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Adapting Dwellings for Heat Waves

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Abstract

The research presented in this paper investigates combinations of interventions for adapting dwellings to help adequately cope with future heat waves. The effectiveness of a series of passive heat wave mitigating interventions was assessed for Victorian (late 19th century) terraced houses in the UK, using dynamic thermal simulation coupled to a nodal airflow model. The interventions comprised a range of additions and modifications to solar shading, insulation and ventilation. It was found that for a predicted test reference weather year in the 2080s, the overheating problem could be addressed by purely passive means. The most effective interventions for reducing overheating were found to be wall insulation (where external performs better than internal) and measures to reduce solar heat gain, such as external window shutters and painting the external walls a lighter colour. Other interventions were found to be less effective, such as a lighter coloured roof and increased levels of loft insulation. Further research is proposed to investigate the effect of different heat wave durations and also more extreme weather years, where additional low energy interventions (for example fans) may be necessary.

Keywords

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

1 Introduction

The UK climate is warming, with the South East of England expected to see a rise in annual average temperature of up to 5⁰C by the end of the century [1]. Winters are expected to be wetter and summers drier, with an increase in both the frequency and intensity of extreme weather events, such as flooding and heat waves [1]. The urban heat island effect raises the temperature in large cities, leading to serious overheating problems for buildings and a large increase in heat related health problems, as well as severe discomfort for occupants. During the 2003 heat wave, the centre of London was up to 10⁰C warmer than the surrounding rural areas [2]. The heat wave of August 2003 resulted in over 2,000 additional mortalities in the UK, mostly in South East England [3].

Approximately 82% of the current UK housing stock was built before 1980 [4]. With very low rebuild rates, which are being further damaged by the current recession, the majority of these dwellings are likely to be with us for many years. It is estimated that 70% of houses that will be in use in 2050 have already been built [5]. Future building regulations, currently in consultation [6], will require further improvements for winter thermal performance, but are also likely to include requirements to limit solar thermal heat gains to avoid or minimise the use of mechanical cooling and reduce CO₂ emissions. The latest proposed cuts in carbon emissions for the G8 nations are 80% by 2050, there will therefore be a need to adapt existing dwellings to future climate change to meet these targets. A report for the Three Regions Climate Change Group states that “uptake of climate change adaptation measures is low because of the lack of information and awareness about adaptation options” [5 p.9]. The London Climate Change Adaptation Strategy [2] suggests further investigation is required on a range of

external and internal adaptation options, including shading, high albedo walls and night ventilation.

There have been several publications in recent years offering advice for adapting dwellings for heat waves. A report by Arup for the Three Regions Climate Change Group [5] suggests selected measures, ranked by cost (Low, Medium, High). The effectiveness of individual interventions to reduce overheating is not considered, but charts show the reduction in percentage of occupied hours that may be achieved by implementing the full range of interventions for current and future climate scenarios. It will be likely that for many low-income households and local authorities, only a few of the most effective and lower cost measures will be considered.

The Energy Saving Trust [7] publish a guide for designers to help reduce overheating in dwellings by incorporating good design. Some of the measures suggested however, can only be economically applied during the design of new properties, such as changing the orientation or the level of thermal mass used in the building, but it also suggests useful adaptations that can be applied to existing dwellings, such as solar shading devices. The report presents the effect of some of the modifications on the number of degree hours over threshold temperatures, a method which demonstrates the severity of the overheating problem.

