Mitigating Occupant Exposure to $PM_{2.5}$s Emitted by Cooking in High Occupancy Dwellings Using Natural Ventilation Strategies

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ABSTRACT

The long term exposure to fine particulate matter with a diameter of ≤2.5 µm ($PM_{2.5}$) is linked to numerous health problems, including chronic respiratory and cardiovascular diseases, and cancer. In dwellings, a primary emission source of $PM_{2.5}$ is cooking, an activity conducted several times per day in most households. People spend over 90% of their time indoors and more time in their homes than any other type of building. Therefore, they are at risk of exposure to elevated levels of $PM_{2.5}$ emitted by cooking if these particles are not removed at source. This is particularly important in dwellings with a high occupancy density where cooking periods are longer than average. In the UK, overcrowding is a significant issue with 1.1 million (5%) of the 23.4m households in England and Wales considered to be overcrowded. This issue affects families the most because more than 66% of overcrowded households have dependent children. Here, the consequences of $PM_{2.5}$ exposure could be significant for two key reasons: (i) children breathe greater volumes of air relative to their body mass than adults, and (ii) their tissue and organs are still growing.

This paper uses theoretical and semi-empirical modelling approaches to investigate the concentrations of $PM_{2.5}$s emitted by cooking in UK dwellings of high occupancy density. Firstly, the effects of increasing the rate of $PM_{2.5}$ emission from cooking in proportion to occupancy density are investigated in an archetypal dwelling located in London where there is evidence of elevated levels of overcrowding that can lead to and poor indoor air quality. It is assumed that the number of cooking activities increases with the number of occupants and that they are consecutive, thus increasing the cooking period while keeping the emission rate constant. The results predict that the average weighted $PM_{2.5}$ concentration emitted by cooking is approximately constant as the number of occupants increases. Although academically interesting, this highlights the need to identify realistic cooking schedules. Therefore a second approach records IAQ parameters and occupant behaviour over a 12-day period in a high occupancy student house in Nottingham. These data inform a pollutant transport model that predicts temporal variations of $PM_{2.5}$ concentrations attributable to cooking. The observed occupant behaviour is predicted to lead to daily weighted concentrations well in excess of the WHO limit. To mitigate the exposure risk, it is found that kitchen windows should be left open for a minimum of 20 minutes after cooking to reduce pollutant concentration to safe levels.

KEYWORDS

Overcrowding, health, ventilation, indoor air quality, kitchen.

1 INTRODUCTION

A household is defined as one or more persons sharing living accommodation (a living room or a sitting room) and who are not necessarily related by blood or marriage (ONS, 2013). In England and Wales 1.1 million (5%) of its 23.4 million households are considered to be overcrowded (ONS, 2014). It is an increasing problem exacerbated by a shortage of suitable and affordable housing (CIH *et al.*, 2012) and there are examples of Rackmanism (Butler, 2015), the practice of charging extortionate rents for inferior properties, especially to poor, disadvantaged or immigrant tenants. The occupants of over-occupied dwellings are subjected to a range of pollutants, diseases, and social situations that can negatively affect their health and wellbeing, academic performance, and economic productivity. These increase the burden on national health care and reduce economic output.

The UK's definition of overcrowding is enshrined in law. The *Room Standard* dates from 1935 (HM Government, 1985) and divides the number of occupants by the number of rooms, but excludes bathrooms, toilets, halls, landings and storage spaces. Accordingly, a kitchen is considered acceptable sleeping accommodation. An overcrowded household is defined as one with more than one person per room (ppr). Many housing authorities use a modern measure of overcrowding (CIH *et al.*, 2012) known as the *Bedroom Standard*, which requires a separate bedroom for each married or cohabiting couple, adult aged over 21 years, pair of adolescents aged 10-20 years of the same gender, and pair of children under 10 years regardless of gender. Thus it defines an overcrowded household as one lacking one or more bedrooms and so it is more likely to consider a household overcrowded than the Room Standard.

