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

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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

Ventilation, 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), V_{50} (m^3/s) or M_{50} (kg^3/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, N_{50} (h^{-1}), or by dwelling envelope area, A_{env} (m^2), to give an *air permeability*, P_{50} ($m^3/h/m^2$). In order to be useful, the ALR must be converted to an operational infiltration rate, and although there are several methods of doing this, the most common for dwellings is the *rule-of-thumb* known as the *leakage-infiltration ratio*, L, given by Sherman (1998) as:

$$V_{50}\quad V_I = M_{50}\quad M_I = N_{50}\quad N_I \quad \approx L \tag{1}$$

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 the 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; for example, 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 climatic conditions and dwelling properties are different from typical European houses. 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 building codes 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 heat losses are less than those 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 could 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. An infiltration model requires three things: a model of dwelling infiltration and exfiltration, knowledge of the properties of a large representative sample of of a dwelling stock that can be applied to the model, and a suitable statistical approach that enables the stock variability to be captured. 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 data requirements (and potential input error) with computational speed. Variations in the predictions of a model are a function of variability and uncertainties in the inputs to the model (parametric uncertainty) and uncertainty in the model itself (structural uncertainty). 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. 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

$$H\ t\ = M_I c \Delta T\ _{T_{ext} \leq\ T_{int} - 3} \tag{1}$$

where M_I is as defined above, c is the specific heat capacity of air ($\mathrm{Jkg}^{-1}\mathrm{K}^{-1}$) and ΔT is the difference between the internal and ambient air temperatures. The internal air temperature, T_{int} (ºC), of an average unheated English house is, on average, 3ºC higher than the ambient air temperature, T_{ext} (ºC), and so the heating system is assumed to function only when the ambient air temperature is ≤3ºC below the internal air temperature (Hamilton *et al.*, 2011). Heat loss is only calculated when the heating system is "on". Equation (1) is integrated over the entire heating season to estimate the total heat loss, H_I (kWh) via exfiltration.

2.2 Model inputs

The English housing stock 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), physical parameters (air permeability, flow exponent, and façade pressure coefficients), and environmental (local wind speed and direction, internal and ambient temperatures, terrain type, and 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 (CISBE, 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 (with equal probability) from the set of possible regions.

2.2.2 Geometric metadata

The EHS assumes that two connecting cuboids can reasonably represent the geometry of ~98% of English dwellings. 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 to estimate energy use and CO_2 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 0 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). In the absence of any direct measurement of block aspect ratio, it is arbitrarily assumed to be a uniformly distributed random variable between 3 and 20. Using variable inputs introduces a distribution of outputs 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 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 percentage 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, inverse cumulative distribution functions are formed from the published histograms (for all dwelling types) of Pan (2010) and Stephen (1998) using Piecewise Cubic Hermite Interpolating Polynomials and are applied if a 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 allows.

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 μ=0.65 with a standard deviation of σ=0.08 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 to the six EHS terrain types with format EHS (BSI){Deru and Burns}: city (city){very heavy}, urban (urban){heavy}, suburban town (urban){heavy}, rural residential (urban){moderate}, village centre (urban){moderate}, rural (country with scattered wind breaks){light}.
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 of a 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. There are four stochastic inputs to DOMVENT3D: the EHS sample (using dwelling weight), dwelling orientation, air permeability, and a flow exponent. Twenty sets of the four inputs are chosen at a time using a Latin Hypercube. Each set is applied to DOMVENT3D to predict N_I (h^{-1}). The total sample size increases incrementally according to the set size, which is arbitrarily chosen to minimize calculation time. After each set of predictions are made, the mean (μ) and standard deviation (σ) of N_I for the whole sample 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 permeability 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, N_I (h^{-1}) Permeability Assumption		Total Heat Loss, H_I (MWh) Permeability Assumption	
	A(1)	A(2)	A(1)	A(2)
Minimum	0.00	0.02	0.00	0.03
2% centile	0.01	0.03	0.02	0.08
25%	0.05	0.14	0.12	0.39
50%	0.12	0.29	0.30	0.75
75%	0.22	0.48	0.59	1.29
98%	0.54	1.08	1.70	3.11
Maximum	0.74	1.60	6.47	8.28
Mean, μ	0.15	0.34	0.45	0.96
Standard deviation, σ	0.13	0.25	0.56	0.82
Mode	0.03	0.11	0.06	0.47

