

A STOCHASTIC APPROACH TO PREDICT THE RELATIONSHIP BETWEEN DWELLING PERMEABILITY AND INFILTRATION IN ENGLISH APARTMENTS

Benjamin Jones^{*1}, Zaid Chalabi², Payel Das³, Michael Davies³, Ian Hamilton⁴, Robert Lowe⁴, Anna Mavrogianni³, Darren Robinson¹, Clive Shrubsole³, Jonathan Taylor³

*1 Department of Architecture and Built Environment
Lenton Firs House, University of Nottingham
NG7 2RD, United Kingdom
*Corresponding author:
benjamin.jones@nottingham.ac.uk*

*2 London School of Hygiene
and Tropical Medicine
15-17 Tavistock Place
London, WC1H 9SH, United Kingdom*

*3 Bartlett School of Graduate Studies
University College London
Central House, 14 Upper Woburn Place
London, WC1H 0NN, United Kingdom*

*4 Energy Institute
University College London
Central House, 14 Upper Woburn Place
London, WC1H 0NN, United Kingdom*

ABSTRACT

Reducing adventitious infiltration in order to save energy is important and is highlighted by the building standards of many countries. This operational infiltration is often inferred via the measurement of the air leakage rate at a pressure differential of 50 Pascals. Some building codes, such as the UK's Standard Assessment Procedure, assume a simple relationship between the air leakage rate and mean infiltration rate during the heating season, the so-called *leakage-infiltration ratio*, which is scaled to account for the physical and environmental properties of a dwelling. The scaling does not take account of the permeability of party walls in conjoined dwellings and so cannot be used to differentiate between the infiltration of unconditioned ambient air that requires heating, and conditioned air from an adjacent dwelling that does not. This article evaluates the leakage infiltration ratio in apartments, which share a large proportion of their envelope area with other dwellings. A stochastic approach is used that applies a theoretical model of adventitious infiltration to predict the distribution of the mean infiltration rate and total heat loss during heating hours for a sample of apartments of the English housing stock (a subset of the UK stock) for two extreme assumptions of party wall permeability. Knowledge of party wall permeability is not provided by a standard measurement of air leakage but is shown to be vital for making informed decisions on the implementation of energy efficiency measures. Accordingly, this paper provides probability distribution functions of operational infiltration in English apartments that can be used to help the policy makers of any country whose housing stock contains a large proportion of conjoined dwellings.

KEYWORDS

Infiltration, House, Stock, Model, Monte-Carlo

1 INTRODUCTION

The infiltration of cold air through adventitious openings located in the envelope of a dwelling, known as air leakage paths (ALPs), is thought to be a significant contributor to its heating load. However, determining a mean infiltration rate during the heating season is time consuming, invasive, expensive, and technically difficult. Therefore, it is often inferred from a measurement of the air leakage rate (ALR), \dot{V}_{50} (m³/s) or \dot{M}_{50} (kg³/s), the rate of airflow

through the fabric of a building at a steady high pressure difference, normally 50 Pascals (Pa), when the effects of wind and buoyancy are effectively eliminated (Etheridge; 2012). The ALR is often scaled by dwelling volume to give an *air change rate* at 50 Pa, \dot{N}_{50} (h^{-1}), or by dwelling envelope area, A_{env} (m^2), to an *air permeability*, \dot{P}_{50} ($\text{m}^3/\text{h}/\text{m}^2$). In order to be useful, the ALR must be converted to an operational infiltration rate, and although there are several methods of doing this (Younes *et al.*, 2012), the most common for dwellings is the *rule-of-thumb* known as the *leakage-infiltration ratio*, L , given by Sherman (1998) as:

$$(\dot{V}_{50}/\dot{V}_I = \dot{M}_{50}/\dot{M}_I = \dot{N}_{50}/\dot{N}_I) \approx L \quad (1)$$

Here, the subscripts 50 and I indicate parameters measured at a steady pressure differential of 50Pa and under operational conditions, respectively. The parameter L is a variable but is often taken to be equal to 20 when Equation (1) is known as the *rule-of-20*. However, L must not be considered to be a constant but should be scaled according to factors such as dwelling height air leakage path (ALP) size, shielding, and climate (Sherman, 1987). The UK government's method for assessing and comparing the energy and environmental performance of dwellings is known as the Standard Assessment Procedure (SAP). SAP uses the *rule-of-20* as a starting point to obtain an initial dwelling infiltration rate from measured ALR. Further infiltration is added if chimney, flues, and fans are present. The figure is revised further according to local shielding, and mechanical ventilation. Other building codes make similar assumptions (MoEoF, 2012).

