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Estimating the Influence of Housing Energy Efficiency and Overheating Adaptations on Heat-Related Mortality in the West Midlands, UK

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Received: 20 April 2018; Accepted: 15 May 2018; Published: 16 May 2018

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Abstract: Mortality rates rise during hot weather in England, and projected future increases in heatwave frequency and intensity require the development of heat protection measures such as the adaptation of housing to reduce indoor overheating. We apply a combined building physics and health model to dwellings in the West Midlands, UK, using an English Housing Survey (EHS)-derived stock model. Regional temperature exposures, heat-related mortality risk, and space heating energy consumption were estimated for 2030s, 2050s, and 2080s medium emissions climates prior to and following heat mitigating, energy-efficiency, and occupant behaviour adaptations. Risk variation across adaptations, dwellings, and occupant types were assessed. Indoor temperatures were greatest in converted flats, while heat mortality rates were highest in bungalows due to the occupant age profiles. Full energy efficiency retrofit reduced regional domestic space heating energy use by 26% but increased summertime heat mortality 3–4%, while reduced façade absorptance decreased heat mortality 12–15% but increased energy consumption by 4%. External shutters provided the largest reduction in heat mortality (37–43%), while closed windows caused a large increase in risk (29–64%). Ensuring adequate post-retrofit ventilation, targeted installation of shutters, and ensuring operable windows in dwellings with heat-vulnerable occupants may save energy and significantly reduce heat-related mortality.

Keywords: heat; mortality; adaptation; dwellings; indoor temperature

1. Introduction

In the UK, as in most settings, the risk of mortality increases during hot weather particularly among vulnerable groups such as the elderly [1]. In England and Wales, the heatwaves of 2003 and 2006 led to an estimated 2091 [2] and 680 [3] excess deaths, respectively. Warming temperatures and an increased frequency of extreme temperatures in the future [4], as well as an aging population, are likely to increase the importance of heat as a public health risk in the UK [5]. High temperatures may also lead to increases in population morbidity due to, for example, heat stress and heat exhaustion, kidney failure, and heart attacks [6].

As people in the UK spend the majority of their time indoors, housing is an important determinant of heat exposure and consequent heat-related mortality. A study of the 2003 heat wave in Paris found that living in top-floor flats and in poorly insulated homes were both associated with increased mortality risk [7]. Moreover, large-scale monitoring studies in the UK have suggested that certain housing types exhibit higher indoor temperatures, with flats generally being warmer than most other dwellings, and detached and solid-walled dwellings cooler [8,9]. Similar conclusions arise from modelling studies [10–12], which also indicate the potential effectiveness of adaptations such as shading, use of external shutters on windows, and using solar reflective coatings [13,14] while dwelling energy-efficiency may increase or decrease internal temperatures [10,11]. The Urban Heat Island (UHI) effect—where urban areas are significantly hotter than surrounding rural areas primarily due to the modification of land surfaces and waste heat—may exacerbate heat exposure during hot weather and increase heat mortality risk [15].

A number of studies have incorporated building overheating markers to predict heat exposure at the population-level. Dwelling characteristics and population demographics have been used to develop a heat risk index for London [16,17], while the same have been used alongside UHI data to identify vulnerable areas in Birmingham, UK [18,19]. Outside of the UK, housing, UHI, and population data have been combined in heat exposure studies in Melbourne, Australia [20], New York City [21], and across the U.S [22].

In the UK, modelled temperature exposures from dwellings and/or the UHI has been combined to estimate heat-related mortality in London, Sheffield, and the West Midlands. Taylor et al. [23] estimated the spatial variation in heat exposure using simulated UHI temperatures, and building physics models of indoor temperatures for individual dwellings in the London housing stock; an age-specific heat-mortality function was then used to estimate heat attributable mortality using underlying census population and age data. Liu et al. [24] also used building physics models of buildings, in combination with high resolution climate projections, to estimate the spatial variation in heat-related mortality risks across the city of Sheffield. Finally, modelled indoor temperatures were used to estimate the changes in population mortality in the West Midlands, UK, prior to and following a number of different energy-efficiency and overheating adaptations to dwellings and the built environment [25].

Using the underlying indoor temperature and health model described in Taylor et al. [25], this paper aims to explore the variation in heat mortality risk across building types in the West Midlands region of the UK, based on dwelling indoor overheating risks and occupant characteristics. The effects of energy efficiency (including wall, floor, or roof insulation, and full retrofit), behavioural (window-opening), and heat adaptations (external shutters and low absorptance surface coatings) on heat exposure, mortality, and energy use are explored. In addition, the reduction in mortality through more realistic implementation of adaptations targeted at dwellings or residents is also examined.

2. Methods

2.1. Building Modelling

The West Midlands region has a population of 5.6 million [26], and contains Birmingham, the second-most populous urban area in the UK. During the 2003 heatwave, the region had an estimated 130 excess deaths due to hot weather [2].

The baseline housing stock and population model is the 2010–2011 English Housing Survey (EHS), which contains regionally-representative housing and occupant data for 1558 dwellings in the West Midlands [27]. Resident age data is available within the database for each dwelling occupant. Data within the EHS is used to inform the geometry, floor area, glazing area, construction type, and insulation levels of each dwelling, while the energy efficiency and airtightness of each dwelling has been estimated using standardised methods [28].

Readers are referred to Symonds et al. (2016) for further information on the indoor temperature model. Briefly, indoor temperatures and energy use for space heating in the West Midlands housing stock were estimated using a series of metamodels derived from the results of simulation studies [29,30] using the building physics model EnergyPlus. Previous studies have compared the underlying EnergyPlus model outputs against a large dataset of monitored indoor temperatures, showing that the model is able to capture the trends in overheating risk between dwelling variants [30]. Here, the model is adapted to model dwellings with and without energy efficiency, occupant behavior, and passive overheating interventions. Air conditioners (A/C) were not modelled due to their rarity in English housing stock—estimated at 3% of dwellings [31]—and because of their high energy demands.

