Using a simulation based approach to adapt the designs of zero carbon homes against a warming climate

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Abstract

Improved standards of air tightness, greater reliance on ventilation and increased levels of insulation especially in new build low and zero carbon homes in the UK, could lead to a rise in instances of overheating unless this is addressed during the early stage design. Indeed recent reports from DECC and the wider industry suggest that instances of overheating are already increasing, to be further exacerbated by predicted warming and climate impacts. This paper uses a dynamic simulation based approach to systematically evaluate the potential for incorporating adaptation strategies into the designs of zero carbon homes in the UK.

The approach adopted is based on risk analysis, which involves assessing the climate change impacts, exposure of the buildings and the needs and vulnerability of the occupants, to arrive at technically-feasible and practical adaptable measures, appropriate for a flagship eco-town development located in Bicester, Oxfordshire. Thermal models of ten house archetypes are built in IES and tested for current and future overheating using IES ApacheSim. A set of future weather data derived from UK Climate Projections 2009 is used to assess the risk of overheating under current climate and 2030s, 2050s and 2080s under a high emissions scenario and 50% probability. Modelling results of indoor temperature are compared with CIBSE Guide A and BS EN 15251 Standard overheating metrics. To tackle overheating, twenty seven individual passive design measures (ventilation, shading, fabric and orientation) are tested in IES model and the most effective measures are combined into three adaptation packages to conduct further testing. Detailed specifications of selected adaptation packages are then discussed with the project team, and incorporated into the design. The practical application of this work is that it creates a replicable methodological approach for adapting new low energy house designs against future climate change. It also helps policy makers and designers to understand the effectiveness of adaption measures in avoiding overheating now, and in the future.

Keywords low energy housing, overheating, climate change, future weather data, adaptation

1. Introduction

The impacts of climate change are being observed in many places around the world. For central England, the temperature has increased by about 1^{o}C since the 1970s[1]. The trend for further climate change is deemed to be unavoidable due to the present and past greenhouse gas emissions. The UK Climate Projection 2009, known as UKCP09, and based on sound science and projections provided by the Met Office, provides an opportunity to quantify the climate change impacts on building performance now, and in the future.

To limit the worst impacts of climate change, the UK government has set its target (the Climate Change Act 2008) [2] to reduce at least 34% in greenhouse gas emissions by 2020 and at least 80% by 2050, against a 1990 baseline. This commitment requires carbon reductions to be made by all sectors, including housing which is responsible for 27%of all UK CO_2 [3]. In 2006, Code for Sustainable Homes [4] was introduced to drive a step-change in sustainable home building practices. It requires that all new build homes in the UK must meet a ‘zero carbon’ standard in 2016. Recent research and publications have confirmed that the move towards zero carbon new homes [5-8] would involve a combination of higher insulation standards (of both opaque and transparent surfaces) and improved air tightness resulting in reduced infiltration rate [9-13], thereby increasing the risk of overheating (and associated health issues). Since these new houses are expected to last for 60-100 years, the risk of overheating is further exacerbated by a warming climate. The evidence of overheating in existing homes has already been reported by Lomas [14] and Gupta [15]. Rodrigues *et al.* [16] investigated the overheating potential in a low-energy steel frame house under future climate scenarios, and they found that there is a risk of overheating which is aggravated in future scenarios. Clearly ‘climate proofing’ new zero carbon homes at the design stage itself, is a big challenge for designers and researchers.

This paper explores the climate change impacts (in term of comfort) on new-built zero carbon homes, and (2050s and 2080s) evaluates the design solutions for tackling overheating now (2030s), and in future. Firstly a range of available overheating metrics are reviewed, and the CIBSE overheating metric is chosen since it is the most robust metric and is also widely used by practitioners. Ten typical house models (bungalow, flats, detached house, mid-terraced house and end-terraced house) are created in dynamic simulation software (IES VE) to test their performance under current and future climate condition without adaptation options. The *worst case*, a *south-facing end-terraced house* is selected for evaluating the performance of 27 individual adaption measures using IES thermal modelling. Three adaptation packages are developed to keep the end-terraced house (and the nine house types) within comfort range by 2080s, with minimal changes in existing design.

1.1 Overheating metrics for housing

‘Overheating’ for building space is defined as an environmental condition which exceeds the upper limit of thermal comfort standard. The first term related with thermal comfort, ‘wet-bulb temperature’, was introduced by Haldane in 1905 [17] , since then 71 terms have developed [18] to index stress and discomfort. The well-known and most widely used terms in industry are Operative Temperature and Predicted Mean Vote (PMV).

In general, all indices could be classified into two groups: cumulative value and instant value. The cumulative value is used to indicate the amount of time or/and the extent of discomfort during certain period, e.g. the hours over certain temperature during certain period; the discomfort degree-hours during certain period; Predicted Percentage Dissatisfied Index (PPD) weighted criterion[19]. The instant value is used to indicate discomfort situation at a particular time. Examples are PMV, Nicol *et al.*'s overheating risk [20]. This type of index is used to indicate the occurrence of overheating.

Another way of classification is the state of threshold (dynamic or fixed). The fixed threshold 26/28^{o}C of operative temperature is recommended by CIBSE Guide A [21]. For dynamic threshold, BS EN 15251 [22] standard suggested adaptive comfort standard which based on the daily running mean temperature. It is a running mean value calculated from outdoor dry bulb temperature. ASHRAE 55 [23] standard suggested adaptive comfort standard which based on the monthly mean temperature. Recently the CIBSE Overheating Task Force [20] suggests that the likelihood of discomfort is not related to a particular threshold but to *ΔT*, the difference between the actual operative temperature and the comfort temperature (based on the outdoor temperature).

Table 1 Available comfort metrics

Source	Description	Cumulative/instant value	State of threshold
CIBSE Guide A	Percentage of occupied hours over operative temperature of 26/28 ^{0}C	Cumulative	Fixed
BS EN 15251	Percentage of occupied hours over EN adaptive comfort upper limit	Cumulative	Dynamic(based on daily running mean)
ASHRAE standard 55	90%/80% acceptability based on ASHRAE adaptive comfort limit	Cumulative	Dynamic (based on monthly running mean)
ISO 7730	PMV and PPD indices	Instant	
Nicol's paper [20]	The difference between the actual operative temperature and the comfort temperature	Instant	

For all comfort standards, the exceedance allowance is an interesting value to discuss. E.g. CIBSE Guide A suggests 1% of occupied hours; Department of Health HTM 03-01 [24] suggests 50 hours per year; BS EN 15251 [22] standard suggests 3 or 5 percent of working hours or total hours. Borgeson and Brager [25] compared American [23], European [22] and Dutch NPR-CR 1752 [26] adaptive standard for mixed-mode buildings located in California climate zones. They found that comfort model choice significantly influences predicted exceedance and the results differed by 10 percentages. Lomas and Giridharan [27] examined BS EN 15251 adaptive comfort standard [22] for category I, II and HTM 03-01 standard [24] for hospital wards at Cambridge using both Test Reference Year and Design Summer Year data.

For building simulation practitioners, the climatic data feeding into simulation engine is another factor to influence the overheating assessment. CIBSE design summer year data are assigned to conduct CIBSE overheating assessment. No climatic information is given in other standards.

In summary, to conduct overheating assessment, an appropriate overheating risk criterion, a standardized calculation method, standardized climatic data and a standardized methodology are needed.

2. Research methodology

For this research project, the following approach has been developed to test adaptation strategies for avoiding overheating in the designs of zero carbon homes.