There are obvious problems with Equation (1). Firstly, the ALR is a physical property of a dwelling that indicates the resistance of its fabric to airflow (Jones *et al.*, 2013a) at high pressure whereas operational infiltration occurs at pressure differences that are both dynamic and an order of magnitude lower. Furthermore, the *rule-of-20* was derived from measurements made in dwellings in the USA (Sherman, 1998) whose properties are different from typical European dwellings. For example, detached dwellings comprise the majority (~86%) of the U.S. stock (Sherman & Matson, 1997) whereas semi-detached houses and apartments comprise >50% of the English housing stock (DCLG, 2011). A dwelling of either of these latter types shares some of its walls, known as party walls, with adjacent dwellings. However, when building codes scale the ALR they do not take account the permeability of party walls in conjoined dwellings and so cannot differentiate between the infiltration of unconditioned ambient air that requires heating, and conditioned air from an adjacent dwelling that does not. When measuring the ALR, Jones *et al.* (2013a) propose that one can make two extreme assumptions about the permeability of party walls at 50Pa: A(1) party walls are permeable and so airflow to and from adjacent dwellings does occur; or A(2) party walls are impermeable and so airflow to and from adjacent dwellings does not occur. They then use two archetypal English dwellings to investigate the potential consequences of these assumptions using a theoretical model. They predict for assumption A(1) that the leakage-infiltration is significantly higher than that used by buildings code whereas for assumption A(2) the leakage-infiltration ratio is predicted to be close to that used in practice. The consequences of these findings are two-fold. Firstly, if A(1) is true then operational energy loss is less than that predicted by building codes (such as SAP), and government funded schemes (such as the UK's Green Deal) that aim to tighten the European housing stock will have longer payback periods than expected. Secondly, if A(2) is true government funded schemes that aim to tighten the European housing stock are appropriate. This predicted dichotomy of outcomes introduces great uncertainty into the effectiveness of any policy that aims to reduce energy consumption through fabric tightening.

An investigation of the variation of infiltration rates found in a stock of dwellings could be used to determine its exfiltration heat loss. Estimated probability distribution functions of infiltration and heat loss are useful tools with which policy makers can determine the likely effectiveness of fabric tightening schemes. Accordingly, this paper asks the questions: how

can one predict distributions of infiltration rates for a housing stock and what effects do the extreme assumptions about the permeability of party walls have on them?

2 METHODS

There are no known large scale measurements or predictions of heating season infiltration rates in English dwellings and so a modelling approach is proposed. Distributions of infiltration rates in U.S. dwellings have been predicted by Persily *et al.* (2010), and their study offers useful guidance. A modelling approach requires three things: a model of dwelling infiltration and exfiltration, knowledge of the properties of a large number of dwellings of a stock that can be applied to the model, and a suitable statistical approach that enables robust predictions to be made. In this section the three requirements are discussed using the English housing stock as a case study, although the approach is readily transferable to housing stocks in other countries. A single dwelling type is used to answer the research question “what effects do the extreme assumptions on the permeability of party walls have on a distribution of infiltration rates?” Here, apartments (defined as low-rise with ≤ 3 stories) are used because they can share up to 5 of their external surfaces with another dwelling and so any difference between predictions for the two permeability assumptions A(1) and A(2) is expected to be clearly observed. If a difference is observed, the method proposed here can be applied to all other dwelling types encompassing the whole stock.

2.1 Modelling infiltration and exfiltration heat loss

For any model there is always a trade-off between model complexity (and associated prediction accuracy) with computational speed. Uncertainty in the predictions of a model is a function of errors in the inputs to the model and model uncertainty (structural and parametric). Striking the right balance in this trade-off must be addressed when considering the model’s tasks; for example, when modelling a stock of dwellings the sample size is expected to be large and so a computationally fast model is desirable. Furthermore, the variation in geometry types across a stock dictates that the model should also be versatile. A final requirement is that the workings and limitations of the model must be documented and its predictions compared against empirical data or, less desirably, corroborated against the predictions of other models.

