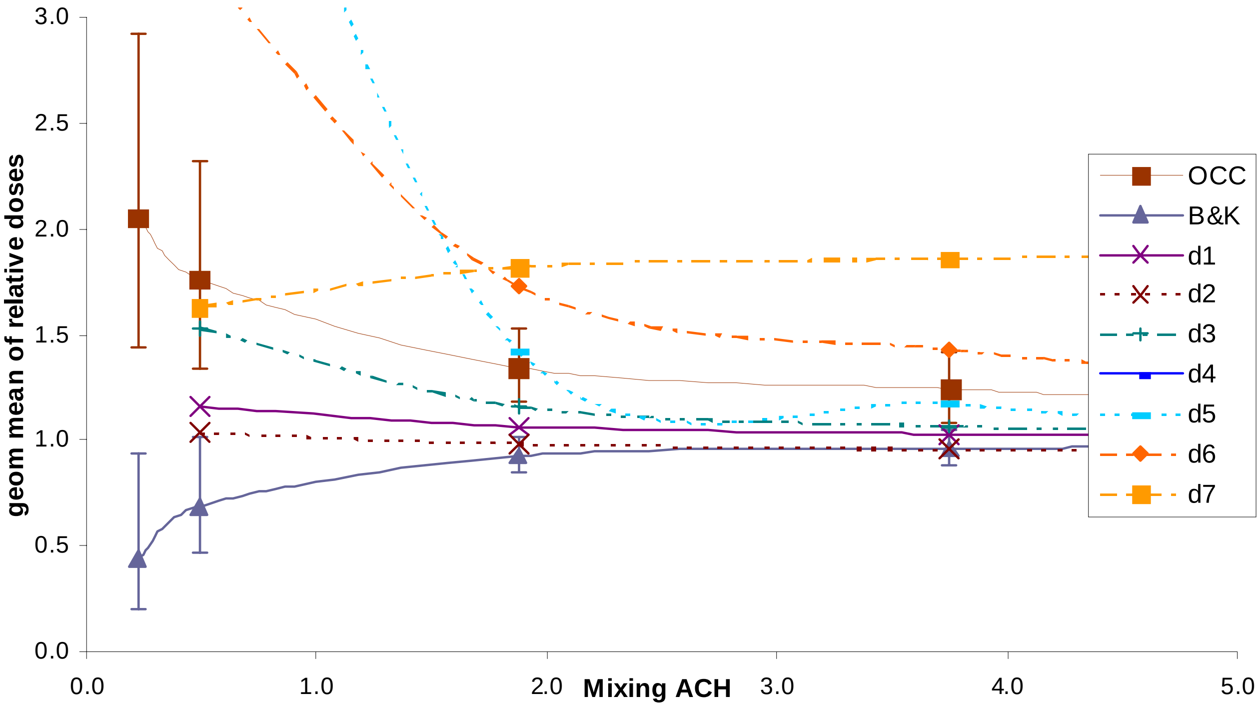


Figure 13: Dependence of mean dose on selected metrics for CFIS



Observations:

- For the exhaust and CFIS cases alike, d_1 and d_2 both show means that are very close to 1. As expected, these metrics are not sensitive to mixing.
- d_4 is much too high to be considered anything realistic, it is in fact off the charts. It may represent extreme-worst-case.
- d_5 behaves in a very different way depending on the system. It seems at low mixing rates cross contamination can be much greater with CFIS. It remains a good measure of cross contamination.
- d_6 in this form is slightly too high to be considered in correlation with results of OCC. To coincide with the OCC profile, another norm could be chosen which would give a lower result and converge towards 1 faster.
- d_7 as such can be a measure of how distant the system is from perfect isolation, however it is bound to have values comprised between 1 and 2. There should therefore be found a way to scale the distance between a system of air flows and “perfect isolation” in the interval of 1 and 2.

Results for new metrics

We compare the results from the metrics to the relative dose results we obtained from simulating occupants (OCC or B&K results) in order to find metrics that coincide with a particular contamination profile. We seek a metric that has a value within the standard deviance interval of the CTM results. Most of the metrics are within the deviance intervals, and most of them are good indicators of how mixing affects relative dose; however very few yielded the same conclusions in both profiles. Since we are trying to develop metrics applicable to all possible flow systems, we concentrated on finding metrics that evolved the same way in both systems.