The Chartered Institute of Building Services Engineers (CIBSE) report TM36 [8] suggests clusters of adaptation measures for a small selection of UK dwelling types, predicting the number of occupied hours for which current CIBSE thermal comfort threshold temperatures [9] will be exceeded under future predicted climate scenarios. Holmes and Hacker [10] expand the research undertaken in TM36 by modelling the effect of some clustered interventions on non-domestic buildings, using the same future

1 climate scenarios, though aimed more at sustainable design rather than climate
2 adaptation.
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5 However, much of the existing literature stops short of quantifying the
6 effectiveness of individual interventions. Research that does provide quantitative
7 information is often limited in scope, either clustering interventions or concentrating on
8 particular individual measures. A briefing paper by the authors [11] introduced the
9 methodology used in this research. However, this paper presents the first of a series of
10 steps to address this problem by providing a more systematic evaluation of the
11 technologies, with emphasis on offering clear insights as well as quantitative ranking
12 information to building design practitioners. The potential of a range of passive
13 interventions to reduce overheating during heat wave periods is considered, avoiding
14 interventions such as mechanical cooling that would contribute to climate change. The
15 cost of running such systems could also be prohibitive for the most vulnerable people in
16 our society. Individual interventions as well as clusters (or combinations) of
17 interventions are modelled in order to determine which ones are the most effective
18 under different climatic scenarios. This will enable targeted adaptation work to make
19 best use of available resources.
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42 The research is linked to an Engineering and Physical Sciences Research
43 Council (EPSRC) funded project, Community Resilience to Extreme Weather (CREW)
44 [12,13], which was formed in response to recent extreme weather events including heat
45 waves and floods. The project will integrate technological measures with socio-
46 economic factors and climate predictions, to produce a set of tools for decision makers,
47 businesses and stakeholders.
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2 Methodology

Computer modelling using multi-zone dynamic thermal simulation, coupled with a nodal airflow model, was used to assess the effect of a range of single and clustered interventions on room dry resultant temperatures.

CIBSE Guide A [9] recommends that for domestic properties in the UK comfort threshold temperatures of 26°C for bedrooms and 28°C for other living areas should not be exceeded for more than 1% of occupied hours. The problem with this approach is the lack of indication of the severity of overheating, because one hour at 29°C would appear to be as bad as 1 hour at 35°C. An alternative approach, and the one considered here, is to use a degree hour method to analyse the severity of the overheating problem, where each one degree centigrade over the threshold temperature for one hour counts as one degree hour. The effect of a range of single and clustered interventions on the number of degree hours over the comfort threshold temperatures is then investigated. The reduction in peak occupied operative temperature has also been included for each intervention.

2.1 Modelling Tools

The targeted dwellings were modelled using Integrated Environmental Solutions Virtual Environment software (IES-VE Version 5.9) [14]. This commercial software package was chosen because it has a comprehensive feature set and is widely used in academia and industry. It is well validated [15] and also approved for use in dynamic thermal simulation by the UK government [16]. IES VE allows complex models to be constructed using a zonal system to model heat and mass transfer by combining several individual packages. The simulations in this paper used the ModelIT construction

package to build the house models, SunCast to calculate the solar shading, MacroFlo to model openings and Apache to perform the dynamic thermal simulations. These are all programme packages contained within the IES-VE suite [14].

Heating systems and loads were not considered for this research because the simulations were run for four summer months only (June to September). However, future simulation work will consider the impact of any proposed interventions on winter heating loads.

2.2 Targeted house types

The study area for the CREW project is the south east of England, which is the UK region predicted to be at greatest risk of overheating under future climate scenarios [1]. The effect of a range of interventions, aimed at reducing summertime overheating, will be modelled for a selection of targeted house types, the first of which (the late 19th century Victorian terraced house) is presented in this paper.

There are approximately 8.5 million terraced houses in the UK, of which 35% (nearly 3 million) were built before 1919 [4], which makes Victorian terraced houses one of the most common types of dwelling in the UK. Housing data from the UK Government [4] was cross-referenced with the Energy Saving Trust's Homes Energy Efficiency Database (HEED) [17], to ensure that the construction, insulation and glazing properties for the simulation models were representative of typical housing stock for the region. Fig. 1 shows the simulation model, which is a row of three

Victorian terraced houses. Basic construction was usually of solid brick walls, with either slate or tiled roofs, single glazed sash windows and no insulation. However, the majority of such properties have been extended and modernised to some extent. The lack of kitchen and bathroom facilities led to the majority being extended at the rear

during the 20th Century, converting the old lean-to sculleries into kitchens, with bathrooms above. Double glazing and loft insulation has also been incorporated in many cases. The room layout (Fig. 2) comprises 3 bedrooms, living room, dining room, kitchen and bathroom.

