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Preventing the overheating of English suburban homes in a warming climate

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As the impacts of climate change become more prominent within the next 50 years and beyond, the risk of overheating in homes is a concern. This is specifically relevant in the UK's suburbs where 84% of the population reside. To assess this future impact and the effectiveness of adaptive retrofitting, probabilistic climate change data for the 2030s and 2050s are used to assess the overheating risk in six suburban house archetypes in three cities in the UK: Bristol, Oxford and Stockport. The risks of overheating in typical constructions are assessed and the possibility of preventing overheating through the use of adaptation packages is evaluated through dynamic thermal simulation. Homes in Oxford show the greatest risk of overheating. The most effective (passive) package for tackling future overheating tends to combine fabric improvements and internal heat gain reduction. To assist planners and policy-makers in assessing and preventing overheating risk at a stock level, this adaptation package is further evaluated in selected neighbourhoods across the three case study cities, using the geographical information system (GIS)-based DECoRuM-Adapt (Domestic Energy, Carbon Counting and Carbon Reduction Model) model. The implications for public policy are that the existing housing stock must be future-proofed for a warming climate, particularly retrofit programmes (*e.g.* the Green Deal) and any upgrading of building regulations.

Keywords: adaptation, climate change, housing, mitigation, overheating, retrofit, suburban

Etant donné que les répercussions du changement climatique vont devenir de plus en plus importantes au cours des cinquante prochaines années et au-delà, le risque de surchauffe dans les habitations constitue un sujet de préoccupation. Ceci revêt une pertinence particulière dans les banlieues du Royaume-Uni dans lesquelles réside 84 % de la population. Afin d'évaluer cet impact futur et l'efficacité du réaménagement adaptatif, les données probabilistes relatives au changement climatique pour les années 2030 et 2050 sont utilisées pour évaluer le risque de surchauffe dans six archétypes de maisons suburbaines situés dans trois villes du Royaume-Uni : Bristol, Oxford et Stockport. Les risques de surchauffe dans des constructions types sont évalués et la possibilité de prévenir l'excès de chaleur par le recours à des trains de mesures d'adaptation est évaluée au moyen d'une simulation thermique dynamique. Les habitations situées à Oxford présentent le plus grand risque de surchauffe. Les mesures (passives) les plus efficaces pour s'attaquer aux futurs excès de chaleur tendent à combiner les améliorations apportées à l'enveloppe des bâtiments et une réduction interne du gain de chaleur. Afin d'aider les planificateurs et les décideurs à évaluer et à prévenir le risque de surchauffe au niveau du parc bâti, cet ensemble de mesures d'adaptation est évalué de manière plus poussée dans des quartiers sélectionnés sur les trois villes faisant l'objet de l'étude de cas, en utilisant le modèle DECoRuM-Adapt (Domestic Energy, Carbon Counting and Carbon Reduction Model – modèle d'énergie domestique, de comptabilisation du carbone, et de réduction du carbone), basé sur un système d'information géographique (SIG). Les implications pour les politiques publiques sont que la pérennité future du parc de logements existant doit être assurée en termes de réchauffement climatique, en recourant en particulier à des programmes de réaménagement (par ex. le New Deal vert) et à toute mise à jour de la réglementation du bâtiment.

Mots clés: adaptation, changement climatique, logement, atténuation, surchauffe, réaménagement, suburbain

Introduction

The adaptation of the built environment to climate change is both timely and critical, since it is now accepted that there is little chance of preventing a rise in global mean surface temperature below 2°C and that the impacts associated with this threshold are now considered to have been severely underestimated (Anderson & Bows, 2011). Specifically in the UK, research has shown that climate change is projected to impact buildings and that adaptation to a warming climate is the missing component in the current UK carbon reduction retrofitting agenda (Gupta & Gregg, 2012; Mavrogianni, Wilkinson, Davies, Biddulph, & Oikonomou, 2012; Porritt, Cropper, Shao, & Goodier, 2012). One impact of particular interest in both research and policy is future projected overheating of existing UK buildings resulting in altered thermal comfort and energy use patterns (Department for Communities and Local Government (DCLG), 2010; Lomas & Ji, 2009; Lomas & Kane, 2012; National Health Service (NHS), 2012; Wilde & Tian, 2010).

For the domestic sector, future overheating is projected to be problematic. Severity depends on location and home characteristics ranging from form typology to occupant behaviour. Moreover, higher insulation and airtightness standards, in an effort to reduce carbon emissions, tend to increase overheating risk in particular cases; however, this is dependent on many factors such as the position of insulation, for example. The most effective adaptation measures share the common purpose in reducing the impact of solar radiation from entering the home through either shading glazing (directly) or solar reflective surfaces (indirectly) (Gupta & Gregg, 2012; Mavrogianni *et al.*, 2012; Peacock, Jenkins, & Kane, 2010; Porritt *et al.*, 2012). There is also a projected positive impact in the domestic sector. This can be seen through a simulated reduction in energy required for heating demand and a documented reduction in cold-related deaths (Christidis, Donaldson, & Stott, 2009; Gupta & Gregg, 2012).

Considering the UK's effort to reduce carbon emissions in both existing and new build, the *Passive-On* project may be of most relevance. This project shows how the Passivhaus standard is attainable in various locations in Europe with a focus on Southern Europe. The South East of England's temperature change is projected to be comparable with that of present-day Southern France by the 2050s at high emissions, 90% probability (however, with higher solar radiation through reduced cloud cover). For a Passivhaus design in Nice to meet comfort requirements (for a free-running home in BS EN 15251) and the Passivhaus energy standard, the following measures were essential: user-operated shutters, insulation placed on the exterior of the building (insulation levels could be reduced from what is typically required in Central Europe), and passive cooling combined with night ventilation. Thermal mass is used only if night ventilation is possible; furthermore, findings suggest that heavy construction is more important in buildings with poor solar protection, poor insulation levels and high internal loads (Ford, Schiano-Phan, & Zhongcheng, 2007).

Whereas most research in the domestic sector is focused on homes in larger cities such as London and Edinburgh (Jenkins, Patidar, Banfill, & Gibson, 2011; Mavrogianni *et al.*, 2012; Peacock *et al.*, 2010; Porritt *et al.*, 2012; Three Regions Climate Change Group, 2008), the impact of the urban heat island (UHI) effect (Mavrogianni *et al.*, 2012), and adaptation for heatwaves (Porritt *et al.*, 2012), this paper contributes to the current body of knowledge by focusing on climate change impact and adaptation for non-extreme conditions in suburbs not subject to a substantial UHI effect. As suburban homes represent the majority of the population, this work serves to demonstrate climate change impact on typical English suburban dwelling types. This work is a result of the Suburban Neighbourhood Adaptation for a Changing Climate (SNACC) project.[1]

The main objective of this paper is to explore the impact of a changing climate and effective adaptation on summertime overheating risk in typical English suburban homes across three English cities. This is achieved by:

- modelling six house archetypes across six English suburban neighbourhoods by using dynamic thermal simulation
- simulating and assessing the overheating risk through adaptive comfort analysis in key rooms
- testing and evaluating through dynamic simulation the impact of incremental adaptation packages on preventing overheating in the house archetypes
- applying the most effective adaptation package across the six neighbourhoods, using a geographic information system (GIS)-based DECoRuM-Adapt model to assist planners and policy-makers in assessing overheating risk rapidly on a stock level

Current conditions

The 2003 heatwave in Europe has been cited as an indicator of the overheating impact and difficulty that Europe and the UK will experience regularly in the future (Eames Kershaw, & Coley, 2011; Mayor of London, 2008). In 2006, the UK experienced temperatures like that of 2003 and in many instances surpassing record highs (Met Office, 2012). Lomas &

Kane (2012) demonstrated through the largest monitoring experiment of summer conditions in dwellings to date that during a cooler-than-normal summer period in 2009, which included a hot spell, in Leicester, a very small percentage of homes had rooms with over 5% of occupied hours (overheated) with temperatures above the British Standard and European Norm (BS EN 15251) Category II thermal comfort range (the suggested acceptable range for normal expectations) (British Standards Institute (BSI), 2008). In the summer of 2011 the authors monitored a small number of homes in both Oxford and Bristol in an attempt to find existing conditions of overheating in unheated homes. No homes were found to have overheated in the Bristol set. The only significantly overheated home in the dataset was from an Oxford home that was clearly being actively heated during the period and excluded from the set for this reason. This was also experienced in some instances by Lomas & Kane (2012). As the monitored period only covered August and September 2011, summer overheating cannot be analysed in full; however, of the 21 homes monitored in Oxford, four rooms over three homes exhibited temperatures that surpassed the maximum for Category II (Figure 1). All four rooms in this instance were south facing (Table 1). Both investigations indicate, however small, that overheating is possible in areas of England even in the current climate during non-heatwave or non-record setting summers.

Methods

The methods used in this study, demonstrated in Figure 2, are as follows:

Data collection and groundwork

- Representative English suburban homes (house archetypes) are selected from the case study neighbourhoods and cities for detailed dynamic thermal simulation
- Review and selection of climate change projections for testing
- Modelling and dynamic thermal simulation of the dwelling types

Simulation

- Assessment of overheating risk
- Review of adaptation measures and development of adaptation packages
- Simulation and assessment of adaptation package effectiveness

Finally, the overheating and adaptation results are applied at a neighbourhood scale and the results calculated and mapped briefly to demonstrate the results on a larger scale.

