A MULTI-CRITERION METHOD FOR EXAMINING THE HEALTH AND ENERGY IMPACTS OF AIR CHANGE RATES IN DWELLINGS

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ABSTRACT

The global requirement to dramatically reduce greenhouse gas emissions places an increased emphasis on reducing energy demand associated with dwellings. Where improved energy efficiency is in part achieved by tighter control of ventilation, there is potential for both positive and negative impacts on health from reduced air exchange in the indoor environment. Although increased air tightness may help improve indoor temperatures and reduce the ingress of pollutants from the external environment, it may increase concentrations of those from indoor sources.

Using archetypal dwellings in London as case studies, this paper explores a method for examining the trade-offs between energy and health in the evaluation of an optimal air change rate. The energy demand and health impacts associated with exposures to indoor and outdoor $PM_{2.5}$ in each case-study dwelling are used as the criteria for determining the optimal ventilation rate.

The outcomes of this paper provide a novel perspective on the determination of an 'optimal' air change rate in dwellings.

KEYWORDS

Indoor air quality; air change rate; health impacts; space heating demand; optimization.

INTRODUCTION

People in developed countries typically spend over 80% of their time inside buildings [1] and in the UK they spend over 70% of time in their homes [2]. The air is a medium of personal exposure to an array of potentially harmful airborne pollutants. Accordingly, it is necessary to supply and to remove air from a dwelling in a controlled manner to improve overall indoor air quality and so Approved Document Part F (ADF) of the UK Building [3] requires a minimum whole dwelling ventilation rate of not less than 0.3 l/s per square metre of internal floor area. For many UK dwellings this corresponds to a minimum whole dwelling air change rate per hour of approximately 0.5/hr, a minimum rate set by many European countries for dwellings, and reported as a threshold rate above which some negative health effects reduce [4,5].

Concurrently, national CO_2 reduction commitments make it necessary to reduce dwelling heat losses via ventilation by reducing the permeability of dwellings that comprise the UK housing stock [6]. It is estimated that ~20% of heat loss from an average UK dwelling is via ventilation [7]. However, a possible unintended consequence of such a measure is a corresponding increase in personal exposure to pollutants such as mould, radon, and particulate matter (PM) [8] through lower ventilation rates. This increased exposure could significantly affect overall population health [9].

This paper aims to determine an optimal ventilation rate given multiple criteria that include energy and health impacts. Health impacts due to exposure to the smaller fractions (diameter of <2.5μm) of particulate matter ($PM_{2.5}$, deemed particularly harmful to health [10]) are modelled in a selection of case-study dwellings in London. $PM_{2.5}$ originates from both internal and external sources. In London, the annual mean ambient $PM_{2.5}$ concentration is 13 $\mu g/m^3$ [11] and its ingress into a dwelling is a function of factors including building permeability, location, height, orientation, and local meteorology [12]. Internally, dominant sources include cooking and tobacco smoking [13]. The optimization approach employed here monetizes and aggregates the relevant criteria to create a single cost objective function that is then minimized.

MODELS OF INDOOR AIR QUALITY

The variation of levels of indoor and outdoor $PM_{2.5}$ in different zones are explored here for the case of a naturally-ventilated London flat and house, of varying permeabilities. CONTAM, a validated multizone ventilation and pollutant transport model [14] is used to undertake the work following the modelling approach of [12].

Dwelling archetypes

The dwelling archetypes are taken from [9] and consist of a flat (assumed to be located on the ground floor) and a detached house. Both are assumed to have a North-South orientation. The flat has a total floor area of $45m^2$ and height 2.4m with two bedrooms, a living room, a kitchen, a bathroom, a store, and a landing. The detached house has an underfloor area (assumed to be unconditioned), a ground floor, a first floor, and a loft (also assumed to be unconditioned), each with floor areas of $48m^2$. The underfloor area extends 0.3m below ground level, the ground and first floors are each 2.4m high, and the loft is 0.7m high. The ground floor has a kitchen, a living room, a toilet, and a landing. The first floor has three bedrooms, an en-suite bathroom attached to the master bedroom, a second bathroom, and a landing connected to that on the ground floor by a staircase.

