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Building characteristics as determinants of propensity to high indoor summer temperatures in London dwellings

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Cities are expected to experience an increasing risk of overheating due to climate change and the urban heat island phenomenon. Although external factors, such as urban morphology and greening, may influence the spatio-temporal variation of overheating risk, the individual building characteristics are also likely to be important. This paper presents the results of EnergyPlus dynamic thermal simulations of 3456 combinations of dwelling types and characteristics selected to represent the London domestic stock. Two Design Summer Year weather files were used to represent the current and future climate: the CIBSE 1984–2004 and a UKCP09 future weather file (50th percentile of external temperature, 2050s, medium emissions scenario). Appreciable variation between dwelling types but generally greater variation *within* dwelling type was found depending on such factors as orientation, surrounding buildings and insulation levels. Under the current climate, the insulation levels had considerable impact on indoor temperatures, with combined retrofitting of roof insulation and window upgrades reducing daytime living room temperatures during the warmest continuous 5-day period of modelling by, on average, 0.76 °C (%95C.I. 0.63, 0.89 °C) for mean temperature and 1.30 °C (%95C.I. 1.05, 1.54 °C) for maximum temperature. On the other hand, internally retrofitted walls and floors tended to increase daytime living room temperatures, with a combined effect of 0.46 °C (%95C.I. 0.33, 0.60 °C) increase in mean temperature and 0.71 °C (%95C.I. 0.47, 0.96) increase in maximum temperature. Within the context of a changing climate, knowledge of insulation characteristics after retrofitting is crucial for the accurate identification of dwellings with greatest overheating potential.

1. Introduction

Climate change currently poses a severe threat to human settlements. In addition, the projected thermal burdens will tend to be exacerbated in cities by the urban heat island phenomenon. It is therefore of critical importance that mitigation and adaptation strategies are considered jointly in an attempt to avoid any adverse effects on the well being of urban populations. Before these strategies are implemented however, research is needed in order to enhance our understanding of the potential unintended consequences of climate change mitigation policies. By way of illustration, the potential impact of increased insulation levels and air tightness in dwellings as part of CO_2 emission reduction targets on summer time indoor overheating levels needs to be assessed. The present study focuses on the development of a tool that would allow the evaluation of such measures at the domestic building stock level. The Greater London Area has been used as a case study but the methodological approach could be easily applied to other UK cities.

1.1. Urban warming trends

The frequency and severity of extreme weather events, such as heat waves, droughts and floods, are projected to increase as a result of future climate change [1]. Although developing countries are expected to be harder hit by the detrimental effects of changing weather patterns [2], the inner city urban poor of high latitude metropolitan areas of industrialized countries are also vulnerable to these changes [3]. With regard to heat wave occurrence in particular, North American and European populations currently living in temperate climates are expected to suffer from an increase in extreme heat event frequency and intensity [4]. According to modelling by the Hadley Centre [5], global warming trends are projected to double the likelihood of such events. High summer

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temperatures, such as experienced during the heat waves in Chicago in 1995 and Paris and London in 2003, are expected to become increasingly common in the future. The 2003 heat wave, in particular, caused approximately 35,000 excess deaths in Europe, of which 2000 were recorded in the UK. According to current projections, extreme heat events of this magnitude are likely to occur every three years by the middle of the century [6,7].

Furthermore, the greenhouse gas driven thermal burdens will tend to be exacerbated in urban environments by the urban heat island phenomenon. This is important given the trend of continuing urbanization: in 2008, for the first time, more than half of the world's population was living in urban settlements compared to one third in 1960 [8]. An urgent need, therefore, emerges to advance our understanding of urban warming phenomena, in terms of both causes and effects [9,10].

Urban warming, or the urban heat island (UHI) effect as it is usually referred to, is a well-established phenomenon of inadvertent climate modification linked to urbanization [11–14]. In brief, the term is used to describe the systematic air temperature increase in urban environments compared to adjacent rural areas. The phenomenon is chiefly attributed to increases in the sensible heat transfer and decreases in both the sensible and latent heat flux transfer processes occurring in the urban canopy and boundary layers. London's night time urban heat island is on average 3-4 °C. It may, however, significantly increase following a period of consecutive hot and dry days such as the August 2003 heat wave when it reached 6–9 °C thus increasing the vulnerability of its population to heat-related health risks [6].

1.2. Impacts on thermal comfort and health

The warming phenomena described above are linked to a series of interconnected impacts on the thermal comfort, energy demand and health risk levels of urban populations [14]. Although urban warming is generally associated with negative implications for warmer climates, their net effects on temperate climates, such as that of the UK, are more complex to assess. During summer, the combined effect of global warming and the urban heat island is expected to increase ambient air temperatures, leading to a rise in indoor overheating levels, reduced thermal comfort, increased cooling demand and heat-related morbidity and mortality. During winter, however, urban warmth is projected to decrease the space heating loads and the cold-related death toll and generally lengthen the growing season. Hence, the wider picture should be considered and the net effects of such phenomena need to be better understood before proceeding to the implementation of adaptation and mitigation strategies [15,16]. Tools are therefore required in order to identify and quantify the benefits and counter-benefits of urban warming trends on the energy demand, thermal comfort and health risk of urban populations.

With regard to London, in particular, several studies have examined the spatial variation of energy use, thermal comfort and health risks. It has been found that both space cooling demand in office buildings [17] and heating demand in domestic properties vary with location [18]. Local microclimatic factors also appear to have a substantial effect on indoor temperatures in naturally ventilated buildings [19]. There has also been an indication of an increase of heat-related mortality risk in London neighbourhoods with high-rise buildings [18]. Although this may be explained by the fact that certain top floor flats may offer low protection to heat, the limited power of the study did not allow a definite conclusion to be drawn.

The majority of existing urban warming impact assessment studies focus on the *external* environmental conditions. Limited research has been carried out to date, however, with regards to the impact of *indoor* conditions, such as the individual dwelling fabric characteristics on energy, comfort and health risk. Monitoring [20,21] and modelling [22] studies have demonstrated that London domestic environments are likely to experience an increased risk of overheating during hot spells or under future climate change scenarios.

1.3. Aims and objectives of the study

This paper seeks to explore which characteristics of London dwellings are determinant factors for overheating risk within the context of current urban warming trends. The objectives of the study are as follows:

(a) To implement dynamic thermal simulations of living room temperatures for dwellings broadly representative of the London housing stock based on data extracted from Geographic Information System (GIS) databases;
(b) To summarise the results of those simulations using linear regression models; and hence
(c) To propose markers of relative propensity to overheat for groups of London dwellings for which only their fabric properties are known without the need to undertake detailed simulations for each individual house.

2. Materials and methods

The study entailed simulation of indoor temperatures for representative housing types in London using the EnergyPlus dynamic thermal modelling software. The simulations were carried out for 3456 unique combinations of dwelling type and characteristics selected to represent the majority of the housing stock within London. Multiple linear regression analysis of the modelling results was then carried out in order to identify critical factors for indoor overheating across the stock. The steps followed in the study are described in detail below.

2.1. Individual building data extraction from GIS databases

Each residential building in London is represented by its footprint polygon in the Ordnance Survey MasterMap Topography Layer [23,24], an extensively validated digital map of land use and land cover, provided and continually updated by the Ordnance Survey. The MasterMap data was complemented by the Cities Revealed database [26], a commercial geographic image product based on the MasterMap Topography Layer. As an additional feature, each polygon is classified to 8 different construction age bands and 18 built form categories. The data is derived from a combination of aerial photography interpretation and on-site surveys. Height information for each polygon is also provided, based on Light Detection And Ranging (LiDAR) surveys and photogrammetric techniques. At the time of the present study, full Cities Revealed data was provided only for a limited number of London areas shown in Fig. 1. These areas are located mostly in the north west of the Greater London Area. Their overall size is 370.7 km^2 and they contain 880,393 household spaces. This accounts for approximately 29.2% of the London domestic building stock which consists of 3,015,997 household spaces in total [27].

Next, each building footprint was divided into individual properties by overlaying the Ordnance Survey Address Point Layer [25], a set of points representing every postal address in Great Britain in conjunction with data on multi-occupancies[1] without

[1] In cases of multi-occupancy or converted flats, two or more households are commonly allocated to one address point e.g. large Victorian terraces that were converted into flats sharing the same mailbox, student accommodation etc.

