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Assessment of interventions to reduce dwelling overheating during heat waves considering annual energy use and cost

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Abstract

Climate change projections indicate that the UK is expected to experience more frequent and more intense heat wave periods over the coming decades. Buildings frequently experience overheating even under the present climate, resulting in discomfort, health complaints and even mortality. Current house building rates are low, resulting in a need to adapt the existing building stock to provide more comfortable and safe environments.

Dynamic thermal simulation computer modelling was used to assess and rank the effectiveness of selected single and combined interventions (adaptations) in reducing overheating during a heat wave period for a range of dwelling types, orientations and occupancy profiles. It is shown that solar protection interventions, such as window shutters and solar reflective coatings, can be amongst the most effective at reducing overheating during heat wave periods, but with a corresponding increase in annual space heating energy use. Whereas the addition of wall insulation, though beneficial for reducing energy use, may in some cases actually increase summer overheating.

The results and guidance are presented in a way that allows identification of parts of the building stock most at risk and rapid selection of the best performing interventions in terms of overheating reduction, cost and annual energy use. It is also shown that above certain cost levels there is a diminishing return in both overheating performance and energy use reduction.

The results of this research will provide important information to support refurbishment decisions of both individual house owners and landlords responsible for multiple properties, such as housing associations and local authorities.

Keywords Heat wave; housing; overheating; adaptation; building simulation

1 Introduction

The emphasis on UK dwelling refurbishment to date has concentrated on reducing energy use and CO₂ emissions during the heating season. However, climate change projections [1] predict an increase in both the frequency and severity of extreme weather events. These include heat waves, such as the one in August 2003, which resulted in the deaths of more than 35,000 people around Europe, over 2,000 of which were in the UK [2]. Future retrofit planning therefore needs to take account of not only winter thermal performance, but also reducing summer overheating to provide a safe and comfortable environment in a changing climate, for which detailed quantitative advice is required.

The Chartered Institute of Building Services Engineers (CIBSE) addresses specifically the impact of climate change on the indoor environment in both Guide A [3] and report TM36 [4]. In TM36 they considered occupied hours over the CIBSE comfort threshold temperatures of 28°C for living areas and 26°C for bedrooms for selected dwellings. Combined building interventions were modelled over a whole summer for each case, using predicted future climate scenarios. For each dwelling type in the report only one building orientation was considered and one occupancy profile was used – in each case leaving the dwellings unoccupied during daytime hours. Consideration of different occupancy types is also absent in other publications, including a technical report by the Energy Saving Trust [5], which suggests useful advice for designers, and a report by Arup for the Three Regions Climate Change Group [6]. The Arup report suggests interventions that may be retrofitted as well as design options for new build, such as higher thermal mass construction methods.

The research presented here expands on this previous published work by quantifying the effect of a range of single and combined interventions during the heat wave period in August 2003. The term *interventions* covers both behavioural changes, such as modifying ventilation strategies, and a range of physical additions or adaptations to the building fabric. Lessons can be learnt from the way that many Southern European dwellings are constructed to cope with current climates similar to those we can expect in the UK later this century. Some of the features (Figure 1) can only be considered for new developments, for example narrow streets for building shading. However other design features, such as light walls, shutters and fixed shading, can be considered as retrofit options suitable for the UK.

Figure 1. Mediterranean dwelling features (Marbella, Spain)

Table 1 summarises the interventions applied in this research split into three categories: insulation, solar control and ventilation. Not all interventions apply to all dwelling types, for example houses with solid brick walls cannot have cavity wall insulation and it would be difficult to justify insulation upgrades for a modern well-insulated house, so they have not been considered. There may be other obstacles in the form of planning constraints, which could limit the range of potential interventions that change the external appearance. Cost may also be a limiting factor for the uptake of some interventions and is addressed later (Section 3.3).