In the UK, people spend over 70% of their time inside their own homes (Lader *et al.*, 2001). Buildings contain airborne pollutants emitted internally by building material and furnishings and by activities undertaken in the building, and also those emitted externally. There is a growing awareness that some bio-accumulating semi-volatile organic compounds and ultrafine particles may negatively affect the health of occupants (Logue *et al.*, 2011) and so building air quality is a cause for concern. The most dangerous pollutant is estimated to be particulate matter with a diameter of ≤2.5μm ($PM_{2.5}$) (Logue *et al.*, 2011). The particles are small enough to bypass biological defences and are linked to chronic respiratory and cardiovascular diseases, and cancer (Lewtas *et al.*, 2007). The WHO (2006) recommends mean maximum $PM_{2.5}$ concentrations of 25μg/m^3 per day and 10μg/m^3 per year. In the USA the inhalation of $PM_{2.5}$s in dwellings is estimated to be responsible for approximately 1000 disability adjusted life years lost per year per 100,000 people (Logue *et al.*, 2011). Primary $PM_{2.5}$ sources in dwellings are cooking and tobacco smoking, but also candle and incense burning, open and stove fires, gas fires, hobs and ovens, and scented oil devices. Following deposition, $PM_{2.5}$s are re-suspended by vacuuming, dusting, and sweeping. Of these sources, cooking is of particular interest because it is an essential activity undertaken in most dwellings.

Elevated risks of lung cancer, particularly in women, are associated with the use of solid cooking fuels (Lissowska *et al.*, 2005) as well as emissions from foods being cooked (Wang *et al.*, 2009). Cooking using traditional Woks in kitchens without extractor hoods is associated with increased lung cancer risk for non-smoking Taiwanese women (Ko *et al.*, 1997). There is an increase in the rate of emission of $PM_{2.5}$s when comparing the use of gas cookers to electric, and when cooking meats rather than vegetables (Dennekamp *et al.*, 2001). In the UK approximately 30% of UK households use gas ovens and 70% use electric, whereas around 40% use electric hobs and 60% use gas (BRE, 2013). Dennekamp shows that they are both associated with $PM_{2.5}$ emissions and so their contribution to poor IAQ and associated negative health effects should be considered. The UK's statutory Approved Document F (ADF) (HM Government, 2010) prescribes intermittent ventilation rates of 30l/s adjacent to the hob (using a hood) or 60l/s elsewhere, or a continuous rate of 13l/s. In new dwellings these are a requirement, whereas existing dwellings only have to maintain ventilation systems present when its kitchen is refurbished.

It is likely that the scale of the cooking activity increases with the size of the household and so the risk of exposure to cooking related $PM_{2.5}$s could be higher in overcrowded dwellings. Accordingly, this paper uses theoretical and semi-empirical modelling approaches to investigate the concentrations of $PM_{2.5}$s emitted by cooking in UK dwellings of high occupancy. Firstly, the effects of increasing the rate of $PM_{2.5}$ emission from cooking in proportion to occupancy density are investigated theoretically using an archetypal dwelling located in London where there is emerging evidence of a relationship between overcrowding, indoor air quality (IAQ), and negative health effects (Kyle, 2011). Secondly, IAQ parameters and occupant behaviour are recorded over a 12-day period in a student house in Nottingham. These data inform a pollutant transport model that predicts temporal concentrations of $PM_{2.5}$s attributable to cooking. Together they ask the question: is there a risk of elevated $PM_{2.5}$ concentrations in high occupancy dwellings attributable to cooking?

2 METHOD

To explore indoor $PM_{2.5}$ concentrations in over-occupied UK dwellings, a validated multi-zone ventilation and pollutant transport tool known as CONTAM is used (Walton & Dols, 2013). Both the theoretical (see Section 2.1) and semi-empirical (see Section 2.2) approaches make identical modelling assumptions in some notable areas. Air exchange between the dwelling and its external environment is assumed to occur through air leakage paths (ALPs) located in facades exposed to the external environment and via open windows. All openings assume one-way-flow and a power law relationship between the airflow rates and the pressure differences across them. The windows are assumed to be sharp-edged and have a flow exponent of n=0.5 whereas the ALPs have n=0.65 (Sherman & Dickerhoff, 1998). All ALP parameters follow Jones *et al*. (2013, 2015). An ALP is located at the floor and ceiling height of each external façade of each zone. Adjacent dwellings are assumed to experience identical environmental conditions and so air is not exchanged between them. Bespoke MATLAB code (MathWorks, 2013) processes the CONTAM predictions to determine weighted daily and annual averages of $PM_{2.5}$ concentrations that can be compared against WHO guidelines.