Home selection and characteristics

The SNACC project selected six neighbourhoods in three cities, Bristol, Oxford and Stockport, as case study locations for climate change impact and adaptation effectiveness research. As the SNACC project utilized a socio-technical approach, criteria for neighbourhood selection included the consideration of

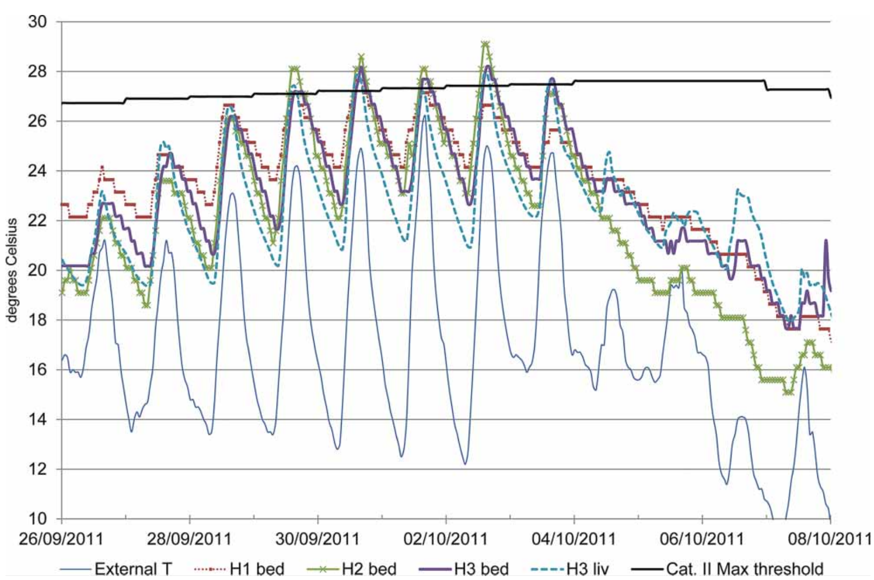

Figure 1 Thermal comfort threshold being surpassed for four homes monitored in Oxford, UK

Table 1 Home and room characteristics for the rooms shown in Figure 1

House	Age band	Type	Wall type	Room	Level	Orientation
H1	1950–1965	Semi-detached	Cavity	Bedroom	First	South
H2	1930–1949	Semi-detached	Solid brick	Bedroom	First	South
H3	1950–1965	Detached	Cavity	Bedroom Living	First Ground	South South

neighbourhood type classification, home age, economic conditions, exposure and vulnerability to existing risk (Williams *et al.*, 2012). Table 2 lists the six neighbourhoods and their characteristics, including age, built form and the orientation selected to represent each neighbourhood. Actual home and neighbourhood characteristics are gathered from historic and current maps, on-site assessment, home occupant questionnaires, and literature describing home characteristics based on age and form (DCLG, 2012a, 2012c; Digimap, 2012; University of the West of England (UWE), 2006). For modelling, the building age and form selection are based on the combination that is most commonly represented in each neighbourhood. Upper Horfield is the exception where 2002–2006 semi-detached is most common at 37%. However, as semi-detached homes are well represented and the Upper Horfield neighbourhood has the most flats of all neighbourhoods, flats are selected as the representative group. The English Housing Survey (DCLG, 2012a) data on age and built-form statistics is also listed for reference. The orientation for each representative home is based on the dominant front-facing orientation for all homes in the neighbourhood from which the home originates, *e.g.* the greatest number of homes from St. Werburghs have a southwest frontal orientation. Figure 3 maps the neighbourhoods and their location in reference to the corresponding climate modelling spatial resolution grid squares (Department for Environment, Food and Rural Affairs (DEFRA), 2012).

Future conditions

Probabilistic climate change data are available for the entire UK from the UK Climate Projections 2009 (UKCP09). UKCP09 provides a probabilistic range for a large number of weather variables that can be assessed for change under three emissions scenarios and seven climate periods (Figure 4). These data are available as either change or absolute values at a 25 km^2 detail which can be further downscaled via the Weather Generator (WG) to 5 km^2. The testing is done using the downscaled probabilistic range of medium emissions, 50% probability to high emissions,[2] 90% probability[3] (DEFRA, 2012). This range is considered to be sufficient for evaluating the higher risk within any climate period.

Physical data and thermal comfort metrics for dynamic thermal simulation

All case study homes were modelled and simulated in Integrated Environmental Solutions – Virtual Environments ModelIT and ApacheSim, respectively (referred to as IES). All homes are modelled in a street context

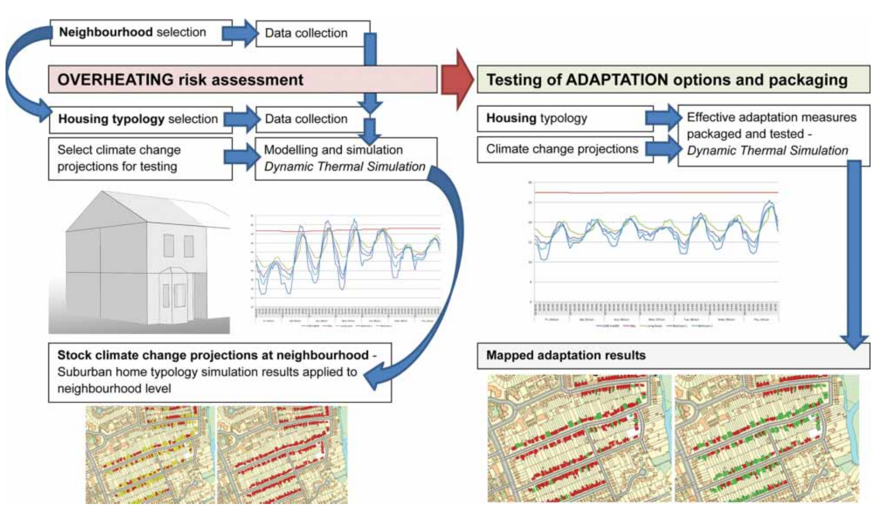

Figure 2 Methodological flow diagram

Table 2 Climate data location, neighbourhood characteristic, built form, age and home orientation for each neighbourhood

	Neighbourhood/ Classification	Class indicator	Age	Characteristics	Demographics	Selected representative age / built form, total %	England age / built form total	Dominant orientation
Bristol [WG 3600175 DSY]	St. Werburghs / **Inner historic suburb**	**IHS**	Pre-1919	Exposed terraced housing with some historic flood risk	Low income / active community	1900-1919 Mid-terrace, 81%	Pre-1919 - 22% Mid-terrace - 18%	Southwest
	Upper Horfield / **Medium**-high **density suburbs**	**MDS**	Mid-1990s – present	Semi-exposed mix of housing types: terraced, semi-detached, detached and flats	Low - moderate income mix / no established community action	2002-2006 Flat, 18%	Post 1990 – 13% Flat – 15%	Northwest
Oxford [WG 4550210 DSY]	Summertown (north Oxford) / Pre-war **'garden city'** type **suburb**	**GCS**	Pre 1919 – recent (majority 1900-1929)	Exposed terraced housing, sheltered large detached and semi-detached homes with large gardens	High income / emerging active community	1900-1919 Semi-detached, 25%	Pre-1919 - 22% Semi-detached & end-terrace - 36%	Southeast
	Botley / **Public transport suburbs**	**PTS**	1930-1944	Semi-exposed lightly coloured semi-detached homes; some low elevation flooding	Medium – high income / active community	1930-1944 Semi-detached, 95%	1919-1944 - 17% Semi-detached & end-terrace - 36%	Northwest
Stockport [WG 3900390 DSY]	Bramhall / **'Car' Suburbs**	**CRS**	1950s-mid-1970s	Semi exposed detached homes	Medium – high income / active community	1965-1976 Detached, 63%	1965-1980 - 21% Detached - 26%	Southwest
	Cheadle / **Social housing suburbs**	**SHS**	1950s – 1980s	Semi-exposed lightly coloured semi-detached homes; Localised exposure to flooding	Lower income / active community	1950-1964 Semi-detached, 92%	1945-1964 - 19% Semi-detached & end-terrace - 36%	Northeast

Note: Homes will always appear in the above order; the classification indicator is used to identify the model's location, age and form throughout the paper.
Sources: Eames Kershaw, & Coley (2011), Department for Communities and Local Government (DCLG) (2012a), Digimap (2012), and Williams *et al.* (2012).

with other homes neighbouring and some tree cover in the rear garden; the front garden is left exposed. The occupancy profile of the homes is detailed in Table 3. The future weather data, processed for use in dynamic thermal simulation software, are attained from the output of the Engineering and Physical Science Research Council (EPSRC)-funded PROMETHEUS project (Eames *et al.*, 2011). The weather files are developed from probabilistic future climate data downscaled for the 5 km grid squares listed in Table 2 (DEFRA, 2012). Design summer year (DSY)[4] files are used to assess overheating in hot summers but not in extreme or heatwave conditions.