Fig. 2

2.3 Construction details of the base case building

The simulation model used for this research represents a row of three Victorian terraced houses, located in a suburban area in the south east of England. Table 1 shows a summary of the construction details for the simulation model.

Table 1

The window and door crack flow coefficient settings were based on values in the MacroFlo Opening Types User Guide [14] and the solar absorptivity of the roof tiles and for the brick walls were based on values in the Apache Tables guide [14]. The infiltration value for the building was calculated using tables from BREDEM [18] and estimated to be 0.5 air changes per hour (ach⁻¹). The chimneys were assumed to be sealed and the living room fireplaces fitted with gas heaters. The lack of open fireplaces and the PVC framed double-glazing improve the infiltration value from that when constructed, which would have been nearer 1 ach⁻¹.

2.4 Casual gains and profiles

Internal gains were set using CIBSE [9] and ASHRAE [19] guideline values for people and appliances. Sensible gain values for adults seated in living rooms were set at 65 W/person; sleeping adults were set at 43 W/person and sleeping children at 30 W/person. Appliance gains of 150W for the living rooms and 100W for children’s bedrooms were set for occupied hours to reflect the use of TVs and computers. Low energy lighting is expected to be the norm in the future, as incandescent lighting is phased out, so small lighting gains of 30W for living rooms were included. The

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2 appliance and lighting gains for living rooms follow the occupancy profiles, whilst the
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4 appliance gains in children's bedrooms assume that they are switched off overnight.

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Occupancy profiles were based on a 'typical' family of two adults and two children, leaving the dwellings unoccupied during the day. Future simulations will consider houses that are occupied all the time (though usually with just one or two adults), which is particularly important for elderly residents. The bedroom 1 (main bedroom) occupied hours were set to be 2200 to 0700 for the adults. Children were assumed to occupy their bedrooms more in the evenings, so the occupancy schedules for bedrooms 2 and 3 were 1800 to 0730. The living rooms were occupied briefly in the mornings from 0700 to 0800 and in the evenings from 1700 to 2200. Windows were allowed to be opened by up to 25% of their area when a room was occupied. Opening would commence when room operative temperature reached 22°C and would be open to the full open able area by 28°C.

2.5 Other simulation settings

Two further Apache settings were established by performing a series of test simulations on the base case model. The simulation time step was adjusted between 1 minute and the default setting of 10 minutes. Very little difference was observed between the results, though there were instabilities in the simulations for time steps over 6 minutes when lower levels of loft insulation were investigated. For this reason a simulation time step of 2 minutes was chosen. The preconditioning period, which is necessary to allow the model to achieve a realistic thermal state, also needed to be set. High mass buildings will require a longer preconditioning period, but it was found that for this model there was no benefit to increasing the preconditioning period to more than 10 days, which is the Apache default setting.

2.6 Weather data

The research aims to assess the impact of interventions during heat wave periods. Whether a hot period is defined as a heat wave varies depending on the normal weather conditions for the location. As people adapt to warmer climates, the threshold temperatures for heat wave onset will also rise.

Some of the previous research identified has used climate data from warmer locations outside the UK, such as Rome [20] and Milan [21]. This allows the use of real weather files in the simulations, which are thought to approximate future climate conditions for the UK, assuming a medium high emissions scenario. The main problem with this approach is that the change in latitude will have a significant effect on any calculations for solar shading effects. Other research [8] uses predicted future climate data, based on current UK weather files that have been modified by a morphing procedure, developed by Belcher et al for CIBSE [22]. This is the approach adopted in this research, which uses a Test Reference Year weather file for London Heathrow in the 2080s under the UKCIP02 Medium High Emissions Scenario [1]. This weather file was chosen to represent a typical weather year towards the end of the century and it includes several periods over the summer where the temperature exceeds 30⁰C (Fig. 3).