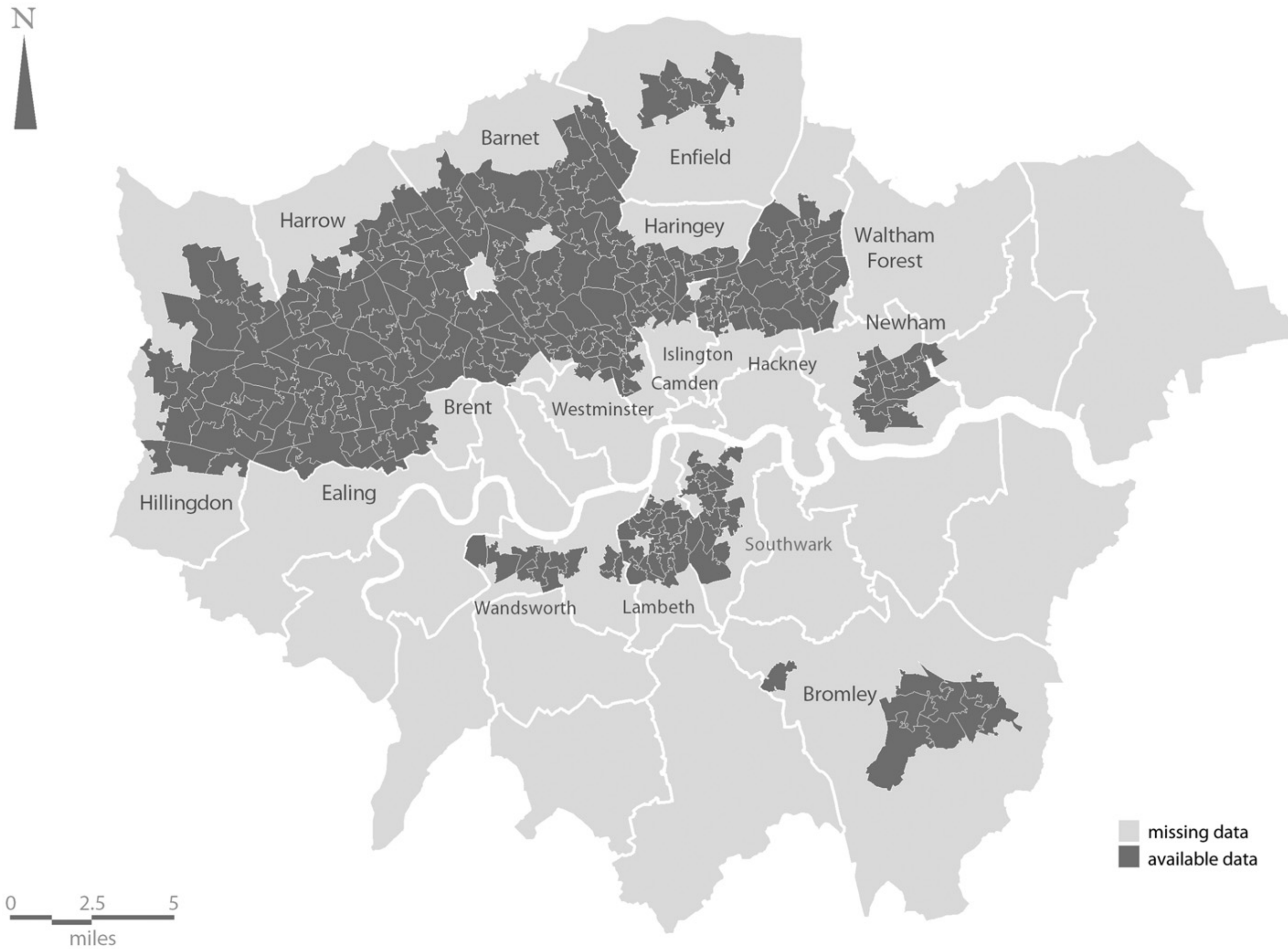

Fig. 1. Construction age and built form data availability in the Cities Revealed database.

a postal address, on the Topography Layer. To calculate the floor space area of individual residential properties, it was assumed that the area of each polygon was equally shared between the address points contained within it. In the case of overlapping address points, i.e. flats, it was assumed that the overall height of the building was also equally divided between individual properties. The overall building height and floor space areas were subsequently deduced following reasonable assumptions on roof height and wall/floor thickness respectively, as a function of building age and informed by the relevant tables in the Government's Reduced Standard Assessment Procedure for the Energy Rating of Dwellings 2005 (RdSAP 2005) [28].

2.2. Development of London dwelling archetypes

The case study areas shown in Fig. 1 contain 92 unique combinations of construction age and built form type. However, the 15 most frequently occurring combinations account for the bulk of the case study stock (approximately 76% of the address points in the case study areas and 76% × 29.2% = approximately 22% of Greater London's residential properties, Table 1). Given that London's domestic building stock is considered rather homogeneous with regard to built form typologies, this sample was deemed sufficient for the purposes of the study.

These 15 construction age and built form combinations formed the basis of a set of London dwelling archetypes. Their average footprint area and overall height were calculated from the GIS maps and are summarised in Table 2. As described elsewhere [29], internal layouts were designed for each combination based on existing literature on typical UK architectural floor plans and facades of various time periods [30–35]. Indicative elevations and ground floor plans of the built form typology of the modelled archetypes are provided in Fig. 2.

Further building geometry and fabric parameters, necessary for full thermal simulation, were derived using the methods described in detail in Oikonomou et al. [29]. In brief, the window area of each archetype was estimated as a function of age and built form [36]. The construction type of external walls, windows, ground floor, loft and roof were specified by assigning them the most commonly occurring construction element type for the corresponding age and built form combination found in the English Housing Survey [37]. In order to take into account of changes made by retrofitting as well as the original building properties, two separate insulation levels were considered for each construction element. The corresponding U-values were provided from the RdSAP 2005 [28]. In particular, all dwellings built before 1960 were modelled with single brick walls whereas the ones built post-1960 with cavity walls. Fabric air leakage characteristics were specified as a function of age [38].

Detailed information on the thermal characteristics of the modelled dwellings pre- and post-retrofit is presented in Table 3. All external walls were modelled as brick walls (material density: 1712 kg/m^3, material thermal conductivity: 0.60 W/mK) of varying

Table 1
Construction age and built form characteristics of the 15 most frequently occurring construction age and built form combinations in the case study area.

Archetype code	Age band	Built form description	Count of address points	% of total address points
TT_1902-13	1902–1913	Two storey terraced houses with large T	113,839	15.4%
T_1914-45	1914–1945	Two storey terraced houses with small or no T	107,337	14.5%
S_1914-45	1914–1945	Large semi detached houses	65,189	8.8%
D_1960-79	1960–1979	Tall purpose shared discrete houses and maisonettes	42,128	5.7%
T_1902-13	1902–1913	Two storey terraced houses with small or no T	40,503	5.5%
D_1946-59	1946–1959	Tall purpose shared discrete houses and maisonettes	34,778	4.7%
D_1980–2008	1980–2008	Tall purpose shared discrete houses and maisonettes	26,432	3.6%
2L_1902-13	1902–1913	Two storey linked and step linked houses	21,369	2.9%
B_1914-45	1914–1945	Bungalows and single storey houses	18,098	2.4%
T_1960-79	1960–1979	Two storey terraced houses with small or no T	17,734	2.4%
3L_1960-79	1960–1979	Three-four storey line built walk up flats and purpose built mews	16,838	2.3%
2L_1914-45	1914–1945	Three-four storey line built walk up flats and purpose built mews	15,404	2.1%
A_1980–2008	1980–2008	Attached houses with shops below	15,222	2.1%
2L_1946-59	1946–1959	Two storey linked and step linked houses	13,901	1.9%
3L_1946-59	1946–1959	Three-four storey line built walk up flats and purpose built mews	13,205	1.8%
		Total	561,977	76.1%

thickness and, in the case of cavity walls, varying air gap size. Internal finishes of gypsum were assumed in all houses. It was also assumed that, in the external wall insulation scenario, solid walls were insulated *internally* with a glass fiber layer (material density: 80 kg/m^3, material thermal conductivity: 0.04 W/mK).

The 3456 unique combinations of dwelling characteristics were thus based on combinations of:

(a) 15 dwelling archetypes (27 variants including ground-, mid- and top-floor level flats);
(b) 2 insulation levels (as-built and post-retrofit) for 4 construction elements (external walls, windows, ground floor, roof/loft);
(c) 4 orientations of the principal facade (0°, 90°, 180° and 270° East of North); and
(d) 2 external environment morphologies (whether stand-alone or part of a larger building structure[2]).

Multiple combinations of the above parameters led to the creation of a theoretical dwelling stock database comprising 3456 variants (Table 4). The present paper has examined the variations in thermal behaviour between these variants. Thus, no attempt was made to assign weight factors to each variant in order to represent their frequency of occurrence in the stock.

2.3. Dynamic thermal simulation

Dynamic thermal simulation of these variants was performed in the EnergyPlus 3-1-0 thermal modelling software package [39]. EnergyPlus has been extensively tested and validated using industry standard methods through analytical, comparative and executable tests [40]. To facilitate the simulation of such a large number of buildings in time effective manner, the input data was fed into EnergyPlus Generator, a novel interface to EnergyPlus for automated batch mode runs written by Biddulph [41] in Visual Basic (Fig. 3).