- Conduct climate risk assessment for the building site using UKCP09 Weather Generator (hazard, exposure, vulnerability triangle approach);
- Select housing archetypes from the project based on built form, orientation, construction and occupancy profile;
- Review relevant overheating metrics and select appropriate overheating metric for the project;
- Review suitable adaptation measures for the project drawing from current literature such as those mentioned in Design for Future Climate report [28] and grade each measure against the following criteria:
    - Measures already included in the design (1);
    - Measures that should be considered for inclusion in the design (2);
    - Measures that could be retrofitted in future but implication worth considering for present design to avoid compromising this possibility (3);
    - Measures that could be retrofitted in the future but need no action at present (4);
    - Measures not suitable for inclusion (5);
- Build detailed room level energy models in a dynamic simulation software such as IES ApacheSim and establish the overheating risk for the housing archetypes under current, 2030s, 2050s and 2080s climate;
- Test the performance of individual adaptation measures (categories 1, 2 and 3) on reducing the overheating risk in the energy models under current, 2030s, 2050s and 2080s' climate;
- If necessary, develop adaptation packages which combine the most effective individual adaptation measures and test them again in building model (s) under current, 2030s, 2050s and 2080s' climate;
- Conduct detailed design and specification for the most effective adaptation measures in collaboration with the design team;
- Deploy adaptation measures in the project;
- Monitor and evaluate the impact of the adaptation measures in practice, for continuous feedback and improvement.

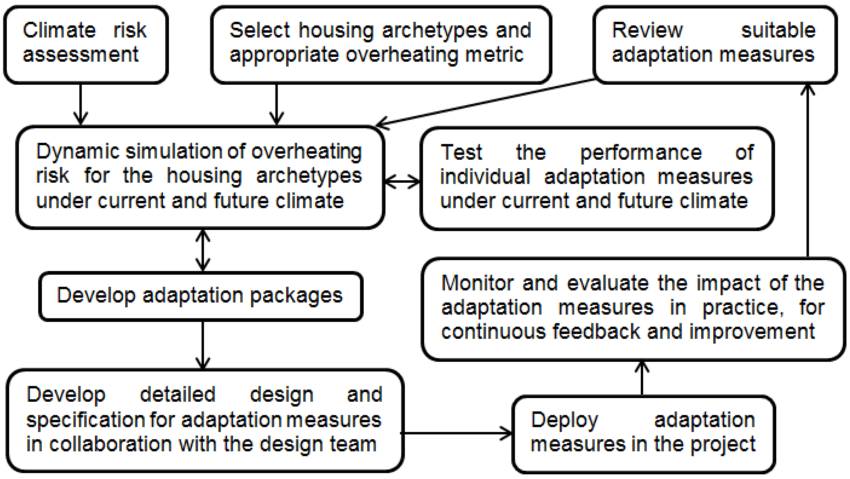

Figure 1 Research method of this work

3. Assessing the overheating risk in zero carbon homes in NW Bicester eco-town project

North West Bicester eco-town development is located on the North West fringe of Bicester in Oxfordshire. It is the UK's first eco-town project funded by DCLG. Cherwell District Council plans to build 5,000 new homes over next 20 years in this area. The first phase exemplar (denoted by light blue in figure 2) of North West Bicester, which expects to have first residents in summer 2013, includes 393 zero carbon homes (including 119 affordable homes), a primary school, a local shop, an eco-pub and a community centre. House designs from the first phase are tested for overheating in this paper.

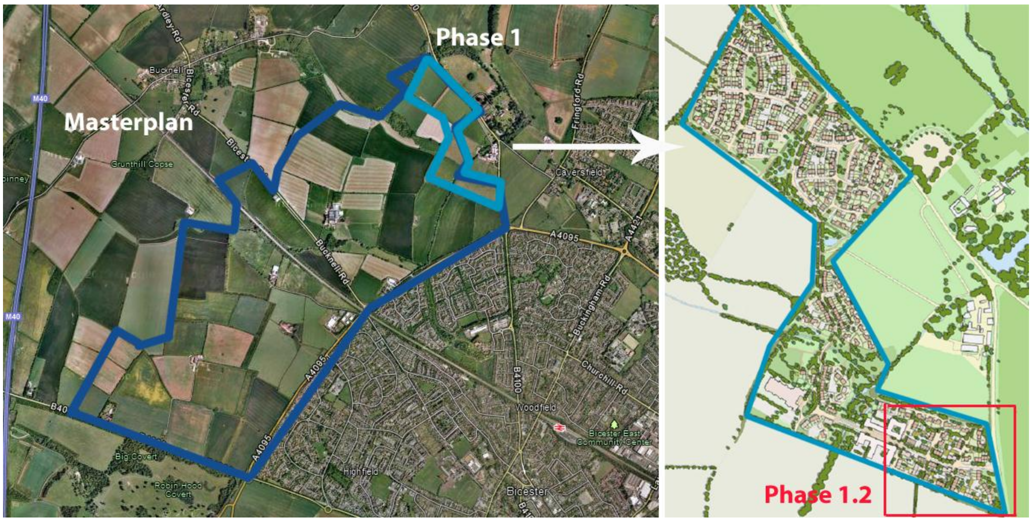

Figure 2 Location of NW Bicester project and its first phase plan[29]

3.1 Housing archetypes

Figure 3 Site plan of phase 1.2 and location of selected building types

Ten house archetypes in Phase 1.2 (denoted by red lines in figure 2) of NW Bicester development are selected for this adaptation study. These include: 5-bed detached house, 3-bed end terraced social house, 3-bed mid terraced social house, 2-bed bungalow and 6 types of 1 or 2-bed flat, covering a wider range of orientations. The location and orientation of the ten house types are given in figure 3 below. Detailed floor plans and IES models for each house types are also shown in Appendix A.

The thermal properties of building elements are listed in table 8 in appendix B. The internal heat gains, ventilation, infiltration rate and their daily running schedules are listed in table 10-11 in appendix B.

3.2 Simulation tool and future weather data

Detailed house level climate change impact and adaptation analysis is undertaken through dynamic building thermal simulation modelling using IES ApacheSim. IES ApacheSim was selected due to its wide international usage by both researcher and practitioners, and also its extensive historical testing and verification [30, 31]. The results from ApacheSim are most likely to reflect the results obtained by building simulation practitioners.

To investigate the impacts of climate changes on the house archetypes, various assumptions are made for selecting suitable future weather data. These include: location, time periods, carbon emission scenarios and risk percentiles.

- Swindon (51.16N, 1.75W) is the nearest location (to Bicester) which has CIBSE historical weather data available. The Design Summer Year for Swindon is selected from 1983 to 2004. The year with the third warmest April-August period during 1983 and 2004 is 1999, which is regarded as the Design Summer Year.
- UKCP09 provides projections for 7 time periods. For each time period, 30 years weather data are made available. The authors have selected three time periods (2030s, 2050s and 2080s) representing short, medium and longer terms.
- UKCP09 offers climate projections based on three carbon emission scenarios (low, medium and high). Since the observed emissions during 2000 to 2010 are very close to the IPCC's high emission scenarios assumed in 2000 [32], therefore UKCP09's high emissions scenario is selected for assessing the overheating risk. No doubt buildings designed for a high emissions scenario would also be climate proofed in both medium and low emission scenarios.
- Due to the probabilistic nature of the UKCP09 projections, data for several probability levels are available. However for this study, the 50th percentile is chosen, since the risk indicated by the 50 percentile DSY is equal to the level of risk projected by CIBSE DSY's.

Based on the assumptions made above, Table 2 summarises the baseline and future weather data files that are used for overheating analysis. Deliberately for cross-comparison, two baseline files are one from the CIBSE historical DSY and a control DSY from PROMETHEUS data. The CIBSE weather data is for Swindon while the PROMETHEUS weather data is for Bicester. A comparison of the future weather data in Figure 4 shows that there is an increase of average summertime temperature during April-September by 4.32-4.7ºC by 2080s over the baselines (CIBSE and Prometheus respectively).

