Housing as a modifier of air contaminant and temperature exposure in Great Britain: A modelling framework

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SUMMARY
This paper presents the development of a modelling framework that quantifies the modifying effect of dwelling characteristics on exposure to indoor air pollution and excess temperature. A georeferenced domestic building stock model of Great Britain was created using national housing surveys, historical weather, and local terrain data. Dynamic building performance simulation was applied to estimate indoor air pollution and overheating risk metrics at the individual building level. These metrics were then aggregated at various geographic units and mapped across Britain within a Geographic Information System (GIS) environment to compare spatial trends. Results indicate that flats and newly built properties are characterised by lower indoor air pollution from outdoor sources, but higher air pollution from indoor sources. Flats, bungalows and newly built, more airtight dwellings are found to be more prone to overheating. Consequently, urban populations may experience higher levels of pollution from indoor sources and overheating resulting from the higher prevalence of flats in cities.

PRACTICAL IMPLICATIONS
As part of ongoing work, the model outputs will be fed into an epidemiological study aiming to explore the relationship between occupant exposure to air contaminants and high indoor temperatures in housing and mortality. This study will contribute to our understanding of the influence of building attributes on indoor environmental quality and adverse health effects.

KEYWORDS
housing, indoor air quality, overheating, health, Geographic Information Systems

1 INTRODUCTION
A large and growing body of literature has investigated the impact of external air pollution and climate conditions on health. A significant healthcare burden is associated with outdoor air pollution: It is estimated that approximately 25,000 deaths in England annually are attributed to long-term exposure to anthropogenic Particulate Matter ($PM_{2.5}$) (PHE, 2014). Understanding heat-related health risk has also emerged as a research priority in Europe following the deadly 2003 heat wave, which was responsible for around 2,000 excess deaths in England and Wales (Johnson et al., 2005), and climate change projections that predict an increase in the frequency of such extreme heat episodes in the coming decades (Murphy et al., 2009). However, despite the wealth of studies that explore the relationship between external conditions and health, there is limited research on the modifying effect of the indoor environment on excess pollution and temperature exposure. People in the UK spend 90% of

their time indoors, around 70% of which is spent at home (ONS, 2005). Both monitoring (Beizaee et al., 2013; Lomas and Kane, 2012; Mavrogianni et al., 2010) and modelling studies (Gupta and Gregg, 2013; Mavrogianni et al., 2012; Peacock et al., 2010) have demonstrated that indoor thermal conditions vary greatly across different dwelling types in the UK. Recent evidence suggests that determinant factors of heat-related health risk include: advanced age or suffering from a chronic health condition (Hajat et al., 2007), living in a care home (Kovats et al., 2006), a top floor flat, a poorly insulated house (Vandentorren et al., 2006), a dwelling with a flat roof (Chan et al., 2001) or a dwelling without air conditioning (O'Neill et al., 2005). Whilst the influence of building type on indoor air contaminant concentrations is less well understood to date, existing studies have assessed the role of ventilation characteristics (Emmerich et al., 2005), room dimensions (Dimitroulopoulou et al., 2006) and energy efficient retrofit (Shrubsole et al., 2012) on the ingress of outdoor air pollutants. Buildings, and housing, in particular, are therefore important modifiers of population exposure to the external climate, pollution, and associated health hazards. The present study builds on existing work that has integrated spatial representation of housing stocks in relation to air pollution and heat exposure (Taylor et al., 2014) and links with sociodemographic characteristics and health impacts (Taylor et al., 2015; Tomlinson et al., 2011; Wolf and McGregor, 2013). It aims to develop a new modelling framework able to map the proportion of air pollution and heat risk attributable to housing characteristics across Great Britain.