Figure 14: best relative dose metrics for OCC

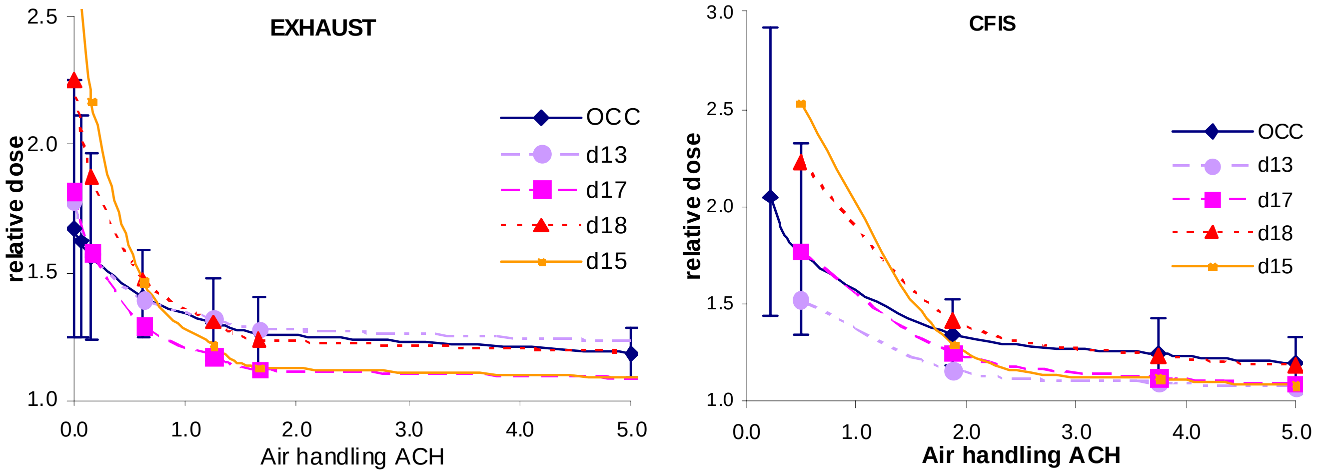
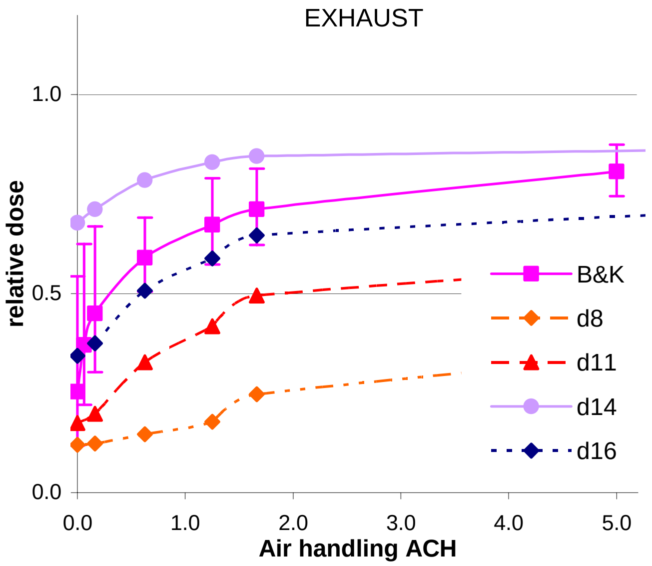


Figure 15: Best relative dose metrics for B&K



Observations:

- d_{13} and d_{15} are generally better at representing proximity to perfect mixing than d_6 since then both tend to converge toward 1 with the OCC and B&K curves. It is the fact that they are not positioned in the same way in the two different systems that prevents us from using them to directly to estimate relative dose.
- The best metrics at representing OCC in both the exhaust and CFIS profile are d_{17}, for optimistic values, slightly under the mean ; d_{18}, for conservative values, slightly over the mean ; and d_{13}, which is always within the deviance interval.
- To mimic B&K, no metrics seemed to evolve the same way in the two profiles, which prompted a combination of d_{11} and d_{14} as d_{16}. d_{16} is the only metric that is always within the deviance interval of B&K in both systems. It would therefore be the best choice to approach B&K.

It is hard to define an activity vector for generic use, which would represent the average behavior of occupants. Moreover, the intricacies of an occupants' exposure in time (correlation between contaminant spread with flows and occupant's movement) cannot be modelized in an averaged model like the distribution matrix.