Metamodels were developed for each combination of dwelling geometry (end terrace, mid-terrace, semidetached, detached, bungalow, converted flats, low-rise flats, and high-rise flats), wall type (cavity or solid), and heat adaptation (shutters or no shutters). For each combination of the above, EnergyPlus models were developed with fabric energy efficiency levels, permeability, floor area, glazing area, and local wind exposure randomly sampled from distributions available from representative samples [27,32] of English dwellings. For this study, roof and wall absorptance was also randomly selected in the range of 0.1–0.6, representing the painting of external surfaces with a low absorptance paint; the indoor temperature threshold above which windows are opened were also randomly selected (18 °C–35 °C) to represent extreme ranges in occupant behaviour. Archetypes, used to represent dwelling geometries, can be seen in Appendix A. Models were run using Test Reference Year weather data, representing the "average" climate for 2030 under a medium emission scenario (A1B-50th percentile) [33], assumed to be representative for the region.

From the results of these simulations, we computed the mean maximum daytime living room temperature at different two-day rolling mean maximum outdoor summer temperatures, as well as annual energy use (kWh) for space heating. A metamodel was then generated using artificial neural networks [34] to determine energy use and indoor temperatures from dwelling characteristics across the West Midlands housing stock. The metamodel was applied to obtain indoor temperature and energy use estimates for individual dwellings in the West Midlands under the adaptation scenarios in Table 1, using weather data that describes "average" Birmingham summers in 2030s, 2050s, and 2080s (A1B-medium emissions scenario, 90% probability [4,33]).

Table 1. The adaptations and underlying assumptions modelled. The reduction in fabric U-value is based on the UK Government's Standard Assessment Procedure (SAP) for Energy Rating of Dwellings, with the lowest possible U-value for the fabric component selected based on the fabric type and dwelling age [35]. The change in permeability is estimated based on the work by [a] Hong et al. [36] or [b] UK SAP, following the methods described by Hamilton et al. [37].

	Adaptation	Details
Energy Efficiency	Cavity wall insulation (CWI)	All cavity walls are modelled as insulated, reducing wall U-value, and the infiltration rate in previously uninsulated dwellings reduced by 0.2 air changes per hour (ach) [a]
	Internal solid wall insulation (SWI)	All solid walls are modelled as internally insulated, reducing wall U-value, and the infiltration rate in previously uninsulated dwellings reduced by 0.3 ach [a]
	Floor insulation (FI)	All floors are modelled as insulated, reducing floor U-value, and the infiltration rate in previously uninsulated dwellings reduced by 0.1 ach [b]
	Loft insulation (LI)	All lofts are modelled as insulated, reducing loft U-value, and the infiltration rate in previously uninsulated dwellings reduced by 0.1 ach [a]
	Full Retrofit	A full retrofit (floors, loft, walls, and triple-glazed windows) is modelled, with reductions in U-value as above and the infiltration rate reduced by 0.7 ach to a Building Regulations minimum permeability of 3 $m^3/h/m^2$
Heat Adaptation	Shutters	External shutters are closed daily between 9 a.m. and 6 p.m. during the summer
	Absorptance	The solar absorptance of the building façade is reduced from 0.7 to 0.1

Table 1. *Cont.*

	Adaptation	Details
Occupant Behaviour	Windows Open	Windows are opened when indoor temperatures exceed 18 °C during summer, representing a scenario were windows are continuously open
	Windows Closed	Windows are opened when indoor temperatures exceed 35 °C, representing a scenario were windows are continuously closed

2.2. Mortality Calculations

Household weighting values in the EHS were used to estimate the mean and distribution of occupant temperature exposures across the West Midlands housing stock. As there is no spatial information for the EHS, we assume the modelled households have equal distributions of UHI temperature exposures. From this, a dwelling-specific indoor temperature anomaly relative to the regional population-weighted mean was calculated:

$$T^*_{max,k,d} = T_{max,out,d} + T_{Indoor\ Anomaly,k,d} \tag{1}$$

where $T_{max,out,d}$ is the two-day rolling mean maximum outdoor temperature for day d; $T_{Indoor\ Anomaly,k,d}$ is a positive or negative temperature anomaly representing the deviation in estimated two-day rolling mean maximum indoor temperature for dwelling k from the population-mean rolling maximum indoor temperature on day d for the West Midlands; and $T^*_{max,k,d}$ is the temperature to which occupants are exposed on day d in household k. For adaptation scenarios, anomalies were calculated relative to the mean of the unadapted stock.

Calculations of heat-related mortality were based on applying region-specific temperature-mortality functions for the West Midlands to the EHS occupant age data and corresponding estimated dwelling indoor temperatures. Heat-associated mortality is described in terms of Relative Risk (RR), or the ratio of the probability of mortality occurring in a heat-exposed group to the probability of mortality in an unexposed group. The all-age heat-mortality RR for the West Midlands was derived from Armstrong et al. [38] from which age-specific (0–64, 65–74, 75–84, 85+) temperature-mortality slopes were derived using the age-specific RRs for England and Wales published by Gasparrini et al. [1]. The underlying age-specific all-cause mortality rates by season were obtained from the Office for National Statistics (ONS); here we adjust these to reflect summer rates. Dwelling-specific heat mortality was then calculated as:

$$D_{k,d} = \sum_i \left[occupants_{i,k} \times deathrate_i \times \left(RR_{heat,i}{}^{(T^*_{max,k,d} - 23\ ^\circ\mathrm{C})} - 1 \right) \right] \tag{2}$$

where $occupants_{i,k}$ is the number of individuals of age-group i in dwelling k; $deathrate_i$ is the summertime daily mortality rate per person for age-group i; $RR_{heat,i}$ is the relative risk (RR) of mortality due to temperature for age group i; and 23 °C is the estimated regional heat mortality threshold for the West Midlands [38]. Readers are referred to Taylor et al. [25] for a detailed description of mortality calculations.