Table 2 Weather data for simulation

Location	Timelines	Name of weather files	Description of weather data
Swindon	Baseline	SwindonDSY05.fwt	CIBSE DSY 1999 (1983-2004)
Bicester	Baseline2	WG_COMBINED_cntr_4600225_DSY	Prometheus 1961-1990 50 percentile DSY
	Short term (2030s)	WG_2030_4600225_a1fi_50_percentile_DSY.EPW	Prometheus 2020-2049 high emission 50 percentile DSY
	Medium term (2050s)	WG_2050_4600225_a1fi_50_percentile_DSY.EPW	Prometheus 2040-2069 high emission 50 percentile DSY
	Long term (2080s)	WG_2080_4600225_a1fi_50_percentile_DSY.EPW	Prometheus 2070-2099 high emission 50 percentile DSY

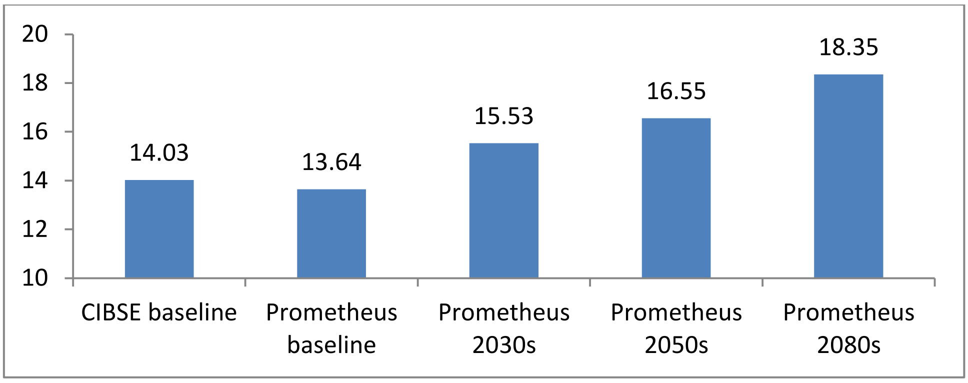

Figure 4 Apr-Sept average temperatures (ºC)

The numbers of hours of external temperature over 26, 27, 28 and 29ºC during April-September period, for the baseline and future weather data files are also shown in figure 5. Both figures 4 and 5 confirm that a warming climate will occur in the latter part of this century.

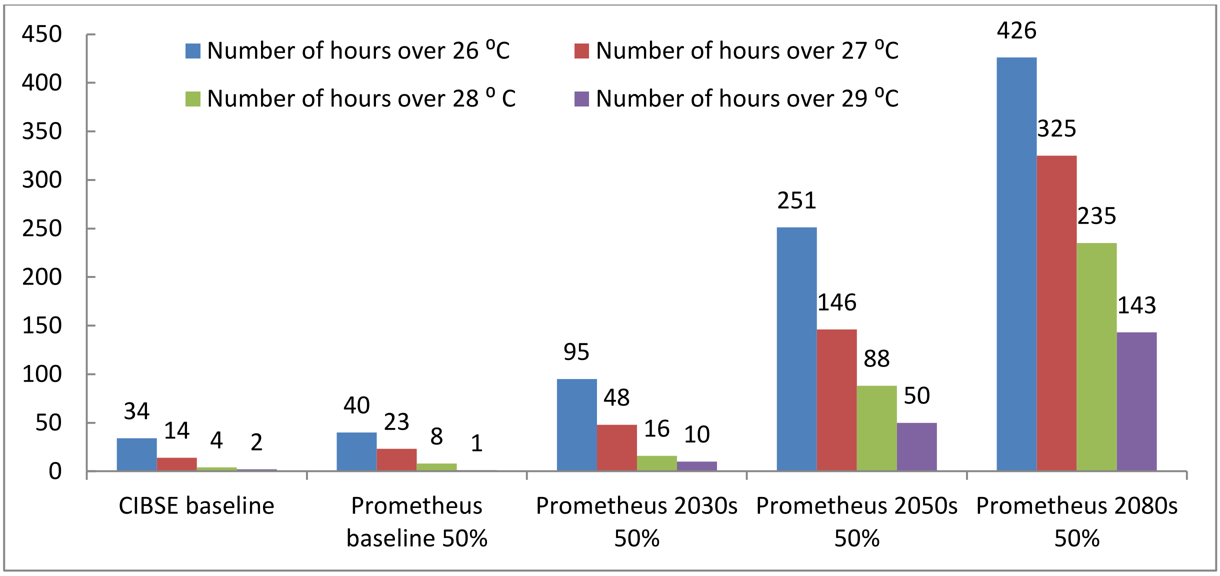

Figure 5 Number of hours of external temperature over 26, 27, 28 and 29 ºC

3.3 Application of overheating metrics to NW Bicester site

Based on the review of current overheating metrics for housing, *overheating percentage* seems to be the most transparent and widely used metric. So for this study, two overheating percentage metrics are used, as follows (Table 3):

- Percentage of occupied hours over 26/28 ºC (26 for bedrooms; 28 for living area, CIBSE benchmark)
- Percentage of occupied hours over adaptive thermal comfort BS EN 15251 upper limit. The BS EN 15251 category II group is the normal level of thermal expectation for new buildings. The upper limit of the adaptive thermal comfort can be calculated by following equation:

$$t = 0.33t_{rm} + 18.8 + 3$$

t_{rm} is running mean temperature calculated based on previous 7 days external dry bulb temperature.

Table 3 Overheating metrics

Source	Assessment metric	Criterion
CIBSE Guide A	Percentage of occupied hours over operative temperature of 26/28 ºC	No more than 1%
BS EN 15251	Percentage of occupied hours over category II adaptive comfort upper limit	No more than 3% or 5%

The upper limits of adaptive thermal comfort zone for CIBSE baseline and PROMETHEUS 2080s are shown in figure 6 below, wherein the red and green lines highlight the CIBSE overheating benchmarks (26/28 ºC). The figure also shows that the adaptive thermal comfort upper limits lie between 23 ºC and 28 ºC during April-September period. It also shows that the upper limits of 2080s' adaptive comfort zone (purple line) are higher than baseline's upper limits (blue line).