It therefore makes sense that no single metric is going to be precisely identifiable to an actual contamination pattern. Metrics d_{16}, d_{17} and d_{18} are proposed as combinations of other metrics and prove reliable in both systems considered. We would therefore advise that when attempting to identify an average relative dose in a given flow system, one use a combination of metrics for best results, the metrics considered individually representing purely hypothetical cases.

Conclusions

The objectives that have been met in this study are: examine how occupants of a dwelling are affected by ventilation systems that distribute fresh outdoor air differently, determine the effects of mixing indoor air and make a recommendation on mixing rates, and develop mathematical predictions of relative dose.

The concept of relative dose was used in an unsteady model to quantify the varying impact that different ventilation systems have on IAQ, as well as the role of mixing indoor air in maintaining IAQ. The comparison of exposure to perfect mixing via relative dose has brought to light important notions: the natural mixing induced by a central exhaust system, limiting the need of an air handler, and the increase of mixing to reduce variability of exposure. We suspect that this is a common benefit from central ventilation systems (exhaust or supply alike), and future research should verify and quantify this benefit. The results reveal that mixing can be good or bad depending on the pollutant source distribution. If we are controlling for occupant generated pollutants mixing is a good idea, whereas for locally generated pollutants or avoiding what is generated by other occupants, then it is bad. For distributed sources mixing has no significant effect. In general, averaging shows that mixing is selectively beneficial, meaning no general rule can be defined as to it’s IAQ benefit or loss. Results also reveal that reflecting on worst-case scenarios can be misleading.

Mixing of indoor air was also shown to be highly dependant on flows through doorways which can vary greatly depending on whether they are open or closed. As encouraged by these notions, further research should explore the scheduling of openings between zones, natural vectors of mixing in indoor space, and comparisons between central and distributed systems, in order to provide institutions that write and implement standards robust tools to take into account distribution patterns in residential ventilation.

What we have achieved in this paper with the pursuit of metrics for estimating relative dose is first of all to expand certain concepts to unsteady multizone air flow patters, and secondly to find a handful of metrics that can potentially be applied to any flow system to represent the relative dose of an actual occupant. These are also good metrics for estimating how distant a system is to perfect mixing from the point of view of exposure. Further analysis from simulation work and distribution matrices obtained from tracer gas measurements should explore this subject further to test the robustness of the metrics on multiple flow systems.