This paper applies DOMVENT3D, a model of infiltration and exfiltration through any number of façades that assumes two things about façades: all are uniformly porous; the pressure distribution over one is linear. DOMVENT3D integrates the airflow rate in the vertical plane to predict the total airflow rate through any number of façades (Jones *et al.*, 2013). DOMVENT3D makes further assumptions about the dwelling. Following Etheridge (2012), it assumes that all rooms of a dwelling are interconnected and that its internal doors are open so that a dwelling can be treated as a single-zone, thus reducing model complexity. Each horizontal and vertical surface of the external envelope requires only a single flow equation linked by a continuity equation, thus reducing computational time. DOMVENT3D’s final assumption follows Jones *et al.* (2013a) who state that adjacent dwellings are assumed to experience identical environmental conditions and thus have the same internal pressure. Therefore, airflow through permeable party walls and floors does not occur under operational conditions and so is only considered through external surfaces. This boundary requires a model of a conjoined dwelling (located within a block) only to consider the surfaces of that dwelling (and not those of the entire block), further reducing computation time. DOMVENT3D is implemented using bespoke MATLAB code (MathWorks, 2013). Its assumptions, merits, limitations, and the corroboration of its predictions are discussed widely by Jones *et al.* (2013a,b).

DOMVENT3D requires inputs that may be unique to each dwelling or are general to a sub-stock of dwellings bounded by geographic region. Unique inputs comprise the flow exponent, internal air density, the dimensions of all permeable external vertical (façades) and horizontal (ceilings and floors) surfaces, scaled wind speed, and façade wind pressure coefficients. General inputs are the ambient air temperature, regional wind speed, and wind orientation. Sources of data are discussed in Section 2.2.

Once the infiltration and exfiltration rates are predicted by DOMVENT 3D, the exfiltration heat loss (W) at an instant in time is calculated by

$$H(t) = \dot{M}_I c \Delta T \quad (1)$$

where \dot{M}_I is as defined above, c is the specific gas constant of air ($\text{J kg}^{-1} \text{K}^{-1}$) and ΔT is the difference between the internal and ambient air temperatures (K). The internal air temperature of an average English house is, on average, 3 C higher than the ambient air temperature and so the heating system is assumed to function only when the ambient air temperature is ≤ 3 C below the internal air temperature (Hamilton *et al.*, 2011). Heat loss is only calculated when the heating system is “on”.

2.2 Model inputs

The English housing stock ~~c-is comprised of~~ 22.3 million dwellings, of which a statistically representative sample of 16,150 dwellings is documented by the 2009 English housing survey (DCLG, 2011). Each sample is weighted so that the sum of the weights equals 22.3m, and provides geographic, geometric, and environmental information. However, the inputs to DOMVENT3D are not always explicitly available despite the data rich EHS. Therefore, metadata must be derived either from the EHS and other sources, or assumed. Data inputs to DOMVENT3D may be divided into four distinct types: geographic (location), geometric (dwelling dimensions, block dimensions, orientation), environmental (local wind speed and direction, internal and ambient temperatures, physical parameters (air permeability, flow exponent, and façade pressure coefficients), and terrain type, local shielding). We now discuss each data type in turn beginning with geographic data.

2.2.1 Geographic metadata

The EHS indicates the region in which each sample is located and allows suitable weather data to be chosen. The CIBSE Test Reference Year (TRY) weather data set (CIBSE, 2002) provides synthesised typical weather years for 10 English regions and is suitable for analysing the environmental performance of buildings. Accordingly, each EHS region is mapped to an appropriate CIBSE TRY region and where more than one CIBSE region is located in an EHS region the CIBSE region is chosen randomly from the set of possible regions.

2.2.2 Geometric metadata

The EHS assumes that two connecting cuboids can reasonably represent ~98% of the sampled stock thus allowing a cuboid model of each storey of a dwelling to be created. The proportion of each surface shared with another dwelling is recorded and we note that this does not always add to 100%; for example, a terrace might be staggered in the horizontal plane. The cuboid model is constructed following the Cambridge Housing Model (CHM) (Hughes *et al.*, 2012) that applies SAP is to estimate energy use and CO₂ emissions in the English stock. Although the EHS gives the number of stories in an apartment block and the location of the apartment within the block, it is desirable to assume that the vertical location of the apartment is a random variable uniformly sampled between the boundaries of the block dimensions and commensurate with the number of apartment floors (some have several floors). Dwelling

orientation is not given by the EHS and so it is assumed to be a uniformly distributed random variable between 1 and 360 degrees. Other geometric parameters must also be assumed. For example, the number of dwellings in a block of apartments is not always given by the EHS but this parameter informs the calculation of physical parameters, such as wind pressure coefficients (see Section 2.2.3). Accordingly, the block aspect ratio is arbitrarily assumed to be a uniformly distributed random variable between 3 and 20. Using arbitrarily inputs introduces error so a sensitivity analysis is undertaken in Section 5 to evaluate their impact on the predictions of DOMVENT3D.