Category	Intervention	19thC Terraced	1930s Semi- detached	1960s Flats	Modern Detached
Insulation	Increase loft insulation	X	X		
	Upgrade flat roof			X	
	External wall insulation	X	X	X	
	Internal wall insulation	X	X	X	
	Cavity wall insulation		X	X	
Solar Control	Reflective internal window blinds, daytime closed	X	X	X	X
	External window shutters, daytime closed	X	X	X	X
	Curtains, daytime closed	X	X	X	X
	External shading above south, east and west-facing windows	X	X	X	X
	Coat all external walls with high performance solar reflective paint	X	X	X	X
	Coat roof tiles/surfaces with high performance solar reflective paint	X	X	X	X
	Replace existing glazing with low-e triple glazing	X	X	X	X
Ventilation	Night ventilation: allow ground floor ventilation with outside air at night	X	X	X	X
	Window rules: prevent window opening if outside air is warmer than inside air	X	X	X	X

Table 1. Interventions modelled on the respective house types (details in Table 3)

2 Methodology

The advent of faster processors and parallel processing has made it possible to perform large-scale parametric simulation studies within a reasonable timescale. This research compares the effectiveness of a range of single and combined interventions on selected dwelling types, assuming different site orientations and occupancy profiles. The simulations were carried out using EnergyPlus dynamic thermal simulation software, developed by the US Department of Energy [7] and validated through the IEA BESTest building load and HVAC tests [8]. One of the main advantages of choosing EnergyPlus was the ability to use a java based parametric control interface (jEPlus [9]) to control the large number of parametric simulations.

2.1 Dwelling types and simulation settings

Figure 2. Simulation models

South East England is the UK region predicted to be at greatest risk of future summer overheating. Four dwelling types (Figure 2), typical of London and South East England, were selected to represent a range of construction methods and ages by using data from the English House Condition Survey (EHCS) [10]. This data was cross-referenced with data from the Energy Saving Trust's Homes Energy Efficiency Database (HEED)[11] to determine the most representative construction, glazing and insulation settings for each dwelling type (Table 2).

	19thC Terraced	1930s Semi-detached	1960s Flats	Modern Detached
External walls	Solid brick	Brick cavity uninsulated	Brick/block cavity uninsulated,	Brick/block cavity insulated
Wall U-Value (W/m ² K)	2.12	1.4	1.4	0.27
Wall solar absorptivity	0.6	0.7	0.7	0.7
Roof	Clay tiles 0.1m insulation	Concrete tiles 0.1m insulation	Cold roof type 0.05m insulation	Concrete tiles 0.3m insulation
Roof U-Value (W/m ² K)	0.36	0.37	0.6	0.13
Roof solar absorptivity	0.8	0.7	0.85	0.7
Internal partitions	Solid brick with plaster	Solid brick with plaster	Plasterboard with air gap	Block with plasterboard
Ground floor	Suspended timber, uninsulated	Concrete uninsulated	Concrete uninsulated	Concrete block and beam, insulated
Ground floor U-Value (W/m ² K)	0.84	1.1	0.9	0.2
Windows	Double glazing, uPVC frame	Double glazing, uPVC frame	Double glazing, uPVC frame	Double glazing, uPVC frame
Window U-Value (W/m ² K)	2.7	2.7	2.7	2.7
Glazing SHGC ¹	0.71	0.71	0.71	0.74
Infiltration (air changes /hour)	0.7	0.55	0.5	0.5

Table 2. Base case models construction and thermal properties

¹ SHGC = Solar heat gain coefficient. EnergyPlus (USA) gives SHGC values rather than g-values (UK)

Internal gains for people and appliances were determined using CIBSE [3] and ASHRAE [12] guideline values. Metabolic rates were set as follows: seated adults 108 W/person; sleeping adults 72 W/person and sleeping children 54 W/person. Appliance gains of 150W for the living rooms (TV) and 100W for children's bedrooms (computers) were set to follow occupied hours (switched off when asleep). Low energy lighting was assumed and 30W lighting heat gains included for living rooms in the evenings.

The scheduled ventilation option was used in EnergyPlus to set air change rates for given room types based on the UK Government's Standard Assessment Procedure for Energy Rating of Dwellings (SAP 2009) [13]. SAP provides effective air change rates (ACH) for dwellings in hot weather, derived from procedures in BS 5925 [14]. The maximum ventilation rate is 8 ACH for rooms in two storey dwellings, where cross ventilation is possible (e.g. living rooms, dining rooms, kitchens), and the minimum is 4 ACH for single storey dwellings where cross ventilation is not possible (e.g. bedrooms in flats). For base case dwellings during occupied hours window ventilation commences when the room operative temperature reaches 22°C and increases linearly until reaching the maximum value by 28°C. These are also the ventilation control set points used in CIBSE Report TM36 [4].