3. Results

3.1. Heat Exposure across Dwelling Variants

The average living room temperatures across a range of dwelling variants when $T_{max,out,d}$ exceeds 23 °C during the 2030s summer can be seen in Figure 1. Certain dwelling variants are hotter than others, including mid-terraced dwellings and flats. Multiple distributions are provided for flats to represent the different floor levels of the flats within the buildings. Buildings with higher indoor temperatures were also found to exceed the 23 °C temperature threshold more regularly during hot weather, with the coolest dwellings exceeding it 39 times and the hottest exceeding it 101 times during the 123 days of summer, 2030s (median 69 days). The sample size for each dwelling variant within the EHS is also shown.

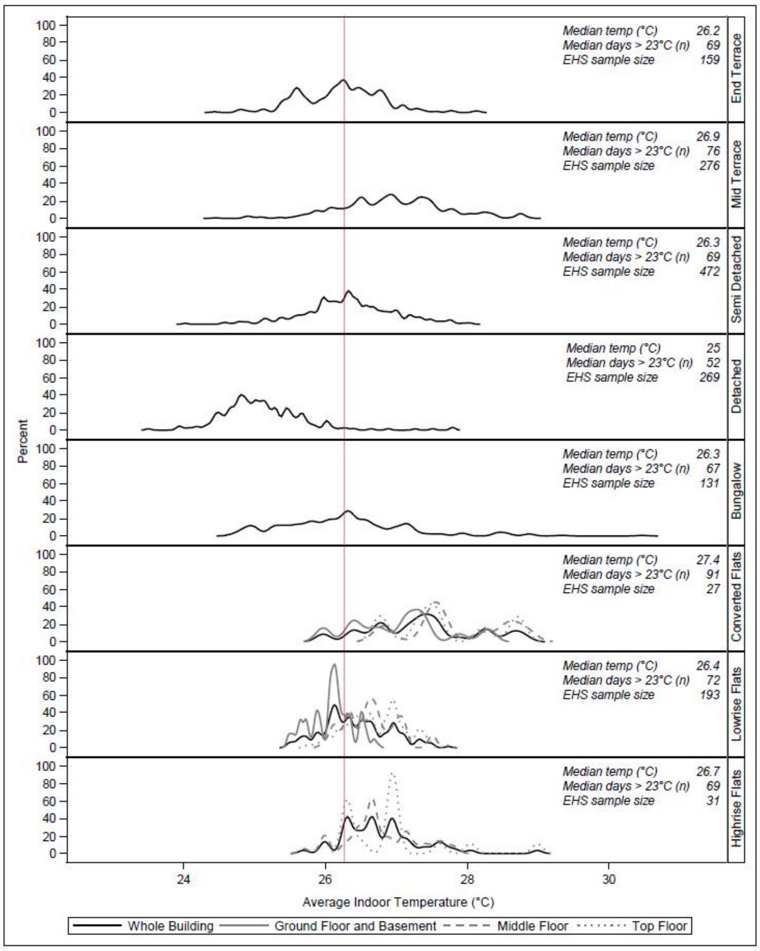

Figure 1. Density plots of the average indoor temperature when $T_{max,out,d}$ exceeds 23 °C during the 2030 summer. The red vertical line shows the median for the stock. There is a lack of data for ground-floor high-rise flats, and so these are not shown. English Housing Survey (EHS).

3.2. Housing Adaptations and Heat Exposure

The distribution of average indoor temperature exposures for a 2030s summer when $T_{max,out,d}$ exceeds 23 °C can be seen in Figure 2, before and after various energy efficiency, heat mitigating, and behavioural adaptations. Individual energy efficiency retrofits generally do not lead to a significant increase in temperature exposure, with the exception of internal solid wall insulation which causes a median temperature increase of 0.1 °C (range: −0.4 to 0.9 °C) in solid-walled dwellings. While individual fabric interventions to not lead to a significant increase in median temperatures, the cumulative effects of different energy efficiency interventions on permeability is reflected in an increase following the full retrofit of all buildings in the stock (median 0.2 °C, range: −1.0–1.7 °C). Full retrofit is predicted to reduce 2030s energy use by 25.5% relative to the current stock, and individual retrofits show comparatively more modest reductions in energy use for space heating. This energy saving is due to reduced ventilative and fabric heat losses only, as changes to heating systems are not modelled. Shutters are able to significantly reduce indoor temperature exposure across the stock (median: −1.4 °C, range: −4.1–0.2 °C), and lead to a small increase in space heating energy consumption as the absence of solar gains means heating is occasionally required to meet setpoint temperatures.

Decreasing the surface absorptance of the external surfaces led to a smaller reduction (median: −0.5 °C, range: −1.5 °C–0.6 °C) as well as an increase in space heating energy use of 4.1% during the 2030 heating season (September–May). Regarding occupant behaviours, keeping windows open when internal temperatures exceed 18 °C had a modest impact on reducing temperatures compared to the threshold of 22 °C modelled in the 'current' stock (median: −0.4 °C, range: −1.1–0.3 °C). The largest risk-factor for heat exposure is keeping windows closed at all times (median 1.4 °C, range: 0.1–3.4 °C).