Multi-zonal contaminant analysis with CONTAM

CONTAM is used to determine hourly values of air changes per hour (ACH) and concentrations of $PM_{2.5}$ from internal and external sources.

Ventilation components

Air exchange between the dwellings and their external environment is assumed to occur via two mechanisms only: firstly, through permeable façades exposed to the external environment and secondly, via the opening of windows. The flat has two exposed façades facing North and

South and the house has exposed façades on all four vertical sides. Permeabilities of 3, 5, 7, 10, 15, 20, 25, 30, 40, and 50 $m^{3/}m^2$/hr@50Pa modelled, reflecting the range of permeabilities measured for the UK housing stock ([15], between 3 and 30 $m^{3/}m^2$/hr@50Pa) and going above the measured maximum to enable a larger range of air change rates to be investigated. Air exchange is possible between the exposed façades of the unconditioned part of the building envelope (i.e. the walls of the underfloor area and attic) and the external environment via airbricks in the underfloor area and vents in the attic. All zones except the store and landing are assumed to have one window in the exposed façade. The windows are partially open in the bathrooms during use and in the kitchen during cooking. They are additionally partially opened during the day in the summer months, if not already open.

Neighbouring flats are assumed to have the same indoor conditions as the modelled flat and hence there is no airflow at the inter-flat boundaries during operating conditions. Air exchange between indoor zones is possible through doors, which are closed when the zones are occupied, but open otherwise. The doors are assumed to be `leaky' when closed. The total annual average ACH of the conditioned zones in the building envelope (ACH_{yr}) is calculated from the hourly outputs of CONTAM.

Weather files, wind pressure coefficients, and indoor temperature profiles

The winter and summer weather files constructed by [12] for London from the CIBSE[1] Test Reference Year (TRY) and Design Summer Year (DSY) data sets are used here and contain hourly outdoor air temperature, air pressure, wind speed, wind direction, and humidity ratio information. Weekly indoor temperature profiles are used from a study by FMNectar [16]. They differ between summer and winter, but are the same in each zone. Outdoor wind pressure coefficients are applied to the ventilation components allowing exchange with the external environment according to the profile of [17] and indoor wind pressure coefficients are assumed to have negligible contribution due to zero air movement indoors.

Internal and external $PM_{2.5}$ sources are modelled separately to enable the ratio of the indoor $PM_{2.5}$ concentration to the outdoor concentration of $PM_{2.5}$ (I/O) to be determined. Internal $PM_{2.5}$ ($iPM_{2.5}$) is assumed to be produced by cooking only and is produced at a constant rate of 1.6 mg/min [18] during breakfast and dinner times on weekdays, and during all three meal times on weekends. External $PM_{2.5}$ ($ePM_{2.5}$) is assumed to have a constant concentration of 13μg/m^3, based on the mean urban background concentration from the Automatic Urban and Rural Network ([19]). Both sources of $PM_{2.5}$ are assumed to have a fixed deposition rate in all zones of 0.39 l/hr [18].

Final outputs of indoor $PM_{2.5}$ exposure in the rooms are aggregated in the ratios 0.45:0.45:0.10 (assuming 45% of an occupant's time is spent in the living room, 45% in the bedroom, and 10% in the kitchen) and then averaged over the year to give annual average concentrations $C_{iPM,yr}$ (μg/m^3) and $C_{ePM,yr}$ (μg/m^3), the latter of which is also calculated as a ratio of the external concentration of $PM_{2.5}$ to give the annual average indoor/outdoor ratio of external $PM_{2.5}$, $C_{I/O,yr}$.