2 MATERIALS AND METHODS

A georeferenced building stock model was constructed using data derived from: (i) the Homes Energy Efficiency Database (HEED) (EST, 2016a), a database containing records of energy efficiency interventions in UK homes, and (ii) the 2010-11 English Housing Survey (EHS, UK DCLG, 2016), a cross-sectional survey of the physical attributes of nationally representative dwellings in England. The analysis of HEED indicated that 1 million dwelling records contained sufficient data to adequately model indoor air pollution and overheating using dynamic thermal simulation. Individual HEED data entries include information about building geometry, construction age, physical properties and postcode-level location of dwellings across England. The building geometry classification was combined with detailed dimensions from the EHS and information about typical layouts of British housing for different architectural eras in order to design detailed architectural drawings for each built form class, following the approach described by Oikonomou et al. (2012): bungalows, detached, semi detached, mid terrace houses, converted flats, low rise flats and high rise flats (a ground, mid and top floor flat was created for each building with flats). The UK Government's Standard Assessment Procedure (SAP) for Energy Rating in Dwellings (BRE, 2009) was then used to derive the building fabric air permeability, and the U-values for walls, windows, roofs, and floors, and window characteristics (e.g. glazing type, trickle vents) for each entry in the HEED database, as a function of construction age, insulation levels and other known physical properties. As the EHS and HEED surveys do not provide data on occupant behaviour and building operation, all records were modelled for two different occupancy scenarios: (i) two working adults with children, and (ii) two pensioners. Windows were assumed to start opening when internal air temperatures reached 25 °C in all rooms in the daytime, and 23 °C in the bedrooms at night, but only if the external temperature was below the internal. Extract fans were also assumed to be on during showering and cooking activities. Occupancy schedules and internal gains followed assumptions and values used in published studies (Mavrogianni et al., 2012; Oikonomou et al., 2012). All buildings were modelled at four orientations (North, West, South, and East). Each HEED entry was assigned: (i) a rural, urban or city terrain based on its location using rural/urban classification data (ONS, 2011), and (ii) a climate region (represented by London, Plymouth and Edinburgh). Two weather file types were used for each location (CIBSE, 2016): The Design Summer Year (DSY, commonly applied for overheating assessments) and the Test Reference Year (TRY, representing a 'typical' year). The indoor concentration of the following air contaminants was modelled covering both indoor and outdoor sources: $PM_{2.5}$, PM_{10}, SO_2, O_3, NO, NO_2, and CO. The indoor pollutant emission schedule specified by Shrubsole et al. (2012) was applied. Existing assumptions on pollutant deposition rates or velocities (Emmerich and Persily, 1996; Grøntoft and Raychaudhuri, 2004; Ozkaynak et al., 1996; Sarwar et al., 2002) and the pollutant emission rates of indoor activities (Dimitroulopoulou et al., 2006; Guo et al., 2008; He at al., 2004) were used (Table 1).

Table 1. Air pollutant deposition rates, velocities and indoor emission rates.

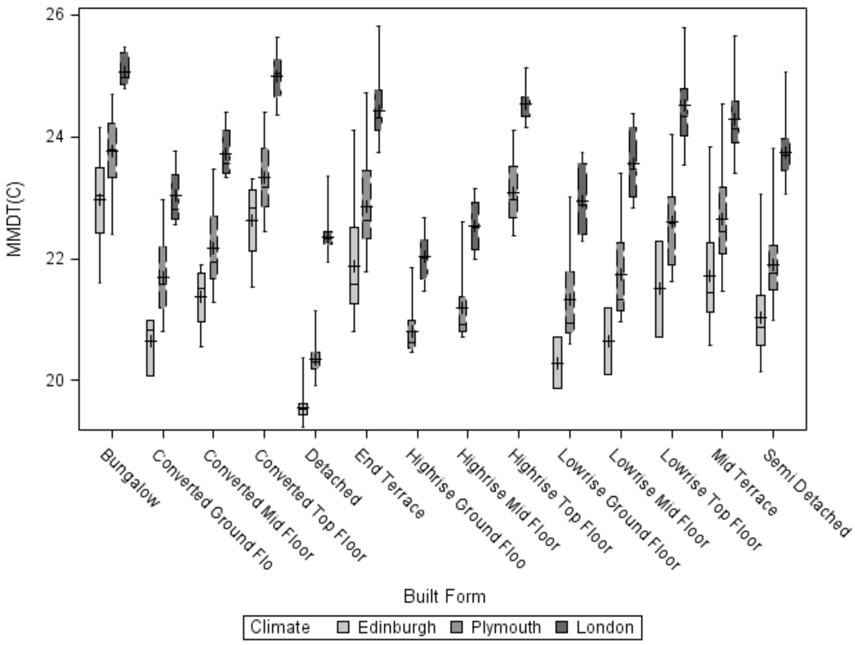
Air pollutant	**Deposition rate (s^{-1})**	**Deposition velocity (ms^{-1})**	**Indoor activity**	**Emission rate (mg/min)**
$PM_{2.5}$	0.00011		Gas cooking	1.600
			Fireplace	0.200
			Shower	0.040
			Smoking	0.900
PM_{10}	0.00018		Cooking	4.100
			Smoking	1.500
CO	0		Cooking	25.000
			Smoking	7.200
NO_2	0.00024		Gas cooking	3.100
			Smoking	0.015
NO	0			
O_3		0.00036		
SO_2		0.00140		