2.1 Theoretical Approach

Table 1: Dimensions of rooms and whole dwelling (Oikonomou *et al*., 2012)

	Hall	**Stair (x2)**	**Kitchen**	**Living**	**Toilet**	**Storage**	**Bathroom**	**Bed 1**	**Bed 2**
Area (m^2)	6.4	9.9	16.7	29.7	2.5	1.9	8.1	23.0	22.2
Volume (m^3)	17.8	27.7	46.7	83.2	7.0	5.3	22.8	64.5	62.2
Dwelling envelope area (m^2): 317.2			Permeability ($m^3/h/m^2$): 12.1			Volume (m^3): 364.6			

Overcrowding is most common in one and two bedroom homes (Shelter, 2005). Accordingly, CONTAM is used to model the $PM_{2.5}$ concentrations in an archetypal two-bedroom terraced house (Oikonomou, 2012) whose dimensions are given in Table 1. The house is first modelled as a single zone and then disaggregated into zones, where each zone represents a room. This is to examine the effect of open plan living on occupant exposure and to investigate the importance of a multi-zone approach.

Internal doors are assumed to remain closed and so are modelled as cracks with length 760mm and width 10mm (HM Government, 2010). Cooking emission rates and schedules follow Shrubsole *et al.* (2012). Households in over-occupied dwellings are likely to comprise multiple groups who each cook separately and so cooking is assumed to be a consecutive activity rather than a concurrent activity. The ambient $PM_{2.5}$ concentration is 13μg/m^3. $PM_{2.5}$s are emitted during cooking at a rate of 1.6mg/min and have a deposition rate of 0.39h^{-1} in each zone. Cooking commences at the same time each day, regardless of the occupancy level, but the duration increases with occupancy. For lunch and dinner we assume 15 minutes plus 5 minutes per occupant, and for breakfast 7.5 minutes plus 2.5 minutes per occupant. The internal air temperature is 21.1˚C for ground floor zones, following Jones *et al.* (2015) and 18˚C for first floor zones following (CIBSE, 2006). The internal air temperature of the single zone model is 21.1˚C. The CIBSE Test Reference Year (TRY) (CISBE, 2002), a synthesised typical year of weather data for London, provides external air temperatures and wind velocity inputs. The dwelling is considered to be in an urban location and the wind speed is scaled appropriately by CONTAM. Wind pressure coefficients are estimated using an algorithm (Jones *et al.*, 2015) that gives a normalized average wind pressure coefficient for long-walled low-rise dwellings, which is a function of the angle of incidence of the wind and local sheltering. General periods of occupancy are given in Table 2 and room patterns for cook and non-cook occupants in the multi-zone model are given in Table 3.

Table 2: Building occupancy periods (hours)

	Occupied Times	
Weekday	0000-0820	1740-2400
Weekend	0000-2400	

Table 3: Indoor occupancy patterns (% time)

	Cook		Non-Cook	
Room	**WD**	**WE**	**WD**	**WE**
Living	56%	40%	62%	58%
Kitchen	8%	10%		
Bed 1	36%	50%		
Bed 2			38%	42%

WD, week day; WE, weekend.

2.2 Semi-Empirical Approach

Table 4: Dimensions of rooms and dwelling

	Kitchen	Living Room	Bedroom	Hallway	Dwelling
Average Height (m)	2.6	2.6	2.6	2.6	
Width (m)	2.7	3.5	3.5	1.0	
Length (m)	6.5	3.7	4.0	7.7	
Floor area (m^2)	17.2	13.0	14.0	7.3	51.3
Volume (m^3)	48.2	32.4	35.0	18.3	133.9
Surface area (m^2)					131.6

A high occupancy dwelling located in Nottingham is investigated during the heating season to investigate its internal $PM_{2.5}$ concentrations over time. Both occupant behaviour and internal and external air temperatures were recorded during a 12 day period from 27th October to 16th November 2014. These data are used to inform a multi-zone CONTAM model that predicts $PM_{2.5}$ concentrations in each room.