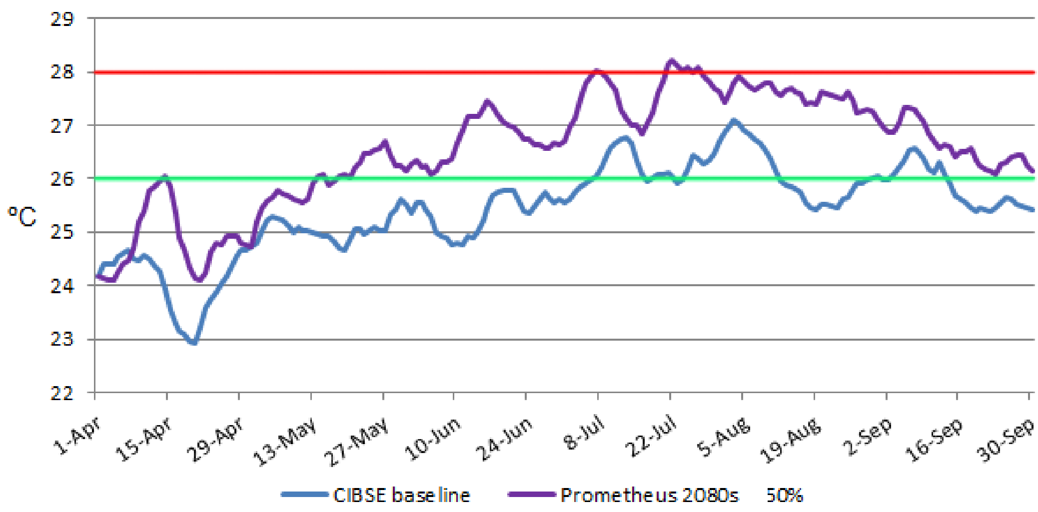

Figure 6 Upper limit of adaptive comfort zone for CIBSE baseline and 2080s

3.4 Assessing future overheating risk in the designs of zero carbon house archetypes

Ten dwelling models (Appendix A, figure 14-17) are run in IES ApacheSim with all the assumptions stated above. The hourly indoor operative temperatures are captured to calculate percentages of occupied hours exceeding 26 ºC (for bedrooms) or 28 ºC (for living rooms) and percentages of occupied hours exceeding BS EN 15251 comfort limits. As shown in figure 7, the results suggest that even for today's climate (as given by CIBSE and UKCP09), the flat and terraced house tend to experience overheating (>1% occupied hours, highlighted in red). This gets worse by 2030s, 2050s and 2080s. For the 5-bed detached house, overheating is beginning to occur in a southwest facing bedroom in 2030s (high emission scenario and 50 percentile). All the bedroom spaces in the detached house experience overheating by 2050s and the situation get worse by 2080s.

The bedrooms in bungalow stay in comfort range at current climate, and overheating is beginning to occur from 2030s. The lounge always experiences overheating for all climate conditions. Comparing the ten house types, detached house performs well under changing climate whereas terraced house (especially the south end-terraced house) has serious issue on overheating even under current climate condition. Based on this finding, the south end-terraced house (the worst case) is selected for testing adaptation measures and developing adaption packages.

Figure 7 also compares CIBSE and BS EN 15251 overheating metrics. It indicates that adaptive thermal comfort limits could allow part of building spaces to stay within comfort range to some extent. For the evaluation of the adaption options study, only CIBSE overheating metric is used, since it is the strictest one. A house designed for this metric would be climate proofed against other metrics.

4. Tackling the overheating risk in zero carbon homes

The main principles of tackling overheating in zero carbon homes are to reduce solar gain during hot periods, and make use of ventilation for cooling. The principle of reducing internal gain (heat gain from occupants and equipment) was not considered for this study, because we wanted to test the performance of mainly passive (fabric-based) adaptation strategies themselves. Air conditioning was also omitted at this stage due to its high carbon impact.

4.1 Potential adaptation measures for Bicester Eco-town

To arrive at appropriate adaptation strategies, firstly the generic adaptation measures suggested by Gething [28] were carefully reviewed for the NW Bicester eco town project. All the measures were graded against the following criteria as shown in Table 4 below:

- Measures already included in the design (1)
- Measures that should be considered for inclusion in the design (2)
- Measures that could be retrofitted in the future but implication worth considering for present design to avoid compromising this possibility (3)
- Measures that could be retrofitted in future but need no action at present (4)
- Measures not suitable for inclusion (5).

		CIBSE					BS EN 15251 3%					BS EN 15251 5%				
		Base1	Base2	2030s	2050s	2080s	Base1	Base2	2030s	2050s	2080s	Base1	Base2	2030s	2050s	2080s
Bungalow	Bedroom 1	0.8%	1.1%	2.8%	7.4%	13.4%	1.3%	1.7%	3.9%	7.6%	11.9%	1.3%	1.7%	3.9%	7.6%	11.9%
	Lounge	2.9%	4.2%	5.2%	9.8%	12.6%	6.9%	9.0%	10.0%	14.6%	18.0%	6.9%	9.0%	10.0%	14.6%	18.0%
	Bedroom 2	0.2%	0.3%	1.1%	4.7%	10.5%	0.3%	0.6%	1.4%	3.9%	8.3%	0.3%	0.6%	1.4%	3.9%	8.3%
Groundfloor 1 bed flat west	Bedroom 0-A	1.7%	1.7%	5.4%	10.5%	18.3%	2.6%	2.9%	6.5%	11.0%	17.3%	2.6%	2.9%	6.5%	11.0%	17.3%
	Livingroom 0-A	1.6%	2.0%	3.9%	8.4%	13.8%	5.8%	7.6%	10.2%	15.9%	21.8%	5.8%	7.6%	10.2%	15.9%	21.8%
Groundfloor 1 bed flat east	Bedroom 0-B	1.8%	1.9%	5.5%	10.7%	18.6%	3.0%	3.0%	6.7%	11.4%	17.7%	3.0%	3.0%	6.7%	11.4%	17.7%
	Livingroom 0-B	1.5%	1.6%	4.0%	9.0%	14.7%	6.7%	7.7%	11.3%	17.8%	23.8%	6.7%	7.7%	11.3%	17.8%	23.8%
First floor 2-bed flat west	Bedroom 1-A1	1.8%	1.9%	5.7%	11.4%	19.0%	2.8%	2.9%	6.9%	11.7%	18.3%	2.8%	2.9%	6.9%	11.7%	18.3%
	Bedroom 1-A2	1.8%	2.0%	5.4%	11.4%	20.2%	2.4%	3.3%	6.5%	12.5%	19.8%	2.4%	3.3%	6.5%	12.5%	19.8%
	Livingroom 1-A	2.3%	3.0%	5.3%	11.6%	18.6%	8.3%	10.9%	13.9%	21.1%	27.0%	8.3%	10.9%	13.9%	21.1%	27.0%
First floor 2-bed flat east	Bedroom 1-B1	2.2%	2.3%	6.2%	11.8%	19.9%	3.3%	3.3%	7.5%	12.6%	19.2%	3.3%	3.3%	7.5%	12.6%	19.2%
	Bedroom 1-B2	2.2%	2.5%	6.6%	12.4%	21.2%	3.5%	3.8%	8.3%	14.2%	21.6%	3.5%	3.8%	8.3%	14.2%	21.6%
	Livingroom 1-B	2.8%	3.5%	6.6%	13.1%	19.9%	10.8%	12.7%	16.3%	24.2%	30.2%	10.8%	12.7%	16.3%	24.2%	30.2%
Secondfloor 2-bed flat west	Bedroom 2-A1	1.4%	1.3%	4.9%	10.8%	18.8%	2.1%	2.1%	5.9%	10.6%	17.8%	2.1%	2.1%	5.9%	10.6%	17.8%
	Bedroom 2-A2	1.4%	1.6%	4.9%	11.0%	20.2%	2.0%	3.0%	5.6%	11.9%	19.5%	2.0%	3.0%	5.6%	11.9%	19.5%
	Livingroom 2-A	2.1%	3.2%	5.4%	12.1%	19.5%	7.9%	11.2%	14.6%	22.4%	28.4%	7.9%	11.2%	14.6%	22.4%	28.4%
Secondfloor 2-bed flat east	Bedroom 2-B1	1.6%	1.5%	5.3%	11.1%	19.2%	2.3%	2.3%	6.3%	11.1%	18.5%	2.3%	2.3%	6.3%	11.1%	18.5%
	Bedroom 2-B2	1.5%	2.0%	5.9%	12.2%	21.1%	2.5%	3.1%	7.4%	13.5%	21.4%	2.5%	3.1%	7.4%	13.5%	21.4%
	Livingroom 2-B	2.7%	3.7%	6.6%	14.0%	21.1%	10.5%	12.9%	16.8%	25.6%	31.2%	10.5%	12.9%	16.8%	25.6%	31.2%
Detached 5-bed house	Livingroom	0.0%	0.0%	0.0%	0.6%	3.3%	0.1%	0.3%	0.4%	2.2%	6.9%	0.1%	0.3%	0.4%	2.2%	6.9%
	Bedroom1	0.0%	0.0%	0.0%	1.8%	6.4%	0.0%	0.0%	0.0%	1.0%	4.4%	0.0%	0.0%	0.0%	1.0%	4.4%
	Bedroom2	0.0%	0.0%	0.0%	1.8%	7.0%	0.0%	0.0%	0.0%	0.7%	4.2%	0.0%	0.0%	0.0%	0.7%	4.2%
	Bedroom3	0.0%	0.0%	0.0%	3.2%	9.5%	0.0%	0.2%	0.1%	2.1%	6.8%	0.0%	0.2%	0.1%	2.1%	6.8%
	Bedroom4	0.1%	0.2%	0.3%	4.1%	10.3%	0.1%	0.3%	0.5%	2.9%	7.7%	0.1%	0.3%	0.5%	2.9%	7.7%
	Bedroom5	0.5%	0.5%	2.0%	5.5%	11.9%	0.8%	1.0%	2.4%	5.0%	9.5%	0.8%	1.0%	2.4%	5.0%	9.5%
Mid-terraced 3-bed house	Bedroom1	4.5%	6.6%	9.4%	16.7%	24.1%	6.2%	8.5%	11.2%	18.2%	24.2%	6.2%	8.5%	11.2%	18.2%	24.2%
	Bedroom2	3.3%	3.8%	7.6%	14.2%	21.5%	4.9%	5.8%	9.4%	15.5%	22.3%	4.9%	5.8%	9.4%	15.5%	22.3%
	Bedroom3	7.6%	9.9%	13.4%	20.7%	26.7%	10.2%	12.6%	15.2%	22.5%	27.6%	10.2%	12.6%	15.2%	22.5%	27.6%
	Livingroom	1.3%	1.5%	3.5%	8.5%	14.3%	6.0%	6.6%	10.2%	16.4%	22.7%	6.0%	6.6%	10.2%	16.4%	22.7%
End-terraced 3-bed house	Bedroom1	12.7%	15.4%	18.8%	26.3%	31.2%	16.9%	19.2%	21.1%	29.0%	33.6%	16.9%	19.2%	21.1%	29.0%	33.6%
	Bedroom2	4.1%	5.1%	9.6%	16.6%	24.0%	6.2%	7.2%	11.7%	18.6%	25.4%	6.2%	7.2%	11.7%	18.6%	25.4%
	Bedroom3	8.0%	10.8%	14.7%	22.3%	28.3%	10.7%	13.9%	16.9%	24.9%	29.9%	10.7%	13.9%	16.9%	24.9%	29.9%
	Livingroom	3.6%	4.6%	7.1%	13.3%	19.2%	10.1%	12.1%	15.2%	22.9%	28.5%	10.1%	12.1%	15.2%	22.9%	28.5%
End-terraced 2-bed house	Living	3.9%	4.6%	7.2%	12.8%	17.7%	10.4%	11.5%	14.1%	20.7%	26.0%	10.4%	11.5%	14.1%	20.7%	26.0%
	Bedroom1	4.6%	5.3%	9.4%	16.4%	23.2%	6.6%	7.3%	11.4%	18.2%	24.4%	6.6%	7.3%	11.4%	18.2%	24.4%
	Bedroom2	4.4%	6.5%	9.5%	16.7%	24.1%	6.2%	8.4%	11.2%	18.3%	24.2%	6.2%	8.4%	11.2%	18.3%	24.2%