EnergyPlus 8.0 (US DoE, 2016) was subsequently applied to produce indoor air pollution and overheating metrics at the individual building level, such as Indoor/Outdoor (I/O) ratio of pollution from outdoor sources and indoor air pollution from multiple indoor sources, and mean daytime and night temperatures. An in-house Python-based tool was used to build the input files in batch mode. 34,604 simulations were run in total for indoor air pollution from outdoor sources, 38,090 for indoor air pollution from indoor sources, and 41,200 for overheating. The outputs were aggregated at the postcode and Large Super Output Area (LSOA) level, a UK statistical boundary area that roughly corresponds to 500 households, and mapped across Britain within a Geographic Information System (GIS) environment.

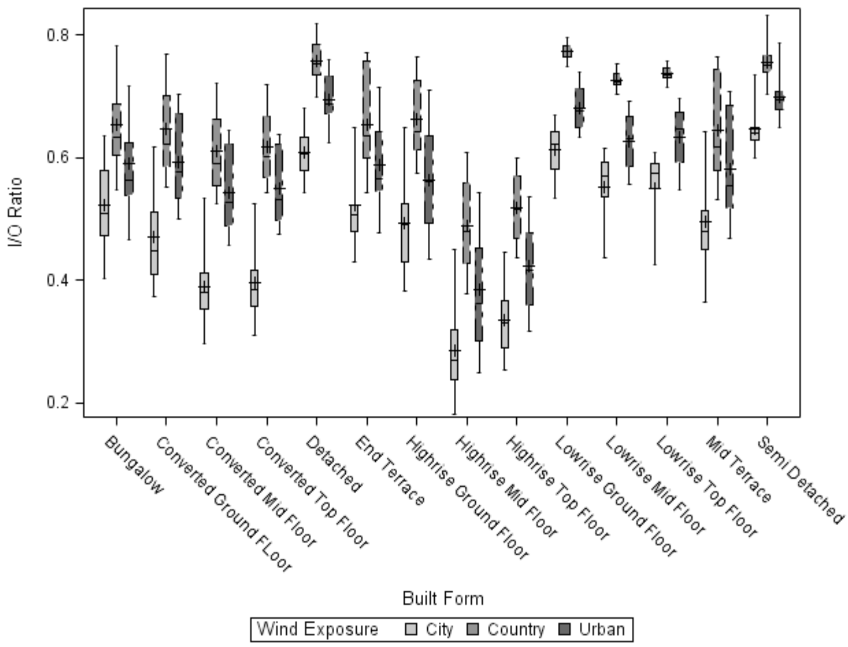
3 RESULTS

Exposure risk by dwelling type

The range of summertime overheating and I/O ratio of outdoor air pollutants across dwelling types is illustrated in Figure 1 a) and b), respectively. The ranges account for variations in building fabric characteristics observed within each climate region or terrain. The modelling results corroborate the findings of previous studies on the overheating risk of UK homes (Oikonomou et al., 2012; Beizaee et al., 2013), as it was indicated that top floor flats and bungalows are the dwelling types most prone to overheating. The risk of elevated temperatures was also associated with low building fabric air permeability and poor roof insulation. Pensioners were assumed to be at home during the daytime in the model, thus generating additional internal heat gains, which contributed to their increased risk of exposure to high temperatures. It was shown that people living in flats and mid terrace houses are less exposed to pollutants entering the dwelling from outdoors compared to more exposed dwelling types, such as bungalows and detached houses, which is in agreement with previous work (Taylor et al., 2014). Higher I/O ratios were observed in rural areas due to higher dwelling wind exposure compared to more sheltered buildings in urban and core city areas.



a)



b)

Figure 1. a) Mean Maximum Daytime living room Temperature (MMDT, ^{o}C) by location, and b) I/O ratios for $PM_{2.5}$ by terrain, for the pensioners' occupancy assumption in the different dwelling types. Average values are represented by a +.