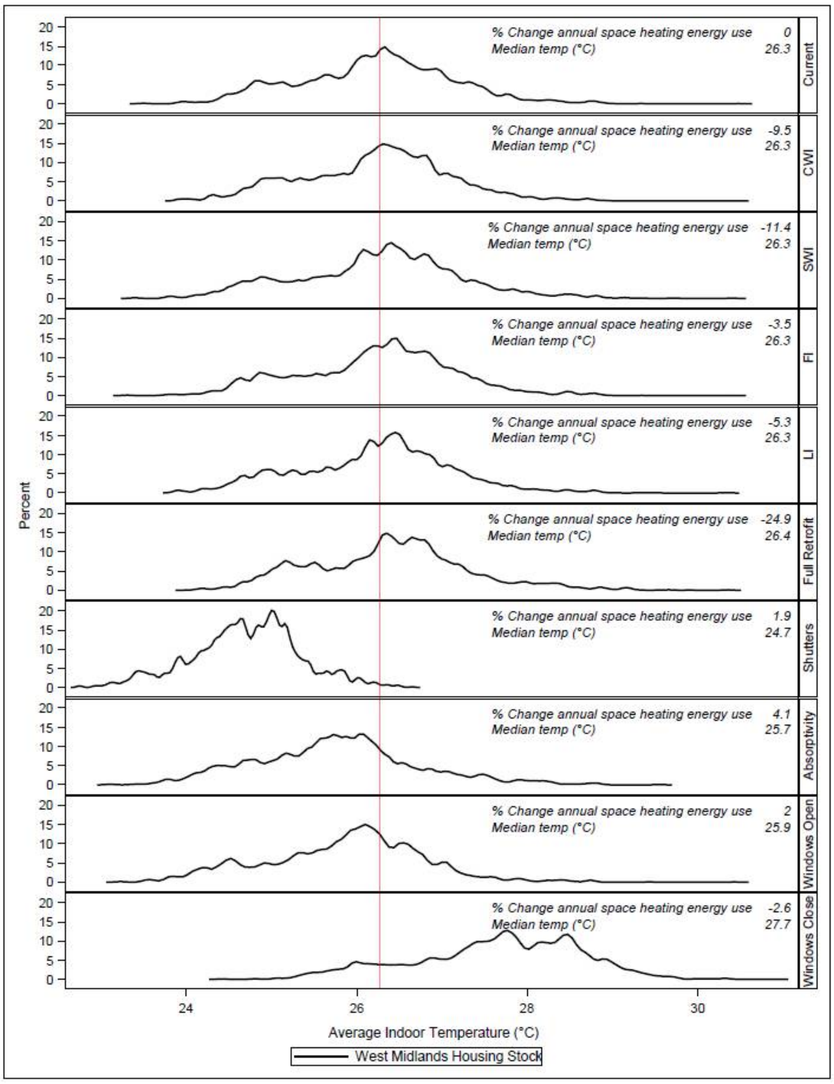

Figure 2. Density plots of the average indoor temperature when $T_{max,out,d}$ exceeds 23 °C during the 2030 summer following energy efficiency, heat, and behavioural adaptations. The red vertical line shows the median for the current (unadapted) stock (26.3 °C).

3.3. Mortality across Dwelling Variants

Analysis of the West Midlands population by age group and dwelling type in the West Midlands from the EHS can be seen in Table 2. A higher proportion of elderly occupants inhabit bungalows and converted flats, while more young individuals live in purpose-built flats and terraced dwellings. The mortality rate per million occupants of each dwelling type at increasing temperatures shows how the relative heat mortality risk varies by dwelling variant (Figure 3A). The rate of increase reflects the housing overheating characteristics and the age profiles of the occupant population. Bungalows show the greatest rate increase in mortality risk with increasing outdoor temperatures, followed by converted and low-rise flats. The different age profiles in dwelling types and their variation in indoor temperatures are reflected in the absolute estimated mortality and risk of mortality across variants. The largest predicted mortality under increasing temperatures were residents of houses rather than flats, primarily semi-detached dwellings, followed by bungalows and detached properties (Figure 3B). This is due to semi-detached and detached properties housing the largest number of individuals in the West Midlands population (34% and 21%, respectively), while the age effects of the occupant population play a significant role in bungalows despite their moderate indoor overheating risk and relative infrequency in the housing stock (5.5%). The mortality in flats was predicted to represent only a small fraction of overall mortality, also due to their infrequency across the West Midlands housing stock.

Table 2. Dwelling type by percent of residents within each age group, West Midlands.

Dwelling Type	Age Group				
	0–64	65–74	75–85	85+	TOTAL
End Terrace	88.3%	7.8%	3.3%	0.6%	541,917
Mid Terrace	91.7%	3.7%	3.8%	0.9%	1,060,700
Semi Detached	85.3%	8.7%	5.6%	0.7%	1,826,175
Detached	83.0%	10.3%	5.8%	0.9%	1,145,396
Bungalow	42.5%	28.1%	22.3%	7.1%	297,168
Converted Flat	78.6%	11.2%	8.0%	2.1%	56,047
Low-rise Flat	83.3%	9.0%	6.1%	1.7%	366,618
High-rise Flat	88.1%	4.8%	7.1%	0.0%	65,942
TOTAL	4,495,026	484,724	325,129	64,301	5,359,963