Table 4 lists the construction characteristics for each home. Wall and ground floor construction vary with age. Alternatively, all homes have loft insulation of 100 mm, given that by 2008 roughly 85% of English homes had 100 mm or more of loft insulation (Palmer & Cooper, 2011). Furthermore, all homes are modelled with double glazing, first as directly observed through physical assessment of the front

Figure 3 Case study neighbourhood locations and 25 km grid squares for which climate data are available. Source: adapted from Department for Environment, Food and Rural Affairs (DEFRA) (2012)

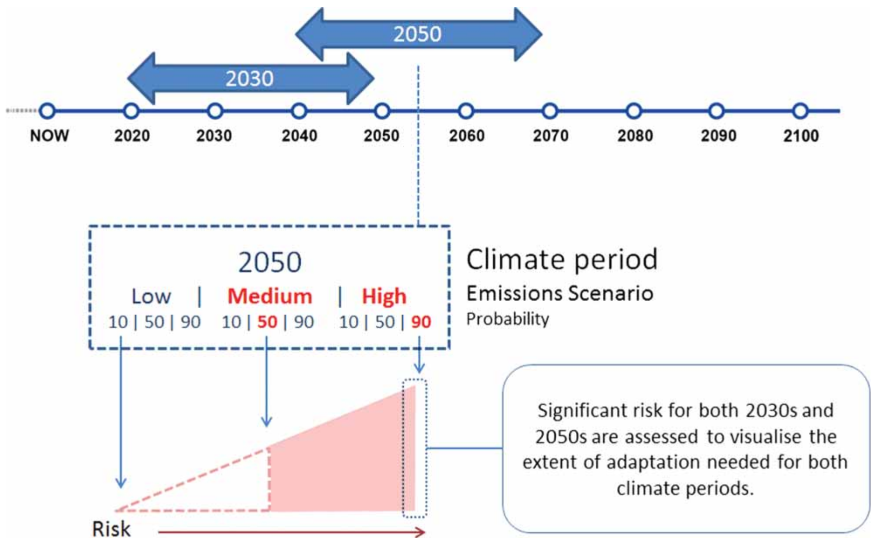

Figure 4 The probabilistic range tested for each climate period is shown to demonstrate the risk significance attached. The example of the 2050s climate period is given for reference

facades of homes in the neighbourhoods and, second, by 2008, 90% of households had some level of double glazing (Palmer & Cooper, 2011). Based on age, all homes except the medium–high density suburb (MDS) flats, are modelled without cylinder or pipework insulation, resulting in higher internal gains. Finally, as a majority of homes from the public transport suburb (PTS) and social housing suburb (SHS) neighbourhood have high albedo rendered facades, the homes were modelled to have a white rendered surface with a solar absorptance value of 0.2 (as opposed to 0.7). For axonometrics, plans and room dimensions of the homes, see Appendix A.

All homes are given ventilation rules which open the windows only when occupants are at home (during specific room occupancy times; Table 4) and when the internal temperature is above 22°C. For overheating analysis, the adaptive thermal comfort standard for free-running buildings in BS EN 15251 is used, specifically Category II described as the 'normal level of expectation' range for thermal comfort (BSI, 2008). This method, as opposed to stationary thermal comfort indicators, is dynamically linked to the external temperature and allows the analysis of thresholds to fluctuate with the change that is expected in future projections. To demonstrate this, the Category II upper level thresholds for the probabilistic ranges in Oxford are presented in Table 5 and Figure 5 for the months of June–August.

Adaptation testing

The following steps outline the process for evaluating the impact of climate change and selecting effective adaptation strategies as a response:

- establish the extent of overheating as a result of climate change
- assess the reasons and origins of overheating in the dwelling(s)
- survey a list of adaption options and formulate and test adaptation packages created around:

Table 3 Home occupancy details

Occupant variables	Occupant variable details	Occupancy pattern
Two adults, two children	Two working adults with two children in school	23:00–07:00 bedroom 1 23:00–07:00 bedroom 2 18:00–22:00 living room
Pensioners	Two pensioners at home most of the time	23:00–06:00 bedroom 08:00–22:00 living room

Note: All simulation was performed using the two adults and single child variable except where noted otherwise.

Table 4 Construction details for all case study homes

Construction	Materials	*U*-value (W/m^2 K)	1	2	3	4	5	6
Glazing	uPVC double glazing	2.0	×	×	×	×	×	×
Internal and party walls	16 mm plaster, 105 mm brick, 16 mm plaster	n.a.	×	×	×	×	×	×
Internal floors	10 mm plasterboard, 200 mm cavity (floor joists), 20 mm timber flooring, 10 mm carpet	n.a.	×	×	×	×	×	×
Roof	10 mm plasterboard, 100 mm glass fibre quilt, loft space, 7 mm tiling board, 10 mm roofing tiles	0.35	×		×	×	×	×
Ground floor (1900–1944)	Clay soil, 150 mm cavity, 100 mm cavity (floor joists), 20 mm timber flooring, 10 mm carpet	1.4	×		×	×		
Ground floor (1950–1976)	Clay soil, 100 mm concrete slab, 38 mm floor screed, 10 mm carpet	1.4					×	×
External walls (1900–1919)	105 mm brick, 105 mm brick, 16 mm plaster	2.0	×		×			
External walls (1930–1976)	105 mm brick, 50 mm cavity, 100 mm concrete clock, 16 mm plaster	1.4				×	×	×
External walls (2002–2006)	105 mm brick, 70 mm insulation, 100 mm concrete block, 16 mm plaster	0.35		×				

Note: 1 = IHS (Inner Historic Suburb), 2 = MDS (Medium-high Density Suburb), 3 = GCS (Garden City Suburb), 4 = PTS (Public Transport Suburb), 5 = CRS (Car Suburb), 6 = SHS (Social Housing Suburb).
Source: University of the West of England (UWE) (2006).

- specific approaches to respond to overheating
- a low-carbon retrofitting approach

Climate change impact: overheating

To assess the climate change impact on overheating risk, simulation was performed for each home for the months of May–September. The living rooms and bedrooms 1 and 2 in each home were analysed to assess the overheating risk. All living rooms are located in the front of the home on the ground level; therefore, the direction of glazing in the living room corresponds with the orientation of the home. The living room results are presented in Figure 6 and the bedroom results, showing minimal threshold exceedance, are presented in Table 6. According to Figure 6, all homes (except those in Stockport) overheat in the 2050s climate period. Overheating in Stockport is technically resolved by natural ventilation alone. The inner historic suburb (IHS) mid-terrace and the GCS (garden city-type suburb) semi-detached overheat at 2030 High emissions 90% probability and overheat for the probabilistic range of the 2050s. These homes, specifically because of the projected climate in the south, are at the greatest risk.

The PTS semi-detached although in Oxford, where higher future temperatures and solar radiation are projected (Eames *et al.*, 2011), exhibits lower overheating risk than the IHS mid-terrace for three reasons:

- PTS has a northwest orientation whereas IHS has a southwest orientation (table 7)
- PTS has a highly reflective facade (PTS facade simulated at 2050 High emissions 90% probability with a solar absorptance value of 0.7 resulted in 13.5% of occupied hours overheated; as opposed to 12%)

Table 5 Category II overheating thresholds for all projections simulated

Current	2030 Medium 50% probability	2030 High 90% probability	2050 Medium 50% probability	2050 High 90% probability
26.5–27.7	26.0–29.1	27.4–29.8	26.7–29.2	27.8–30.7

Note: Data are from future weather file WG 4550210 DSY (Oxford), and Eames Kershaw, & Coley (2011).

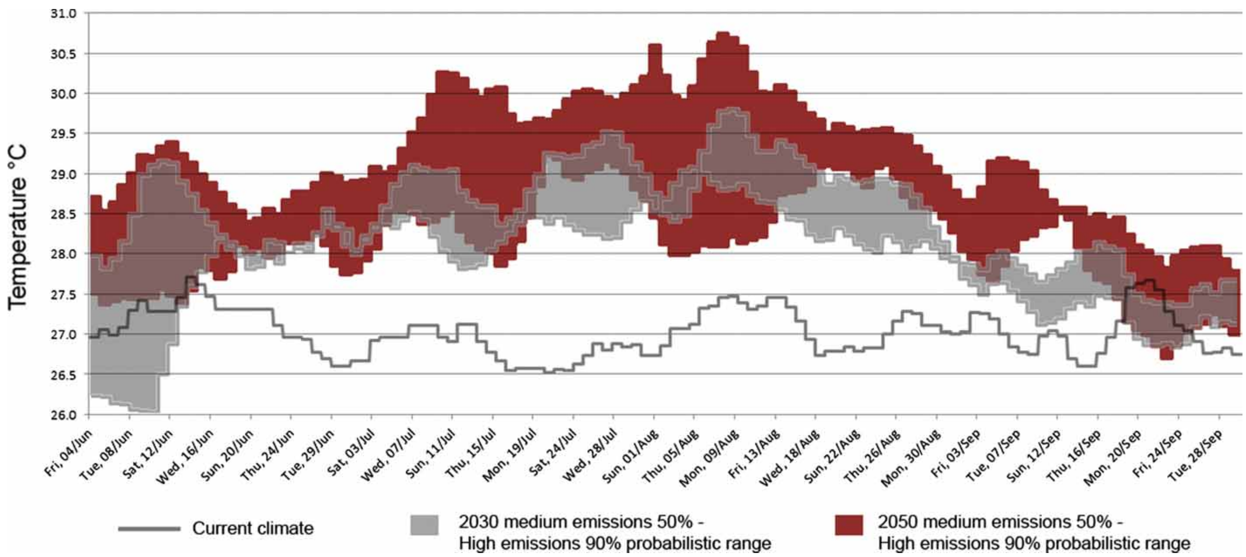

Figure 5 Upper level thermal comfort thresholds for the current and future probabilistic ranges selected to represent climate change for the 2030s and 2050s. Sources: data from future weather file WG 4550210 DSY (Oxford), and Eames Kershaw, & Coley (2011)

- mid-terrace homes generally have a greater risk of overheating as related to the semi-detached form (Gupta & Gregg, 2012)

The latter point is exhibited in a line graph (Figure 7) where the GCS semi-detached home was simulated using the Bristol weather data (2050 High emissions 90% probability) and the same orientation as the IHS mid-terrace. The two homes already have the same occupancy and construction characteristics. The living room of the semi-detached home simulated in the above described context had an overheating percentage of 7.9%, whereas the mid-terrace home has an overheating percentage of 14.9%.