National level mapping of exposure

The modelling outputs were aggregated at LSOA level and mapped across Britain (Figure 2).

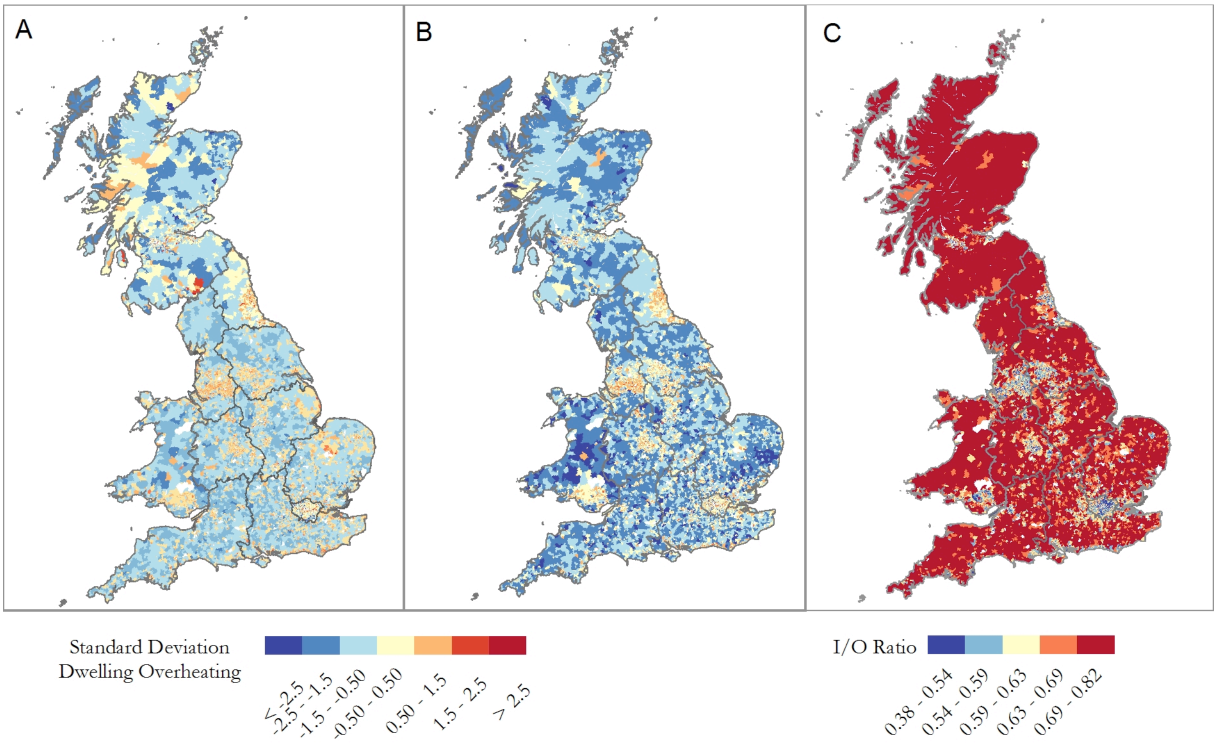


Figure 2. a) Mean Maximum Daytime living room Temperature (MMDT, ^{o}C), b) Mean Maximum Night time bedroom Temperature (MMNT, ^{o}C), and c) I/O ratios for $PM_{2.5}$, for the pensioners' occupancy assumption aggregated at the LSOA level.