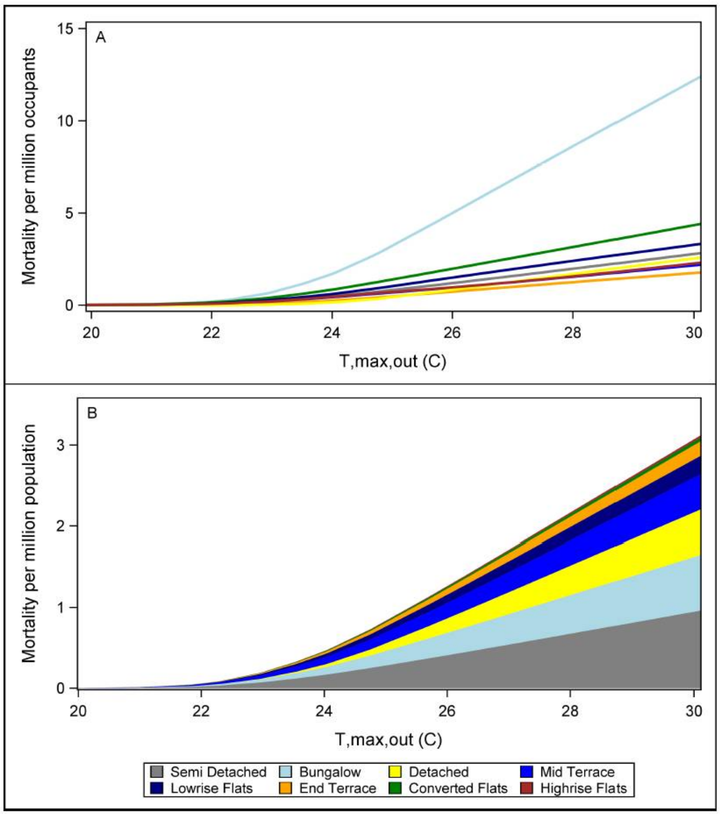

Figure 3. (**A**) The mortality per million occupants per day of each dwelling type at increasing outdoor temperatures; (**B**) The mortality per million population per day in the West Midlands at increasing outdoor temperatures, stacked by dwelling variant.

At the population level, appreciable risk of heat mortality (here defined as 100 per million occupants) under 2030s conditions exists only in 15% of the population, with risks increasing with age band (Figure 4). The wide range of risk within each age group is attributable to indoor temperature exposures, with the differences between the coolest and hottest dwellings causing a fivefold increase in mortality risk amongst the 75–84 age group, and a fourfold increase in those over 85.

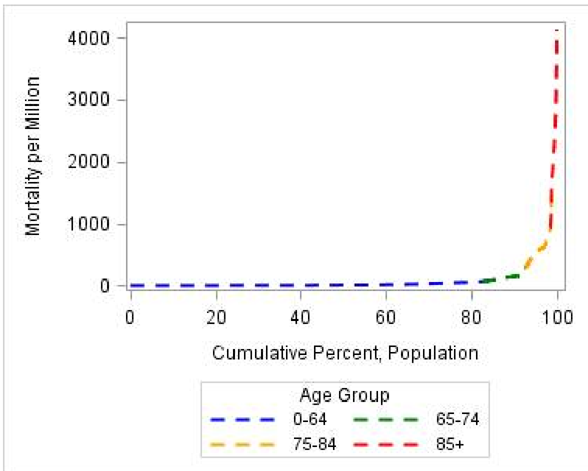

Figure 4. The heat-related mortality risk per million population for summer 2030, by cumulative population percent and age classification.

3.4. Housing Stock Adaptation and Mortality

The estimated mortality of occupants in the current stock under typical 2030s, 2050s, and 2080s climates, and following a range of adaptations, can be seen in Table 3. Individually, energy efficiency adaptations did not cause significant changes in heat mortality relative to the current stock, apart from loft insulation which reduced mortality. Full retrofit led to a small increase in heat mortality risk (2.5–4.4%), driven primarily by the increased indoor temperatures associated with internal solid wall insulation and the cumulative reduction in permeability that restricts ventilation and convective heat dissipation. Any small increase in summertime heat-related mortality from full retrofit is likely to be offset by a much larger reduction in winter mortality due to warmer housing, as well as benefits from the significant energy savings for space heating.

Of the modelled heat-mitigation scenarios, installation of external shutters was the most effective, causing an estimated reduction in heat-related mortality of 43%, 40%, and 37% in weather conditions representative of typical 2030s, 2050s, and 2080s summers, respectively, while reducing absorptance was less effective (15%, 14%, and 12%). Of the occupant behaviours modelled, reducing the window opening threshold to 18 °C had only modest reduction in heat mortality risk (6–10%), while keeping windows closed led to a substantial increase in population heat mortality risk of 29–64%. The significant increase in risk associated with closed windows indicates that occupant behaviour or housing where windows cannot be opened due to inadequate windows, outdoor pollution, crime, or noise-may be the single largest modifier of indoor heat exposure and consequent heat-related mortality risk.

Targeted interventions were assessed to determine how population heat-related mortality might decrease under more realistic levels of adaptation. Installing shutters in properties with residents over the age of 85 (2.8% of the stock) decreased heat-related mortality risk by 5–9% (Scenario 1), while installing them in the 12.1% of dwellings with residents over 75 decreased heat-related mortality risk by 28–33% (Scenario 2). It may not be straightforward to install shutters on certain dwellings (e.g., high-rise flats), or there may be local regulations that prevent changes to the external façade (e.g., listed buildings, assumed here to be all buildings built prior to 1918). Installation of shutters in all buildings, excluding these, is estimated to reduce population heat-related mortality by 32–38% (Scenario 3).

Table 3. The estimated heat-related mortality per million population in the West Midlands prior to and following adaptation.

	Mortality Per Million (Percent Change from Unadapted Stock)					
Adaptation	***2030***		***2050***		***2080***	
Current	***93***		***126***		***194***	
Adaptation-Energy						
CWI	***93***	*(0%)*	***126***	*(0%)*	***194***	*(0%)*
SWI	***93***	*(0%)*	***126***	*(0%)*	***194***	*(0%)*
FI	***93***	*(0%)*	***126***	*(0%)*	***194***	*(0%)*
LI	***92***	*(−0.6%)*	***126***	*(0%)*	***193***	*(−0.6%)*
Full Retrofit	***97***	*(4.4%)*	***131***	*(3.5%)*	***199***	*(2.5%)*
Adaptation–Heat						
Shutters	***53***	*(−42.9%)*	***76***	*(−39.9%)*	***122***	*(−36.9%)*
Absorptivity	***78***	*(−15.3%)*	***108***	*(−14.2%)*	***170***	*(−12.4%)*
Adaptation-Behaviour						
Windows Open	***83***	*(−10.1%)*	***116***	*(−8.1%)*	***182***	*(−5.9%)*
Windows Closed	***151***	*(63.5%)*	***184***	*(45.9%)*	***249***	*(28.7%)*
Targeted Intervention						
Scenario 1	***85***	*(−8.5%)*	***117***	*(−7.3%)*	***184***	*(−4.8%)*
Scenario 2	***62***	*(−32.7%)*	***88***	*(−30.3%)*	***139***	*(−28.1%)*
Scenario 3	***58***	*(−37.5%)*	***82***	*(−34.8%)*	***131***	*(−32.2%)*