The dwelling is a typical 1930s red brick terrace whose geometry is given in Table 4. Average room heights are given because they vary. The kitchen and living room dimensions are given separately but the rooms comprise a single open plan space. The dwelling's air permeability is estimated to be $13m^3/h/m^2$ based on its age and condition.

The kitchen contains an electric oven and 4 gas rings and occupants recorded their use. Each appliance is assumed to generate $PM_{2.5}$ at a rate of 1.6mg/min (Shrubsole *et al.*, 2012). A maximum of 3 appliances were used concurrently over the cooking period and so the maximum generation rate used is 4.8mg/min. The ambient $PM_{2.5}$ concentration is $12\mu g/m^3$ (DEFRA, 2014) and each zone contains a sink with a deposition rate of $0.39h^{-1}$ (Shrubsole *et al.*, 2012).

The use of ventilation was recorded. The kitchen contains a fan above the cooker, two small windows, a large window and a door. None of these were used during monitoring and so a *closed window* scenario provides an appropriate baseline. For comparison, three other scenarios are considered: *partially open*, where the small windows are open 50% during cooking; *fully open*, where one small window and the large window are open 100% during cooking; and *always open*, where all windows are 100% open all of the time.

Air temperatures were recorded at 1 minute intervals with dataloggers (Onset, 2015) that have a precision and error at 25˚C of 0.1˚C and ±0.4˚C, respectively, and averaged for each hour of the day. The internal temperature was recorded at head height in the middle of the kitchen away from heat sources. Appropriate wind velocity data is taken from the CIBSE TRY for Nottingham (CIBSE, 2002). Temperatures for all other rooms are assumed: 14˚C for the bedroom and 12˚C in the hallway. The recorded occupancy schedule is aggregated to produce a typical occupancy schedule, see Table 5. Occupants spend time in the kitchen/living area when cooking and to eat and socialise. The remainder of their time spent is spent in their bedroom or out of the house, see Table 6.

Table 5: Dwelling occupancy (hours)

	Occupied from	Occupied until
WD	0000	1000
	1600	2400
WE	0000	1200
	1500	2100
	2400	2400

WD, week day; WE, weekend.

Table 6: Indoor occupancy patterns (% time)

Room	WD	WE
Kitchen	20%	40%
Bedroom	80%	60%

WD, week day; WE, weekend.

3 RESULTS

3.1 Theoretical Approach

The predicted weighted annual mean exposures for the open plan and multi-zone models are given in Table 7. They show that the annual mean total exposures for the open plan (OP) scenario and for non-cooks in the multi-zone (MZ) scenario increase linearly with occupancy, but that this increase is minimal, and that all remain below the WHO maximum annual mean concentration of 10µg/m^3. Although this is academically interesting, it highlights the need to identify more realistic cooking schedules. The mean concentrations are higher for occupants in the OP scenario than for non-cooks in the MZ scenario. This suggests increased risks of $PM_{2.5}$ exposure for those in open plan dwellings and shows the importance of considering building geometry and occupancy patterns. Most notably, cooks in the MZ scenario are exposed to much higher $PM_{2.5}$ concentrations, which increase with occupancy and exceed the WHO guideline at all occupancy levels.

Table 7 also shows the number of days per year where the predicted weighted internal $PM_{2.5}$ concentrations exceed the WHO 24-hour mean guideline of 25µg/m^3. The data reflect the annual mean exposures and show that the OP and MZ non-cook scenarios never have a daily mean that exceeds 25µg/m^3. However, the number of days where the daily mean exceeds 25µg/m^3 increases non-linearly with occupancy for the MZ cook scenario reaching 311 days when the household comprises 12 occupants.

Both metrics show increased risks for cooks but not to occupants who spend no time in the kitchen (see Table 3). This suggests a need for additional kitchen ventilation to remove contaminants at source. CONTAM assumes uniform air within a zone (Walton & Dols, 2013), however, in reality the distribution of $PM_{2.5}$ is likely to be non-uniform and so actual occupant exposures could vary. The external $PM_{2.5}$ concentration is assumed to be constant and is considered to be both the default concentration for all simulations and the concentration of $PM_{2.5}$s to which occupants are exposed when they are away from the house.