In Figure 2 a) and b), the LSOA level indoor overheating metrics were normalised as standard deviations from the Government Office Region (GOR) average so as to highlight variability in exposure due to housing characteristics rather than differences driven by the external climate. Whilst indoor overheating risk is shown to be higher in urban areas, clusters of at-risk dwellings are also observed in rural settings due to the high percentage of highly exposed bungalows. As illustrated in Figure 2 c), rural dwelling types are characterised by higher outdoor $PM_{2.5}$ infiltration as a result of increased exposure to wind. However, the outdoor pollution levels were not varied for urban and rural areas for the purposes of this study; outdoor air pollution is expected to be higher in urban environments in absolute terms. The spatial variation of levels of $PM_{2.5}$ from indoor sources was also examined. Unsurprisingly, concentration levels were largely dominated by the type of activity. For instance, as shown in Table 1, cooking produces the highest level of $PM_{2.5}$. Inverse relationships to those observed for indoor air pollution from outdoor sources were obtained. It was found that the less exposed a dwelling type, the higher the indoor concentration of internally generated pollutants. The presence of extract fans reduced the observed variability.

4 DISCUSSION

The study findings are consistent with previous monitoring and modelling work on the impact of building attributes on exposure to indoor environmental hazards. The large inter-dwelling type differences found in this study further highlight the importance of dwelling geometry, orientation, thermal insulation and airtightness on indoor exposure to heat and pollutants. Some caution is advised in the interpretation of the results: HEED was the largest, most comprehensive database of domestic building fabric characteristics in the UK at the time of the study. The occurrence of different dwelling types and construction age bands within HEED is broadly similar to those in the nationally statistically representative sample of the EHS. However, HEED overall contains a smaller number of flats and semi detached dwellings, and a smaller proportion of privately owned housing, thus reflecting the lowest rates of energy retrofit in these particular dwelling types. This may potentially introduce a certain bias into the model by underestimating the number of dwellings that have never undergone any energy efficient interventions. Furthermore, the aim of the study was to isolate the impact of housing on outdoor air pollution infiltration and indoor thermal conditions rather than map absolute levels of occupant exposure; a constant outdoor air pollution concentration value and only three weather files were, thus, applied. Both outdoor air pollution and temperature will, however, be higher in cities, although urban-rural differences in external conditions are also likely to vary temporally, both diurnally and seasonally.

The GIS mapping component of the modelling framework facilitates the quick visual comparison of urban-rural differences in exposure at the national level. To the knowledge of the authors, this paper presents the first national level, locally aggregated model of housing modifiers of air pollution and heat exposure risk and vulnerability. This tool will be invaluable to local government decision makers and public health policymakers aiming to assess the impact of housing, energy, transport and air pollution policies on population health. As part of ongoing work, the model outputs will be used in epidemiological analyses for the *'Air Pollution and WEather-related Health Impacts: Methodological Study based On spatio-temporally disaggregated Multi-pollutant models for present day and futurE'* (AWESOME) project (LSHTM, 2016). Future versions of the model will replace the HEED inputs with data from the newly available Home Analytics Database (EST, 2016b), which offers probabilistic estimates of building fabric characteristics covering more than 95% of dwellings in Britain. Further refinements of the model are planned that will include spatiotemporally varying concentrations of outdoor air pollutants, which are likely to be higher in urban areas due to traffic, and localised ambient air temperatures in order to take into account the Urban Heat Island (UHI) effect. The housing stock model will also be extended in the future to be able to quantify the impact of housing stock growth, urban transformations, climate change and behaviour change on indoor exposures within the context of the National Institute for Health Research (NIHR) *Health Protection Research Unit (HPRU) in Environmental Change and Health, Theme 2: Sustainable Cities* (NIHR, 2016).

5 CONCLUSIONS

The development of a novel, national level housing stock model of indoor environmental quality was described. The model produces markers of indoor air pollution and overheating exposure, hence adding to a growing body of research in the intersection of built environment science and epidemiology on the role of buildings as modifiers of health risk. The findings emerging from this study relate specifically to climate change mitigation and adaptation strategies in the housing sector. Urban and energy efficient dwellings were found to amplify exposure to excess pollutants and temperatures generated indoors in some of the modelled scenarios. Conversely, more exposed dwellings that are prevalent in rural environments were shown to be more vulnerable to externally generated pollutants. Housing characteristics should, thus, be taken into account in health-driven local planning policy decisions.

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