Several behavioural models have been developed in recent years aiming to predict occupant-controlled window opening in naturally ventilated buildings [42,43]. Unfortunately, the emphasis of these models has been on office buildings rather than domestic environments. Monitored data of summertime occupant behaviour in UK dwellings is also scarce. Although individual occupant behaviour may significantly alter the thermal performance of a dwelling, such an analysis exceeded the scope of the present study. Therefore, standard occupancy, domestic hot water, lights and appliances use and window opening schedules were assumed for all modelled dwellings based on various studies [44–51]. The number of occupants and hot water internal gains in each dwelling was calculated as a function of its total floor area [52]. Occupant metabolic rates were obtained from CIBSE [47] and ASHRAE [53] tables. With regard to occupant-controlled ventilation, it was assumed that occupants will tend to open windows when the temperature reached a threshold temperature and leave them open for as long as the internal temperature remained above this threshold and the external temperature was below the internal. The specified thresholds were 25 °C for living rooms and 23 °C for bedrooms, in line with the CIBSE Guide A recommendations on general summer indoor comfort temperatures for non-air conditioned dwellings assuming warm summer conditions [47]. Given that this study focuses on urban dwellings, it was assumed, for the scenarios examined here, that no night time ventilation is provided due to likely security and noise issues.

2.4. Weather data

2.4.1. Current

A standardised weather file (CIBSE Design Summer Year, DSY, for London Heathrow) [54] was used to represent the external weather conditions for the period 1 May to 30 September (the cooling season) under *current climate* conditions. The DSY represents a year with a hot, but not extreme, summer. It consists of an actual one-year sequence of hourly data that was selected from 20-year datasets (1983–2004) based on dry bulb temperatures during the period April–September. The selected year corresponds to the mid-year of the upper quartile. Whilst it is currently widely used by UK building professionals to assess overheating levels inside buildings during summer, it has been shown that this it does not necessarily produce the third warmest *internal* temperature over the same period and is likely to underestimate overheating risk [56]. However, the default DSY was used in the present study as it allows the comparison of the 'baseline climate' findings with UK building overheating studies published in the past.

2.4.2. Future

To explore the impact of future climate change on the indoor overheating levels of the modelled archetypes, an additional set of

[2] In order to take into account of urban overshadowing and wind sheltering effects, each dwelling archetype was multiplied in order to create a uniform urban pattern in the 3D environment of the thermal modelling software i.e. detached houses were surrounded by similarly sized detached buildings in low density areas, mid-terraces formed rows with adjacent buildings, flats were surrounded by similar high-rise buildings etc.

Table 2
Geometrical characteristics of the 15 dwelling archetypes.

	Building footprint area (m^2)	Building height (m)	Living room height (m)	Living room floor level (m)	Bedroom height (m)	Bedroom floor level (m)
TT_1902-13	64.0	9.1	3.0	0.0	3.0	3.0
T_1914-45						
S_1914-45	58.3	8.5	3.0	0.0	3.0	3.0
D_1960-79_a	48.8	8.3	3.0	0.0	3.0	3.0
D_1960-79_b	322.2	11.4	2.8	0.0	2.8	0.0
D_1960-79_c				2.8		2.8
T_1902-13				5.6		5.6
D_1946-59_a	57.3	9.3	3.0	0.0	3.0	3.0
D_1946-59_b	290.7	11.4	2.9	0.0	2.9	0.0
D_1946-59_c				2.9		2.9
D_1980–2008_a				5.8		5.8
D_1980–2008_b	319.8	11.5	2.8	0.0	2.8	0.0
D_1980–2008_c				2.8		2.8
2L_1902-13				5.6		5.6
B_1914-45	80.1	9.9	3.0	0.0	3.0	2.7
T_1960-79	90.4	8.4	3.7	0.0	3.7	0.0
3L_1960-79_a	63.4	8.5	3.0	0.0	3.0	3.0
3L_1960-79_b	463.8	16.1	2.8	0.0	2.8	0.0
3L_1960-79_c				5.6		5.6
2L_1914-45_a				11.2		11.2
2L_1914-45_b	690.2	16.9	2.8	0.0	2.8	0.0
2L_1914-45_c				5.6		5.6
A_1980–2008				11.2		11.2
2L_1946-59	101.5	9.3	2.7	0.0	2.7	2.7
3L_1946-59_a	58.1	8.3	3.0	0.0	3.0	3.0
3L_1946-59_b	487.0	16.1	2.8	0.0	2.8	0.0
3L_1946-59_c				5.6		5.6
				11.2		11.2

runs was performed using a projected climate file. The latest climate change projections for the UK are provided by the UK Climate Projections program (UKCP09) [7]. UKCP09 has adopted a novel probabilistic approach that attempts to quantify the uncertainties involved in climate modelling by assigning a probability factor to each modelled scenario. The EPSRC-funded PROMETHEUS project ('The Use of Probabilistic Climate Change Data to Future-proof Design Decisions in the Building Sector') [55] has further processed the UKCP09 data in order to generate weather files in a format that is suitable for building simulation studies.

In the present paper, a PROMETHEUS DSY weather file representing the 50th percentile of external temperature under a medium emissions scenario (A1B) in the 2050s was used. This means that, for the given emissions scenario, it is 50% likely that the external temperature increase will be lower than the projected change contained in the weather file and 50% likely that it will be higher. The 2050s time slice was selected by taking into consideration the current lifetime of UK buildings (approximately 60–80 years). This future climate weather file has been generated from a baseline time series dataset that is different from the one used to represent the current climate in the present study. Although this may not allow for a direct quantification of future changes in internal temperatures on a day-to-day basis, the outcome of the climate change scenario runs still offer an indication of the stock's future thermal performance.

2.5. Statistical analysis

The thermal performance of the indoor environment and, in particular, overheating effects, are complex phenomena with multiple confounding factors. In addition, these factors are possibly correlated with each other e.g. the construction age of a dwelling may potentially function as a good predictor of glazing ratios, the thermal conductivity of external walls may be related to their thermal mass etc. Furthermore, factors such as individual occupant patterns and ventilation habits are highly likely to be key determinant factors of both temperature magnitude and variation. At the individual building level, overheating prediction can be performed only through dynamic thermal simulation with detailed inputs.

As mentioned in the Introduction, however, limited research has been conducted to date with regards to the identification of determinant factors for overheating at the building stock level. To achieve this in the present study, linear models were adopted as they have low computation time requirements and are designed to cope with highly correlated regressors. We acknowledge that simple linear models will never be fully capable of describing the complex mechanisms underlying indoor overheating events for an individual dwelling due to behavioral issues etc. They may, however, be useful in evaluating overheating risk relating to the basic thermal properties of dwellings. If detailed survey data of building fabric characteristics is made available in the future, such modelling techniques could be extended in order to rank the propensity of individual dwellings to overheat based on non-behavioural parameters.

Therefore, data derived from the simulations were summarized using tabulation and graphical methods, and analysed by multiple linear regression to provide simplified summaries of the effect of dwelling characteristics on both average and maximum living room temperature. These regression models examined the effect of four key explanatory factors:

- dwelling archetype (combination of built form and construction age);
- morphology of the external environment;
- orientation;
- retrofitting of the floor, walls, windows and roof/loft (which affects thermal conductivity and the associated U-values)

Regression results are shown as the change in temperature for each level of each explanatory factor with 95% confidence intervals. All analyses were carried out in Stata 11 [57].