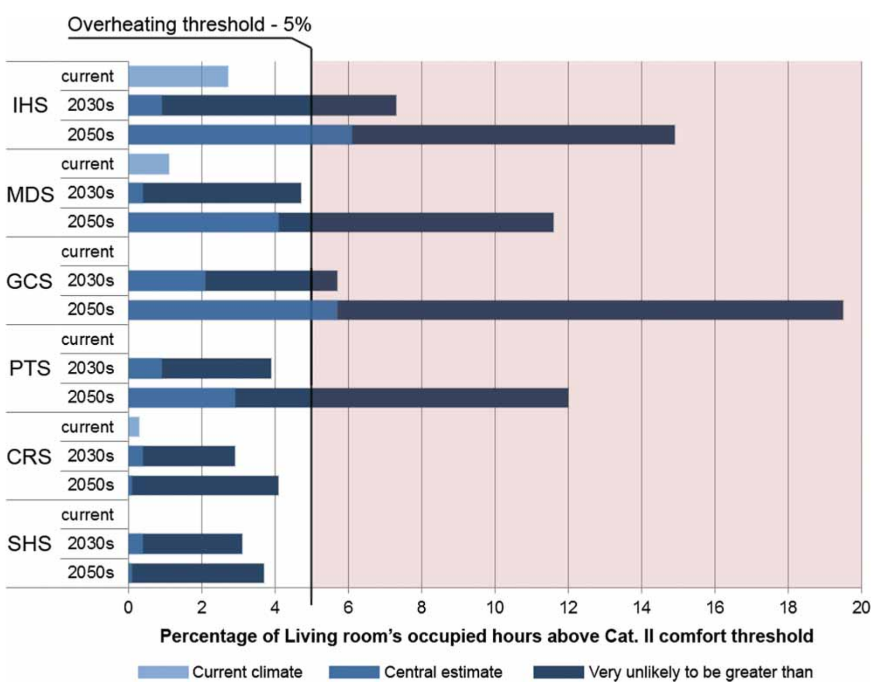

Figure 6 Probabilistic overheating results for the living room of all homes measured as the percentage of occupied hours above the Category II threshold for all climate periods and projections. Note: Central estimate = 50% probability, and Very unlikely to be greater than = 90% probability.

Table 6 Probabilistic overheating results for the bedrooms of all homes measured as the percentage of occupied hours above the category II threshold for 2030 High emissions 90% probability and 2050 High emissions 90% probability

	IHS		MDS		GCS		PTS		CRS		SHS	
	B1	B2	B1	B2	B1	B2	B1	B2	B1	B2	B1	B2
2030 High 90%	0.1	0	0.1	0.1	0.5	0.4	0.2	0.2	0	0	0	0
2050 High 90%	0.2	0.3	0.3	0.2	1.2	1.1	0.5	0.4	0.1	0	0	0.1
Room orientation	NE	SW	SE	SE	SE	NW	NW	SE	SW	NE	NE	SW

Note: IHS = Inner Historic Suburb), MDS = Medium Density Suburb, GCS = Garden City Suburb, PTS = Public Transport Suburb, CRS = Car Suburb, SHS = Social Housing Suburb.

According to Table 7, a west-facing orientation will result in the greatest percentage of overheating relative to occupied hours. The analysis is based on occupancy hours in specified locations, so it is a logical outcome that the greatest overheating percentage would occur where the incident solar radiation is penetrating the glazing of the occupied space immediately before and during occupied hours.

The MDS flat as compared with the IHS mid-terrace is at less overheating risk for two reasons:

- the flat is a newer construction with reduced internal gains
- the flat has a northwest orientation as opposed to a southwest orientation

Occupancy variation

Table 8 compares a change in occupancy. The occupancy of two adults with children with a use pattern of being away during the day and occupying the living room in the evening is subject to a greater percentage of overheating than the pensioners' occupancy profile. For the pensioners there is a greater percentage of the occupied time spent in the living room which is not overheated. If this were instead measured simply as hours of threshold exceedance, then the pensioners' scenario would show a considerably higher count as is shown below and in Gupta & Gregg (2012) and Porritt *et al.* (2012). Table 8 suggests that using percentages of occupied hours to indicate overheating risk may not be appropriate for immobile or otherwise vulnerable occupants.

Shaded variation

Figure 8 displays a representative week of overheating in the living room of the GCS semi-detached for two variations. The variations represent the exposed condition which is the baseline model without tree cover and a condition where there are trees in the front garden. The trees tend to reduce the time the interior temperature is above the threshold and reduce the peak to a smaller degree. The percentage of occupied time overheated in the living room for the model with the trees is 16.0%, whereas the baseline percentage is 19.5%.

In summary, a higher likelihood of overheating in a home is attributed to a combination of characteristics and cannot simply be attributed to individual factors. However, when all but one variable can be identical or closely matched, the following variables can be identified, *e.g.* built form, orientation, occupancy pattern, internal gain, albedo of external material (solar radiation impact), and extent of shading. As a result of the assessment of the overheating and adaptation effectiveness throughout the SNACC project (including overheating analysis above), methods for passively cooling dwellings can be summarized in

Table 7 Probabilistic overheating results in the living room comparing different frontal orientations for the public transport suburb (PTS) semi-detached home measured as the percentage of occupied hours above the Category II threshold for the 2050s High emissions 90% probability

2050 High 90% probability	North	Northwest	West	Southwest	South	Southeast	East	Northeast
IHS	11.7	14.1	15.1	<u>14.9</u>	13.7	14.9	14.6	13.6
PTS	10.0	<u>12.0</u>	12.9	12.7	11.7	12.7	12.4	11.6

Note: The dominate orientation is underlined. values are percentages.

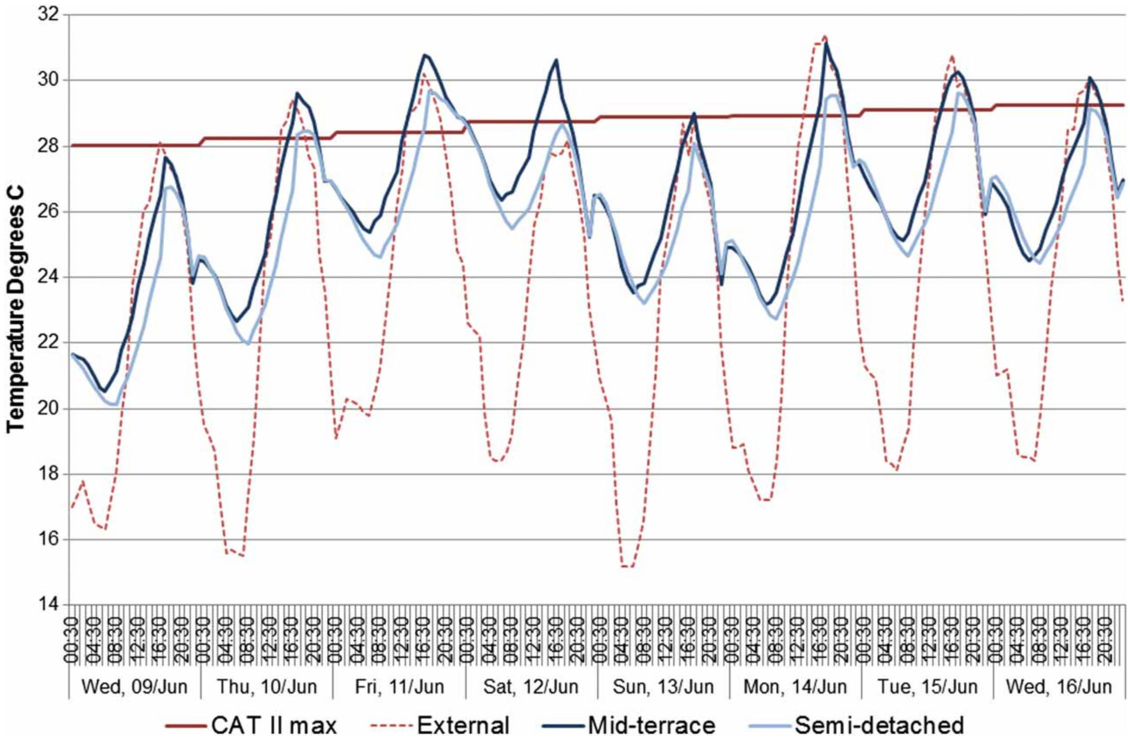

Figure 7 One representative week of living room temperatures in a mid-terrace and semi-detached home modelled with identical occupancy patterns, construction details and orientation; simulated in Bristol at 2050 High emissions 90% probability

three key principles (Gupta & Gregg, 2012; Williams *et al.*, 2012):

- reduce external temperatures by managing the microclimate (non-fabric changes)
- exclude or minimize the effect of direct or indirect solar radiation into the home (fabric changes)
- limit or control heat within the building (*e.g.* reduced internal gains or manage heat with mass) (can include ventilation)

Adaptation for a changing climate

The SNACC project is concerned with the passive adaptation of suburban environments to climate change including mitigation of further change. To reduce the risk of overheating in the home through passive measures, adaptive changes in line with the principles above will need to be made to the homes. Table 9 lists passive adaptation measures by others that have been either field tested or simulated for hot climates or for the future projected climate in the UK. The measures selected for evaluation in this study are listed in the right column. These measures are a combination of typical low-carbon retrofit measures and measures considered to be potentially effective based on the overheating analysis in the previous section.