Table 7: Weighted annual mean total exposure and days exceeding 24hr Mean guideline total exposure 25µg/m^3

Number of Occupants	Weighted annual mean exposure (µg/m^3)			Days exceeding 24hr Mean Guideline		
	Open Plan	Cook	Non-Cook	Open Plan	Cook	Non-Cook
3	9.00	14.73	4.95	0	0	0
6	9.06	19.44	5.02	0	2	0
9	9.28	24.27	5.09	0	104	0
12	9.63	28.92	5.15	0	311	0

3.2 Semi-Empirical Approach

The observations of occupancy in the monitored house show that its occupants are most likely to cook alone. This is significant because it provides support for the consecutive cooking behaviour used to develop the theoretical models of $PM_{2.5}$ concentrations in Section 3.1. The behaviour also has a significant impact on the generation of $PM_{2.5}$s in the house. UK

households cook for an average of 34 minutes per day (min/day) (Jackson, 2014) whereas each occupant of the Nottingham House cooks a meal separately. During the twelve days of monitoring, the mean cooking time was 126.3min/day, nearly 4 times the household average.
The weighted mean total $PM_{2.5}$ concentrations over the 12-day period for each scenario are given in Table 8. When compared against the WHO annual mean guideline of 10µg/m^3 all scenarios are shown to exceed it, except the always open scenario. However, the extrapolation of 12 days of data to a whole year is problematic because weather, occupant behaviour, and the probability of the use of ventilation openings will all vary throughout the year effecting airflow rates and $PM_{2.5}$ concentrations within the building.
The weighted daily mean $PM_{2.5}$ concentrations over the 12-day period are given in Table 9. The WHO 24-hour guideline of 25µg/m^3 is exceeded on 11 of the 12 days by the *closed* scenario, whereas this is reduced to 4 days by the *partially open* scenario. This highlights that the provision of a small amount of additional purpose-provided ventilation can significantly lower occupant exposures to $PM_{2.5}$. The WHO guideline is only exceeded once by the *fully open* scenario coinciding with the longest recorded cooking time. The WHO guideline is never exceeded by the *always open* scenario.

Table 8: Whole period average concentration by scenario (µg/m^3)

Scenario	**Total Weighted Mean**
Always Closed	52.67
Partially Open during cooking	21.95
Fully Open during cooking	16.14
Always Open	9.05

Table 9: Weighted daily mean exposure [November 2014] (µg/m^3)

Day	**Scenario**			
	Always Closed	**Partially Open during cooking**	**Fully Open during cooking**	**Always Open**
5	14.49	11.23	10.20	7.20
6	38.83	25.63	16.55	9.14
7	68.59	35.16	24.40	11.10
8	59.75	30.55	19.54	10.26
9	102.14	45.21	24.06	14.11
10	41.97	17.95	11.97	7.57
11	51.15	15.85	9.83	7.30
12	64.29	12.93	8.50	7.48
13	76.78	20.25	27.40	8.62
14	41.06	19.18	19.46	7.16
15	41.97	17.84	12.86	9.72
16	31.23	11.71	8.98	8.93
Days >25µg/m^3	11	4	1	0

4 DISCUSSION

The paper uses a modelling approach to investigate the risk of elevated $PM_{2.5}$ concentrations in high occupancy dwellings. Although care has been taken to use model inputs with provenance this has not always been possible and so there is great uncertainty in the predictions.
Das *et al.* (2014) use a two-zone CONTAM model of an apartment and a probabilistic framework to estimate the variation in indoor $PM_{2.5}$ concentrations attributable to cooking. A sensitivity analysis shows that they are most sensitive (in order of significance) to window opening area, $PM_{2.5}$ generation rate, and IAT. It is reassuring that the window area and IAT were monitored and used as empirical inputs to the semi-empirical model. However, a probabilistic approach would have helped to establish uncertainty in assertions made here.
The emission rate of $PM_{2.5}$ is likely to be a function of many parameters, such as the make, model and cleanliness of the cooker and hobs, and the food types (Lewtas, 2007). However, these variables were not recorded and so it is impossible to quantify uncertainty in the predicted concentrations. Only a modest number of studies in the literature present measurements of $PM_{2.5}$ emission rates from cooking. They are given as mean values and so, in the absence of further information, they are assumed to be constant or Gaussian when a

standard deviation is given. There is a need for probability density functions of emission rates so that uncertainty in the mean can be evaluated. It is also likely that emission rates of different cooking activities change with time and so there is a clear need for data that reflects this. A new measurement approach and the creation of a large dataset are required.