Figure 1 shows the relation between ACH_{yr} for each archetype and the assumed permeability of the exposed façades. As expected, ACH_{yr} is higher in the house as all vertical façades are exposed to the external environment, while in the flat only two façades are exposed. In

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addition, the lower overall height of the flat results in a reduced stack effect. Both relations of ACH_{yr} with permeability are almost linear, but the relation for the house is steeper.

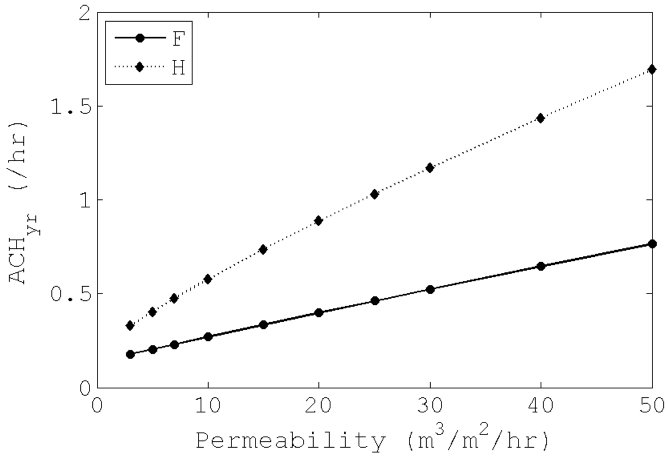

Figure 1: Relation between annual average air change rate of the building envelope and permeability for a naturally-ventilated flat (F) and house (H).

Figure 2 shows the variation of $C_{iPM,yr}$, and $C_{I/O,yr}$ with ACH_{yr}. $C_{iPM,yr}$ decreases as the dwelling becomes more permeable, both in the case of the flat and house. $C_{I/O,yr}$ increases as permeability increases as a greater proportion of external $PM_{2.5}$ is able to infiltrate the dwelling from the outdoor air.

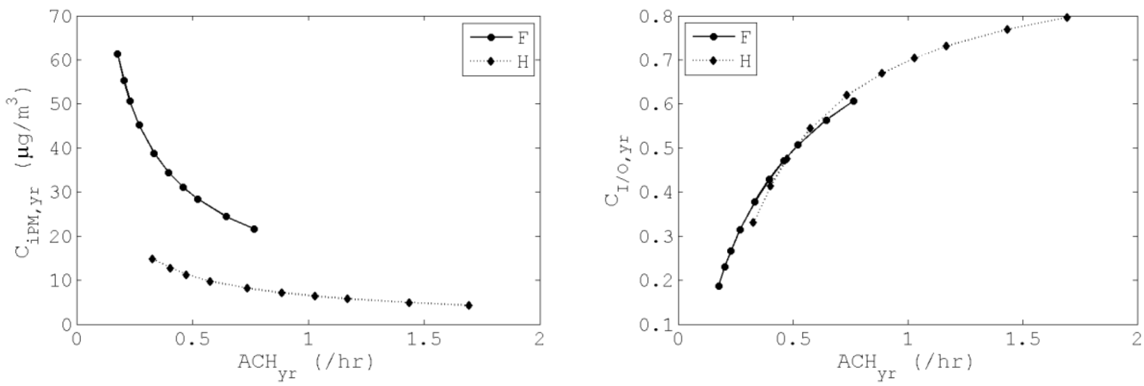

Figure 2: Variation in concentration of internal $PM_{2.5}$ (left) and indoor/outdoor ratio of external $PM_{2.5}$ (right) with annual average air change rate of the building envelope for a naturally-ventilated flat (F) and house (H).

HEALTH IMPACT ASSESSMENT

A health impact model is used to estimate changes in mortality due to changes in indoor exposure to both internally and externally generated $PM_{2.5}$ for the exposure-response pathways shown in Table 1. The health impacts model calculates changes in mortality for an individual in England and Wales at each year of age (assumed to be comparable to London's population), using a standard life table methodology [20]. Mortality rates are adjusted in response to the change in exposures compared to a reference dwelling (see below) using the relative risks given in Table 1. The final output is a population-weighted average change in quality-adjusted life-years (QALYs) per year, calculated separately for males and females. The change in QALYs for males and females are then averaged to give the change in QALYs per individual per year. The mortality outputs are multiplied by the average UK dwelling occupancy of 2.4 before summing to obtain the total health impacts in QALYs per dwelling per year. An increase in QALYs signifies a positive health impact.