Fig. 3

Two further options are the future weather files based on the CIBSE Design Summer Years (DSY), and data files for real heat wave years (e.g., 2003). However, due to the way in which future DSY data are generated, using such data would mean setting the mean summer temperature much higher than what would be reasonable, with consequences for simulation accuracy. For example, some effects of the thermal inertia

of the building fabric would be lost if the heat wave period was starting in a period of elevated temperatures. Using real weather data from real heat wave years would mean ignoring the possible impact of the future climate but this approach is not affected by the artificial adjustment of data and the associated problems mentioned above. Further exploration of appropriate use of weather files will be presented in a future paper.

2.7 Modelled interventions for passive cooling

This research project is considering a range of interventions to adapt UK dwellings for heat wave periods. The selections for each dwelling type will be made on the basis of their suitability for each case, for example internal insulation of external walls could be an appropriate modification to consider for older solid brick or stone

properties, but not for modern, highly insulated ones. In reality, cost and other acceptability factors will also be important considerations. The interventions can be split into three categories: *insulation*, to reduce the transfer of heat through the building fabric; *solar control*, to prevent the absorption and transmission of solar radiation by shading or reflection; and *ventilation modifications* to either prevent the infiltration of warm air from the outside or to increase the ventilation from the outside during cooler periods.

Three insulation options were modelled, the first of which was to increase the loft insulation. The base case model has 100mm of glass fibre quilt loft insulation, because this level of insulation was found to be the most common for properties of this type in the HEED database [17]. The intervention involved increasing loft insulation thickness to 300mm, to meet the current building regulations U-value of $0.16 \text{ W/m}^2\text{K}$ [23]. The other two insulation interventions involved adding either internal or external wall insulation, to a level that produced a U-value for the wall of $0.35 \text{ W/m}^2\text{K}$. This is the level of wall insulation required in the current building regulations [23] for extensions to existing properties and as such considered an appropriate value to use here. In the case of external wall insulation this also involved the addition of a layer of render to the outside surface, the colour of which was set to provide the same solar absorptivity as the bricks in the base case model for single intervention modelling.

Four different solar control interventions, aimed at reducing solar gain through windows, were modelled. External shutters and internal blinds for window shading were introduced by using features in the Apache constructions database within IES. The external shutters provide a total block to solar radiation at all angles and were set to be closed during the day from 0900 to 1800. Internal blinds were modelled in the same way, using a shading coefficient value of 0.61 and short wave radiant fraction of 0.3,

which corresponds to typical venetian blind values. The operation schedule for the blinds was set to be the same as that used for the shutters. The effect of fixed shading to south facing windows was also modelled by adding overhangs. The aim was to reduce direct solar penetration through the windows during the summer, when the solar altitude is high. A range of overhang depths was considered and their effectiveness modelled using the SunCast module in IES. An overhang depth of 1.0m was found to be effective in blocking most direct solar radiation during the summer months, whilst still being a realistic size of device to fix to a house. The final window solar intervention was the replacement of the existing uncoated double glazing with Pilkington K low emissivity double glazing, consisting of two 6mm panes with the outer surface of the inner pane coated and an air-filled 12mm gap. This resulted in a lower transmittance of 0.69, compared to 0.78 for the standard glazing and an increased resistance of 0.3247 m²K/W, compared to the base case glazing value of 0.173 m²K/W.