A constant deposition rate is assumed for $PM_{2.5}$ from cooking and external sources. However, recent research suggests lower deposition rates that vary according to their source may be appropriate (Shrubsole *et al.,* 2015). These would concurrently increase mean indoor $PM_{2.5}$ concentrations and occupant exposure.

Constant external $PM_{2.5}$ concentrations are assumed for the theoretical and semi-empirical models. Urban $PM_{2.5}$ concentrations are higher than those in rural areas and are affected by traffic. Annual concentrations vary considerably; for example, annual means varied between $12\mu g/m^3$ and $22\mu g/m^3$ across Greater London for the period 2008 to 2015 (DEFRA, 2015). They are also likely to vary over short periods of time and so a static value represents a source of uncertainty.

Neither the theoretical nor the semi-empirical models consider the use of a kitchen extractor fans. The semi-empirical model used observed occupant behaviour to justify this omission, whereas the theoretical model is used to investigate a worst case scenario. Not all UK houses have kitchen extractor fans and there is no evidence that they function correctly when present; for example, many are recirculating types that require high-efficiency filters to improve IAQ. The IAQ in UK domestic kitchens is currently unknown and requires further investigation. Here, it is important to identify the appropriateness of the ventilation rates currently required in domestic kitchens and the potential dangers associated with high or over-occupancy of dwellings. If cooking behaviour is consecutive, as modelled here, then a prescribed ventilation rate may suffice. Concurrent cooking could lead to $PM_{2.5}$ concentrations that are significantly higher than those predicted here.

Section 3.2 shows that natural ventilation can effectively reduce concentrations of $PM_{2.5}$. A time-step analysis of the *always closed* scenario shows that $PM_{2.5}$ concentrations only return to ambient levels after many hours. In the *partially* and *fully open window* scenarios, the time taken is 2.5 and 1.5 hours, respectively, and just 10-20 minutes for the *always open* scenario. This suggests that windows should be left open for a minimum of 20 minutes after cooking. However, natural ventilation offers no control over the direction of airflow and so pollutants can spread to living areas. The concurrent use of kitchen extractor fans and windows could increase $PM_{2.5}$ in living spaces and an investigation is required. A ventilation strategy that minimizes occupant exposure to $PM_{2.5}$ must simultaneously extract cooking related pollutants at source and limit airflow out of the kitchen into other zones using depressurization.

Internal $PM_{2.5}$ concentrations occasionally fell below the ambient concentration. This can appear counterintuitive but occurs when the $PM_{2.5}$ deposition rate is greater than both their indoor emission rate and the rate at which they are brought into the dwelling via ventilation. Occupants who spend time in the spaces with lower $PM_{2.5}$ concentrations have a reduced mean exposure to cooking related $PM_{2.5}$ and associated health risks.

The occupancy patterns in Section 2 assume that the occupants do not occupy their dwelling between 0820-1740hrs. However, income poor households, or those with three or more children, are much more likely to be living in persistently overcrowded accommodation (Barnes et al., 2011) and so the occupancy patterns used here may not be appropriate. Changes to sleeping patterns observed in many overcrowded households, where they become disrupted and irregular, or where household members frequently sleep in the living room, kitchen, or hall (Shelter, 2005) were not examined. Additionally, window opening behaviour is assumed to occur year-round and does not consider variations in IAT or security. Internal doors are assumed to remain closed, which may prevent the spread of pollutants between zones. The semi-empirical model uses occupancy patterns that are simplified and aggregated models of observed daily routines. However, the presence of each occupant varied and so their individual exposures will be different to those predicted here.