2.2.3 Physical metadata

To the best of the authors' knowledge, there are no large-scale measurements of operational infiltration rates in the English housing stock. However, there are a limited number of databases of \dot{P}_{50} values for U.K. dwellings (Pan, 2010); for example, Pan (2010) gives air permeability values for 287 *new* English houses constructed after 2006, and Stephen (1998) gives air permeability values for 384 U.K. dwellings (also reported in Orme *et al.*, 1998) constructed before 2000. Although U.K. housing developments constructed after 2006 are required to record the air permeability of a proportion of them (HM Government, 2010) new dwellings represent a small proportion of the total stock, ~4% (DCLG, 2011). Therefore, there is only a cursory knowledge of the operational infiltration rates one expects to find in the majority of English dwellings. In their model of infiltration in U.S. dwellings, Persily *et al.* (2010) assign a permeability value to a dwelling according to its age and type, representing an appropriate approach. However, the limited quantity of empirical data for English dwellings makes this approach impossible. Instead, the distributions of Pan (2010) and Stephen (1998) are applied if the dwelling is constructed pre-2000 and post-2000, respectively. It is acknowledged that Pan's data is for post 2006 houses, but this is the best compromise that the EHS dwelling age distribution allow.

The flow exponent variable characterises the airflow regime through an ALP and is a function of its geometry and surface roughness. Its value affects both the pressure difference across an ALP and the airflow rate through it. Most infiltration models assume a constant value of 0.66 (Orme *et al.*, 1998), but Sherman (1998) shows that a mean value of $\mu=0.651$ with a standard deviation of $\sigma=0.077$ best represents more than 1900 measurements made in U.S. dwellings. Sherman's distribution is very similar to the smaller international AIVC data set (Orme *et al.*, 1998) and so is applied with confidence as a Gaussian random variable.

Wind pressure coefficients are defined for the horizontal and vertical surfaces. For the latter, the algorithm of Swami and Chandra (1987) gives a normalized average wind pressure coefficient for long-walled low-rise dwellings and is a function of the angle of incidence of the wind (for wind direction see Section 2.2.1), local sheltering (Section 2.2.4), and the block aspect ratio (Section 2.2.2). The coefficient is then scaled to account for local shielding (Section 2.2.4). Horizontal surfaces are assumed to be completely shielded from the effects of the wind following Sherman and Grimsrud (1980).

2.2.4 Environmental metadata

Local wind speed, wind direction, and ambient air temperature are taken from an appropriate CIBSE TRY file (see Section 2.2.2) but the wind speed must be scaled according to the terrain and dwelling height using a standard power law formula (BSI, 1991). Dwelling height is obtained from the cuboid model and the terrain is indicated by the EHS. The four BSI terrain types and the local wind pressure shielding coefficients (Section 2.2.3) of Deru and Burns (2002) are mapped using expert judgement to the six EHS terrain types.

DOMVENT3D is not a thermal model and so the internal air temperature must be prescribed. Here, a constant value of 18.5°C is chosen following Palmer *et al.* (2011) who estimate this

figure for the U.K. domestic average internal air temperature in 2005. There is no evidence on the fluctuation of this value and so it is assumed to be a constant.

2.3 Stochastic methods

A Monte Carlo (MC) approach is used to predict distributions of winter infiltration and heat loss in English apartments and their sensitivity to model inputs. Inputs to DOMVENT3D are provided by multiple Latin Hypercubes each of 20 sets (balance between computation and accuracy, convergence) of four stochastic input variables comprising the EHS sample (using dwelling weight), the dwelling orientation, the air permeability, and the flow exponent. All other random variables are a function of these parameters and are chosen independently when required. After each set of 20 samples the mean (μ) and standard deviation (σ) of the predicted infiltration rate, \dot{N}_I (h^{-1}), of all samples are calculated and used to decide if a stopping criterion has been met. The number of samples is deemed adequate if the change in σ from one set of 20 samples to the next is less than 0.1%. The model is run twice because a distribution is required for each of the two assumptions, A(1) and A(2).