3.5. Mortality across Adapted Dwelling Variants

Figure 5 shows the variation in mean heat mortality risk by dwelling, occupant age group, and heat mitigating (shutters) or deleterious behaviour (windows closed). The greatest risk is estimated in those aged over 85 living in mid terraced dwellings. Bungalows, which showed a rapid increase in mortality with increasing temperatures, have a relatively low rate of mortality within each age category. This low rate of mortality is due to the modest temperatures within the modelled bungalows, while the rapid rise in mortality per thousand occupants is due to bungalows being homes to the largest proportion of elderly in the West Midlands. The dwelling types do not show a consistent order of risk within each age classification due to the variation in the fabric and geometry characteristics of the dwellings.

Heat mitigating (shutters) or deleterious behaviour (windows closed) (Figure 5) also has a significant impact on mortality risk, varying by dwelling and occupant vulnerability. In most cases, application of shutters greatly reduces the risk of heat mortality in dwellings with vulnerable occupants. For those aged over 85, shutters led to a median reduction of 40% mortality risk, with a range of 37–78%, while for those between 75 and 85 the median reduction was 59% (range: 37–90%). Shutters were less effective in ground floor flats and dwellings with low glazing areas. Leaving windows closed led to a median increase in risk for occupants over 85 of 164% (range: 130–219%), and a median increase of 164% (range: 119–257%) for those between 75 and 85.

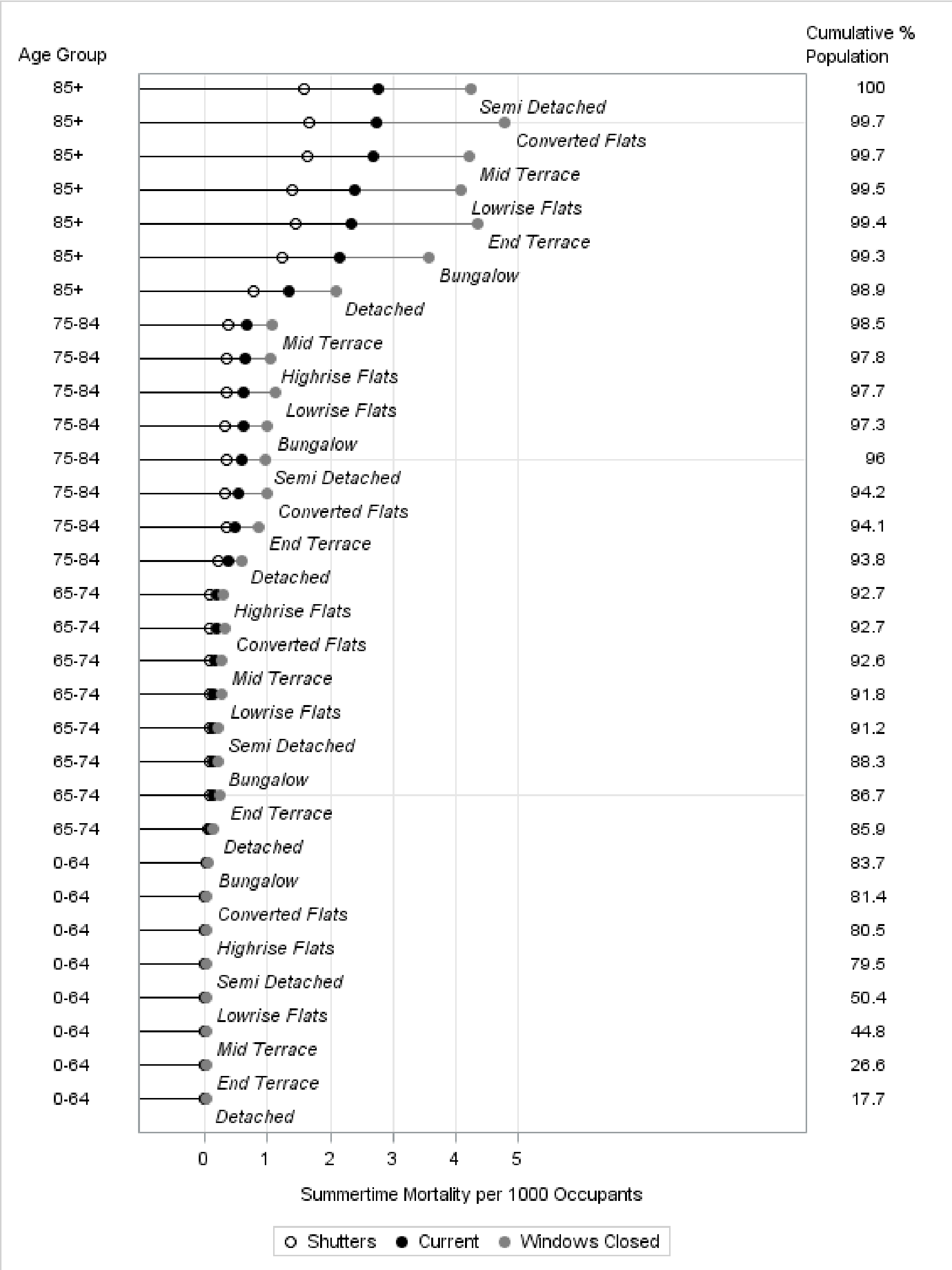

Figure 5. The median mortality per 1000 occupants over the 2030 summer by occupant age classification and dwelling type for the current stock, and with shutters or windows closed. The cumulative frequency of each age class/dwelling variant is shown on the secondary axis.