The other solar control interventions were aimed at reflecting solar radiation. The base case house has brick walls with a solar absorptivity of 0.6 and red clay roof tiles with a solar absorptivity of 0.7. The effect of painting the walls and roof a lighter colour was simulated by changing the solar absorptivity settings for the walls and roof to 0.3, though this figure would increase over time as the surfaces become less clean.

The modelled ventilation interventions were both modifications to window opening strategies. The base case rules had assumed that, during occupied hours, if the occupants felt warm they would open the windows regardless of the outside air temperature. The first ventilation intervention was to allow windows to be opened only if the outside air temperature was lower than the inside air temperature. The other ventilation modification was to allow opening of ground floor windows during the

night. This had been excluded from the base case due to the security issues associated with unoccupied ground floor rooms.

The interventions considered so far are all passive, though some low energy ones (such as low power fans to improve ventilation) will be considered in future simulations. Not all interventions will be easy to implement, for example applying external wall insulation could be expensive and have local planning or aesthetic issues. However, the purpose of this research is to model the effects of the widest possible range of interventions and provide information for decision makers. Table 2 shows a summary of the range of single interventions applied to the Victorian terraced house model.

Table 2

2.8 Clustered Interventions

Initially 16 clusters of interventions have been modelled, split into solar control; insulation; insulation and ventilation; insulation and solar control and finally “full measures”. The full measures simulation applied all interventions excluding internal wall insulation, blinds and low emissivity double glazing, as these would have doubled-up on other interventions that were already included, i.e. external shutters, external wall insulation and in the case of the low-e glazing, it would have little or no effect with external shutters selected. Table 3 shows the key to the clustered intervention combinations. The combination of interventions was designed to determine the effect of a range of complementary technologies. There are obviously many more clusters that may be considered and future work will include further parametric studies on more combinations.

Table 3

3 Results and discussion

Dynamic thermal simulations were performed for the base case model and then for single and clustered interventions for the four months of June to September, using the 2080s medium high emissions scenario test reference year weather data. The simulations produced hourly values for the dry resultant temperature for each room in the three houses, from which the average dry resultant temperature each for hour for each room type was calculated. The results presented here show the effect of the interventions on the living rooms (ground floor, north facing) and main bedrooms (bedroom 1, first floor, south facing), as shown in Fig. 2.

3.1 Effects of single interventions

Fig. 4 shows the effect of some of the key interventions on bedroom 1 dry resultant temperature for a hot day (28th June) in the middle of a 4 day heat wave period in the 2080s weather file (Fig. 3), where the outside dry bulb temperature (DBT) peaked at over 35°C. It can be seen that for the south facing bedrooms (i.e. bedroom 1), external shutters over the windows (S5) have the greatest effect on peak daytime temperature, reducing it by up to 1.7°C. However, during occupied hours the most effective single intervention is seen to be external wall insulation (S3), reducing dry resultant temperature by up to 1.4°C. A similar result is observed in the living rooms (Fig. 5), where introducing night ventilation (S10) is the most effective intervention, reducing dry resultant temperature by up to 2°C during the night, when the room is unoccupied. During occupied hours, external wall insulation (S3) is again the most effective intervention, reducing dry resultant temperature by up to 1.4°C.

Fig. 6

Fig. 6 shows the reductions in the peak occupied dry resultant temperature on the 28th June for the range of single interventions for both living rooms and main bedrooms.

Figs. 7 and 8

The simulation output was then used to determine the number of degree hours over the CIBSE comfort threshold temperatures. Fig. 7 shows the reduction in degree hours for single interventions for the whole summer, whilst Fig. 8 shows the degree hour reductions for the 4-day heat wave period. The base case model shows that during occupied hours in a 2080s 'typical' summer there will be 350 degree hours over the CIBSE comfort threshold temperature (26°C) for the main bedrooms. The problem appears to be lower for living rooms, at 150 degree hours, but the threshold temperature is higher for living rooms, at 28°C , and the number of occupied hours is lower for living rooms than bedrooms.