3 RESULTS

Table 1: Statistical summary of mean infiltration rate (h^{-1}) and total winter heat loss (MWh) samples. Assumption A(1): permeable party walls. Assumption A(2): impermeable party walls.

Statistical measure	Mean Infiltration Rate, \dot{N}_I (h^{-1})		Total Heat Loss, H_I (MWh)	
	Permeability Assumption		Permeability Assumption	
	A(1)	A(2)	A(1)	A(2)
Minimum	0.001	0.016	0.004	0.029
2% centile	0.010	0.031	0.022	0.078
25%	0.054	0.145	0.124	0.395
50%	0.117	0.292	0.300	0.748
75%	0.215	0.477	0.589	1.287
98%	0.541	1.079	1.696	3.110
Maximum	0.736	1.603	6.470	8.282
Mean	0.151	0.338	0.448	0.959
Standard deviation	0.129	0.249	0.565	0.820

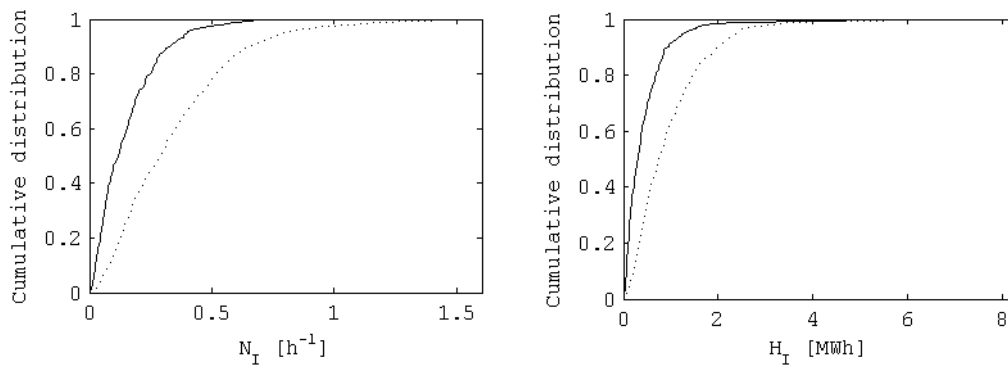


Figure 1a (left) and 1b (right): Predicted cumulative distribution of mean infiltration rate (left) and total winter heat loss (right). —, Assumption A(1); ·····, A(2).

Figure 1a shows the predicted cumulative distribution of mean infiltration rate, \dot{N}_I (h^{-1}), in English apartments during the heating season for both permeability assumptions. Figure 1b shows the same for total winter heat loss, H_I (MWh). Table 1 gives descriptive statistics for each sample and extreme permeability assumption. The number of samples required were 360 and 860 for permeability assumptions A(1) and A(2), respectively.

Table 1 and Figures 1a and 1b show that all distributions are positively skewed and so median values are used herein. A clear difference between the predictions made for each of the two permeability assumptions is observed. \dot{N}_I and H_I are predicted to be lower for permeability

assumption A(1) than for A(2), and that assumption A(2) increases the variance of the sample. The difference in predicted mean winter infiltration for A(1) and A(2) is explained by considering both assumptions applied to an apartment of fixed permeability with at least one party wall. Whatever the permeability assumption of the party walls, the total leakage area (equal to the sum of the cross sectional areas of all ALPs) of the apartment is identical because the permeability is fixed. If assumption A(1) is assumed and the party walls are permeable then the total leakage area is uniformly distributed over all surfaces of the apartment's envelope. If assumption A(2) is assumed and the party walls are impermeable then the total leakage area is only uniformly distributed over the exposed surfaces, A_I (m^2), of the apartment's envelope, thus increasing the operational infiltration rate. Jones *et al.* (2013a) show that the ratio of the predicted infiltration rate for the two permeability assumptions is equal to a ratio of permeable envelope area at a pressure differential of 50 Pascals A_{50} (m^2) where

$$A_{50,A(1)}/A_{50,A(2)} = \dot{N}_{I,A(2)}/\dot{N}_{I,A(1)} \quad (2)$$

Here, the subscripts indicate the pressure differential and the permeability assumption. Equation (2) shows that for apartments, the ratio is likely to be $\gg 1$ because apartments tend to have more than one party wall and so $A_{50,A(1)} \gg A_{50,A(2)}$. For detached houses, one expects the ratio to approach unity because they have no party walls and so $A_{50,A(1)} \approx A_{50,A(2)}$. Note that Equation (2) is valid for a single dwelling and not for an entire distribution. Therefore it is reassuring that Table 2 shows that Equation (2) is approximately true for the sample medians of the two permeability assumptions. Table 2 also shows that the median air permeability, apartment volume, envelope area, and exposed envelope area for both samples are also similar because they are unaffected by the permeability assumptions.