Shrubsole *et al*. (2012) consider 2010 and 2050 exposures of occupants to $PM_{2.5}$ in London dwellings. The 2010 scenario finds average total exposures of 28.4μg/m^3, 60.5μg/m^3, and 15.5μg/m^3 for the whole household, cook, and non-cook, respectively. When compared to the semi-empirical model the household average is similar to the 21.95μg/m^3 period average for the partially open scenario. The theoretical model predicts annual averages of 14.73μg/m^3 and 4.95μg/m^3 are predicted for a cook and non-cook, respectively, when there are 3 occupants, which are very different to those of Shrubsole. This emphasises the importance of model inputs, such as occupancy schedules, window areas, and building geometry. However, both studies agree that cooks are exposed to higher $PM_{2.5}$ concentrations than non-cooks.

Fabian *et al*. (2012) predict annual mean concentrations of 27.8μg/m^3 for households in dwellings without an extractor fan, and 10.9μg/m^3 when they are installed. This compares well to 21.95μg/m^3 predicted by the semi-empirical model, but we note that they are higher than the theoretical model averages. This emphasises the potential benefits of local extraction.

There is a growing concern about high external $PM_{2.5}$ concentrations in London, which had an annual mean of 14.9μg/m^3 in 2014 (DEFRA, 2014). However, this is significantly lower than some of the annual mean indoor $PM_{2.5}$ concentrations predicted here and by others. People spend the vast majority of their time inside buildings and so air quality should be a cause for concern for policy makers who seek to minimize its negative health effects and the consequent burden on national health care and tax payers. Furthermore, Section 3 shows that over-occupied dwellings could have $PM_{2.5}$ concentrations that are significantly above those of households that conform to the Bedroom Standard. More than 66% of overcrowded households have dependent children and so families are affected the most. Children breathe greater volumes of air relative to their body mass than adults and their tissue and organs are still growing. The negative health consequences attributable to exposure to elevated levels of $PM_{2.5}$ could last a lifetime, bringing emotional, educational, and financial costs for both individuals and society. This highlights the importance of effective ventilation, and the need for ventilation strategies that adequately and efficiently remove harmful pollutants from any dwelling, particularly those that are over-occupied.

5 CONCLUSIONS

This paper uses theoretical and semi-empirical approaches to investigate the risk of elevated $PM_{2.5}$ concentrations in high occupancy dwellings attributable to cooking. Firstly, an archetypal dwelling located in London is used to investigate the effects of increasing the rate of $PM_{2.5}$ emission from cooking in proportion to occupancy density. It is assumed that the number of cooking activities increases with the number of occupants and that they are consecutive, thus increasing the cooking period while keeping the emission rate constant. It is predicted that the average weighted $PM_{2.5}$ concentration attributable to cooking is approximately constant as the number of occupants increases. A comparison of the predicted $PM_{2.5}$ concentrations in open and zoned representations of the dwelling shows that non-cooks are exposed to higher concentrations when the building is open plan, although they are below WHO annual maximum levels. The zonal approach further increases the risk to cooks because $PM_{2.5}$ concentrations are above WHO annual maximum levels when there are 9 occupants.

Secondly, IAQ parameters and occupant behaviour are recorded over a 12-day period in a naturally ventilated high occupancy house in Nottingham where cooking behaviour is indeed found to be consecutive. These data inform a pollutant transport model that predicts temporal variation of $PM_{2.5}$ concentrations attributable to cooking. The observed occupant behaviour is predicted to lead to daily weighted concentrations well in excess of the WHO limit. A low ventilation rate through available windows during, but not beyond, the cooking period is shown to reduce daily mean concentrations to safe concentrations after 1.5-2.5 hours. However, to mitigate the risk of exposure to $PM_{2.5}$ it is found that kitchen windows should be left wide open during cooking and for a minimum of 20 minutes after cooking to reduce pollutant concentration to safe levels.

Overcrowded and high occupancy dwellings represent more than 5% of UK households and there is there is emerging evidence of a relationship between overcrowding, IAQ, and negative health effects. Accordingly, the cooking related IAQ in these dwellings should be a cause for concern for policy makers who seek to minimize national health care costs and increase national economic output.

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