Minimize the effect of solar radiation

From a number of studies looking at the reduction of overheating, shading is considered to be most effective in reducing overheating, followed by increased surface reflectance (high albedo) (Ford *et al.*, 2007; Gupta & Gregg, 2012; Porritt *et al.*, 2012). As high albedo surfaces are effective in reducing overheating, this measure is highly recommended but should be bundled with a full insulation package to cover the loss of winter solar irradiance (Gupta & Gregg, 2012; Porritt *et al.*, 2012). The adverse impact of high albedo surfaces on space heating requirements also suggests adaptation could be phased, where immediately, for example, a retrofit would involve full insulation and user-controlled shading. When the change in climate naturally eventually reduces space heating demand and increases overheating, then the external walls and roof could be upgraded with high albedo surfaces.

Management of internal heat

The UK climate is projected to remain a heating-dominated climate. Therefore, to align adaptation with current CO_2 reduction efforts, the use of insulation will remain a significant measure (Collins, Natarajan, & Levermore, 2010). The authors' previous simulation

Table 8 Probabilistic overheating results comparing two different occupancy scenarios measured as the percentage of occupied hours above the Category II threshold for the 2050s High emissions 90% probability in the garden city-type suburb (GCS) semi-detached

	Percentage of the day occupied	Two adults, two children		Percentage of the day occupied	Pensioners (two adults)	
		Occupied % overheated	Total occupied hour count[a]		Occupied % overheated	Total occupied hour count[a]
Living	21	19.5	146	63	12.8	288
Bedroom 1	30–40	1.2	151	29	1.3	209
Bedroom 2	30–40	1.1	127	0	1.1[b]	200[b]

Notes: [a]Total hour count considers all hours in the space overheated during occupied hours.
[b]Bedroom 2 is not normally occupied in the pensioner scenario, however it is calculated as if occupied.

work has revealed that improved fabric *U*-values increased the probability of overheating in mid-terrace homes and flats but showed a potential decrease in overheating for semi-detached and detached homes in Oxford. Furthermore, the position of insulation (*i.e.* external or internal) is an essential consideration when attempting to mitigate overheating. Internal insulation (as opposed to external and cavity wall) is found to have a higher probability of overheating, whereas external insulation is found to be the lowest risk and in some cases will reduce overheating risk. Though external insulation can in some instances slightly increase the probability of overheating risk, the observed reduction in CO_2 emissions suggests that the measure is advisable (Gupta & Gregg, 2012).

Packaging adaptation measures

Packages were developed for the homes that approach the retrofit process with different aims. The packages (Table 10) were developed to assess how reducing heat gain from both internal and external sources will impact homes. A fabric approach to the adaptive retrofit is split into two packages, 1 and 2. The third package is a heating systems approach formulated to reduce internal gains alone. These packages allow a homeowner to focus on different aspects of the home individually or as a complete retrofit package (Package 4). Element *U*-values are based on 2010 Building Regulations (NBS, 2012). The fabric adaptation measures are relatively modest because it is possible that lower insulation levels will be sufficient in a

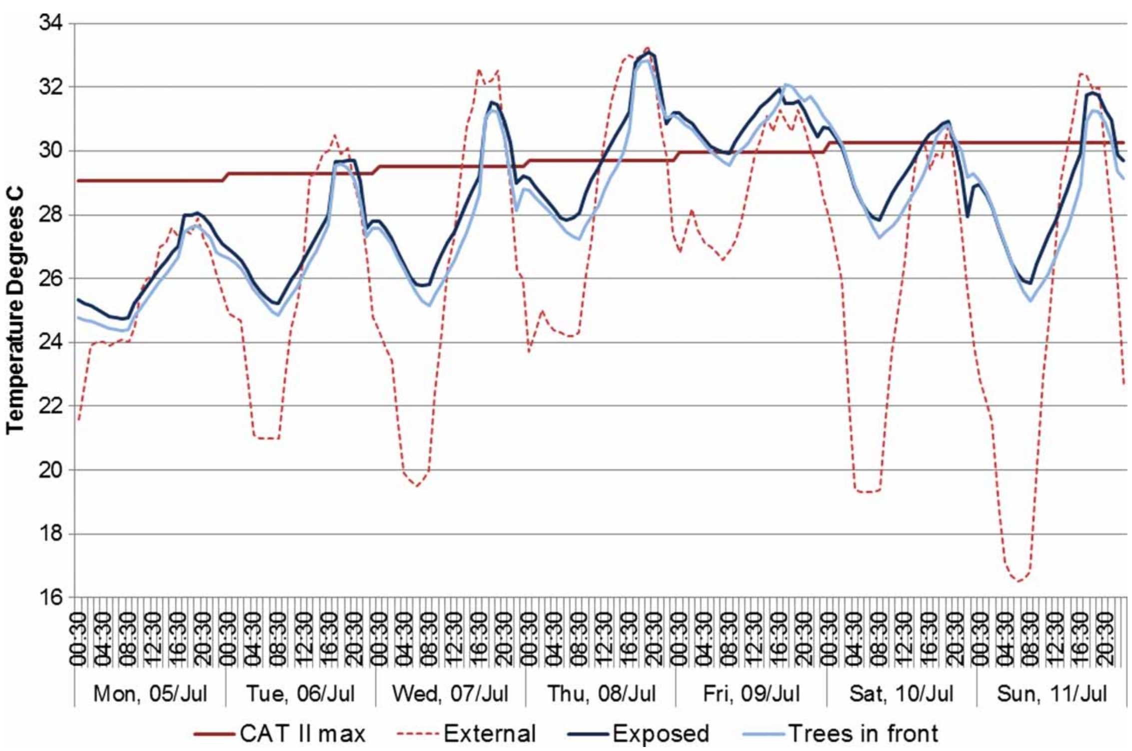

Figure 8 One representative week of living room temperatures in the garden city-type suburb (GCS) semi-detached home modelled with and without trees in the front garden; simulated in Oxford at 2050 High emissions 90% probability

Table 9 Passive measures that have been shown to reduce temperatures (either alone or in packages) in otherwise overheated conditions in buildings through either simulation or field study

Passive measures	Hot, arid climates	Hot, humid climates	Projected English climate	Tested at home scale (IES VE)[f]
Personal				
Remove clothing (reduce clo-value)	Measures known to be effective in reducing the risk of heat related stress or worse (National Health Service (NHS), 2012)			
Increase hydration				
Use water to assist the skin with thermoregulation				
Seek a cool refuge outside of the home				
Home and proximity				
Daytime cross-ventilation (open windows)	–[a]		×	×[e]
Night ventilation	×	×[b]	×	×[e]
Reduce internal gains			×	×
Shading — Trees or deciduous vegetation	×	×	×	
External shading devices, *e.g.* louvers, fixed horizontal and vertical, porches, and awnings	×	×	×	×
Internal shading devices, *e.g.* curtains and blinds			×	
External wall insulation			×	×
Loft insulation			×	×
Floor insulation				×
Decreased floor insulation (limited to the perimeter)		×		
Solar selective low-e glazing			×	
High albedo surfaces	×[c]	×	×	×
Thermal mass	×	×[d]	×	
Passive ground cooling		×		
Passive downdraught evaporative cooling	×			
Enclosed courtyard	×	×		

Notes: Where a box is crossed it does not indicate that the measure does not work or has never been evaluated.
[a]At times the air can be so hot that daytime ventilation is not beneficial.
[b]Dehumidification required at times.
[c]Greater impact in hot, arid climates.
[d]Thermal mass was found to be effective in some instances; however, night ventilation purging is essential and effectiveness would depend on the ability to night-ventilate.
[e]Ventilation was already a consideration in the overheating analysis as it is assumed occupants already do this to mitigate overheating.
[f]Integrated Environmental Solutions – Virtual Environment.
Sources: Givoni (1998), Gill, Handley, Ennos, & Pauleit (2007), Ford, Schiano-Phan, & Zhongcheng (2007), Three Regions Climate Change Group (2008), Peacock, Jenkins, & Kane (2010), Sadafi, Salleh, Haw, & Jaafar (2011), Berkovic, Yezioro, & Bitan (2012), Ford *et al.* (2012), Porritt, Cropper, Shao, & Goodier (2012), and Sanusi, Shao, & Ibrahim (2012).

future climate (Ford *et al.*, 2007). Optimal insulation values in a changing climate are a crucial subject of future research.

Figure 9 indicates the impact of the adaptation packages on all homes. Notably, combining all adaptation measures (Package 4) is found to be most effective in reducing overheating for all homes. For most homes, Package 1 is the most effective stand-alone package and is also potentially the most expensive due to the external wall insulation (Energy Saving Trust (EST), 2012). Package 3, potentially the least expensive, is most effective in smaller homes where the reduction is most needed, homes like IHS and SHS. The other homes (with the exception of the modern construction flat), in contrast, have living spaces segregated from the service areas or have either larger windows or more exposed external walls for heat loss. In Bristol, Package 4 is successful in mitigating overheating for the IHS mid-terrace but the MDS flat is just over the line. Considering the similar characteristics (post-retrofit) and the northwest orientation of the flat over the southwest orientation of the mid-terrace, this would indicate that the flat might be at greater risk of overheating.