4. Discussion and Conclusions

With a changing climate and aging population, there is an urgent need to identify ways to mitigate against heat exposure without increasing greenhouse gas emissions in order to reduce population heat mortality. There is, however, little empirical evidence to help identify the best solution with respect to population heat mortality and energy consumption. We have described the application of a heat risk model to the housing stock and population of the West Midlands, UK, and estimated how adaptations to the housing stock may alter the risk of heat-related mortality. Modelled indoor temperatures showed a wide variation across different dwelling variants, indicating that housing type is a significant modifier of heat exposure risk during hot weather. Certain dwelling variants, such as flats, mid terraced houses, and bungalows were found to be at elevated risk of high indoor temperatures. Heat-related adaptations to dwellings showed decreases in indoor temperatures in line with previous modelling studies on overheating in housing [13,14], while changes to indoor temperatures following energy efficiency adaptations also reflect those from previous modelling studies [11,12].

The application of the mortality model to the indoor temperature estimates indicates that building adaptations have the potential to alter the mortality of building occupants during warm and hot weather. The most effective adaptation to reduce heat-related health effects was using external shutters during the daytime, which was able to reduce heat-related mortality by over 43% under the 2030, 40% under 2050, and 37% under 2080 summer weather scenarios. Reducing the absorptance of the external façade led to a more modest reduction in estimated mortality of 12%, 14%, and 15% under the same climate scenarios, but with the unintended consequence of increasing 2030 winter space heating energy consumption by 4%. These results therefore indicate that external shutters are a more effective and efficient means of reducing internal temperature exposure during summer months.

Full retrofits led to a small increase in overheating risk and heat mortality, driven primarily by internal solid walled insulation and reductions in ventilation due to decreased permeability. The impacts of energy efficiency improvements on energy use for space heating were significant, particularly following the whole-building retrofit. It should be noted that, while these adaptations may marginally increase risks during hot weather, they may significantly reduce mortality risks during cold weather [39]. Cold weather is currently associated with a much higher burden of mortality than hot weather in the UK, and while heat-related mortality is predicted to increase in the future due to climate change, cold-related mortality is expected to remain the greater risk [5,40]. Consequently, modest increases in heat-related risks should not discourage the installation of energy-efficient retrofits, but retrofits should ensure adequate ventilation and in certain cases would be best done in conjunction with adaptations to reduce overheating risk.

While individual dwelling variants showed a range of indoor temperatures, occupant age was the largest risk factor for heat mortality. Targeted interventions found that installation of shutters in dwellings with vulnerable elderly occupants could significantly reduce summertime mortality risk, by 5–33% while only requiring adaptation of 3–12% of the housing stock. Similarly, the scenario where windows are closed increased heat-related mortality risk by as much as 260% in certain dwellings amongst the elderly, and so interventions should also ensure that windows are openable and operable by occupants and that support is provided at a community level for heat vulnerable or low mobility individuals. Housing interventions offer an advantage over local built environment adaptations such as urban greening, in that they may be targeted specifically at the homes of the most vulnerable with lower financial costs. Based on the results, future policies may wish to encourage energy-efficient retrofits in parallel with adaptations to prevent overheating, prioritise the installation of external shutters in dwellings with vulnerable, elderly occupants, and to ensure that the vulnerable can adequately ventilate their houses during hot weather.

There were a number of assumptions necessary in the building physics modelling. We assume a complete implementation of adaptations in either the whole or targeted stock. In the case of shutters, it is assumed that they are functional and closed throughout the day. In reality, this is unlikely to be the case: it may not be possible to install operable shutters in all dwellings, and occupant shutter closing behaviour is likely to have a similar broad range as window-opening behaviours. Amongst the most vulnerable, those currently unable to open windows due to mobility issues will also likely to be unable to operate shutters. We have not modelled active heat adaptations such as Air Conditioning (A/C), as they require significant energy expenditure and should be discouraged, and because we assume perfect installation and operation across the housing stock would reduce heat mortality to very low levels. Energy saving calculations from retrofits are presented as an indicator of the maximum potential energy savings, and do not account for occupant 'take-back', where occupants opt for increased thermal comfort rather than the energy savings provided by such adaptations.

The application of the mortality model also has limitations which should be acknowledged. We assume heat exposure occurs in the home. While it is likely much of the population will be out during the day, mortality is dominated by deaths among the more vulnerable groups, who are more likely to spend the day at home. We also assume that the Armstrong heat-mortality risk function—derived using outdoor temperatures—applies to exposures in the indoor environment, a necessary assumption due to a lack of direct evidence on indoor temperatures and mortality. We do not include local variations in outdoor temperature from Urban Heat Island effects in the model due to the lack of spatial information in the EHS, however previous studies have estimated that the UHI leads to an increase of 21–50% in heat-related mortality during hot weather in the West Midlands [15,25]. We therefore assumed that all dwelling variants and occupant age groups have equivalent exposures to elevated UHI temperatures, which may not be the case [19]. Modelled dwelling adaptations, such as white roofs, may themselves affect the UHI. Some dwelling variants, particularly high-rise and converted flats, have small sample sizes (Figure 1), while the sample of these dwelling variants with occupants over 85 is smaller still. This means that mortality estimates for elderly occupants is subject to a large amount of uncertainty due to limited data on building characteristics.