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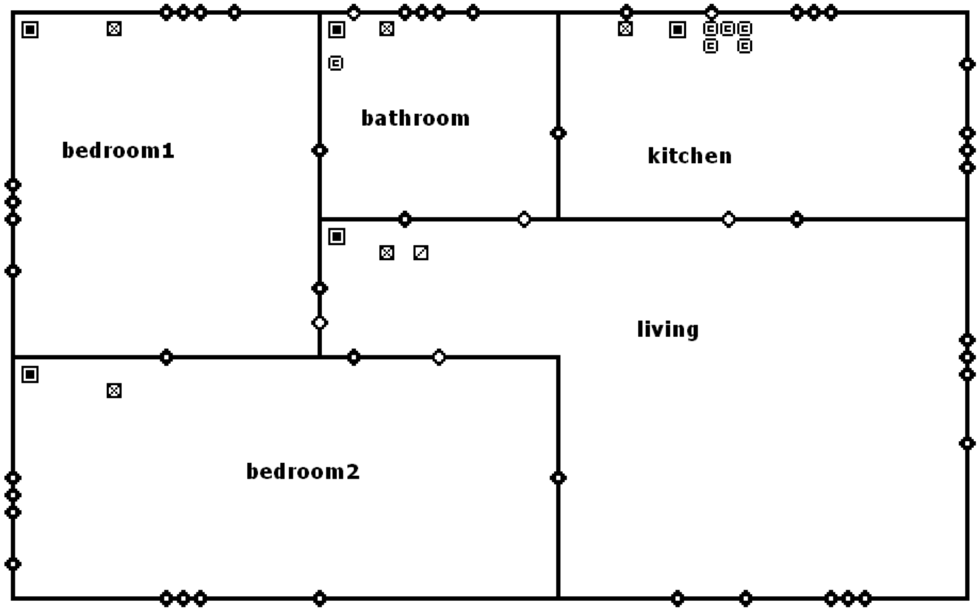
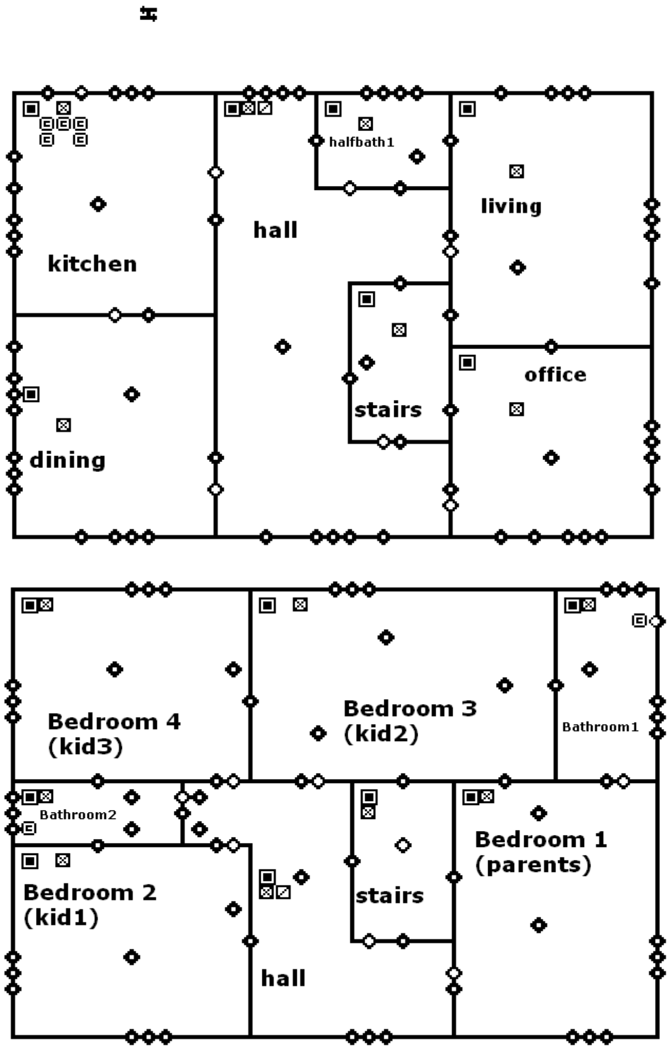
Appendix 1: House details

House 1:



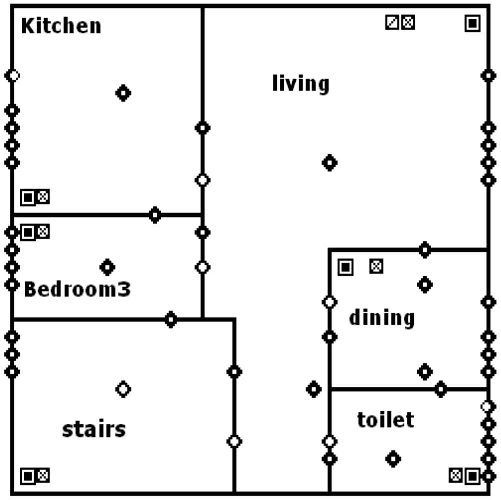
	Area (m^2)
Bd1	15.6
Bd2	16.7
living	29.1
kitchen	19.2
bath	5.6

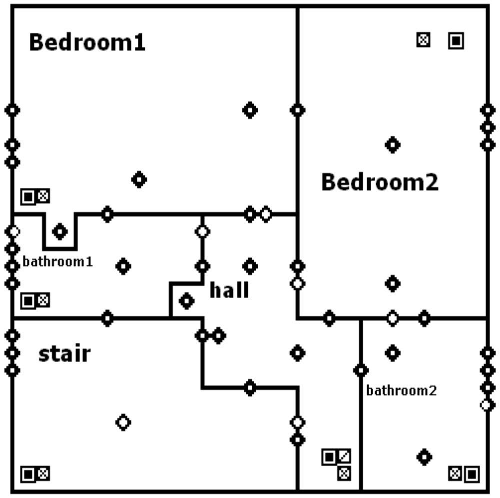
House 2:

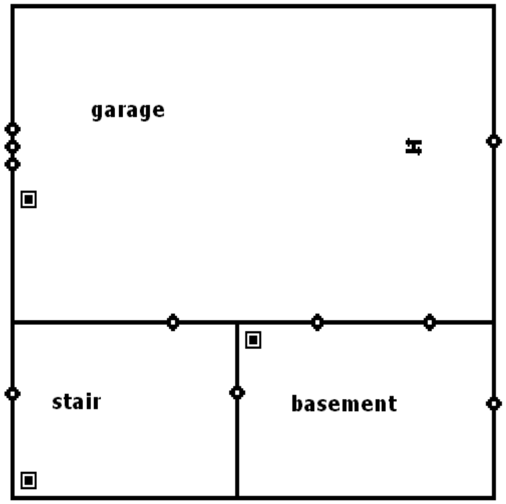


	Area (m^2)
Lev 2 bedroom4	19.7
Lev 2 bedroom3	24.2
Lev 2 bathroom1	11.1
Lev 2 bathroom2	7.6
Lev 2 stair	8.2
Lev 2 bedroom1	33.1
Lev 2 bedroom2	19.7
Lev 2 hall	14.1
Lev 1 kitchen	20.8
Lev 1 hall	25.2
Lev 1 halfbath1	4.7
Lev 1 living	33.1
Lev 1 stair	8.2
Lev 1 office	22.0
Lev 1 dining	23.8

House 3:







	A (m^2)
Lev 0 garage	32.1
Lev 0 bedroom2	9.4
Lev 0 stairs	6.7
Lev 1 stairs	8.2
Lev 1 bedroom3	7.4
Lev 1 kitchen	7.4
Lev 1 living	12.0
Lev 1 dining	9.3
Lev 1 toilet	4.3
Lev 2 bedroom4	9.2
Lev 2 bathroom2	4.6
Lev 2 stairs	6.7
Lev 2 hall	7.1
Lev 2 bedroom1	15.7
Lev 2 bathroom1	4.9

Appendix 2: flow elements

One way flows using power law

House 1				**References :**		
	% of ELA	**area leakage (in2/ft2)**	**linear leakage (in2/ft)**	**Pressure drop**	**discharge coefficient**	**Flow exponent**
ceiling	35	0.001227213		4	1	0.65
walls	30	0.001052171		4	1	0.65
floor	35		0.009820262	4	1	0.65

House 2				**References :**		
	% of ELA	**area leakage (in2/ft2)**	**linear leakage (in2/ft)**	**Pressure drop**	**discharge coefficient**	**Flow exponent**
ceiling	35	0.002399936		4	1	0.65
walls	50	0.002001100		4	1	0.65
floor	15		0.009605281	4	1	0.65

House 3				**References :**		
	% of ELA	**area leakage (in2/ft2)**	**linear leakage (in2/ft)**	**Pressure drop**	**discharge coefficient**	**Flow exponent**
ceiling	35	0.007818063		4	1	0.65
walls	30	0.001675299		4	1	0.65
half basement	35	0.002898218		4	1	0.65

Common elements				**References :**		
	% of ELA	**area leakage (in2/ft2)**	**linear leakage (in2/ft)**	**Pressure drop**	**discharge coefficient**	**Flow exponent**
closed door		1.86		4	1	0.65
Interior Wall		0.0288		4	0.6	0.65

	cross sectional (ft2)	**Hydraulic diameter (ft)**	**transition Reynolds number**	**Discharge coefficient**	**Flow exponent**
open door	21	5.17	30	0.6	0.5

Constant Volume Flows

	flow rate (cfm)
Intermittent Bathroom fan	50
Intermittent Kitchen fan	100

Appendix 3: occupancy schedules

The following occupancy schedules are for the 1-story detached house (house 1), though the other houses have additional rooms and 1 additional occupant,, the occupancy schedules remain very similar.