Exposure	Health outcome	Exposure-response function	
		Relative Risk	Reference
$iPM_{2.5}$ and $ePM_{2.5}$	Cardiopulmonary mortality	1.082 per 10 μg/m^3	Pope et al. (2002; 2004)
	Lung cancer mortality	1.059 per 10 μg/m^3	Pope et al. (2002; 2004)

Table 1: Mortality outcomes modelled and exposure-response relationships

The required inputs to the health impact models are changes in exposures relative to the exposures in a chosen reference dwelling. Exposures in flats and houses are are compared to their equivalent having an annual average ACH of 0.5/hr, both denoted by $ACH_{yr,ref}$. Piecewise cubic-hermite interpolation is used to estimate each exposure at $ACH_{yr,ref}$ in the flat and house and the reference exposures are then subtracted from the exposures calculated in the CONTAM models in order to obtain the changes in exposures.

SPACE HEATING DEMAND

The space heating demand due to ventilation heat losses is estimated using the degree-hour method [21-22], that counts degree-hours based on the balance-point temperature t_{bal}. This is defined as the external temperature t_e at which the building does not require supplementary heating or cooling, and is assumed to be 15.5°C here [23]. In the heating season, the internal heat gains provide sufficient heating down to the balance-point temperature. Below that temperature, the rate of energy consumption is proportional to the difference between the balance-point temperature and the external temperature:

$$\dot{q} = \frac{H(\tau)}{\eta}[t_{bal} - t_e(\tau)] \text{ when } t_e < t_{bal} \text{ and 0 otherwise} \quad (1)$$

where η is the average efficiency of the heating system, $H(\tau)$ is the heat-loss coefficient (W/K/m^2) and τ is time (hr). With the assumption that η and t_{bal} are constant, the annual space heating demand can be written as an integral:

$$q_{yr} = \frac{1}{\eta}\int H(\tau)\,[t_{bal} - t_e(\tau)]^+ \mathrm{d}\tau \quad (2)$$

where the plus sign above the bracket indicates that only positive values are included in the integral. As the space heating demand due to ventilation heat losses only is considered here, the heat-loss coefficient is given by:

$$H(\tau) = \rho c_p V \times \mathrm{ACH}(\tau) \quad (3)$$

where ρ is the density of air (kg/m^3) at atmospheric pressure and a temperature of 20°C, c_p is the specific heat capacity of air (J/kg/K), at constant pressure, and V and ACH(τ) are the volume (m^3) and the ACH (/hr) of the conditioned part of the building envelope, respectively. These formulae are used to calculate the annual space heating demand due to ventilation losses in each archetype/permeability combination, assuming an average UK heating efficiency of 77% [7].

THE OPTIMAL AIR CHANGE RATE

Let us assume that there are several performance criteria (e.g. health impacts, energy demand, etc.) that vary with ACH_{yr}, from which a single optimum value for ACH_{yr} is to be derived. In a multi-criteria optimization framework, some of the criteria are to be maximized (e.g. positive health impacts) whilst others are to be minimized (e.g. energy use). Without loss of generality, we can assume that all the criteria are to be minimized because each performance criterion f_i can always be replaced by $-f_i$. Instead of using a multi-criteria framework for optimization, in this work the health impact and energy use performance criteria are combined to produce a single criterion (objective function) to be minimized. This is done by first converting each criterion to a monetary value (cost) and then summing the two costs.

In the evaluation of health technologies, the National Institute of Clinical Excellence (NICE) generally considers a treatment to be not cost-effective (relative to a comparator) if it costs more than £20,000-£30,000 per QALY [24]. In this work, we monetize QALYs assuming a value of £20,000 per QALY i.e. the lower end of the range. Positive costs correspond to money saved.