The difference in variance between the samples (indicated by σ) is attributable to the variation of A_{50} governed by the permeability assumptions. For the A(1) sample, $A_{50} = A_{env}$ for the vast majority of cases (ground floor apartments with impermeable solid floors are an exception), whereas for the A(2) sample, $A_{50} \neq A_{env}$ for the vast majority of cases (when at least one party wall is assumed), they vary instead between $0 \ll A_{50} \ll A_{env}$.

Figure 1 shows that 97% and 78% of apartments for permeability assumptions A(1) and A(2), respectively, have a mean infiltration rate below 0.5ac/h. This is significant because 0.5ac/h is a threshold ventilation rate, recommended by many European countries, above which some negative health effects reduce (Jones *et al.*, 2013a). This suggests that English apartments should be fitted with purpose provided ventilation in order to minimize health risks to occupants and is an important consideration for policy makers.

Table 2: Median values of key descriptive parameters of sampled apartments. Assumption A(1): permeable party walls.
Assumption A(2): impermeable party walls.

Sample median	A(1)	A(2)
Air permeability, \dot{P}_{50} ($m^3/h/m^2$)	9.4	9.1
Apartment volume (m^3)	132.3	134.6
Envelope area, A_{env} (m^2)	184.2	185.6
A_I (m^2)	63.8	60.7
A_{50} (m^2)	161.9	60.7
$A_{50,A(1)}/A_{50,A(2)}$	2.7	2.7
$\dot{N}_{I,A(2)}/\dot{N}_{I,A(1)}$	2.5	2.5

A_{50} , permeable envelope area at a pressure differential of 50 Pascals.

A_I , exposed envelope area able to transfer mass under operational conditions.

Table 3: Predicted leakage infiltration ratio L and performance statistics.

Assumption A(1): permeable party walls.
Assumption A(2): impermeable party walls.

	A(1)	A(2)
L	66.90	32.07
R^2	0.01	0.41
RMSE	7.33	5.43
MAE	26.01	25.14

4 ASSESSING THE LEAKAGE INFILTRATION RATIO

Equation (1) is evaluated by the linear regression of \dot{N}_I and \dot{N}_{50} to estimate L and by the calculation of key performance statistics: the Coefficient of Determination (R^2), the Root Mean Squared Error (RMSE), and the Maximum Absolute Error (MAE). Here, R^2 quantifies the proportion of the total variation in the data that is explained by the regression model. When $R^2=1$, all variation in the data is explained by the model; whereas when $R^2=0$ the opposite is true. The RMSE is a measure of the average performance of the model's outputs, and the MAE is a measure of the largest deviation of the model's outputs. Values of L are given in Table 3 by permeability assumption along with the performance statistics. These statistics show that $L \neq 20$ and that Equation (1) is a poor model of the relationship between \dot{N}_I and \dot{N}_{50} in English apartments, whatever the permeability assumption. This outcome suggests that building codes that apply Equation (1) with $L = 20$ (in the first instance) are over predicting exfiltration heat loss in apartments. Table 2 shows that the mean total heat losses are 300kWh and 748kWh for permeability assumptions A(1) and A(2), respectively. For assumption A(1) and A(2) this is equivalent to running approximately three and eight 11W light bulbs non-stop for an entire year, respectively, or equivalent to the continuous occupancy by a single adult (assuming 100W per adult) for approximately 34% and 85% of a year, respectively.

An alternative model of the relationship between \dot{N}_I and \dot{N}_{50} is required and further work should apply meta-modelling techniques that minimize the prediction errors in a least-squares sense and that use the predictions given here as training and validation data.

5 SENSITIVITY ANALYSIS

Table 4: Sensitivity of outputs to inputs, confidence, and rank of key model inputs.