Table 4

The single interventions were ranked in order of reduction in degree hours over the CIBSE comfort threshold temperatures, for both the whole summer period (June to September) and the 4-day heat wave period, 27th – 30th June (Table 4).

External wall insulation (S3) emerges as the best single intervention for reducing the number of degree hours for both living rooms (43% reduction) and main bedrooms (32% reduction) during the heat wave period, but external shutters (S5) have a slightly greater effect over the whole summer for living rooms (51% reduction). Though the U-value of the walls with internal and external insulation was set to be the same, at $0.35 \text{ W/m}^2\text{K}$, it can be seen that external wall insulation performs considerably better in reducing overheating. The external walls are solid brick, with a high conductivity of 0.84 W/mK . They also have a fairly high solar absorptivity value of 0.6, which means that solar radiation will quickly heat the walls on a sunny day. External wall insulation

1 shields the walls from the solar radiation and leaves the thermal mass exposed on the
2 inside, providing a radiative cooling benefit.
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5 External shutters (S5) perform very well for both the bedrooms and living
6 rooms, even though the living rooms are north facing, reducing degree hours over
7 threshold temperatures during the heat wave period by 22% in the main bedrooms and
8 33% in the living rooms. This is due to the reduction in solar gain through the south
9 facing dining room windows, which heats the dining rooms and then the living rooms
10 by convection through the open doors. Further research will extend the simulations to
11 look at the effect of modifying occupant behaviour, including internal door-opening
12 schedules. Internal blinds (S4) perform less well than external shutters, as would be
13 expected, resulting in reductions in degree hours of 9% for main bedrooms and 14% for
14 living rooms. This is partly due to the fact that they do allow some solar radiation to be
15 transmitted directly, but also the solar radiation that is reflected is largely trapped in the
16 room.
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35 The fixed shading over south facing windows (S6) produced only modest
36 reductions in degree hours of 6% for the main bedrooms and 4% for the living rooms
37 during the heat wave period. It is difficult to specify overhang depths that will block all
38 direct solar radiation for the whole summer without them becoming very large. Future
39 simulations will investigate larger (temporary) external shading devices, such as
40 awnings.
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51 Lighter coloured (high albedo) walls (S7) were found to be one of the most
52 effective single interventions in the south facing bedrooms, producing an 18% reduction
53 in degree hours during the heat wave period. Lighter coloured roofs (S8) are less
54 effective in conventional houses with attic spaces, due to the presence of loft insulation.
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The effectiveness will reduce further if the loft insulation is upgraded to the latest building standards.

Changing the window opening rules (S9) so that windows are kept closed if the outside air temperature is greater than the inside air temperature produced modest but useful reductions for the main bedrooms of up to a 12% reduction in degree hours over threshold temperature. The reduction for living rooms was more significant, mainly due to the fact that the outside temperature is still quite high in the early evenings. This is a fairly simple measure, but requires education of the occupants and also possibly the installation of thermometers to inform them when the windows should remain closed.

Low emissivity double glazing (S11) was also shown to have very little benefit and could only be recommended if upgrading to double glazing for the first time. Night ventilation to the ground floor rooms (S10) was shown to have some benefit for the living rooms, producing a 16% reduction in degree hours over 28°C during the heat wave period (assuming security and noise issues can be overcome). It had little effect for the bedrooms, due mainly to the fact that bedroom doors were assumed to be closed at night. Again, the effect of internal door opening schedules will be assessed to determine the effect of improving the cross flow ventilation at night. Increasing loft insulation from the base case value of 100mm to 300mm (S1) was found to be of little benefit, though is likely to be fitted to many dwellings over the coming years to reduce winter heating loads.