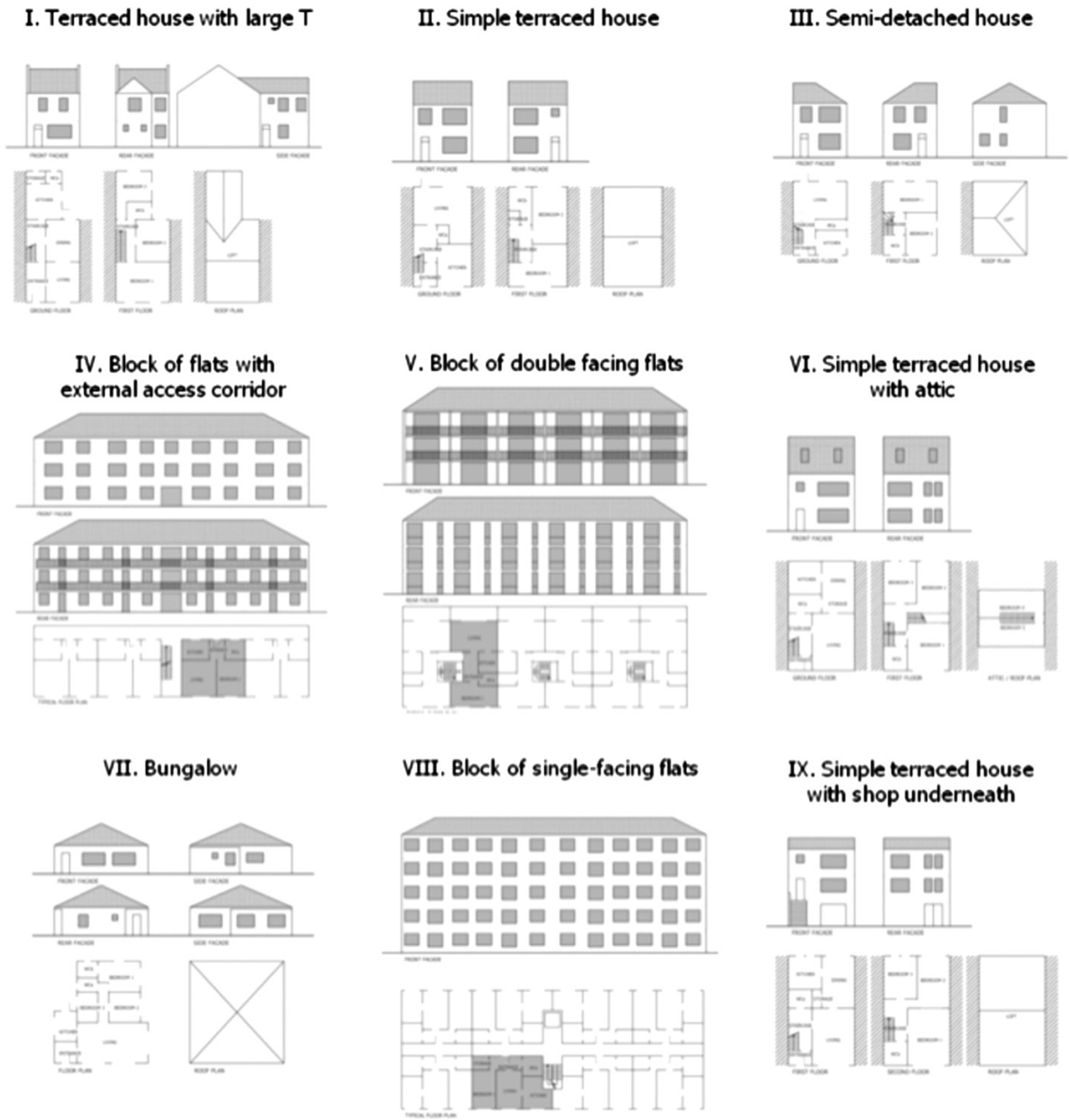

Fig. 2. Built form typology of modelled dwelling archetypes.

3. Results

3.1. Indoor overheating risk by built form and construction age

To assess the impact of building form and age on internal air temperatures, year-round simulations were performed. The variation in maximum and average living room temperature during daytime was then examined by archetype for the hottest five-day period in the CIBSE DSY weather (i.e. ‘current’) file (21–25 July). For this period the mean outdoor temperature was 26.3 °C, the minimum 17.5 °C and the maximum 33.4 °C.

The simulation results suggested appreciable variation in both mean and maximum daytime living room temperature by dwelling type—the combination of built form and dwelling age (Table 5) – with the variation being greater for maximum than for mean temperatures (Figs. 4 and 5). The dwelling types with generally highest mean and maximum temperatures included three- or five-storey line built walk up flats and purpose-built mews, built 1914–1945, and bungalows and single storey houses, built 1914–1945. In general, overheating risk seems to increase with floor level in high-rise structures, with top floor flats being warmer, followed by mid floor flats.

Table 3
Building fabric characteristics – input to EnergyPlus thermal simulations.

Archetype	Retrofit state	U-value (W/m^{2}K)					Thermal admittance (W/m^{2}K)		
		Walls	Floor	Windows	Loft	Roof	Walls	Floor	Roof
TT_1902-13	As built	2.10	1.20	4.80	0.40	3.10	4.22	5.45	4.43
	Retrofitted	0.60	0.51	2.00	0.15	3.10	4.35	5.46	4.43
T_1914-45	As built	2.10	1.20	4.80	0.40	3.10	4.22	5.45	4.43
	Retrofitted	0.60	0.51	2.00	0.15	3.10	4.35	5.46	4.43
S_1914-45	As built	2.10	1.20	4.80	0.40	3.10	4.22	5.45	4.43
	Retrofitted	0.60	0.51	2.00	0.15	3.10	4.35	5.46	4.43
D_1960-79	As built	1.60	1.20	3.10	0.40	3.10	4.25	5.45	4.43
	Retrofitted	0.50	0.51	2.00	0.15	3.10	4.52	5.46	4.43
T_1902-13	As built	2.10	1.20	4.80	0.40	3.10	4.22	5.45	4.43
	Retrofitted	0.60	0.51	2.00	0.15	3.10	4.35	5.46	4.43
D_1946-59	As built	2.10	1.20	4.80	0.40	3.10	4.22	5.45	4.43
	Retrofitted	0.60	0.51	2.00	0.15	3.10	4.35	5.46	4.43
D_1980–2008	As built	0.45	0.45	3.10	0.29	3.10	4.52	5.46	4.43
	Retrofitted	0.35	0.25	2.00	0.15	3.10	4.54	5.46	4.43
2L_1902-13	As built	2.10	1.20	4.80	0.40	3.10	4.22	5.45	4.43
	Retrofitted	0.60	0.51	2.00	0.15	3.10	4.35	5.46	4.43
B_1914-45	As built	2.10	1.20	4.80	–	2.30	4.22	5.45	4.37
	Retrofitted	0.60	0.51	2.00		0.15	4.35	5.46	5.97
T_1960-79	As built	1.60	1.20	3.10	0.40	3.10	4.25	5.45	4.43
	Retrofitted	0.50	0.51	2.00	0.15	3.10	4.52	5.46	4.43
3L_1960-79	As built	1.60	1.20	3.10	–	1.50	4.25	5.45	4.52
	Retrofitted	0.50	0.51	2.00		0.15	4.52	5.46	5.97
2L_1914-45	As built	2.10	1.20	4.80	–	2.30	4.22	5.45	4.37
	Retrofitted	0.60	0.51	2.00		0.15	4.35	5.46	5.97
A_1980–2008	As built	0.45	0.45	3.10	0.29	3.10	4.52	5.46	4.43
	Retrofitted	0.35	0.25	2.00	0.15	3.10	4.54	5.46	4.43
2L_1946-59	As built	2.10	1.20	4.80	0.40	3.10	4.22	5.45	4.43
	Retrofitted	0.60	0.51	2.00	0.15	3.10	4.35	5.46	4.43
3L_1946-59	As built	2.10	1.20	4.80	–	2.30	4.22	5.45	4.37
	Retrofitted	0.60	0.51	2.00		0.15	4.35	5.46	5.97

There was, however, considerable overlap between dwelling types in simulated temperatures, with generally greater variation *within* dwelling types than between them. There was 3.8 °C difference in mean daytime living room temperature between the dwelling types with the highest (B_1914-45) and lowest (3L_1946-59_b) average temperatures, and a 5.3 °C difference in maximum daytime living room temperature between dwelling types with the highest (B_1914-45) and lowest (3L_1946-59_b) maximum temperatures (Fig. 4, Appendix Table A1). For the individual dwelling type with the greatest within group variation, type 2L_1914-45_b, the range of mean temperatures varied by 5.2 °C (from 26.1 to 31.2 °C), and the range of maximum temperatures by 8.3 °C (from 28.0 °C to 36.3 °C).

Building age was an important determinant of temperature. Many of the hottest dwellings were those built between 1914 and 1945, while the particular archetypes that fell in the most recent building age category (1980–2008) were slightly below median in terms of both mean and maximum daytime living room temperature (Fig. 5[B]).

3.2. *Effect of retrofitting*

Among the most important determinants of daytime living room temperature was the degree of retrofitting of energy efficiency (insulation) measures. The effects of all permutations of energy efficiency retrofits to the roof, windows, walls and floor are shown in Table 5. In combination, roof/loft and window retrofitting reduced average daytime living room temperatures by 0.76 °C (95% C.I. 0.63–0.89 °C) and maximum daytime living room temperatures by 1.30 °C (95% C.I. 1.05–1.54 °C).

In contrast, wall insulation and, to minor degree, floor retrofitting tended to *increase* living room temperatures (Table 5). On average, wall insulation alone was found to increase mean daytime living room temperatures by 0.38 °C (95% C.I. 0.25-0.51 °C) and maximum daytime living room temperatures by 0.61 °C (95% C.I. 0.36–0.85 °C). The average effect of floor retrofitting appeared to be a marginal increase of both these temperatures by less than 0.1 °C (Table 5).

The effect of retrofitting on the change in daytime living room temperatures for all individual dwelling types modelled is shown in Fig. 6. In this figure, arrows connect points for the pre-retrofitting and post-retrofitting temperatures for the same dwelling. It is clear that the net effect of combined retrofitting of all four elements (roof/loft, windows, walls and floor) is to decrease temperatures, though a small proportion of dwellings experienced an increase in temperatures (Fig. 6 [A] and [B]). Retrofitting of the roof/loft and windows only, however, appears to have an overall beneficial effect for indoor overheating (Fig. 6 [C] and [D]).

Dwellings that showed the greatest reductions in daytime maximum living room temperatures are shown in Appendix Table A2. For combined retrofitting of all four elements, a number of dwellings showed reductions in maximum temperatures of greater than 4 °C (mainly dwelling types 2L_1914-45_c and 3L_1946-59_c), while for the same dwellings the simulated temperature reductions were greater still, at up to 6 °C, for retrofitting of roof/loft and windows only. Table A3 lists those dwellings that showed the larger increases in maximum daytime living room temperatures following combined walls and floor retrofitting. Temperature increases of up to 2.4 °C were observed, with the

Table 4
Combinations of modelled dwelling variants.