Family 1:

WEEK DAY	kid (10)	kid (4)	mum	dad
00:00	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
00:15	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
00:30	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
00:45	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
01:00	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
01:15	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
01:30	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
01:45	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
02:00	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
02:15	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
02:30	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
02:45	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
03:00	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
03:15	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
03:30	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
03:45	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
04:00	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
04:15	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
04:30	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
04:45	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
05:00	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
05:15	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
05:30	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
05:45	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
06:00	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
06:15	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
06:30	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
06:45	Bd1 - sleep	Bd1 - sleep	Bd2	Bath
07:00	Bd1 - sleep	Bd1 - sleep	Bath	Kitchen
07:15	Bd1	Bath	Kitchen	Bd2
07:30	Bath	Kitchen	Kitchen	Out
07:45	Kitchen	Bd1	Kitchen	Out
08:00	Out	Out	Out	Out
08:15	Out	Out	Out	Out
08:30	Out	Out	Out	Out
08:45	Out	Out	Out	Out
09:00	Out	Out	Out	Out
09:15	Out	Out	Out	Out
09:30	Out	Out	Out	Out
09:45	Out	Out	Out	Out
10:00	Out	Out	Out	Out
10:15	Out	Out	Out	Out
10:30	Out	Out	Out	Out
10:45	Out	Out	Out	Out
11:00	Out	Out	Out	Out
11:15	Out	Out	Out	Out
11:30	Out	Out	Out	Out
11:45	Out	Out	Out	Out
12:00	Out	Out	Out	Out
12:15	Out	Out	Out	Out

12:30	Out	Out	Out	Out
12:45	Out	Out	Out	Out
13:00	Out	Out	Out	Out
13:15	Out	Out	Out	Out
13:30	Out	Out	Out	Out
13:45	Out	Out	Out	Out
14:00	Out	Out	Out	Out
14:15	Out	Out	Out	Out
14:30	Out	Out	Out	Out
14:45	Out	Out	Out	Out
15:00	Out	Out	Out	Out
15:15	Out	Out	Out	Out
15:30	Out	Out	Out	Out
15:45	living	living	kitchen	Out
16:00	Bd1	living	living	Out
16:15	Bd1	living	Bd2	Out
16:30	Bd1	living	Bd2	Out
16:45	Out	Bd1	Bd2	Out
17:00	Out	Bd1	Bd2	Out
17:15	Out	Bd1	Bd2	Out
17:30	Out	Bd1	living	Out
17:45	Out	living	living	Out
18:00	Out	living	living	Out
18:15	Out	living	kitchen	Out
18:30	Bd1	bath	kitchen	Bd2
18:45	bath	kitchen	kitchen	Bd2
19:00	living	living	living	living
19:15	living	living	living	living
19:30	living	living	living	living
19:45	living	living	living	living
20:00	Bd1	Bd1	Kitchen	Kitchen
20:15	Bd1	Bd1	Kitchen	Kitchen
20:30	Bd1	bath	living	living
20:45	bath	Bd1	Bd1	living
21:00	living	Bd1 - sleep	living	living
21:15	living	Bd1 - sleep	living	living
21:30	living	Bd1 - sleep	living	living
21:45	living	Bd1 - sleep	living	living
22:00	Bd1 - sleep	Bd1 - sleep	living	living
22:15	Bd1 - sleep	Bd1 - sleep	living	living
22:30	Bd1 - sleep	Bd1 - sleep	bath	living
22:45	Bd1 - sleep	Bd1 - sleep	Bd2	bath
23:00	Bd1 - sleep	Bd1 - sleep	Bd2	Bd2
23:15	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
23:30	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
23:45	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep

Family 2:

WEEK DAY	kid (10)	kid (4)	mum	dad
00:00	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
00:15	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
00:30	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
00:45	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
01:00	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
01:15	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
01:30	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
01:45	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
02:00	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
02:15	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep

02:30	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
02:45	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
03:00	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
03:15	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
03:30	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
03:45	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
04:00	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
04:15	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
04:30	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
04:45	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
05:00	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
05:15	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
05:30	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
05:45	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
06:00	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
06:15	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
06:30	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
06:45	Bd1 - sleep	Bd1 - sleep	Bd2	Bath
07:00	Bd1 - sleep	Bd1 - sleep	Bath	Kitchen
07:15	Bd1	Bath	Kitchen	Bd2
07:30	Bath	Kitchen	Kitchen	Out
07:45	Kitchen	Kitchen	Kitchen	Out
08:00	Out	Out	Bd2 - sleep	Out
08:15	Out	Out	Bd2 - sleep	Out
08:30	Out	Out	Bd2 - sleep	Out
08:45	Out	Out	Bd2 - sleep	Out
09:00	Out	Out	Bd2 - sleep	Out
09:15	Out	Out	Bd2 - sleep	Out
09:30	Out	Out	Bd2 - sleep	Out
09:45	Out	Out	Bd2 - sleep	Out