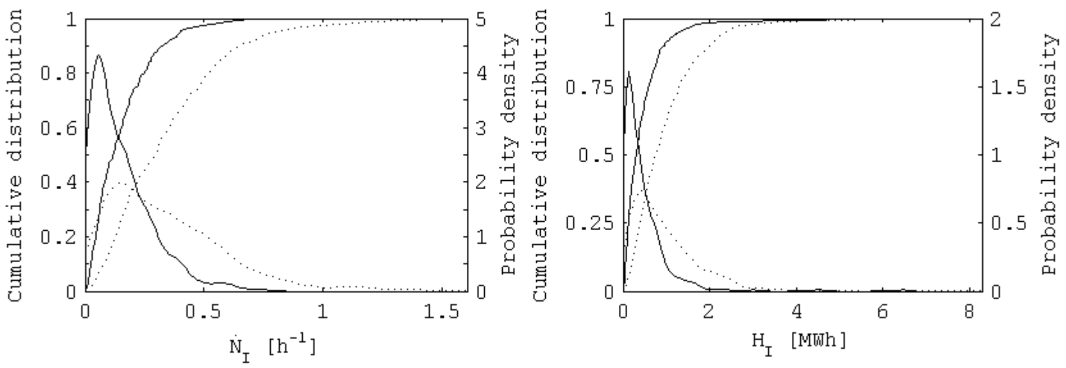

Figure 1a (left) and 1b (right): Predicted cumulative distributions and probability density functions of mean infiltration rate (left) and total winter heat loss (right). □ □ □ □ □, Assumption A(1); ⋯⋯, A(2).

Figure 1a shows the predicted cumulative distributions (CDF) and probability density functions (PDF) of the mean infiltration rate, 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. One-sided Kolmogorov-Smirnov tests of the null hypothesis that the A(1) and A(2) samples come from populations with the same distributions compared against the alternative that the A(1) CDFs are larger than the A(2) CDFs are rejected (at significance p <0.05) for both N_I ($p = 6 \times 10^{-33}$) and H_I ($p = 3 \times 10^{-31}$).

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 made 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 made 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

$$A_{50,A(1)} \;\; A_{50,A(2)} = N_{I,A(2)} \;\; N_{I,A(1)} \qquad (2)$$

Here, the subscripts indicate the pressure differential and the permeability assumption. Equation (2) shows that for apartments, the ratio is likely to be ≫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 $0 \ll A_{50} \ll A_{env}$.

Table 2: Meadian 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, 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
$N_{I,A(2)} \;\; N_{I,A(1)}$	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 condition

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

Figure 1 suggests 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 (all be it with great uncertainty), 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 to minimize health risks to occupants and is an important consideration for policy makers.
Table 1 shows that the median 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.

4 ASSESSING THE LEAKAGE INFILTRATION RATIO

Equation (1) is evaluated by the linear regression of N_I and N_{50} to estimate L and by the calculation of key performance statistics: R^2, Root Mean Squared Error (RMSE), and Maximum Absolute Error (MAE). Values of L are given in Table 3 by permeability assumption along with the performance statistics. These statistics imply that $L \neq 20$ and that Equation (1) is a poor model of the relationship between N_I and 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) could be over predicting exfiltration heat loss in apartments. However, it is acknowledged that sub-groups of these samples may exhibit a correlation but further work is required to determine if it is appropriate for building codes to scale L (as described in Section 1) or if another type of relationship is needed.
An alternative model of the relationship between N_I and N_{50} may be required. In the long term, an exhaustive field survey is required to give a reliable empirical basis for the prediction of N_I from dwelling characteristics. In the short term, further work could apply meta-modelling techniques, such as multiple linear regression, 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	**Mean infiltration rate, N_I**			**Total heat loss, H_I**		
Inputs	τ	p	**rank**	τ	p	**rank**
Air permeability, P_{50} (m^3/h/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 (º)	-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, ΔT (ºC)	-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 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 τ where the lowest rank is the most significant; see Table 4. The inputs assessed in Table 4 are continuous numerical variables that are uncorrelated with each other; for example, P_{50} ($m^3/h/m^2$) 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) to test for a non-zero correlation between the input and the output, assuming that the null-hypothesis is true. Table 4 shows that 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 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 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, ΔT, 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 statistical 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.

Concern is raised about the use of the *leakage-infiltration* ratio predict an apartment's mean winter infiltration rate from a measurement of its air leakage rate. This 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 unless it is scaled. Further work is required to reassess the use of the relationship by building codes.

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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