Figure 7 Comparison of CIBSE and BS EN adaptive comfort limits

Table 4 Generic adaptation measures for keeping cool

Adaptation measures		Adapted element	Grade
Keeping cool for internal spaces			
Shading - manufactured	Interstitial blinds	Window	5
	Internal blinds	Window	2
Shading - building form	External fixed shades	Window	2
	External adjustable shading - time control	Window	2
	External adjustable shading - radiation control	Window	2
	Orientation	Building	3
Glass technologies	Double glazing	Window	5
	Triple glazing	Window	1
Film technologies	Window film technology	Window	2
Green roofs/transpiration cooling	Green roof	Roof	5
Shading - planting	Deciduous planting on south façade	Facade	5
Reflective materials	Reflective coatings on external walls	Wall	2
	Reflective coatings on roof	Wall	2
Conflict between maximising daylight and overheating	Adjust window size	Window	5
Secure and bug free night ventilation	Secure and bug free night ventilation	Window	2
Interrelationship with noise & air pollution	Acoustic	HVAC system	5
	Air purifier	HVAC system	5
	Mechanical ventilation	HVAC system	2
Interrelationship with ceiling height	Adjust ceiling height	Wall	5
Role of thermal mass in significantly warmer climate	Apply concrete floor	Floor	2
	Apply concrete internal wall	Wall	2
	Apply heavy weight external wall	Wall	2
Enhancing thermal mass in lightweight construction	Apply concrete staircase and fireplace	Internal space	5
	Install phase change material	Wall	5
Energy efficient/ renewable powered cooling systems	Heat Recovery Ventilation (operation in summer, when outdoor T> indoor T)	HVAC system	5
Groundwater cooling	Groundwater cooling	Space nearby	5
Enhanced control systems - peak lopping	Enhanced control systems - peak lopping	HVAC system	5
Maximum temperature legislation	Change building regulation	Building regulation	3/4
Keeping cool for spaces around buildings			
Built form - building to building shading	building to building shading	Planning	5
Access to external space - overheating relief	Access to external space	Planning	1
Shade from planting	Listed above		2
Manufactured shading	Listed above		2
Interrelationship with renewables	Listed above		5
Shading parking/ transport infrastructure	Shading parking/ transport infrastructure	Planning	1
Role of water - landscape/ swimming pools	Role of water - landscape/ swimming pools	Landscape	5

Table 4 lists all the measures suggested by Gething and highlights (in grey) the adaptation measures used for this study. Some of the measures given in the table have already been incorporated (such as triple glazing) in the base model itself (therefore graded as ‘1’). Changing orientation is not suitable at this stage of the project, but it might be useful for the later phases of the eco-town development.

4.2 Modelling of adaptation measures and packages

The specification of the base model and adaptation measures used for this study are described in table 5 below. The exact procedures for implementing these adaptation measures in IES model are explained in appendix C.

Table 5 Description of adaptation measures

Adaptation measures		Descriptions of adaptation measures
Base model		No shading devices, constant 1 air change ventilation rate, timer frame structure (light weight).
High albedo surface	1. White paint	Paint outside surface of roof and external wall in white colour.
	2. Cream paint	Paint outside surface of roof and external wall in cream colour.
Windows film	3. Light film	The light reflective window film allows 48% of light through [33].
	4. Dark film	The dark reflective window film allows 18% of light through [33].
Thermal mass	5. Masonry wall (medium weight external wall)	External wall made by brickwork, insulation and low density concrete.
	6. Heavy weight external wall	External wall made by brickwork, insulation and high density concrete.
	7. Heavy weight external wall and heavy weight internal partition	Internal wall made by plaster and concrete.
Ventilation	8. Two air change rate	Building space with constant 2 air change rate ventilation rate which provided by exhaust fans or windows opening.
	9. Three air change rate	Building space with constant 3 air change rate ventilation rate which provided by exhaust fans or windows opening.
	10. Nigh time ventilation (three air change rate at nigh time)	Building space with 3 air change rate ventilation rate at night-time only (18:00-08:00) which provided by exhaust fans or windows opening.
	11. Conditional windows opening	This ventilation strategy assumes that top hung windows (10% overall windows area) open 10^0 when indoor air temperature is higher than 23 ^{0}C and higher than external air temperature. The opening could be implemented by building occupants or automatic control system. The simulation of this ventilation strategy was conducted in IES MacroFlo using network ventilation calculation method.
Shading	12. Internal curtain with control	This shading strategy assumes that building occupants draw curtains closed when incident radiation is higher than 100 W/m^2.
	13. Internal curtain without control	Curtains are closed during 10am to 6pm.
	14. Internal blinds with control	This shading strategy assumes that building occupants close blinds when incident radiation is higher than 100 W/m^2.
	15. Internal blinds without control	blinds are closed during 10am to 6pm (for empty houses, e.g. working couples).
	16. Fixed shading	The design of a fixed shading device was modelled for south facing windows using Ecotect. The designed shading could cover direct sunshine during 11:00 to 16:00, 1st May to 31st Aug. The dimension of overhang is 0.8m × windows width. The height of left and right fin is 0.8m which is a third of windows height.
	17. External shutter with control	This shading strategy assumes that building occupants close the shutter when incident radiation is higher than 100 W/m^2.
	18. External shutter without control	Shutters are closed during 10am to 6pm.
	19. External louver with control	This shading strategy assumes that building occupants turn louver closed when incident radiation is higher than 100 W/m^2.
	20. External louver without control	Louvers are closed during 10am to 6pm.
Orientation	21-27. Orientations	Set site rotation angle in IES as 79, 79+45, 79+90, 79+135, 79+180, 79+225, 79+270, 79+315-360.