The results highlight the importance of shading and adequate ventilation in housing as temperatures increase, and that targeted adaptation of vulnerable dwellings can reduce summertime heat mortality risk without needing to adapt a large proportion of the existing stock. Adaptations to buildings should be performed in conjunction with other public health measures, such as providing public cool spaces, heatwave advice, and UHI mitigation, while active adaptations such as A/C should be discouraged as this may increase energy consumption. While this study has focused on the West Midlands, UK, the results can provide insight into potential heat exposure, mitigation, and mortality risk in other temperate regions with housing stocks dominated by naturally-ventilated, older dwellings. Areas with large or increasing elderly populations may be at greater risk of heat mortality effects during hot weather. Studies have shown the existence of heat-mortality relationships worldwide [41], and while the threshold and age-specific slope of this relationship may vary internationally, there are opportunities to passively modify housing in order to reduce heat exposure and subsequent heat mortality. While we have estimated mortality—and reductions in heat mortality—under future climate scenarios, we have not accounted for population aging, adaptation to heat, nor any transformation of the housing stock due to demolition and construction. Future research could refine the model to enable predictions of future mortality under a range of climate, population, and adaptation scenarios. In addition, the model will be applied nationally, and using spatially-varying housing data and local air temperatures which include the urban heat island effect.

Author Contributions: J.T. performed the modelling, results analysis, and lead the writing of the paper. P.S., J.T., and A.M. developed the underlying building physics model, while P.W. developed the means of linking indoor temperature exposures to health outcomes. Funding was obtained by P.W. and M.D. All authors contributed to the writing the manuscript.

Acknowledgments: The research was funded by the National Institute for Health Research Health Protection Research Unit (NIHR HPRU) in Environmental Change and Health at the London School of Hygiene and Tropical Medicine in partnership with Public Health England (PHE), and in collaboration with the University of Exeter, University College London, and the Met Office. The views expressed are those of the author(s) and not necessarily those of the NHS, the NIHR, the Department of Health or Public Health England.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

Appendix A

Figure A1. *Cont.*

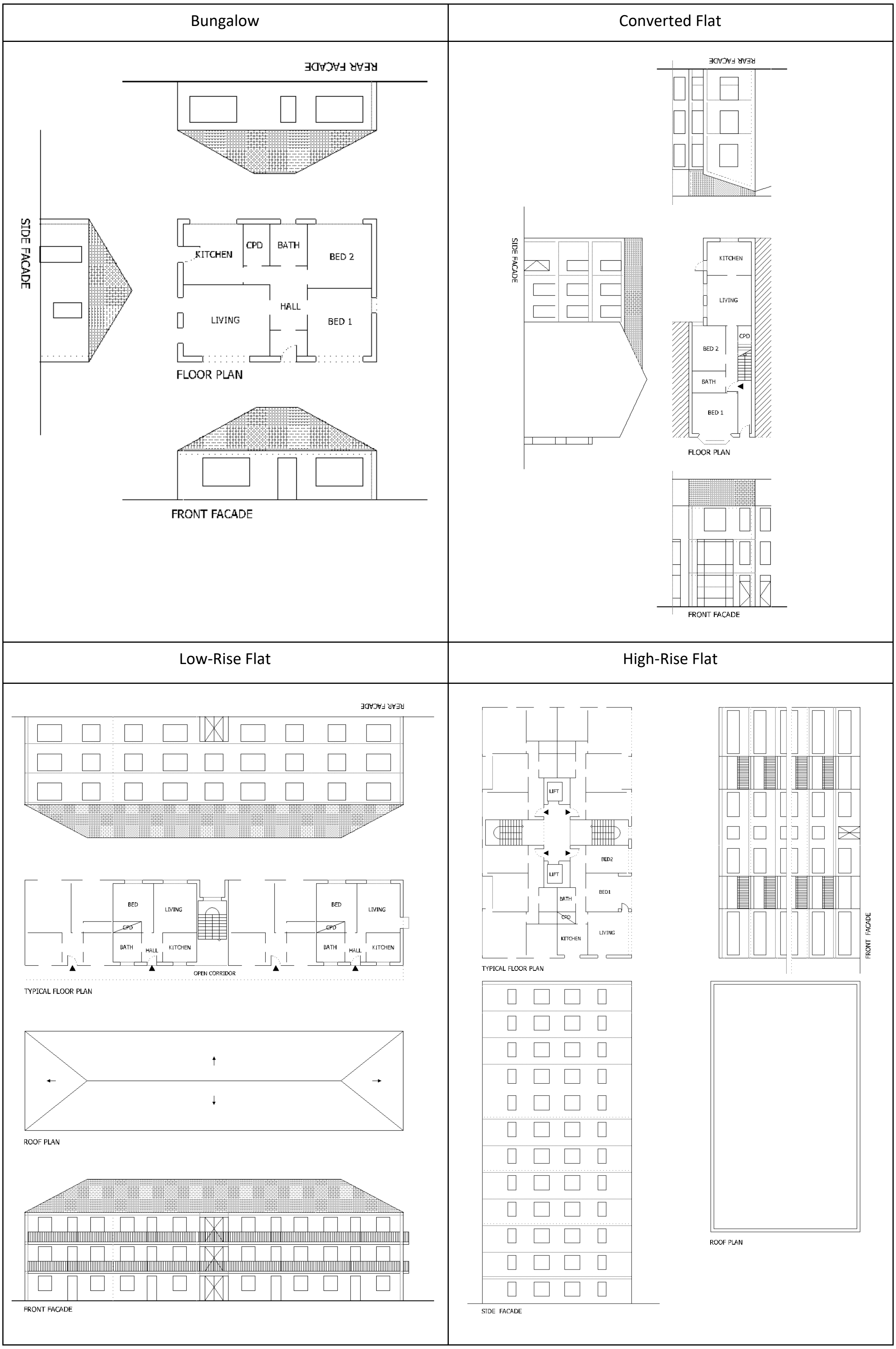

Figure A1. Building Geometries.

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