Domestic electricity and gas cost a minimum of 5p/kWh and 2.7p/kWh respectively in 2012 [25]. Assuming total energy consumption in kWh is divided in a 1:5 ratio[2] between electricity and gas, this gives a minimum domestic energy price of 3.3p/kWh. Therefore we monetize annual space heating demand due to ventilation losses assuming a price in real terms between 3p/kWh and 10p/kWh, a possible future price on the extreme end of the scale. The health costs are subtracted from the energy costs to create a single objective function, representing total costs per dwelling in terms of health and energy. If a minimum point exists (i.e. if the objective function is convex), the function is minimized to determine the optimal ACH_{yr}. Otherwise, ACH_{yr} corresponding to the minimum cost over the range of ACH_{yr} modelled is used as the optimal ACH_{yr}.

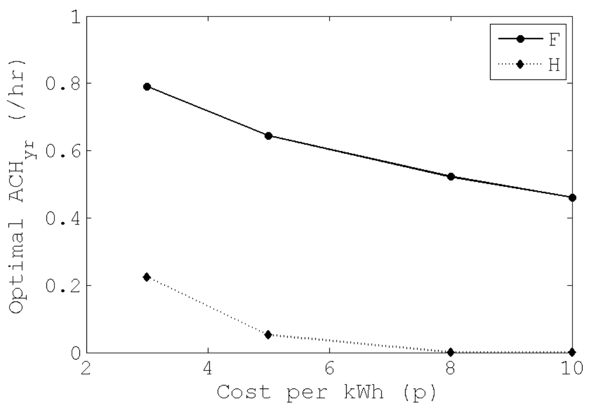

Figure 3: Optimal annual average air change rate against cost per kWh in pence.

The variation of the optimal ACH_{yr} with the cost per kWh is shown in Figure 3. The optimal ACH_{yr} for houses lies in the range 0.0-0.2/hr, depending on the relative costing between energy use and health impacts, showing that for the range of health impacts considered in houses, costs of energy use due to ventilation heat losses dominate. Optimal ACH_{yr} in flats is at least 0.5/hr, and could be higher, showing that costs of health impacts in flats are more

[2] http://www.ofgem.gov.uk/Markets/RetMkts/Compl/Consumption/Pages/ConsumptionReview.aspx

comparable to costs of energy use due to ventilation heat losses. The optimal ACH_{yr} is considerably higher in flats than in houses.

DISCUSSION AND CONCLUSIONS

This paper shows that:

1. The optimal air change rate may vary according to the built form. The analysis in this paper suggests a far greater value in typical London flats compared to houses.
2. Using a monetization approach for multi-objective optimization can be very useful if costs associated with the various objective functions are comparable, as in the case of the typical London flat. In the case of the typical London house however, costs of energy use swamp out costs of health impacts therefore pointing towards the need for a more generalized multi-objective optimization approach.

This research can be extended along several pathways :

1. $PM_{2.5}$ of indoor and outdoor origin might have different toxicities, so the optimization could be done assuming a range of independent exposure-response functions for indoor PM (the outdoor one is well established), including (as an extreme) one where indoor $PM_{2.5}$ is not toxic at all.
2. The health impacts calculations can be extended to include the health effects of exposures to an array of pollutants.
3. Alternative methods of carrying out multi-objective optimization can be explored particularly when some of the criteria cannot be easily monetized.
4. Optimal air change rates can be determined for a representative set of London or UK archetypes to further explore whether there is a dependence on building morphology.
5. The sensitivity of the estimated space heating demand to the assumed balance-point temperature can be further investigated.
6. A deeper study into the effect of response time of health effects to step changes in exposures can be carried out.

The extension of health impacts to cover a wider range of exposures and the use of a more generalized optimization approach are treated in a forthcoming paper.

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