Dwelling archetypes	Wall insulation	Floor insulation	Windows insulation	Roof/loft insulation	Orientation	External environment	Total
27	× 2	× 2	× 2	× 2	× 4	× 2	= 3456

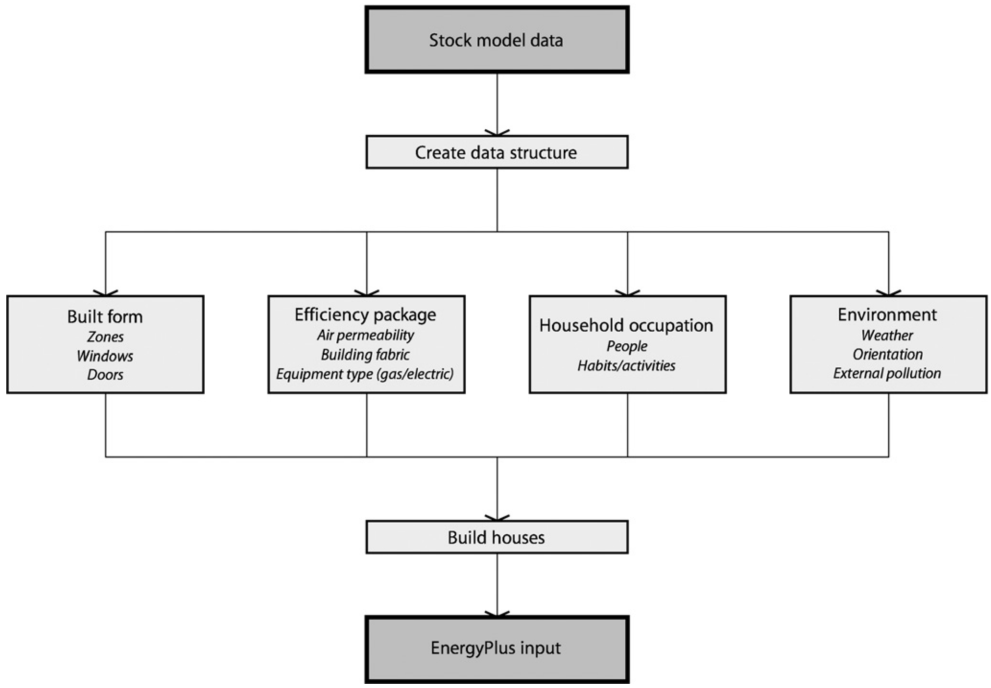

Fig. 3. Algorithm structure of EnergyPlus Generator (Modified from: Biddulph 2010).

greatest changes affecting a variety of dwelling types. The increases in maximum daytime living room temperature for these same dwellings were substantially less with combined retrofitting of all four elements (see last column of table).

As demonstrated in Fig. 7, a strong correlation was observed between the daytime living room and night time bedroom temperatures during the 5-day hottest period of the current climate CIBSE DSY weather file, with the former generally being higher - the average difference is approximately 1 °C.

3.3. *Effect of future climate change*

An additional set of modelling results was obtained from the simulations of the thermal performance of the stock using the UKCP09 PROMETHEUS weather file. As noted earlier, the climate change weather file has resulted from a different baseline time series with the current climate DSY used for this study and, as a consequence, no direct comparison of the two sets of results is possible. Nevertheless, the analysis of the latter still allows for the investigation of the stock's performance under a future warmer climate.

Fig. 8 shows the distribution of seasonal average temperatures for all simulations under [A] current and [B] future climate scenarios, with selected retrofitting subgroups superimposed: no-retrofitting for [A] and full retrofitting for [B]. These superimposed bars are an attempt to explore the impact of full retrofitting on the mitigation of higher future temperatures. However, retrofitting appears to have little influence on seasonal average temperatures (unlike for the mean and maximum temperatures during the 5-day hottest period).

Table 5
Regression estimates of the effect of retrofitting on simulated *average* and *maximum* daytime (8 am–11 pm) living room temperatures.

	Retrofit to…				Increase in temperature (95% confidence interval) estimates adjusted for building form/age and external environment morphology	
	Floor	Walls	Windows	Roof	Average daytime living room temperature (°C)	Maximum daytime living room temperature (°C)
Effect of retrofitting					0.00	0.00
				✓	−0.30 (−0.43, −0.17)	−0.56 (−0.81, −0.32)
			✓		−0.39 (−0.52, −0.26)	−0.61 (−0.85, −0.36)
			✓	✓	−0.76 (−0.89, −0.63)	−1.30 (−1.54, −1.05)
		✓			0.38 (0.25, 0.51)	0.61 (0.36, 0.85)
		✓		✓	0.03 (−0.10, 0.16)	−0.04 (−0.28, 0.21)
		✓	✓		−0.03 (−0.16, 0.10)	−0.13 (−0.37, 0.12)
		✓	✓	✓	−0.47 (−0.60, −0.33)	−0.94 (−1.18, −0.70)
	✓				0.06 (−0.07, 0.19)	0.07 (−0.18, 0.31)
	✓			✓	−0.24 (−0.38, −0.11)	−0.50 (−0.75, −0.26)
	✓		✓		−0.33 (−0.46, −0.20)	−0.53 (−0.78, −0.29)
	✓		✓	✓	−0.70 (−0.83, −0.57)	−1.23 (−1.48, −0.99)
	✓	✓			0.46 (0.33, 0.60)	0.71 (0.47, 0.96)
	✓	✓		✓	0.12 (−0.02, 0.25)	0.06 (−0.18, 0.31)
	✓	✓	✓		0.05 (−0.08, 0.18)	−0.02 (−0.27, 0.22)
	✓	✓	✓	✓	−0.38 (−0.51, −0.25)	−0.83 (−1.07, −0.59)

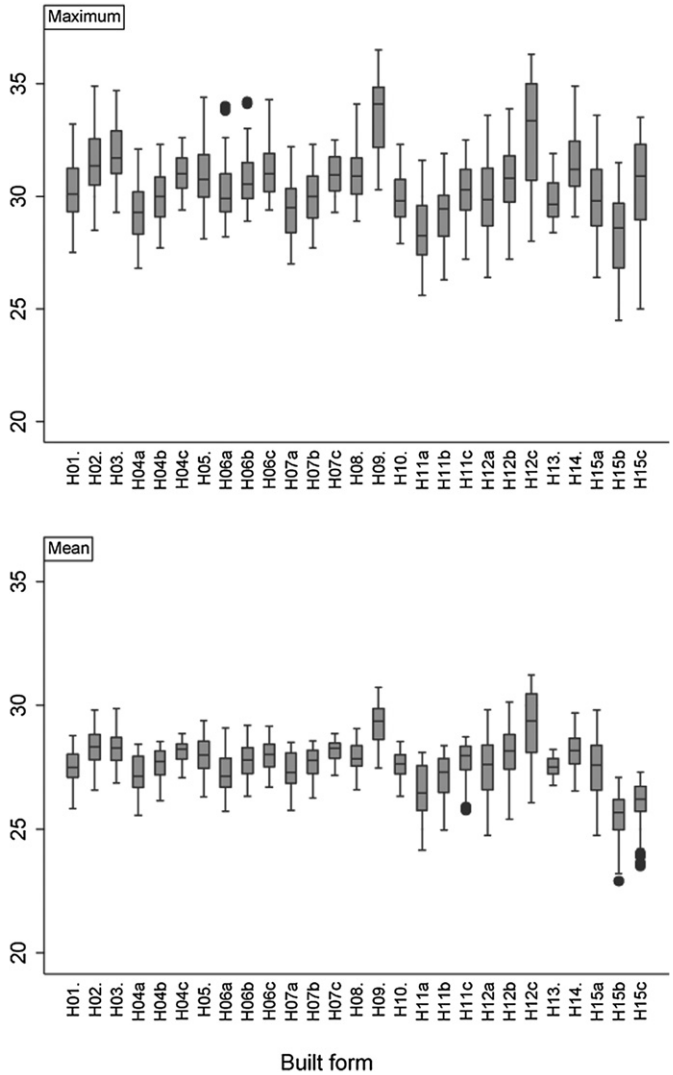

Fig. 4. Simulation results for maximum and mean daytime (8 am–11 pm) living room temperatures for the hottest five-day period of summer heat (21–25 July in the CIBSE design year temperature series).