Table 10 Adaptation packages modelled in Integrated Environmental Solutions (IES) and the changes to construction details

	Construction changes	Material descriptions	U-value (W/m^2 K)
Package 1: Wall retrofit	External insulation added to external walls	1900–1919: **70 mm external insulation**, 105 mm brick, 105 mm brick, 16 mm plaster	0.30
		1930–1976: **65 mm external insulation**, 105 mm brick, 50 mm cavity, 100 mm concrete clock, 16 mm plaster	0.30
		2002–2006: **12 mm external insulation**, 105 mm brick, 70 mm insulation, 100 mm concrete block, 16 mm plaster	0.30
	Solar reflective (high albedo) coating added to the external walls	**Render surface is applied to the external insulation with a solar absorptance value of 0.2**	No change
	Louvered shutter shading applied to double glazing	**Occupant-operated shading**: windows shaded during daylight hours outside of the heating season	No change
Package 2: Roof/floor retrofit	Ground floor	1900–1949: Clay, 150 mm cavity, **100 mm insulation** (floor joists), 20 mm timber flooring, 10 mm carpet	0.25
		1950–1976 (No change): clay soil, 100 mm concrete slab, 38 mm floor screed, 10 mm carpet	No change
	Roof–loft insulation tripled	10 mm plasterboard, **300 mm glass fibre quilt**, loft space, 7 mm tiling board, 10 mm roofing tiles	0.16
	Solar reflective (high albedo) coating added to the roof	**Surface coating is applied with a solar absorptance value of 0.2**	No change
	Louvered shutter shading applied to existing glazing	**Occupant-operated shading**: windows shaded during daylight hours outside of the heating season	No change
Package 3: Heating systems retrofit		Internal gains reduced: **insulation for the hot water tank (80 mm jacket)** and a further 100 W reduction via **primary pipework insulation and cylinder temperature controls**	n.a.
Package 4: Full retrofit		Combination of all the changes listed above	n.a.

Note: Specific changes to the construction are noted in bold. All packages include natural ventilation.

The Oxford climate clearly presents the greatest overheating risk. The GCS semi-detached house with a southeast orientation is showing a higher risk of overheating as opposed to the northeast-facing PTS semi-detached. To explore the effectiveness of the adaptation packages in Oxford, Figure 10 shows all homes with a south orientation at the 2050s probabilistic range in Oxford with Package 4 applied. The graph indicates a hierarchy of risk for built-form being detached, semi-detached, mid-terrace and flat.

Mapping the results

A method explored in the SNACC project for visualizing the impact of future overheating and adaptation effectiveness on a stock level (here case study neighbourhoods), through a spatial mapping approach based on urban energy modelling, is DECoRuM-Adapt (Gupta, 2009; Williams *et al.*, 2012). This stock level approach is especially useful for planners, policy-makers and local decision-makers to assess overheating risk when planning for Green Deal[5] implementation for neighbourhoods or local authority districts. For every home on the maps, actual home and neighbourhood characteristics are gathered from historic and current maps, on-site assessment, home occupant questionnaires, and literature describing home characteristics based on age and form (UWE, 2006; DCLG, 2012a, 2012c; Digimap, 2012). These are input into the DECoRuM-Adapt model which identifies homes at risk of overheating using a crude (but government-approved) calculation method reinforced with high risk property characteristics as revealed through the dynamic thermal simulation.

DECoRuM (Domestic Energy, Carbon Counting and Carbon Reduction Model) is a GIS-based toolkit for carbon emissions reduction planning with the capability to estimate current energy-related CO_2 emissions and effectiveness of mitigation strategies in existing UK

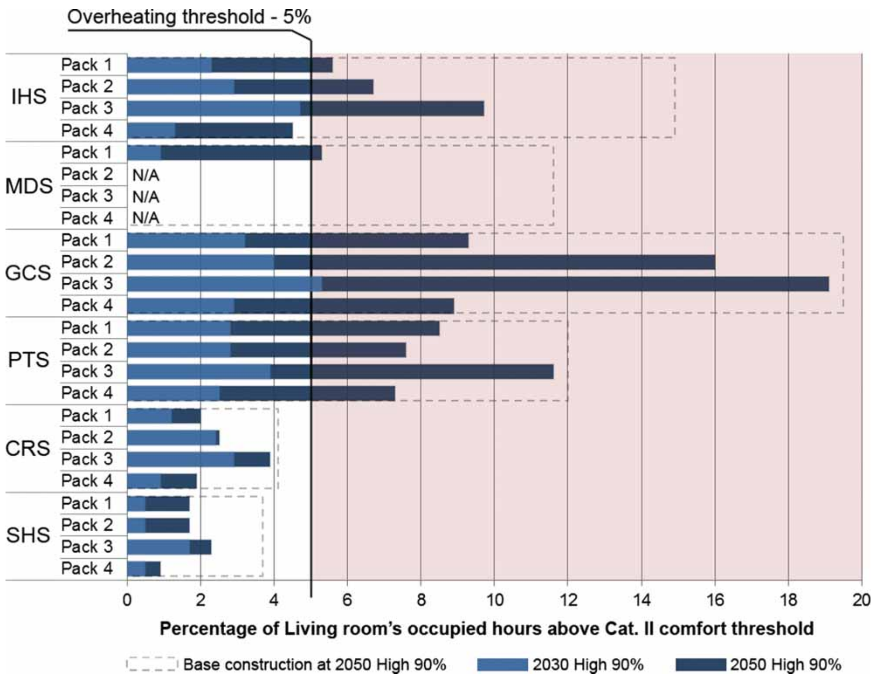

Figure 9 Post-adaptation probabilistic overheating results for the living room of all homes measured as the percentage of occupied hours above the Category II threshold for all climate periods and projections

dwellings, aggregating the results to a street, district and city level (Gupta, 2008, 2009). The aggregated method of simulation and map-based presentation allows the results to be scaled up for larger application and assessment. For the SNACC project DECoRuM was further developed as DECoRuM-Adapt to assess rapidly the impact of climate change on energy use and comfort. The background calculations of

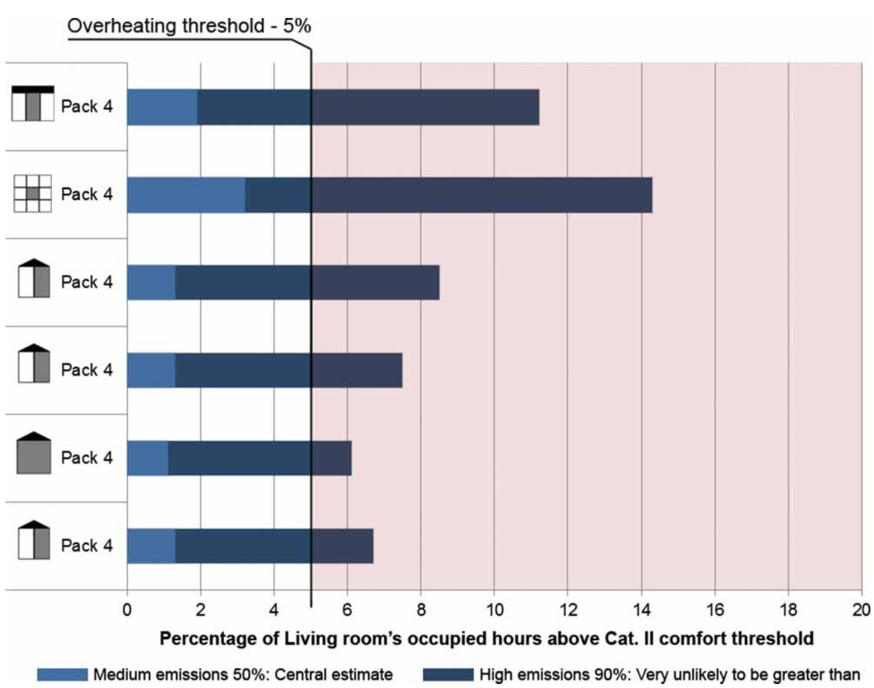

Figure 10 Probabilistic overheating results for the living room of all home types south facing measured as the percentage of occupied hours above the Category II threshold for the 2050s probabilistic range in Oxford after the application of Package 4

DECoRuM are performed by BREDEM-12 and SAP 2009,[6] both of which are dynamically linked to create the model and perform the analysis. For detailed information on how DECoRuM is assembled, data are collected and calculations performed (Gupta, 2009; Williams *et al*., 2012).

Figure 11 is a matrix of mapped results for the case study neighbourhoods. As the overheating results behind the maps are aggregated from typical domestic stock examples, there is an additional level of uncertainty. This uncertainty is denoted by the terms *less likelihood* or *high likelihood* of overheating. These maps in combination with detailed home simulation findings for age and dwelling types can be useful for localized decision-making on what adaptations are most effective for large-scale application. A notable limitation is occupancy consideration. As was demonstrated in the analysis above, there are potentially more vulnerable occupancy profiles which are at greater risk of overheating. Unless the occupancy of each individual home in a neighbourhood is known, the maps are developed using default occupancy profiles. In the case of this study, the occupancy matches that used for the individual home simulation.