2.2 Weather data

Three options were considered for providing simulation weather data. CIBSE TM36 [4] uses future morphed weather data developed by Belcher et al [15] to predict whole summer overheating. Although these morphed weather files provide elevated summer temperatures, they are based on current test reference and design summer year weather files. They are constructed from a number of years, avoiding the most extreme months containing heat wave periods (e.g. June 1976). Other research [16,17] has used European weather data to approximate the predicted future UK climate later this century. However, the change in latitude would affect solar shading calculations and other weather factors, such as wind speed and humidity, may also be different. The third option, and the one chosen for this research, was to use real UK heat wave periods from 1976, 1995 and 2003. The results presented in this paper use the heat wave from August 2003. The weather file was constructed using data from the British Atmospheric Data Centre [18]. Figure 3 shows that during the August 2003 heat wave the London daytime temperature peaked at over 37°C and the night time temperature did not drop below 18°C.

Figure 3: Simulation weather period dry bulb temperature

2.3 Occupancy profiles

Two occupancy profiles (Table 3) were modelled to represent different patterns of house use. The elderly occupancy profile assumes an elderly couple occupying the living room during the daytime hours and the main bedroom at night. The family occupancy profile assumes a family with adults and children leaving the dwelling unoccupied during the daytime and using the living rooms during the evening before bedtime.

	Living rooms	Main bedrooms
Family	1800 - 2300	2300 - 0730
Elderly Couple	0900 - 2230	2230 - 0730

Table 3. Occupancy profiles

2.4 Passive cooling interventions selected for investigation

Category	Intervention	Description
Insulation	Loft insulation (terraced/semi)	Increase loft insulation to 0.25m (U-value of 0.16 W/m ² K)
	Upgrade roof (flats)	Felt, plywood deck, 0.14m EPS insulation, 0.0095m plasterboard (U-value 0.25 W/m ² K)
	External wall insulation	Addition of 0.06m phenolic foam and 0.02m render to outside face of external walls (U-value 0.35 W/m ² K). Background infiltration reduced to 0.5 ACH for terraced and semi
	Internal wall insulation	Addition of 0.06m phenolic foam and 0.013m plasterboard to inside face of external walls (U-value 0.35 W/m ² K) Background infiltration reduced to 0.5 ACH for terraced and semi
	Cavity wall insulation	Addition of 0.05m mineral wool insulation to cavity (U-value 0.5 W/m ² K)
Solar Control	Internal blinds	High reflectivity slats, solar transmittance 0, solar reflectance 0.8, material conductivity 0.9 W/m-K, closed from 0900 to 1800
	External shutters	High reflectivity slats, solar transmittance 0, solar reflectance 0.8, material conductivity 0.9 W/m-K, closed from 0900 to 1800
	Internal curtains	Close weave medium drapes, solar transmittance 0.05, solar reflectance 0.3, material conductivity 0.1 W/m-K, closed from 0900 to 1800
	Fixed shading	Add 1.0m deep overhangs above south, east and west windows (2.0m deep awnings for east and west ground floor windows, except terraced houses for front elevations)
	Light walls	Coat external walls with high performance solar reflective paint to reduce solar absorptivity to 0.15
	Light roof	Coat roof tiles with high performance solar reflective paint to reduce solar absorptivity to 0.15
	Low e triple-glazing	Replace double-glazing with low emissivity coated triple-glazing: 3 x 0.003m panes with 0.012m air gaps, inner and outer panes coated, SHGC 0.472, light transmission 0.661, U-value 1.6 W/m ² K
Ventilation	Night ventilation	Ventilation of ground floor rooms with cooler outside night air at 8 air changes per hour (may require low power fans if security or noise is an issue, preventing window opening)
	Window rules	Prevent windows from being opened (reduce ventilation to background infiltration only) if outside air temperature is greater than inside air temperature

Table 4. Intervention details

The aim of this research is to evaluate a range of passive interventions (Table 1 and details in Table 4) that can reduce or eliminate the need for mechanical cooling. Insulation additions were selected to comply with current UK Building Regulations for extensions to existing properties [19]. It has also been assumed that some improvement to draught proofing would occur during the installation of wall insulation. Window shading by blinds, shutters and curtains was selected from the EnergyPlus materials database.