10:00	Out	Out	Kitchen	Out
10:15	Out	Out	Kitchen	Out
10:30	Out	Out	Kitchen	Out
10:45	Out	Out	Kitchen	Out
11:00	Out	Out	living	Out
11:15	Out	Out	living	Out
11:30	Out	Out	living	Out
11:45	Out	Out	living	Out
12:00	Out	Out	living	Out
12:15	Out	Out	Out	Out
12:30	Out	Out	Out	Out
12:45	Out	Out	Out	Out
13:00	Out	Out	Out	Out
13:15	Out	Out	Out	Out
13:30	Out	Out	Out	Out
13:45	Out	Out	Out	Out
14:00	Out	Out	Out	Out
14:15	Out	Out	Out	Out
14:30	Out	Out	kitchen	Out
14:45	Out	Out	kitchen	Out
15:00	Out	Out	kitchen	Out
15:15	Out	Out	Out	Out
15:30	Out	Out	Out	Out
15:45	living	living	Kitchen	Out
16:00	Bd1	living	living	Out
16:15	Bd1	living	Bd2	Out
16:30	Bd1	living	Bd2	Out
16:45	Out	Bd1	Bd2	Out
17:00	Out	Bd1	Bd2	Out
17:15	Out	Bd1	Bd2	Out

17:30	Out	Bd1	living	Out
17:45	Out	living	living	Out
18:00	Out	living	living	Out
18:15	Out	living	kitchen	Out
18:30	Bd1	bath	kitchen	Bd2
18:45	bath	kitchen	kitchen	Bd2
19:00	living	living	living	living
19:15	living	living	living	living
19:30	living	living	living	living
19:45	living	living	living	living
20:00	Bd1	Bd1	Kitchen	Kitchen
20:15	Bd1	Bd1	Kitchen	Kitchen
20:30	Bd2	bath	living	living
20:45	bath	Bd1	Bd1	living
21:00	living	Bd1 - sleep	living	living
21:15	living	Bd1 - sleep	living	living
21:30	living	Bd1 - sleep	living	living
21:45	living	Bd1 - sleep	living	living
22:00	Bd1 - sleep	Bd1 - sleep	living	living
22:15	Bd1 - sleep	Bd1 - sleep	living	living
22:30	Bd1 - sleep	Bd1 - sleep	bath	living
22:45	Bd1 - sleep	Bd1 - sleep	Bd2	bath
23:00	Bd1 - sleep	Bd1 - sleep	Bd2	Bd2
23:15	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
23:30	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep
23:45	Bd1 - sleep	Bd1 - sleep	Bd2 - sleep	Bd2 - sleep

Retired couple:

WEEK DAY	woman	man
00:00	Bd2 - sleep	Bd2 - sleep
00:15	Bd2 - sleep	Bd2 - sleep
00:30	Bd2 - sleep	Bd2 - sleep
00:45	Bd2 - sleep	Bd2 - sleep
01:00	Bd2 - sleep	Bd2 - sleep
01:15	Bd2 - sleep	Bd2 - sleep
01:30	Bd2 - sleep	Bd2 - sleep
01:45	Bd2 - sleep	Bd2 - sleep
02:00	Bd2 - sleep	Bd2 - sleep
02:15	Bd2 - sleep	Bd2 - sleep
02:30	Bd2 - sleep	Bd2 - sleep
02:45	Bd2 - sleep	Bd2 - sleep
03:00	Bd2 - sleep	Bd2 - sleep
03:15	Bd2 - sleep	Bd2 - sleep
03:30	Bd2 - sleep	Bd2 - sleep
03:45	Bd2 - sleep	Bd2 - sleep
04:00	Bd2 - sleep	Bd2 - sleep
04:15	Bd2 - sleep	Bd2 - sleep
04:30	Bd2 - sleep	Bd2 - sleep
04:45	Bd2 - sleep	Bd2 - sleep
05:00	Bd2 - sleep	Bd2 - sleep
05:15	Bd2 - sleep	Bd2 - sleep
05:30	Bd2 - sleep	Bd2 - sleep
05:45	Bd2 - sleep	Bd2 - sleep
06:00	Bd2 - sleep	Bd2 - sleep
06:15	Bd2 - sleep	Bd2 - sleep
06:30	Bd2 - sleep	Bd2 - sleep