Outputs Inputs	Mean infiltration rate, \dot{N}_I			Total heat loss, H_I		
	τ	p	rank	τ	p	rank
Air permeability, \dot{P}_{50} ($\text{m}^3/\text{h}/\text{m}^2$)	0.54	0.00	1	0.53	0.00	1
Airflow exponent	-0.35	0.00	2	-0.35	0.00	2
A_{50} (m^2)	-0.22	0.00	3	-0.19	0.00	3
Mean wind speed at dwelling height (m/s)	0.08	0.00	4	0.09	0.00	4
Orientation ()	-0.04	0.02	5	-0.05	0.01	5
Apartment volume (m^3)	-0.03	0.16	6	0.04	0.03	7
Block aspect ratio	0.02	0.33	7	0.02	0.24	8
Mean temperature difference, $\overline{\Delta T}$ (C)	-0.01	0.66	8	-0.01	0.52	9
A_I (m^2)	0.00	0.90	9	0.05	0.02	6

A_{50} , permeable envelope area at a pressure differential of 50 Pascals.

A_I , exposed envelope area able to transfer mass under operational conditions.

It could be argued that the salient assertions made in Sections 3 and 4 are dependent upon the assumptions made in Section 2. Accordingly, a sensitivity analysis is used to determine the relative importance of inputs. All of the inputs are perturbed simultaneously by the Monte Carlo sampling method (see Section 2.3) and so any interactions between them (including those that are synergistic) are accounted for (Lomas and Eppel; 1992). To test the dependence of the inputs on the outputs \dot{N}_I and H_I , the Kendall τ correlation coefficient (a number between ± 1) is used. Here, $\tau = 1$ indicates perfect positive correlation between the input and the output, whereas $\tau = -1$ indicates perfect negative correlation. Inputs are ranked by $|\tau|$ where the lowest rank is the most significant; see Table 4. The inputs assed in Table 4 are continuous numerical variables that are uncorrelated with each other; for example, \dot{P}_{50} ($\text{m}^3/\text{h}/\text{m}^2$) is considered instead of envelope area, A_{env} . Moreover, the inputs are chosen to represent implicitly the geographic, geometric, environmental, physical, and terrain

parameters discussed in Section 2, thus avoiding the need to test categorical variables, such as the region.

Table 4 evaluates both samples in concert using MATLAB's "corr" function (with "kendall" as an input) that gives τ and a confidence interval (p) used to test for a non-zero correlation between the input and the output, assuming that the null-hypothesis is true. Table 4 shows that \dot{N}_I is sensitive to 5 of the 9 inputs (at $p < 0.05$) and H_I is sensitive to 6 of the 9 inputs. Both outputs are most sensitive to \dot{P}_{50} whose limitations are identified in Section 2.2.3. The accuracy of the predictions given here could be improved with more robust distributions of \dot{P}_{50} by dwelling type and age. It is reassuring that the model is insensitive to block geometry, given that its imposed limits are arbitrary (see Section 2.2.2), and to the mean temperature difference, $\overline{\Delta T}$, given the uncertainty in the variance of the internal air temperature (Section 2.2.4).

6 CONCLUSIONS

This paper provides a stochastic method for predicting distributions of mean infiltration rates in winter and total winter heat loss in a stock of dwellings. The method is used to investigate mean winter time infiltration rates in apartments, which share at least one wall with another dwelling, based on two extreme assumptions of party wall permeability. The first assumes that the party walls are permeable whereas the second assumes that they are not. A clear difference between the distributions for each of the two permeability assumptions is predicted. The distributions show that the mean infiltration rate and total heat loss are significantly less for the first assumption than for the second, and that at least 78% of apartments require additional purpose provided ventilation to limit negative health consequences.

The *leakage-infiltration* ratio is shown to be an unsuitable method of predicting an apartment's mean winter infiltration rate from a measurement of its air leakage rate. This finding is independent of the assumption of party wall permeability, because the *leakage-infiltration* ratio cannot account for the variation in geographic, geometric, environmental, physical, and terrain parameters. Building codes that use this ratio should reassess their use of the relationship.

The modelling approach detailed here can be applied to any stock of dwellings. The application of the approach to apartments highlights significant health and energy ramifications. The predicted distributions of the mean infiltration rate and total heat loss in winter for the two extremes of party wall permeability are a useful tool with which policy makers of any country whose housing stock contains apartments can make informed decisions about fabric tightness and exfiltration heat loss.

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