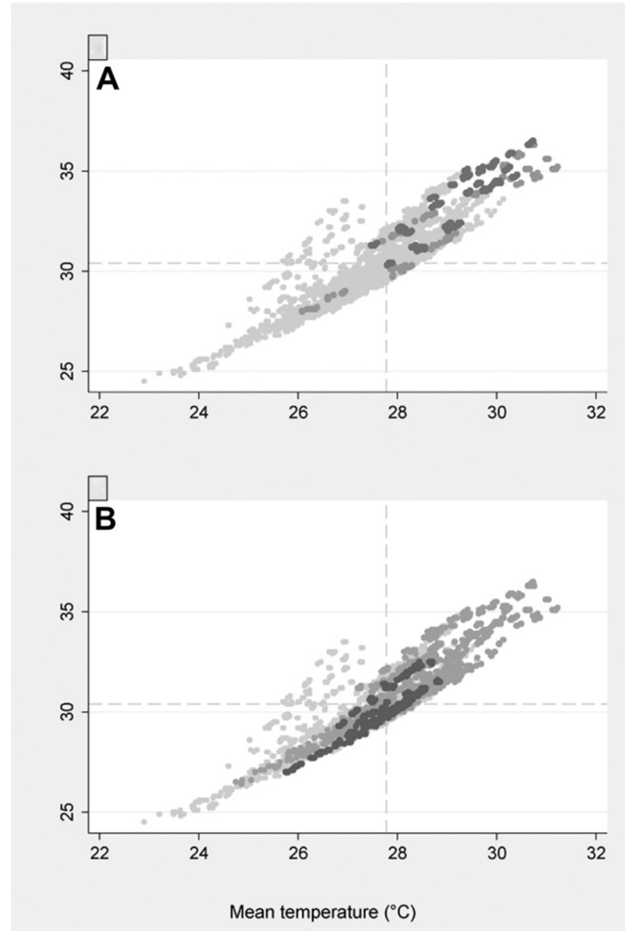

Fig. 5. Plot of simulated maximum daytime (8 am–11 pm) living room temperature *vs.* mean daytime living room temperature for the hottest five-day period of summer heat in the CIBSE design year temperature series: [A] dark grey – archetype 2L_1914-45_c; medium grey – archetype B_1914-45; [B] dark grey – building age 1980-2008; medium grey – building age 1914–1945. Dashed lines indicate the median for each temperature distribution.

4. Discussion

This paper set out with the aim of assessing the importance of building morphology and thermal fabric characteristics for overheating in typical London dwellings during a hot period. The regression results obtained from the detailed thermal modelling exercise of a theoretical building stock of 3456 dwelling variants indicated that there is a large variation in average and maximum daytime temperatures for a five-day period of consecutive hot days by archetype. A strong relationship between insulation levels and internal air temperatures was also shown.

A key finding of the current study was that although the combination of built form and construction age accounted for an appreciable degree of variation in daytime living room temperatures, there was generally greater variation within dwelling types than between them.

Another interesting observation was the relationship between floor level and indoor temperature with top floor flats in high-rise structures being in higher risk of overheating compared to the floors underneath them. This is in accordance with prior studies that have indicated that top-floor flats are likely to offer less protection to heat during a hot period. Although the archetypes were generated for a case study area containing 22% of London houses, the whole of the Greater London Area will inevitably be characterized by a greater variety of building types. Hence, the results should be treated with some caution and should not be viewed as generic.

Variations in overheating performance could be partially explained by both differences in the size of exposed surface areas and thermal fabric characteristics across the archetypes. The impact of different thermal conductivity values on indoor overheating as a result of potential retrofit packages was therefore quantified through regression. The most interesting finding that emerged from this analysis was that, in broad terms, the insulation interventions appeared to *reduce* overheating risk for this stock. In some cases, however, wall insulation led to an increase of internal temperatures. It needs to be noted that the majority of modelled dwellings featured solid brick walls that were insulated *internally* in the post-retrofit scenario. It is likely that the location of the insulation for solid walls will be important for overheating. Additional work is needed to investigate the combined effects of insulation and thermal mass. By way of illustration, for the modelled insulation scenario, the decrement delay (time lag) increased from 6.0 h for the uninsulated brick solid wall to 8.1 h for the internally insulated wall. Furthermore, although window upgrade was found

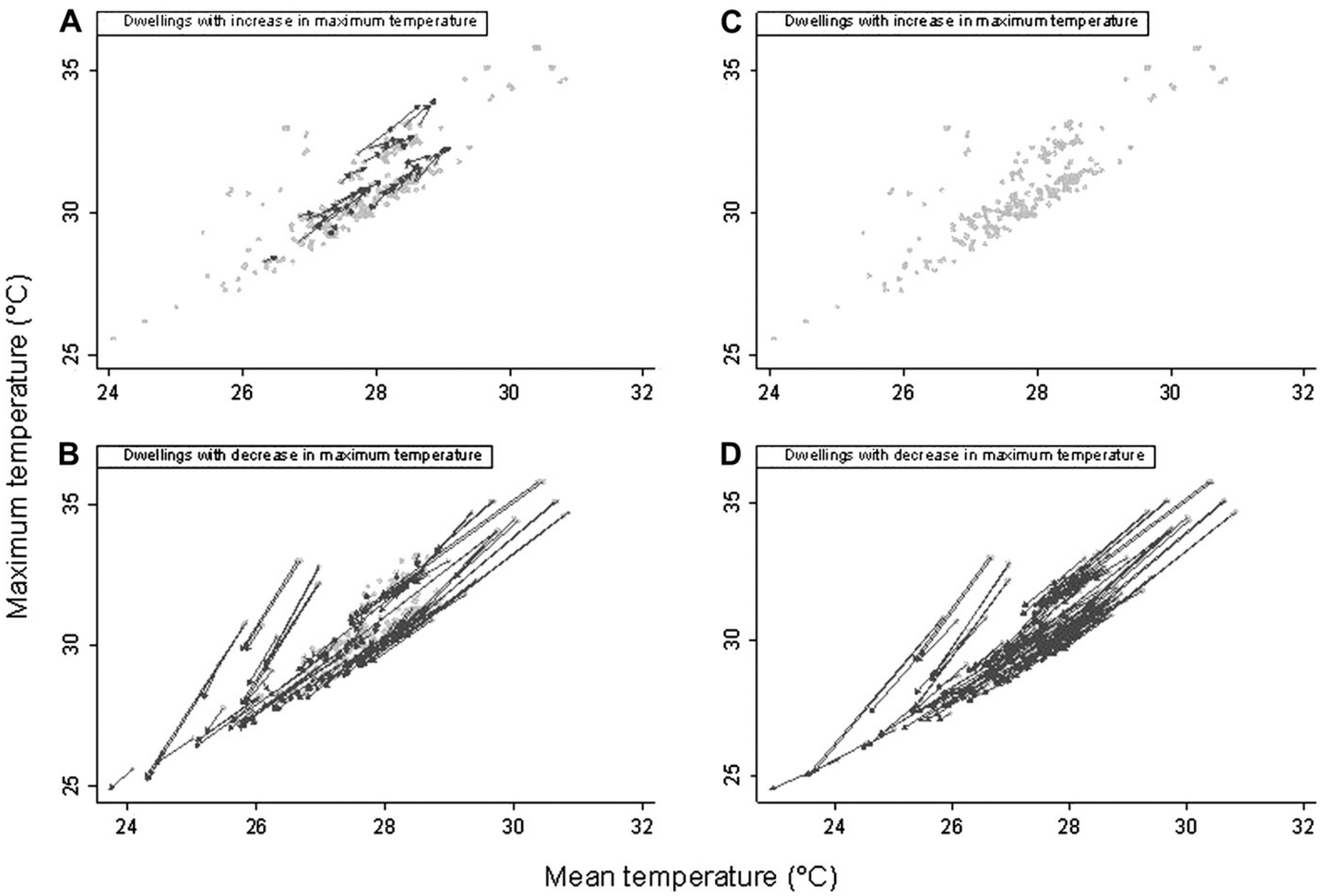

Fig. 6. Comparison of simulated daytime (8 am–11 pm) living room temperatures before and after retrofitting of energy efficiency (insulation) measures. [A] and [B]: combined retrofitting of floor, walls, windows and loft/roof insulation; [C] and [D]: retrofitting of windows and loft/roof only. Arrows point from pre-retrofitting to post-retrofitting temperatures for the same dwelling. [A] and [C] display results for dwellings that show an increase in maximum living room temperature with retrofitting, [B] and [D] the results for dwellings that show a decrease in maximum living room temperature. Light grey dots indicate temperature data for all dwellings before any retrofitting.

to decrease internal temperatures, windows are likely to have been modelled as opened during the daytime rendering their conductivity values less relevant. Further research is thus needed in order to quantify the relative performance of various insulation options.

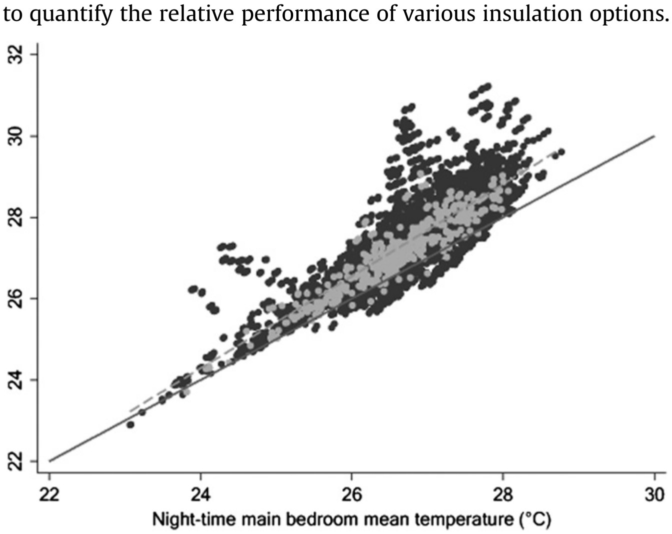

Fig. 7. Relationship between mean daytime living room temperature and mean night time main bedroom temperature. Light grey dots indicate dwellings with full retrofitting of energy efficiency measures; solid line is the line of equality; dashed line shows the fitted values of the regression of daytime living room mean temperature on night time bedroom mean temperature.