For the 3-bed end terraced house, the individual adaption measures (given above) are modelled using IES VE and the average percentage of occupied hours over 26/28^{o}C over 3 bedrooms and living room are shown in table 6. Results show that *shading* (in the form of external window shutters), *ventilation* and *orientation* have a significant impact in reducing overheating percentages.

Table 6 individual measures

Adaptation measures		CIBSE baseline	2050s H 50%	2080s H 50%	Package 1	Package 2	Package 3
Base model		7.1%	19.6%	25.7%			
High albedo surface	1. White paint	6.5%		24.8%		√	√
	2. Cream paint	6.8%		25.4%			
Windows film	3. Light film	5.5%		23.3%			
	4. Dark film	5.3%		22.9%			
Thermal mass	5. Masonry wall (medium weight external wall)	6.6%	20.1%	26.5%			
	6. Heavy weight external wall	6.1%	19.8%	26.7%			
	7. Heavy weight external wall and heavy weight internal partition	5.3%	19.1%	26.2%			√
Ventilation	8. Two air change rate	2.9%	10.9%	16.0%			
	9. Three air change rate	1.9%	7.7%	11.7%			
	10. Nigh time ventilation (three air change rate at nigh time)	4.2%	12.5%	17.2%			
	11. Conditional windows opening	1.2%	5.8%	8.4%	√	√	√
Shading	12. Internal curtain with control	2.6%	12.2%	19.1%			
	13. Internal curtain without control	3.7%	14.5%	21.2%			
	14. Internal blinds with control	2.6%	12.2%	19.1%			
	15. Internal blinds without control	3.7%	14.5%	21.2%			
	16. Fixed shading	0.3%	4.0%	8.8%			
	17. External shutter with control	0.0%	0.5%	2.4%	√	√	√
	18. External shutter without control	0.4%	4.4%	9.7%			
	19. External louver with control	0.0%	0.5%	2.4%			
	20. External louver without control	0.4%	4.4%	9.7%			
Orientation	21. 79+45	5.6%	17.7%	24.4%			
	22. 79+90	2.4%	11.3%	18.5%			
	23. 79+135	1.3%	7.4%	14.6%			
	24. 79+180	0.9%	6.6%	13.4%			
	25. 79+225	1.2%	7.3%	14.5%			
	26. 79+270	2.3%	10.6%	17.9%			
	27. 79+315-360	5.3%	16.5%	23.0%			

Based on the effectiveness of the individual measure, appropriate measures are combined into three adaptation packages, wherein:

- **Package 1** combines the two most effective adaptation measures (external shutter and conditional windows opening).
- **Package 2** includes white paint in addition
- **Package 3** also includes heavy weight external/internal partitions.

Since windows film would have limited effect due to installation of shading devices, therefore such films are not included in packages 2 and 3. The performances of three packages are then tested under current climate and 50 percentile of high emission scenario of 2030s, 2050s and 2080s projections. The overheating percentages of each room in the 3-bed south-facing end-terraced house are listed in table 7 and overheated rooms are highlighted in red. The average values of whole house are shown in figure 8.

Table 7 Performance of adaptation packages on end-terraced house

Percentage of occupied hours over 26 /28 ^{o}C		CIBSE baseline	2030s H 50%	2050s H 50%	2080s H 50%
End-terraced 3-bed house without adaptation	Bedroom1	12.7%	18.8%	26.3%	31.2%
	Bedroom2	4.1%	9.6%	16.6%	24.0%
	Bedroom3	8.0%	14.7%	22.3%	28.3%
	Living room	3.6%	7.1%	13.3%	19.2%
	Average	**7.1%**	**12.6%**	**19.6%**	**25.7%**
Adaptation package 1 (shutter and windows opening)	Bedroom1	0.0%	0.0%	0.5%	1.9%
	Bedroom2	0.0%	0.0%	0.2%	1.3%
	Bedroom3	0.0%	0.0%	0.1%	1.0%
	Living room	0.0%	0.0%	0.0%	0.1%
	Average	**0.0%**	**0.0%**	**0.2%**	**1.1%**
Adaptation package 2 (white paint + package 1)	Bedroom1	0.0%	0.0%	0.2%	1.1%
	Bedroom2	0.0%	0.0%	0.0%	0.4%
	Bedroom3	0.0%	0.0%	0.0%	0.3%
	Living room	0.0%	0.0%	0.0%	0.0%
	Average	**0.0%**	**0.0%**	0.1%	0.5%
Adaptation package 3 (heavy weight + package 2)	Bedroom1	0.0%	0.0%	0.0%	0.0%
	Bedroom2	0.0%	0.0%	0.0%	0.1%
	Bedroom3	0.0%	0.0%	0.0%	0.0%
	Living room	0.0%	0.0%	0.0%	0.0%
	Average	**0.0%**	**0.0%**	**0.0%**	**0.0%**

Results show that adaptation package 1 (shutter and windows opening) allows the end-terraced 3-bed dwelling in NW Bicester project to stay within comfort range by 2050s, although the control of shutter and windows opening relies on users' expectation and experience. For vulnerable occupants, automatic control system could be introduced. To address overheating in 2080s, white paint (package 2) could be applied to the outside surfaces of roof and external walls at that time. This could allow the building to stay within comfort range by 2080s in general (just 0.1% over the comfort limit in one of bedrooms). A heavy-weight building with shutters, openable windows and white paint on external surfaces (Package 3) would allow the building to stand by 2080s without any overheating issue.