A parameter tree was constructed using jEPlus [9] to select combinations of interventions for simulation. Certain combinations can be eliminated, for example only one type of wall insulation would be chosen, not both types together, and the modern detached house has no insulation interventions. This resulted in a total of 2,048 simulations for each orientation for the flats and semi-detached house, 1,536 simulations for each orientation of the terraced houses and 256 simulations for each orientation of the detached house. This was repeated for the two occupancy profiles, producing a total of 47,104 simulations for each weather file.

2.5 Costs and effect on heating energy use

The simulations were carried out for the 2003 heat wave period and for September through to May to calculate the space heating energy use during the cooler seasons for each dwelling. A simple heating system was modelled and the zone sensible heating results reported by EnergyPlus.

The costs of the interventions were estimated using building works cost reference guides [20,21]. These are approximate UK costs and may vary, particularly with economies of scale for developers. However, they give a guide to those single and combined interventions that produce good reductions in overheating and lower space heating energy use at the lowest cost.

3 RESULTS AND DISCUSSION

Dynamic thermal simulations were carried out for the base case model and then for the range of interventions listed in Tables 1 and 3 for each dwelling type. The operative temperatures for the living room and main bedroom of each dwelling type were computed for every hour over the heat wave period. The operative (or dry resultant) temperature combines the room air temperature and mean radiant temperature to provide a thermal comfort index temperature.

3.1 Base case dwellings – assessment of overheating

The results presented in this paper show the effect of the interventions on the number of degree hours over the CIBSE comfort threshold temperatures (26°C for bedrooms and 28°C for living rooms) for the main bedroom and living room for each dwelling type over the 9-day August 2003 heat wave period. The number of degree hours quantifies the extent to which the overheating threshold has been exceeded and has been used in other research [5,22].

The base case dwelling simulation results (Table 5) show that the top floor 1960s flat experiences the worst overheating, with a combined total (living room plus bedroom) of 897 degree hours over the threshold temperatures for the west facing variant, assuming elderly occupancy. Orientations with east and west facing windows lead to the greatest overheating and the results also highlight the much higher exposure to overheating experienced by the elderly residents, who occupy the dwellings during the hotter daytime periods.

	Windows facing		End terraced	Semi-detached	Detached	Top floor flat
Living room	North	Elderly	68	122	299	448
		Family	21	36	97	203
	South	Elderly	120	162	470	624
		Family	37	43	140	274
	East	Elderly	146	207	504	652
		Family	49	61	150	282
	West	Elderly	110	180	507	646
		Family	34	61	179	328
Main bedroom	North	Elderly	95	94	148	166
		Family	87	78	123	152
	South	Elderly	100	108	155	216
		Family	95	96	132	207
	East	Elderly	89	141	204	201
		Family	70	122	165	192
	West	Elderly	142	129	211	251
		Family	131	113	179	238

Table 5. Degree hours over CIBSE threshold temperatures for base case dwellings (worst overheating cases for each occupancy type highlighted in bold)

The results were compared to monitored air temperature data from London houses recorded during the 2003 heat wave [23]. Although there are no exact matches for house type within the monitored dwellings, there is a solid walled semi-detached house, with 90% double-glazing and an east-facing living room, which would be similar in construction to the 19th century end terraced house. Table 6 shows that there is a good agreement between the simulated temperatures and those from the monitored dwelling.

Temperature (°C)	Min	Mean	Max
Monitored dwelling [23]	24.0	27.0	31.9
Simulation model:			
Family profile	22.9	27.1	31.0
Elderly profile	23.0	27.7	32.2

Table 6. Monitored and simulated living room temperatures

3.2 Single interventions

To contrast the effects of interventions on different dwelling types, orientations and occupancy, four sample case studies have been selected (the full results will be published in future papers). The charts in Figure 4 show the total overheating

exposure experienced by the residents, simulated for the 9-day August 2003 heat wave, combining the degree hours over 28°C when they occupy the living room and degree hours over 26°C when they are in the bedroom.