3.2 Effects of clustered interventions

When simulating the effect of clustered interventions (Table 3), the full measures option (C16) is shown to reduce peak occupied dry resultant temperature on a

heat wave day by up to 4.6°C for living rooms and 4°C for main bedrooms (Fig. 9). Fig. 10 shows the degree hour results for clustered interventions over the whole summer and Fig. 11 shows the results for the 4-day the heat wave period. Employing the full range of interventions, the number of degree hours over comfort threshold temperatures during the heat wave period is reduced to zero for living rooms and to just 4% of the base case value for main bedrooms, resulting in just 3 degree hours over 26°C during the 4-day heat wave.

Figs. 10
and 11

When considering smaller clusters of interventions, the most effective pairing was found to be external wall insulation and shutters, which was further improved, though only marginally, by the addition of high albedo walls. The clustered intervention rankings are presented in Table 5. Due to space constraints in the Table, the key has been used (see Tables 2 and 3). A combination of external shutters with high albedo walls and roof (C6) reduce the number of degree hours over comfort threshold temperatures by 42% in the main bedrooms and 54% in the living rooms during the heat wave period. However, it is combinations of solar and insulation measures that provide the best results. The highest ranked cluster pair is external wall insulation with shutters (C14), which resulted in a 58% reduction in degree hours for main bedrooms and a 75% reduction for living rooms during the heat wave period.

Table 5

4 Conclusions

The simulation results show that by applying a full range of interventions it is possible to reduce the dry resultant temperature of the living rooms in these 19th century terraced houses to below the CIBSE comfort threshold temperature for all occupied hours, purely by passive means, for a 2080s test reference year assuming a medium high emissions scenario. The bedroom dry resultant temperature can also be reduced to the extent that there are only 4 degree hours over 26°C over the whole summer and 3 degree

hours over the threshold temperature for the 4 day heat wave period, reductions of 99% and 96% respectively over the base case. The most effective single intervention for heat wave periods was found to be external wall insulation, which reduced the number of degree hours over the CIBSE comfort threshold temperatures by 43% for the living rooms and 32% for the main bedrooms.

Further research will perform additional parametric simulations, using a variety of weather files, to investigate the effect of single and clustered interventions under different types of heat wave scenario. Short heat waves (up to 4 days) will be compared to longer ones (over one week, such as the one in August 2003 in the UK). Simulations will be carried out on a selection of targeted dwellings to cover a variety of housing types in the South East of England, the area predicted to be most at risk of future overheating in the UK and the target area for the CREW project [12]. The simulations will also include dwellings that are occupied 24 hours a day, for example by elderly residents, where interventions to reduce peak daytime temperatures will be important.

The effect of interventions on the winter heating loads will also be simulated to provide information for decision makers on any possible drawbacks or further benefits associated with the proposed interventions. Some low energy interventions, such as fans to boost night ventilation and low speed ceiling fans, will also be considered. Validation of the simulations will be carried out by monitoring selected dwellings during warm summer periods.

These results are for one simulation model and may be different for other dwellings of a similar type. The absolute values of temperature reduction may also vary, but this research presents results that enable the effectiveness of different interventions to be compared.

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Figure captions

Fig. 1 Terraced houses IES model

Fig. 2 Terraced house floor plan

Fig. 3 Weather file: Dry bulb temperature (DBT) for 2080s medium high emissions scenario test reference year (TRY)

Fig. 4 Effect of selected single interventions on bedroom 1 temperature

Fig. 5 Effect of selected single interventions on living room temperature

Fig. 6 Reduction in peak occupied dry resultant temperature for single interventions on the 28th June (2080s TRY)

Fig. 7 Degree hours over threshold for single interventions, June – September (2080s TRY)

Fig. 8 Degree hours over threshold for single interventions, heat wave period June 27-30 (2080s TRY)

Fig. 9 Reduction in peak occupied dry resultant temperature for clustered interventions on the 28th June (2080s TRY)

Fig. 10 Degree hours over threshold for clustered interventions, June – September (2080s TRY)

Fig. 11 Degree hours over threshold for clustered interventions, heat wave period June 27-30 (2080s TRY)