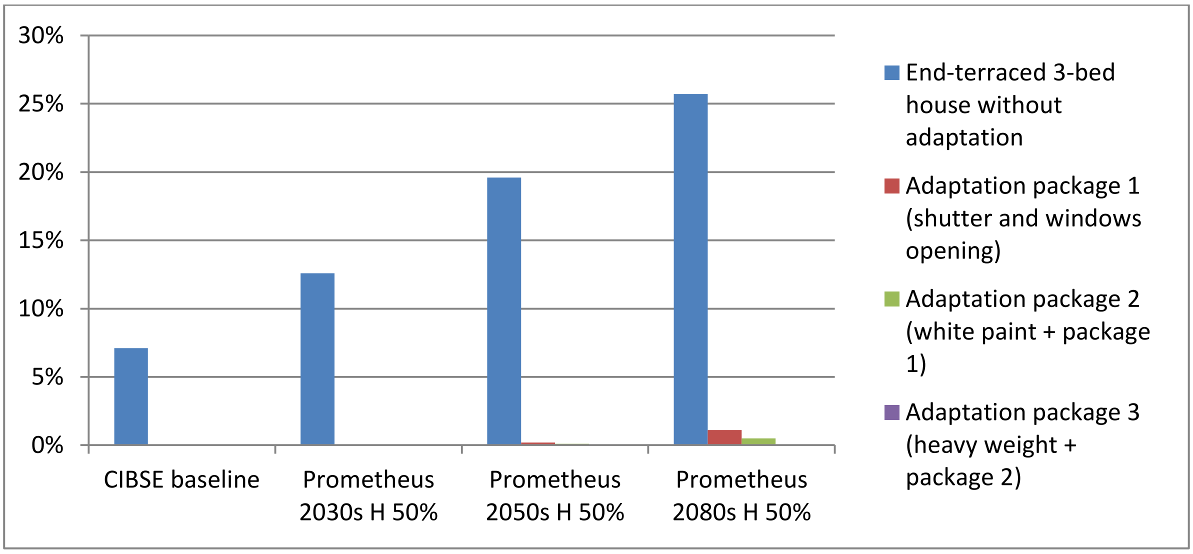

Figure 8 Performance of adaptation packages on 3-bed end terraced house

4.3 Performance of adaptation packages on other house types

The three adaptation packages developed above are also applied to other nine house types in NW Bicester development. The simulation results of overheating percentages are shown in figures 10-12 below. For comparison, figure 9 shows the overheating percentages without any adaptation measures.

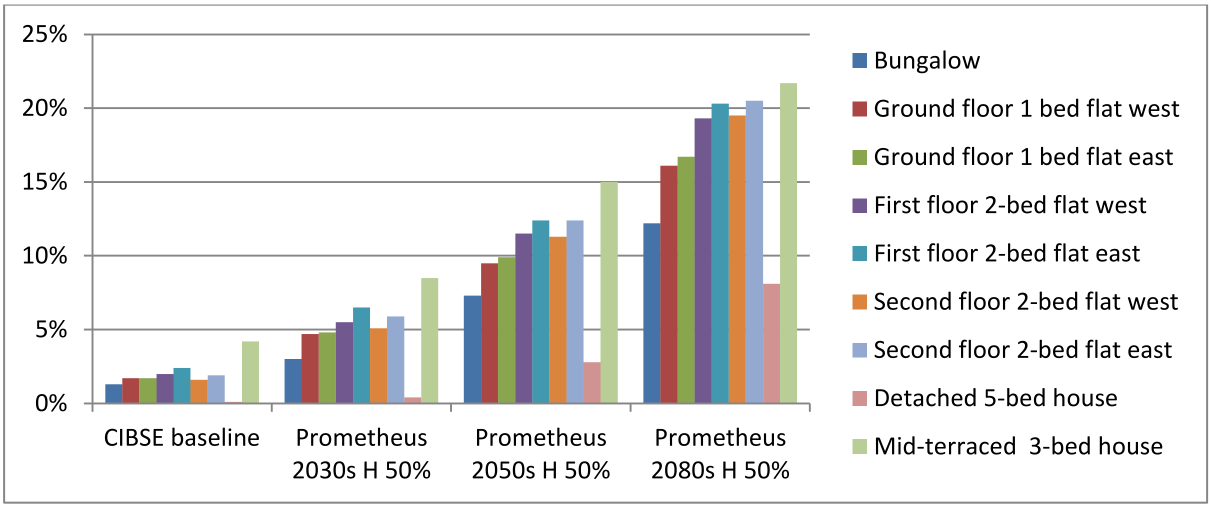

Figure 9 Average overheating percentages (without any adaptation measures)

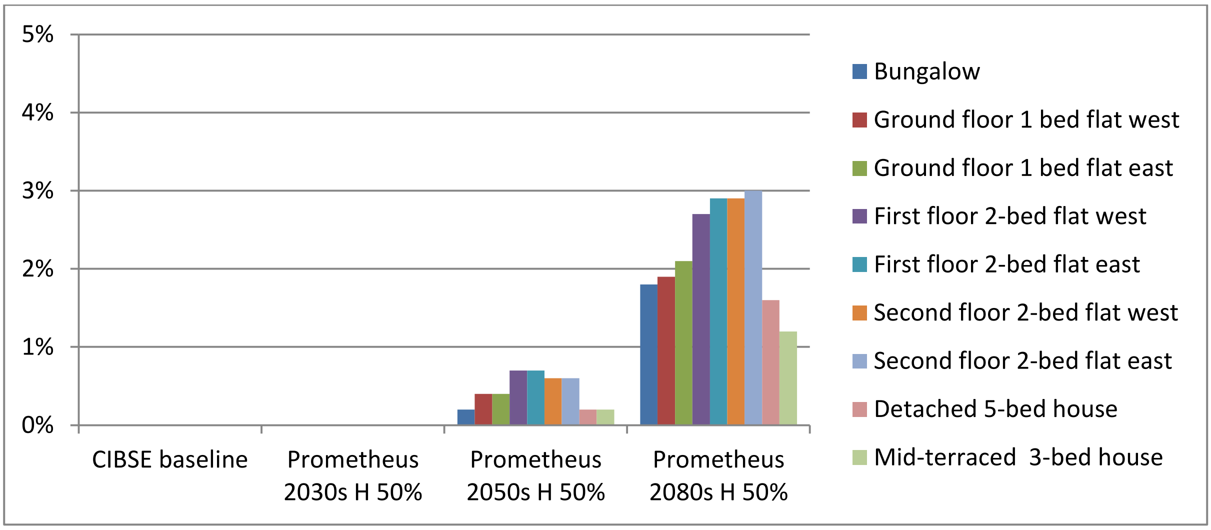

Figure 10 Average overheating percentages (adaptation package 1)

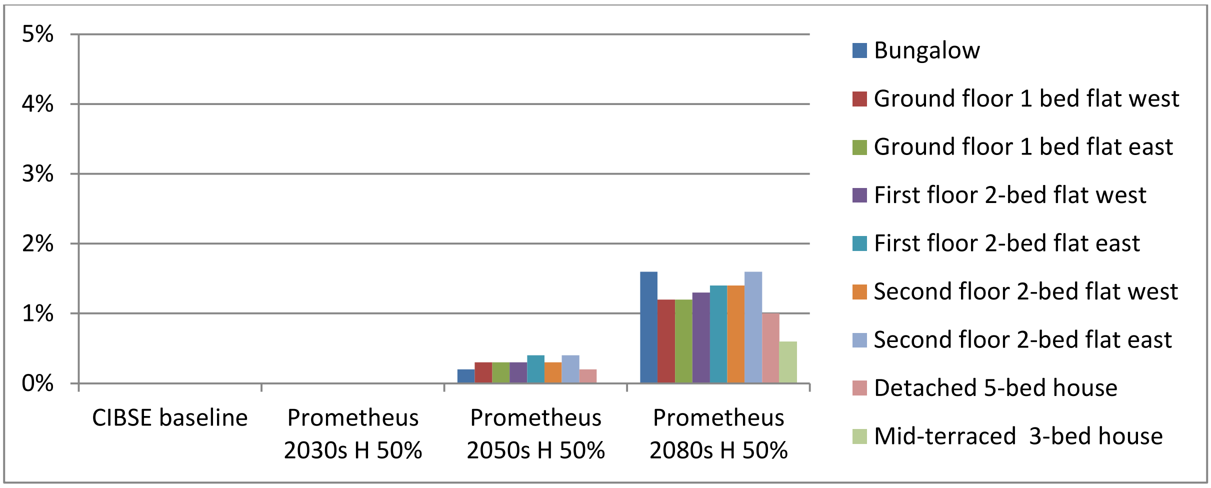

Figure 11 Average overheating percentages (adaptation package 2)