Another interesting result to emerge from the runs with the climate change weather file was that although full retrofitting measures are generally beneficial during the 5-day hot period, their impact on summer seasonal temperatures is limited. Potential explanations for this may be the differences observed in the spread of external temperatures as well as the changes in diurnal temperature difference. Further analysis is required to disentangle the impact of individual retrofit measures on a house-by-house basis.

The present study assumed that no windows were opened during the night time. Although this may be a realistic scenario in general for urban environments, further work is required in order to fully explore the effect of various nocturnal ventilation regimes coupled or not with exposed high thermal mass elements on overheating.

Another caveat lies in the fact that occupancy patterns were not varied and results were only analysed for the living room during daytime and bedroom during night time. Further analysis will investigate the indoor temperature profiles and occupant exposure to high temperatures in different rooms and at different times of the day for various occupant patterns and lifestyles.

Although we attempted to model the existing stock as accurately as possible, another limitation of the study stems from the low variation in the fabric characteristics modelled e.g. only two U-values for each construction element (as-built and post-retrofit) were tested. Future work will cover not only a wider range of insulation materials and corresponding U-values, but also materials with varying thermal capacity characteristics.

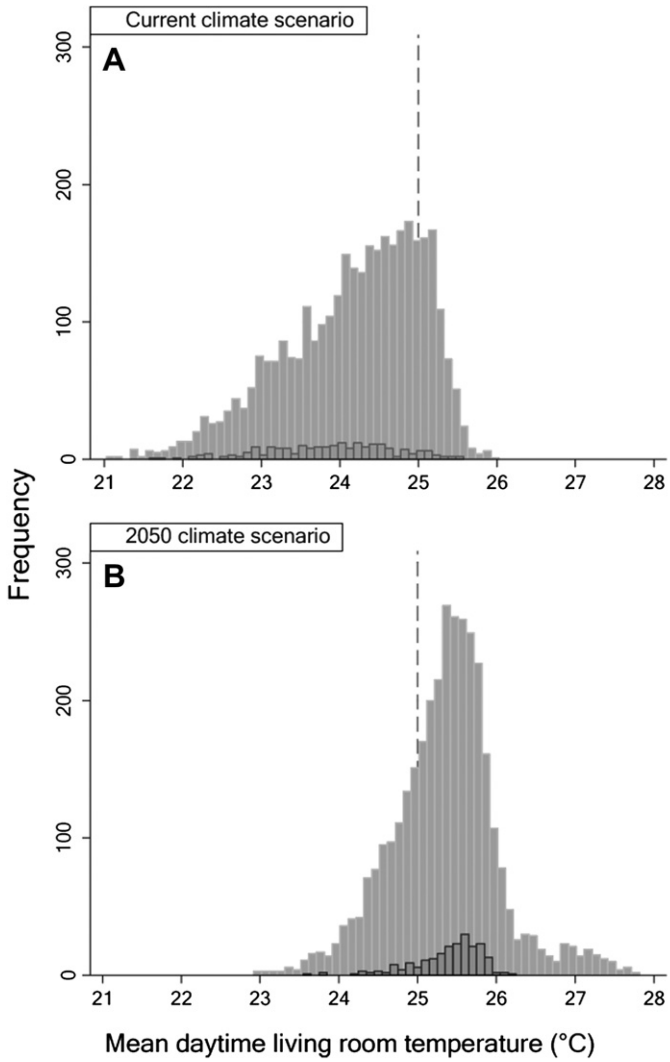

Fig. 8. Distribution of simulation results for mean summer (June, July, August) daytime living room temperatures: [A] current climate (CIBSE DSY); [B] future climate (UKCP09 50th percentile of external temperature, 2050s, medium emissions scenario, PROMETHEUS DSY). Dark grey bars in [A] indicate dwellings with no retrofitting; dark grey bars in [B] indicate dwellings with full retrofitting.

Caution must also be applied as the study focused on the hottest five-day period of the London DSY, a warm but not extreme summer weather file, in conjunction with a future medium emissions climate change scenario. Although this represents a realistic scenario of a hot weather period by current and future climate standards, factoring in trends of a changing climate through the use of a broader range of emissions scenarios (ranging from low to high) should allow a more holistic evaluation of benefits and disbenefits of insulation measures over the given time-frame, i.e. by the middle of the century.

A recent trend in climate change impact assessment studies is the shift towards a probabilistic approach that attempts to bracket overheating risk estimate in probabilities. Due to limitations in computing power, the present modelling study was limited to two illustrative points in time. However, as part of ongoing work, a full-scale climate change impact assessment study is envisaged that will use the full range of UKCP09 weather files.

Finally, the same weather file was used for all archetypes. In order to map the spatial variation of indoor overheating risk, urban heat island effects and local microclimatic factors need also to be considered. Taken the above into account, simulating the thermal performance of the same theoretical stock under climate change weather files (e.g. UKCP09) [7], in conjunction with tailored location-specific London weather files is part of ongoing work.

The present paper has demonstrated the methodological framework that would allow us to build a set of equations that could function as a shortcut to detailed thermal modelling work. Such a technique could be applied in building stock level studies in order to rank the propensity to overheat of any random set of UK dwellings for which only their fabric properties are known without the need to rerun EnergyPlus for each individual house. Such a tool would enable one to rapidly scan the entire stock and map the spatial variation of overheating risk across London that is attributed to individual dwelling characteristics, assuming that the relevant input data is available.

5. Conclusions

Within the context of a changing climate, the present study was designed to determine the effect of individual fabric attributes on indoor overheating across the existing London residential stock. It was shown that the combination of geometry and construction age can function as reliable predictors of indoor overheating risk. Another important finding of this study was that although the particular combined insulation measures appear to decrease internal temperatures, internal solid wall insulation may potentially increase overheating during a warm period if no night time ventilation is provided. An implication of this finding is that careful consideration of insulation options needs to be made in the future in the context of energy efficiency retrofit strategies as part of national carbon reduction targets such as the UK Government's Green Deal [58]. It is recommended that the specification of thermal upgrade solutions should not only evaluate the overall year-round benefits of various insulation measures but also preferably tailor said solutions to specific occupancy patterns.

The statistical regression investigation presented in this paper has indicated the potential for the development of a linear prediction model of relative ranking of individual dwellings with regard to indoor overheating levels that uses a limited number of known building characteristics. Such a tool could be applied in order to enhance our understanding of overheating risk variations across the city to the extent that it is attributed to indoor rather than outdoor environmental (i.e. non-behavioural) characteristics. For instance, various markers for overheating —such as predicted average temperature or exceedance of given thresholds for a various external climatic scenaria— could be rapidly produced by applying regression equations with limited sets of inputs, i.e. dwelling attributes that are known from GIS databases. The set of these markers could be subsequently weighted according to their significance from an epidemiological point of view and be combined into a heat wave vulnerability index at the citywide level. The development of this tool may be of interest to urban planners and public health policy makers and will add to a growing body of literature aiming to assess the micro-spatial variations of heat-related vulnerability in cities.

Acknowledgements

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Appendix

Table A1
Regression estimates of the effect of dwelling characteristics on simulated *average* and *maximum* daytime (8 am–11 pm) living room temperatures.

Variable (units)	Levels	Increase in daytime living room temperature (95% confidence interval) per unit change in explanatory factor. Estimates adjusted for all variables in model.	
		Average temperature (°C)	Maximum temperature (°C)
Built form	TT_1902-13	0.00	0.00
	T_1914-45	0.78 (−0.17, 0.95)	1.35 (−0.32, 1.67)
	S_1914-45	0.78 (−0.17, 0.95)	1.65 (−0.32, 1.96)
	D_1960-79_a	*−0.32 (−0.17, −0.15)*	*−0.86 (−0.32, −0.54)*
	D_1960-79_b	0.08 (−0.17, 0.25)	*−0.17 (−0.32, 0.15)*
	D_1960-79_c	0.61 (−0.17, 0.78)	0.84 (−0.32, 1.16)
	T_1902-13	0.46 (−0.17, 0.63)	0.72 (−0.32, 1.04)
	D_1946-59_a	*−0.19 (−0.17, −0.01)*	*−0.05 (−0.32, 0.27)*
	D_1946-59_b	0.23 (−0.17, 0.40)	0.56 (−0.32, 0.88)
	D_1946-59_c	0.46 (−0.17, 0.63)	0.99 (−0.32, 1.30)
	D_1980-2008_a	*−0.17 (−0.17, 0.00)*	*−0.75 (−0.32, −0.44)*
	D_1980-2008_b	0.13 (−0.17, 0.30)	*−0.21 (−0.32, 0.11)*
	D_1980-2008_c	0.66 (−0.17, 0.83)	0.81 (−0.32, 1.13)
	2L_1902-13	0.37 (−0.17, 0.54)	0.79 (−0.32, 1.11)
	B_1914-45	1.72 (−0.17, 1.89)	3.40 (−0.32, 3.72)
	T_1960-79	0.08 (−0.17, 0.25)	*−0.24 (−0.32, 0.08)*
	3L_1960-79_a	*−0.96 (−0.17, −0.79)*	*−1.69 (−0.32, −1.38)*
	3L_1960-79_b	*−0.41 (−0.17, −0.24)*	*−0.97 (−0.32, −0.66)*
	3L_1960-79_c	0.23 (−0.17, 0.40)	0.03 (−0.32, 0.34)
	2L_1914-45_a	*−0.05 (−0.17, 0.12)*	*−0.32 (−0.32, 0.00)*
	2L_1914-45_b	0.52 (−0.17, 0.69)	0.46 (−0.32, 0.78)
	2L_1914-45_c	1.67 (−0.17, 1.84)	2.56 (−0.32, 2.88)
	A_1980-2008	0.03 (−0.17, 0.20)	*−0.32 (−0.32, 0.00)*
	2L_1946-59	0.66 (0.83, 0.83)	1.30 (0.68, 1.62)
	3L_1946-59_a	*−0.06 (−0.17, 0.11)*	*−0.33 (−0.32, −0.01)*
	3L_1946-59_b	*−2.06 (−0.17, −1.89)*	*−1.92 (−0.32, −1.61)*
	3L_1946-59_c	*−1.45 (−0.17, −1.27)*	0.12 (−0.32, 0.44)
External environment	Stand-alone building	0.00	0.00
	Adjacent buildings	*−0.57 (−0.61, −0.52)*	−0.85 (−0.94, −0.77)
Retrofitting to	Floor	0.07 (0.03, 0.12)	0.09 (−0.00, 0.17)
	Walls	0.35 (0.31, 0.40)	0.51 (0.43, 0.60)
	Windows	*−0.44 (−0.48, −0.39)*	*−0.74 (−0.83, −0.66)*
	Roof	*−0.36 (−0.41, −0.32)*	*−0.68 (−0.77, −0.59)*