06:45	Bd2	Bath
07:00	Bath	Bath
07:15	Bath	Kitchen
07:30	Kitchen	Kitchen
07:45	Kitchen	Bd2
08:00	Bd2	living
08:15	Bd2	living
08:30	Bd2	living
08:45	Bd2	living
09:00	Bd2	living
09:15	Bd2	living
09:30	Bd2	living
09:45	Bd2	living
10:00	Out	Out
10:15	Out	Out
10:30	Out	Out
10:45	Out	Out
11:00	Out	Out
11:15	Out	Out
11:30	Out	Out
11:45	living	living
12:00	living	living
12:15	living	living
12:30	living	living
12:45	Kitchen	living
13:00	Kitchen	living
13:15	Kitchen	Kitchen
13:30	Kitchen	Kitchen
13:45	living	Bd2
14:00	living	Bd2
14:15	living	Bd2
14:30	living	living
14:45	living	living
15:00	living	living
15:15	Out	Out
15:30	Out	Out
15:45	Out	Out
16:00	Out	Out
16:15	Out	Out
16:30	Out	Out
16:45	Out	Out
17:00	Out	Out
17:15	Bd2	Bd2
17:30	living	living
17:45	living	living
18:00	living	living
18:15	Kitchen	living
18:30	Kitchen	living
18:45	Kitchen	Kitchen
19:00	Kitchen	Kitchen
19:15	living	living
19:30	living	living
19:45	living	living
20:00	Kitchen	Kitchen
20:15	Kitchen	Kitchen
20:30	bath	living
20:45	bath	living
21:00	living	bath
21:15	living	bath
21:30	living	living

21:45	living	living
22:00	living	living
22:15	living	living
22:30	living	living
22:45	Bd2	living
23:00	Bd2	Bd2
23:15	Bd2 - sleep	Bd2 - sleep
23:30	Bd2 - sleep	Bd2 - sleep
23:45	Bd2 - sleep	Bd2 - sleep

Single occupant:

WEEK DAY	man
00:00	Bd2 - sleep
00:15	Bd2 - sleep
00:30	Bd2 - sleep
00:45	Bd2 - sleep
01:00	Bd2 - sleep
01:15	Bd2 - sleep
01:30	Bd2 - sleep
01:45	Bd2 - sleep
02:00	Bd2 - sleep
02:15	Bd2 - sleep
02:30	Bd2 - sleep
02:45	Bd2 - sleep
03:00	Bd2 - sleep
03:15	Bd2 - sleep
03:30	Bd2 - sleep
03:45	Bd2 - sleep
04:00	Bd2 - sleep
04:15	Bd2 - sleep
04:30	Bd2 - sleep
04:45	Bd2 - sleep
05:00	Bd2 - sleep
05:15	Bd2 - sleep
05:30	Bd2 - sleep
05:45	Bd2 - sleep
06:00	Bd2 - sleep
06:15	Bd2 - sleep
06:30	Bd2 - sleep
06:45	Kitchen
07:00	Kitchen
07:15	bath
07:30	Bd2
07:45	living
08:00	Out
08:15	Out
08:30	Out
08:45	Out
09:00	Out
09:15	Out
09:30	Out
09:45	Out
10:00	Out
10:15	Out
10:30	Out
10:45	Out
11:00	Out
11:15	Out
11:30	Out

11:45	Out
12:00	Out
12:15	Out
12:30	Out
12:45	Out
13:00	Out
13:15	Out
13:30	Out
13:45	Out
14:00	Out
14:15	Out
14:30	Out
14:45	Out
15:00	Out
15:15	Out
15:30	Out
15:45	Out
16:00	Out
16:15	Out
16:30	Out
16:45	Out
17:00	Out
17:15	Out
17:30	Out
17:45	Out
18:00	Out
18:15	Out
18:30	Out
18:45	Out
19:00	Out
19:15	Kitchen
19:30	living
19:45	living
20:00	Kitchen
20:15	bath
20:30	Bd2
20:45	Out
21:00	Out
21:15	Out
21:30	Out
21:45	Out
22:00	Out
22:15	Out
22:30	Out
22:45	living
23:00	Bd2
23:15	Bd2 - sleep
23:30	Bd2 - sleep
23:45	Bd2 - sleep