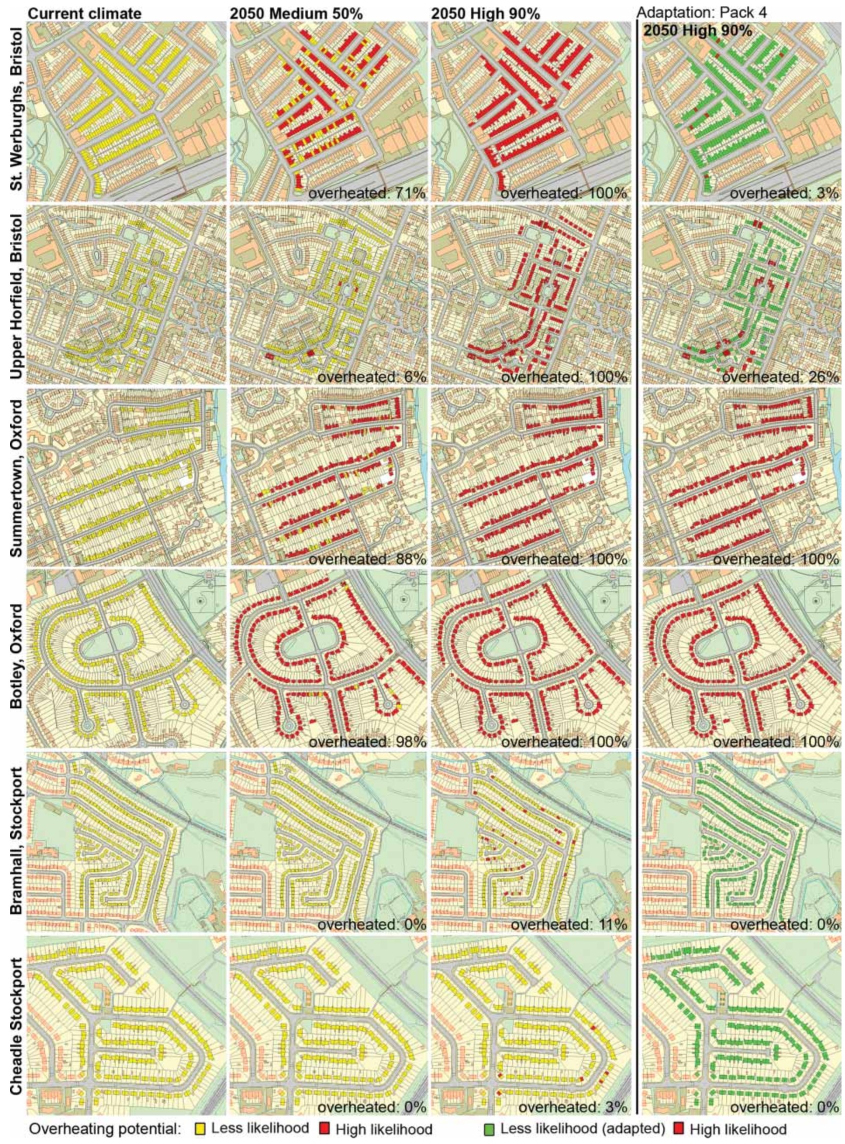

Figure 11 Overheating and adaptation effectiveness maps for St.Werburghs and Summertown overheating mapped for current climate, 2050s probabilistic range and adaptation for 2050s High emissions 90% probability. Source: Digimap (2012). Map © Crown Copyright/database right 2012. An Ordnance Survey/EDINA supplied service

Discussion

According to the above study, existing detached and semi-detached homes in Stockport and other suburban homes in the North of England should be at lower risk of overheating throughout the 2050s provided natural ventilation is possible without concern for noise, local pollution or security. In contrast, Package 4, the most effective package across the board, will not mitigate overheating risk for all dwelling types simulated in Oxford by the 2050s when conditions reach those that are *very unlikely to be surpassed* (Figure 10). These homes and others like them in the South East of England may require mechanical cooling systems or community cool spaces for vulnerable residents. As the overheating percentage *very unlikely to be surpassed* throughout the 2030s climate period is successfully mitigated by packaged adaptation, more complex, mechanical systems to cope with the difficulty presented for the 2050s climate period can be phased in at a later time if necessary. As Figure 10 indicates, future climate projections are probabilistic and it should be emphasized that the homes are showing low risk in the *central estimate* at medium emissions and high risk at high emissions where the outcome is *very unlikely to be greater than* the projected value.

Findings from this research have significant implications for public policy. It is suggested that just as the Zero Carbon Hub's Fabric Energy Efficiency Standard[7] (consultation for the UK's future Building Regulations) provides prescriptive CO_2 emission rates along with semi-prescriptive *U*-values, prescriptive projected future summer thermal comfort boundaries such as those given in BS EN 15251 (BSI, 2008) should also be considered to avoid future overheating in all new-builds (DCLG, 2012b; Zero Carbon Hub, 2009).

Furthermore, as the Green Deal implementation programme is soon to be initiated in the UK, there is a growing need to identify and prevent overheating in properties to be retrofitted. It is vital to alert Green Deal assessors, providers and installers to the risk that some retrofitting measures, in certain situations, may cause homes to overheat, as an impact of a warming climate. Some of the high-risk property characteristics as revealed through the dynamic thermal simulation include:

- *Built form:* flats are identified as being at highest risk followed by mid-terrace homes.
- *Fabric characteristics:* examples such as internally insulated homes, homes with dark-coloured facades, and large exposed areas of glazing.
- *Orientation and exposure:* homes with east or west orientation, and homes on streets with less tree cover are especially problematic for daytime occupied dwellings. South-facing rooms can also experience overheating but are easier to shade from the high angle summer sun.
- *Occupancy and behaviour:* as explained in the analysis, an occupant who stays at home all day will experience more overheating than an occupant who is not. With certain adaptations that depend on user control, *e.g.* opening windows for ventilation and adjusting shading elements, the immobile and highly vulnerable will likely have more difficulty avoiding overheated conditions.
- *Limited ventilation:* where noise and security issues may discourage the use of window opening for cooling.

Adaptation measures and packages, if implemented at the same time as the Green Deal measures, can significantly reduce the risk of overheating. Minimizing the effect of direct or indirect solar radiation into the home (fabric changes) and limiting or controlling heat within the building (*e.g.* reduced internal gains or managing heat with thermal mass and ventilation) tend to be most effective. More specifically:

- External shading is tremendously effective in reducing overheating in homes. This shading can take many forms, but for optimal seasonal effectiveness (*i.e.* not reducing winter solar gain) it is suggested that shading elements be user-operated. This could potentially require a new level of occupant interaction with the home.
- External insulation is the most effective insulation for reducing overheating risk. Internal insulation, on the other hand, is least effective in reducing overheating and is projected in most cases to lead to more overheating. This will most likely be a conflict when considering the cost limitations of the Green Deal.
- Existing internal gains could potentially be an underappreciated source of significant overheating in older homes. Proper insulation of systems like the hot water tank can be beneficial both for mitigation of overheating and CO_2 emissions.

No doubt consensus needs to be achieved on which emissions scenario and probabilistic range should be used to assess the risk of future overheating when evaluating the impact of various retrofitting interventions on energy consumption.

Conclusions

The adaptation and mitigation of climate change in UK suburban homes should be considered together as many measures to address these concerns are mutually beneficial. Although the UK is projected to remain a heating-dominated climate, wherein improving the thermal properties of the building fabric will be essential, other adaptive measures to reduce the risk of future overheating at a house level are urgently needed. A fabric-based future-proofing approach comprising both mitigation and adaptation measures (*i.e.* wall, roof and floor insulation, shading with shutters and high albedo surfaces) is recommended for the large-scale refurbishment of existing housing.

As the current UK Building Regulations and retrofitting programmes are primarily concerned with heat retention (and CO_2 reduction), it is essential that the implementation of the Green Deal and future revisions to Building Regulations tackle the risks of, and potential for adapting to, climate change-driven overheating to ensure a comfortable environment for occupants now and in the future. In the South East of England, implications of increased mechanical cooling on future energy use and grid strain should be investigated further by both the building and the energy sectors.

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Endnotes

[1]SNACC is a UK Engineering and Physical Sciences Research Council (EPSRC)-funded three-year consortium-based project with the objective 'to identify effective, practical and acceptable means of suburban re-design in response to climate change projections'.

[2]The emissions scenarios represent different paths of economic, technological, energy intensity and social change in the 21st century. The Intergovernmental Panel on Climate Change (IPCC) suggests that the emissions scenarios do not relationally have probabilities and that they are non-interventionist. The Medium emissions scenario (SRES A1B) represents a future of very rapid economic growth and population increase with an intermediate use of non-fossil fuel energy sources; the High emissions scenario (SRES A1FI) represents the same scenario but with intensive fossil fuel use (Warren, 2010).

[3]Probabilities used by the IPCC and UKCP09 represent the relative degree to which a possible climate outcome is supported by the evidence. In the cumulative distribution curve, 50% probability is the median of the distribution (also referred to as the *central estimate*) and 90% probability provides a value where an outcome is *very unlikely to be greater than* the projected value (Murphy *et al.*, 2010).

[4]The DSY represents a year with a hot, but not extreme, summer. It is a single year of hourly data that was selected from 1961 to 1990 for the current condition and UKCP09 generated 30-year datasets for future climate periods. The DSY format is typically used by UK building professionals to assess summer overheating levels (Eames *et al.*, 2011).

[5]The Green Deal is a UK government initiative that provides private investment in the carbon reduction of the existing building stock. Energy efficiency improvements will be offered by the private sector to homeowners and businesses at little or no upfront cost with payment recouped through customers' energy bills (Department of Energy and Climate Change (DECC), 2012).