Table A2
List of dwellings which show the largest decreases in temperature (>3 °C fall) with retrofitting of roof/loft, windows.

			No retrofit		Retrofit of loft/roof and windows			Retrofit of loft/roof, windows, walls and ground floor		
Built form	External environment	Principal façade orientation	Maximum temperature (°C)	Average temperature (°C)	Maximum temperature (°C)	Average temperature (°C)	Difference in maximum temperature (°C) compared to the no retrofit scenario	Maximum temperature (°C)	Average temperature (°C)	Difference in maximum temperature (°C) compared to the no retrofit scenario
2L_1914-45c	urban	N	34.0	29.7	28.0	26.1	−6.0	28.1	26.3	−5.9
2L_1914-45c	rural	N	34.1	29.7	28.1	26.2	−6.0	28.2	26.4	−5.9
3L_1946-59c	urban	N	30.7	25.8	25.0	23.5	−5.7	25.3	24.3	−5.4
3L_1946-59c	rural	N	30.8	25.8	25.1	23.6	−5.7	25.4	24.3	−5.4
2L_1914-45c	rural	S	35.1	30.7	30.1	27.9	−5.0	30.3	28.2	−4.8
2L_1914-45c	urban	S	35.1	30.6	30.1	27.9	−5.0	30.2	28.1	−4.9
2L_1914-45c	urban	E	34.6	30.8	29.7	27.9	−4.9	30.1	28.1	−4.5
3L_1946-59c	urban	E	32.1	26.9	27.3	25.3	−4.8	27.9	25.7	−4.2
2L_1914-45c	rural	E	34.7	30.8	30.0	28.1	−4.7	30.3	28.3	−4.4
3L_1946-59c	rural	E	32.2	27.0	27.5	25.4	−4.7	27.9	25.8	−4.3
2L_1914-45c	urban	W	35.8	30.4	31.5	27.7	−4.3	31.8	27.9	−4.0
3L_1946-59c	urban	S	32.7	27.0	28.6	25.6	−4.1	29.2	26.1	−3.5
3L_1946-59c	rural	S	32.8	27.0	28.7	25.7	−4.1	29.3	26.1	−3.5
2L_1914-45c	rural	W	35.8	30.4	31.7	27.9	−4.1	31.9	28.1	−3.9
3L_1946-59c	urban	W	33.0	26.6	29.2	25.3	−3.8	29.8	25.8	−3.2
B_1914-45	urban	E	34.0	29.7	30.3	27.8	−3.7	31.1	28.5	−2.9
B_1914-45	rural	E	34.1	29.7	30.4	27.8	−3.7	31.1	28.6	−3.0
3L_1946-59c	rural	W	33.0	26.7	29.4	25.5	−3.6	29.9	25.8	−3.1
B_1914-45	urban	N	34.7	29.3	31.3	27.5	−3.4	31.9	28.2	−2.8
B_1914-45	rural	N	34.7	29.3	31.3	27.5	−3.4	32.0	28.3	−2.7
B_1914-45	urban	S	34.5	30.0	31.2	28.3	−3.3	32.4	29.1	−2.1
B_1914-45	rural	S	34.4	30.0	31.2	28.3	−3.2	32.4	29.1	−2.0

Table A3
List of dwellings which show an increase of more than 1.5 °C in temperature with retrofitting of walls and floor.

			No retrofit		Retrofit of loft/roof and windows			Retrofit of loft/roof, windows, walls and ground floor		
Built form	External environment	Principal façade orientation	Maximum temperature (°C)	Average temperature (°C)	Maximum temperature (°C)	Average temperature (°C)	Difference in maximum temperature (°C) compared to the no retrofit scenario	Maximum temperature (°C)	Average temperature (°C)	Difference in maximum temperature (°C) compared to the no retrofit scenario
2L_1946-59	rural	E	31.0	29.0	34.0	30.0	2.4	32.0	29.0	1.0
T_1914-45	rural	S	31.0	29.0	34.0	29.0	2.3	32.0	29.0	0.4
2L_1946-59	rural	S	31.0	28.0	33.0	29.0	2.2	32.0	29.0	0.5
B_1914-45	rural	S	34.0	30.0	37.0	31.0	2.1	32.0	29.0	−2.0
2L_1946-59	urban	S	31.0	28.0	33.0	29.0	2.0	31.0	28.0	0.3
T_1914-45	urban	S	31.0	28.0	33.0	29.0	2.0	31.0	28.0	0.2
2L_1946-59	urban	E	31.0	28.0	33.0	29.0	2.0	31.0	28.0	0.7
S_1914-45	urban	W	32.0	28.0	34.0	29.0	2.0	33.0	28.0	0.9
T_1914-45	urban	W	32.0	28.0	34.0	29.0	2.0	33.0	28.0	0.4
T_1914-45	rural	E	32.0	29.0	34.0	30.0	2.0	32.0	29.0	0.6
T_1902-13	rural	W	33.0	28.0	34.0	29.0	1.9	33.0	29.0	0.2
S_1914-45	rural	S	32.0	29.0	34.0	29.0	1.9	32.0	29.0	0.2
B_1914-45	urban	S	35.0	30.0	36.0	31.0	1.9	32.0	29.0	−2.1
T_1902-13	urban	W	32.0	28.0	34.0	29.0	1.9	32.0	28.0	0.3
T_1914-45	urban	E	31.0	28.0	33.0	29.0	1.9	31.0	29.0	0.6
S_1914-45	rural	E	32.0	29.0	34.0	30.0	1.9	32.0	29.0	0.4
T_1902-13	rural	S	31.0	28.0	33.0	29.0	1.9	31.0	28.0	0.2
T_1914-45	rural	N	30.0	28.0	32.0	28.0	1.9	31.0	28.0	0.7
T_1914-45	rural	W	33.0	29.0	35.0	29.0	1.8	34.0	29.0	0.9
2L_1946-59	rural	W	33.0	28.0	35.0	29.0	1.8	34.0	29.0	0.7
2L_1902-13	rural	W	32.0	28.0	34.0	29.0	1.8	32.0	28.0	0.1
2L_1946-59	urban	W	32.0	28.0	34.0	29.0	1.8	33.0	28.0	0.3
T_1902-13	urban	N	29.0	27.0	31.0	28.0	1.8	30.0	27.0	0.6
S_1914-45	rural	N	31.0	28.0	32.0	29.0	1.7	31.0	28.0	0.4
S_1914-45	urban	S	31.0	28.0	33.0	29.0	1.7	31.0	29.0	0.0
S_1914-45	urban	E	31.0	28.0	33.0	29.0	1.7	32.0	29.0	0.4
T_1902-13	urban	E	30.0	28.0	32.0	29.0	1.7	31.0	28.0	0.5
T_1914-45	urban	N	30.0	27.0	31.0	28.0	1.7	30.0	27.0	0.7
S_1914-45	rural	W	33.0	28.0	35.0	29.0	1.7	34.0	29.0	0.8
T_1902-13	rural	E	31.0	29.0	33.0	29.0	1.7	32.0	29.0	0.4
S_1914-45	urban	N	30.0	27.0	32.0	28.0	1.7	31.0	28.0	0.6
TT_1902-13	rural	N	30.0	27.0	31.0	28.0	1.6	30.0	27.0	0.4
2L_1946-59	rural	N	30.0	27.0	32.0	28.0	1.6	31.0	28.0	0.5
T_1902-13	urban	S	30.0	28.0	32.0	29.0	1.6	30.0	28.0	0.0

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