Figure 4. Single interventions ranked for overheating reduction

The most effective single intervention for cases (a), the top floor flat and (b), the modern detached house, was found to be the addition of external shutters to the windows, reducing the number of degree hours by 35% and 52% respectively. For case (c), the semi-detached house with south facing windows, external fixed shading above the windows was the most effective intervention, reducing degree hours by 55%. In case (d), the end terraced house with solid brick walls, the most effective intervention was coating the walls with high performance solar reflective paint (light walls). The light walls intervention was also effective for the flat and semi-detached house, but less effective for the highly insulated detached house.

For the case of the west facing top floor flat with the elderly occupancy profile, adding wall insulation on its own was shown to increase the overheating problem. The biggest increase occurred with the addition of internal wall insulation, increasing the number of degree hours by 6% to 951. Cavity wall insulation led to an increase in degree hours of 5% to 943 and external wall insulation had little effect, increasing overheating by just over 1% to 909 degree hours. Internal wall insulation was also seen to increase overheating for the end-terraced house (d) by 18%, but external wall insulation produced a 20% reduction in degree hours. For the south facing semi-detached house (c) internal wall insulation produced a 13% reduction in degree hours, whilst external wall insulation reduced degree hours by 29%.

3.2.1 Single interventions discussion

Solar control interventions for walls and windows were found to be the most effective way of reducing overheating. Shielding glazed areas from solar radiation by external fixed shading or fitting external shutters was more effective than using internal blinds or curtains. When using internal shading, solar radiation has already passed through the windows before being absorbed by the blinds or curtains and transmitted to the room as heat. The reflective blinds absorbed less of the solar energy than the curtains and were more effective. Low e triple glazing reflected some of the solar radiation and was comparable in overheating reduction performance to curtains and blinds. Specialist low SHGC (or g-value) glazing is available for solar control, but at the expense of reduced visible transmittance, which would affect daylight levels all year round. For dwellings with solid external walls and larger external wall areas, such as the end-terraced house, coating the walls with a high performance solar reflective paint was particularly effective in reducing overheating. The light walls intervention was less successful for the modern detached house, which has highly insulated cavity walls. The light roof intervention was very effective for the top floor flat, which has a poorly insulated flat roof covered with dark asphalt, but was less effective for houses with pitched roofs containing loft insulation.

External wall insulation performed better for overheating reduction than internal wall insulation, with the performance of cavity wall insulation falling between the two. External wall insulation shielded the outer brickwork from solar radiation, leaving existing thermal mass exposed inside the rooms to provide some radiant cooling benefit, whereas internal wall insulation isolated the thermal mass from the rooms. However, adding wall insulation also increased the effect of internal heat gains, which were more effectively retained within the dwellings. Increasing loft insulation from 100mm to 250mm was seen to have little effect on overheating reduction.

Controlling ventilation by use of the window rules intervention was effective for the end-terraced house with elderly (daytime) occupancy. However, in the case of the top floor flat with elderly occupancy, the room temperatures were much higher during the peak daytime hours, often exceeding the outdoor air temperature and therefore giving less opportunity to use this intervention. In all cases, cooling the building fabric with cooler night air (night ventilation) was seen to be beneficial, recharging the coolth in the building mass to provide a cooling benefit during the daytime.

The effects on overheating reduction of all the single interventions have been discussed in detail in previous papers [24,25].

3.3 Combined interventions with cost and energy use

The combined interventions were then modelled for each dwelling type. Terraced houses were further split into end terraced and mid terraced and the block of flats into a ground floor, mid floor and top floor flat. The resulting seven dwelling variants (one detached, one semi-detached, two terraced and three flats) were simulated in EnergyPlus, using the De Montfort University 256 core cluster, for four orientations and two occupancy profiles – a total of 56 sets of combined interventions (see Section 2.4). Figure 5 shows one of the case studies from Section 3.2, the top floor flat with west facing windows and elderly occupancy, to demonstrate the output presentation. Each point in the scatter plot is a simulation result for either a single intervention or a combination of interventions. The chart also shows the effect of the interventions on space heating energy use, the shape and size of the markers indicating the amount that the energy use is increased or reduced by the intervention(s).