[6]The UK Building Research Establishment's Domestic Energy Model (BREDEM-12) combined with the government-approved Standard Assessment Procedure (SAP) 2009 home energy rating methodology are the underlying energy models in DECoRuM, which calculate annual energy use, fuel costs and CO_2 emissions (Gupta, 2008).

[7]FEES is a performance metric developed by task groups to be implemented in 2016 as a consultation for the improvement of building regulations. FEES resulted in individual standards developed for different dwelling types. For details, see Zero Carbon Hub (2009).

Appendix A

The modelled house forms are shown in Figures A1–A6. The dimensions and forms of all homes but Figures A3 and A4 are adapted from Allen & Pinney (1990) and Figures A3 and A4 are adapted from Rightmove (2011) and Digimap (2012). Figure A2 is modelled from an actual purpose-built flat based on the authors' measurements.

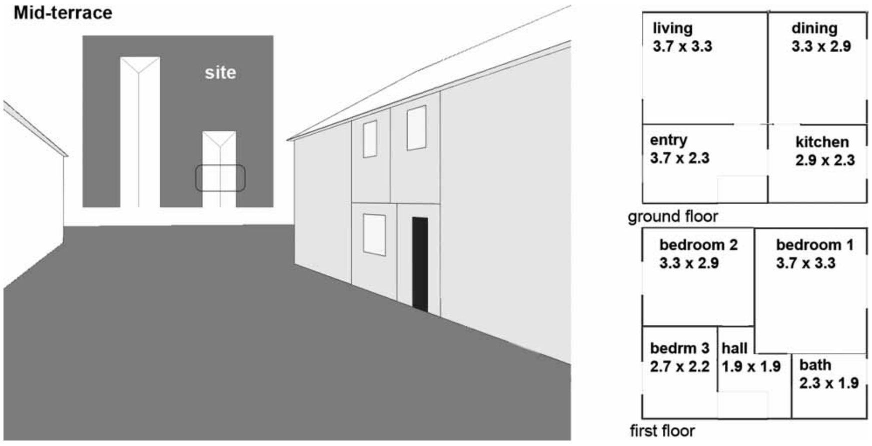

Figure A1 Perspective image, site plan and floor plans of the inner historic suburb (HIS) mid-terrace home. Source: adapted from Allen & Pinney (1990)

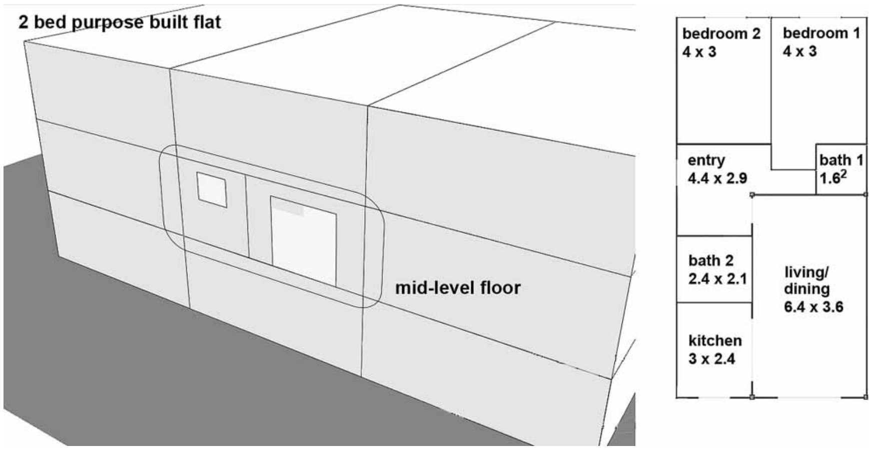

Figure A2 Perspective image, site plan and floor plans of the medium–high density suburb (MDS) flat

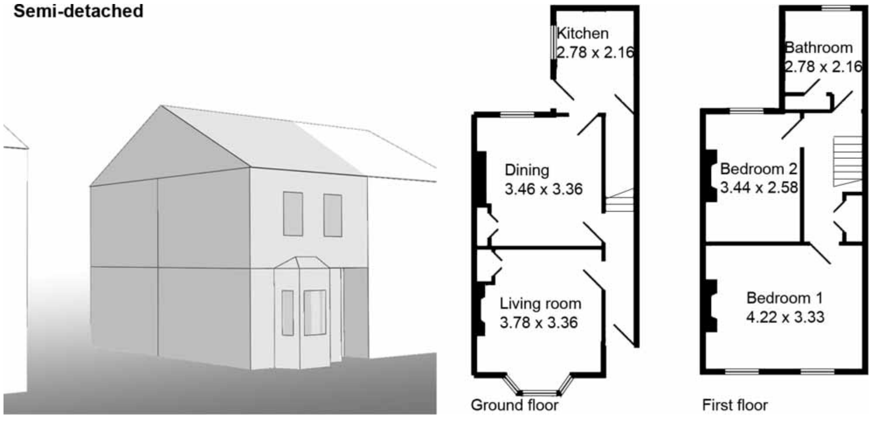

Figure A3 Perspective image, site plan and floor plans of the garden city-type suburb (GCS) semi-detached home. Source: plans redrawn from Rightmove (2011)

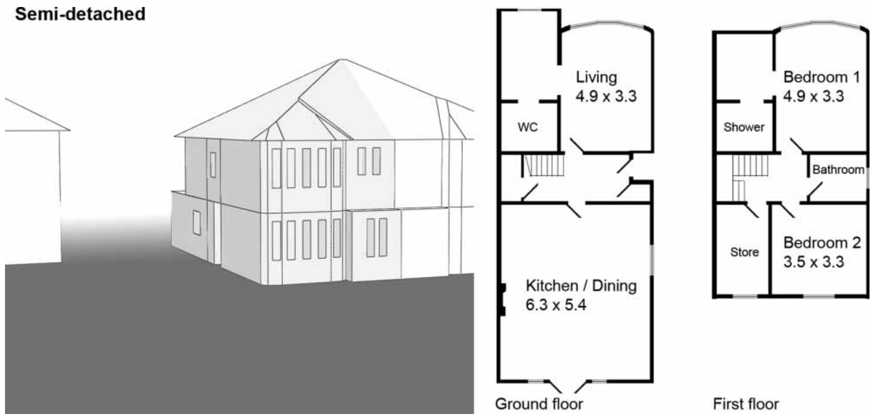

Figure A4 Perspective image, site plan and floor plans of the public transport suburb (PTS) semi-detached home. Source: plans redrawn from Rightmove (2011)

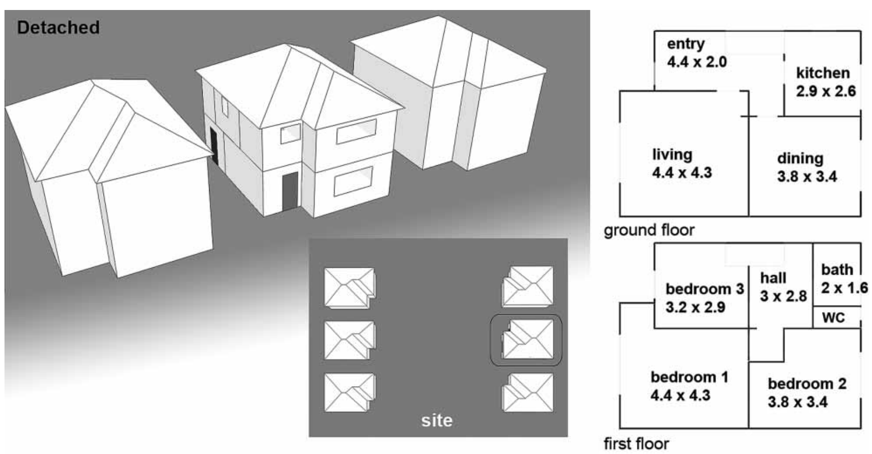

Figure A5 Perspective image, site plan and floor plans of the car suburb (CRS) detached home. Source: adapted from Allen & Pinney (1990)

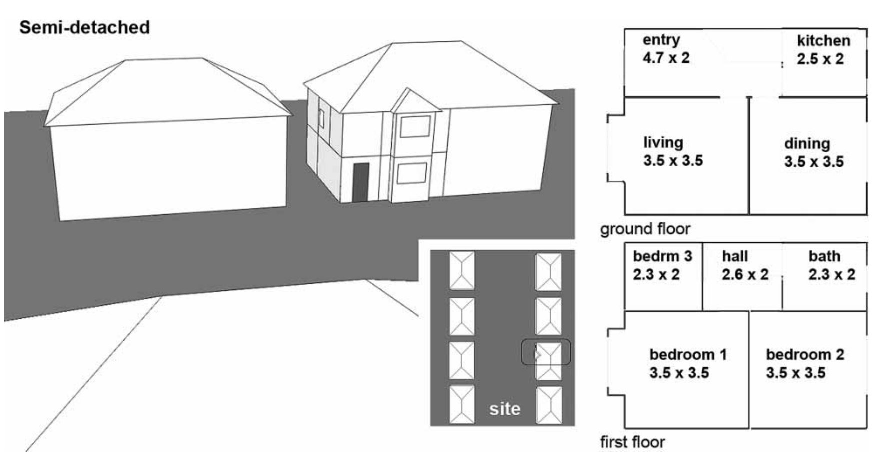

Figure A6 Perspective image, site plan and floor plans of the social housing suburb (SHS) semi-detached home. Source: adapted from Allen & Pinney (1990)