Figure 5. Combined interventions for top floor 1960s flat (see also Table 7)

Two zones of particular interest are highlighted by shaded areas: Zone A contains interventions which result in an increase in overheating compared to the base case dwelling and Zone B highlights the best interventions for reducing overheating at various given prices. Selected simulation results, marked 1 to 7 in Figure 5 (and detailed in Table 7) have been highlighted to demonstrate how the results may be used to inform retrofit decision-making.

Point 1 in Figure 5 shows that the overheating can be reduced to 638 degree hours, a 29% reduction from the base case, by keeping the curtains closed during the day and using cooler night air in the night ventilation intervention. These are behavioural interventions, at zero cost (assuming the flat has curtains and that the windows can be opened at night). Point 2 is the addition of internal wall insulation without any other interventions, which leads to the greatest overheating as mentioned before (Section 3.1). However, if internal wall insulation is combined with other interventions (Point 3), the overheating can be reduced by 56% from the base case. Points 4 and 5 show two combinations that are very similar in overheating reduction performance and cost, but one (4) reduces space heating energy use by the addition of cavity wall insulation, whilst the other (5) results in increased energy use.

The base case overheating is 897 degree hours and it is shown that this can be reduced by 94% to 58 degree hours (Point 6), though at an approximate cost of £22,000. This combination of interventions also reduces the space heating energy use by 29%. The interventions that would lead to the best reduction in space heating energy use (Point 7) may well be considered to be an ultimate retrofit package: external wall insulation, a new roof and high performance low e triple glazing. However, it can be seen that this would still leave a significant overheating problem during very hot weather if no other heat wave mitigating interventions were considered.

Point on Figure 4	1	2	3	4	5	6	7
Overheating Degree hours	638	951	393	160	141	58	656
% Change in heating energy use from base case	0	-37	-29	-22	+14	-29	-58
Approx. cost £	0	3,520	4,750	5,100	4,800	22,000	16,200
Interventions:							
New flat roof							X
External wall insulation						X	X
Internal wall insulation		X	X				
Cavity wall insulation				X			
Internal blinds							
External shutters				X	X	X	
Curtains	X		X				
Fixed shading						X	
Light walls			X	X	X	X	
Light roof			X	X	X	X	
Low e triple glazing						X	X
Night ventilation	X		X	X	X	X	
Window rules			X	X	X	X	

Table 7. Details of selected interventions highlighted in Figure 4

4 CONCLUSIONS

Dwelling retrofit in the UK has to date concentrated on reducing space heating energy use. However, adapting dwellings to provide safe and comfortable environments in a changing climate will require accurate technical guidance to target resources and meet the dual aims of reducing overheating and energy use.

The type of dwelling, its orientation and occupancy profile were found to have a significant impact on overheating exposure, where elderly residents in a top floor flat could experience over 8 times the overheating exposure of a family in an end terraced house. The base case dwelling simulation results would help a local authority, housing association or other owners/managers of sizeable residential building stock to identify which part of their housing portfolio is most at risk, thereby concentrating efforts and resources.

The intervention simulation results demonstrate the potential for both reducing overheating during heat wave periods and reducing annual heating energy use, for a range of single and combined passive interventions. Interventions that reduce solar gains by shading or reflecting are very effective, but they can also reduce beneficial gains during cooler seasons. Conversely insulation improvements, carried out to improve winter thermal performance, can result in increased overheating during heat waves. Therefore retrofit decision making should be considered in annual performance terms. It should also be noted that implementation of some of the interventions may not be possible due to external factors. For example local planning constraints may prevent changes to the external appearance and urban issues, such as noise, security and air quality may limit the availability of ventilation through windows.

This research presents information about the effectiveness of a range of passive measures for reducing overheating, with costs and impact on space heating energy use, in a highly user friendly single diagram. The method allows easy identification of the best and most appropriate combinations of interventions.

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