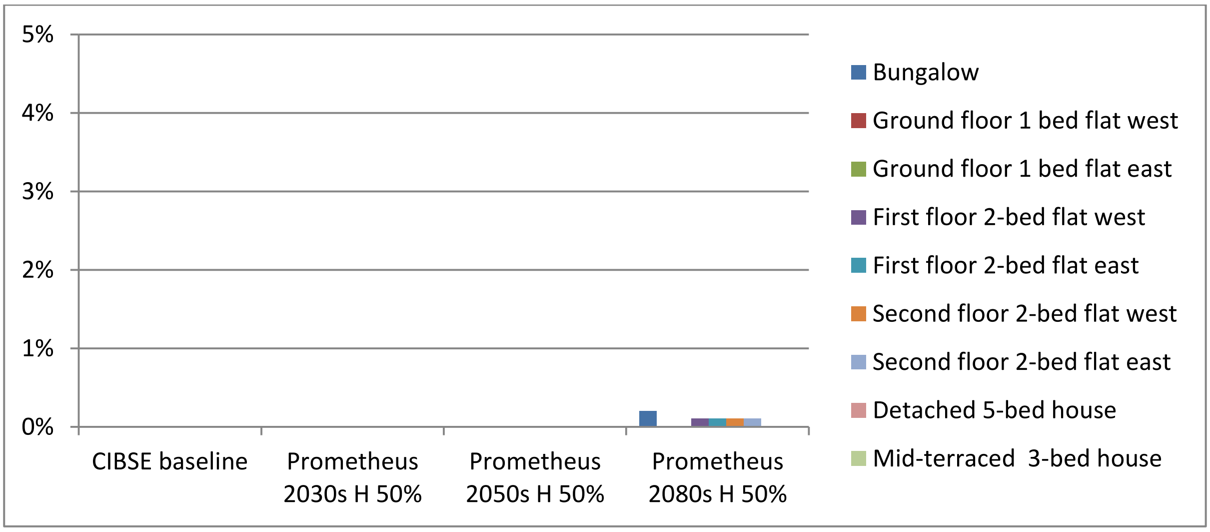

Figure 12 Average overheating percentages (adaptation package 3)

Figure 10 shows that adaptation package 1 could allow bungalow, detached house, mid-terraced house and most rooms of flat (with exception of 2 bedrooms) to stay within comfort limits in 2050s. Figure 11 shows that adaptation package 2 could allow mid-terraced house to stay within comfort limits in 2080s. Figure 12 shows that adaptation package 3 could allow all building types to stay within comfort limits in 2080s. This reinforces the need to incorporate shading, ventilation, light-coloured external surfaces combined with heavy weight construction materials to future proof zero carbon houses built today.

5. Discussion

The sum total of this work is to present a new methodological approach in selection and evaluation of adaptation measures to tackle overheating in low and zero carbon houses during the design stage, using dynamic thermal simulation in a way that is familiar to the design team. This is why, in case of NW Bicester Ecotown project, the most effective adaptation measures and packages tested through modelling, were then discussed with the design team and further evaluated for their cost-effectiveness using cost-benefits analysis. This enabled a realistic take-up of suitable measures such as shading, which was included as a design feature in the NW Bicester homes by the architects, as shown in figure 13 below.

Figure 13 Example of shading design[34]

Through this work, it has been realised that to have confidence in overheating risk assessment for future climate, there is a need to have consistent metrics for all projects. This includes agreeing an appropriate overheating risk criterion, a standardized calculation method for assessing risk and future climate data (for different locations in the UK). The metrics may differ for building typologies but would still have a common approach. This is necessary if the central Government and local authorities would like to incorporate a requirement for designers and developers to undertake overheating risk analysis for new housing against future climate, as part of future building regulations or planning requirements.

6. Conclusions

It is increasingly recognised that future warming climate may cause overheating in zero carbon homes due to the improved thermal efficiency of building fabric and reduced infiltration rate. To tackle this problem at the design stage, energy models of ten house archetypes (bungalow, flats, detached house, mid-terraced house and end-terraced house) were built in IES as part of the NW Bicester eco-town project to establish the risk of overheating now and in the future using the CIBSE overheating metric. The worst case, a south facing end-terraced house, was subject to further analysis.

From a checklist of adaptation measures developed by Technology Strategy Board, a range of measures were identified based on the criteria of whether they could be included in the design or retrofitted in the dwellings in future. About twenty seven individual adaption measures were simulated in IES in the south facing end-terraced house, followed by three adaptation packages to minimise the overheating risk by 2080s, leading to minimum change in the existing building design. The three adaptation packages were applied to other nine house types. It was realised that key adaptation packages for tackling overheating combine shading, ventilation strategies, colour of fabric and material of construction elements (thermal mass).

The practical application of this work is that it creates a replicable methodological approach for adapting new homes against future climate change. It also helps policy makers and designers understand the effectiveness of adaption measures in avoiding overheating now, and in the future. Although the method developed in this paper is for tackling overheating risk based on UKCP09, the method could be applied to other risks, such as winter temperature, building energy consumption, structure and water management/flood. However the testing procedure and assessment metrics may differ.

Acknowledgement

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Appendix A

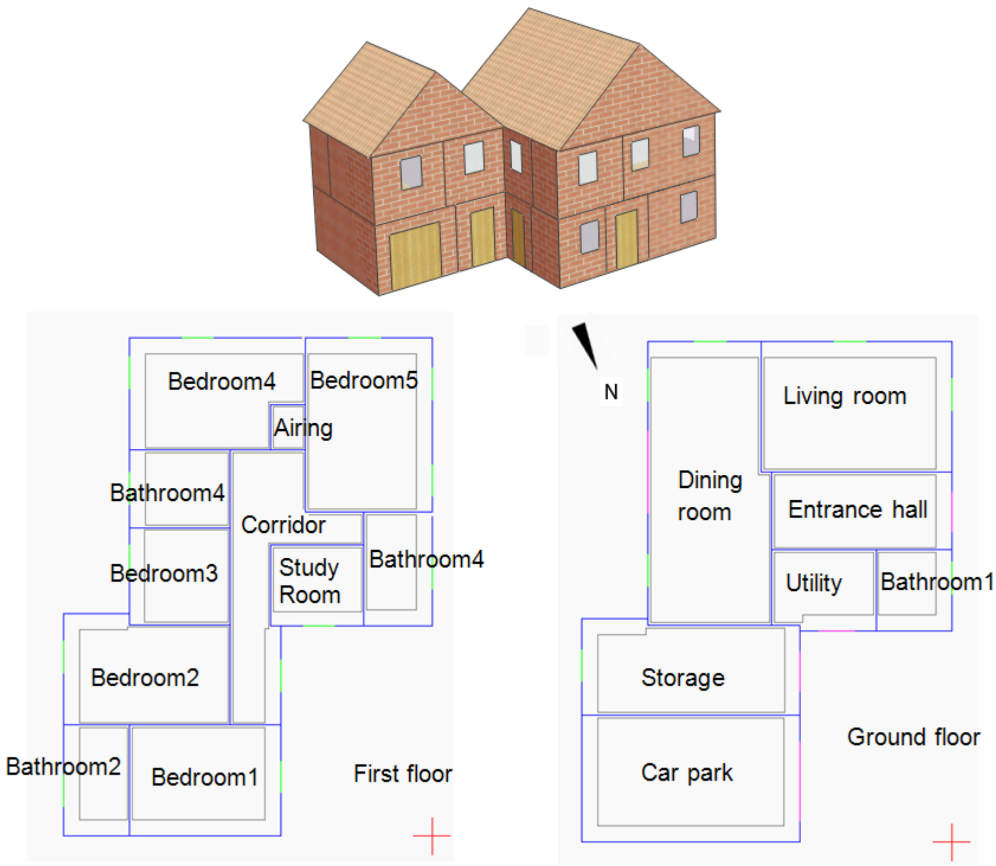

Figure 14 IES model of 5-bed detached house and its floor plans

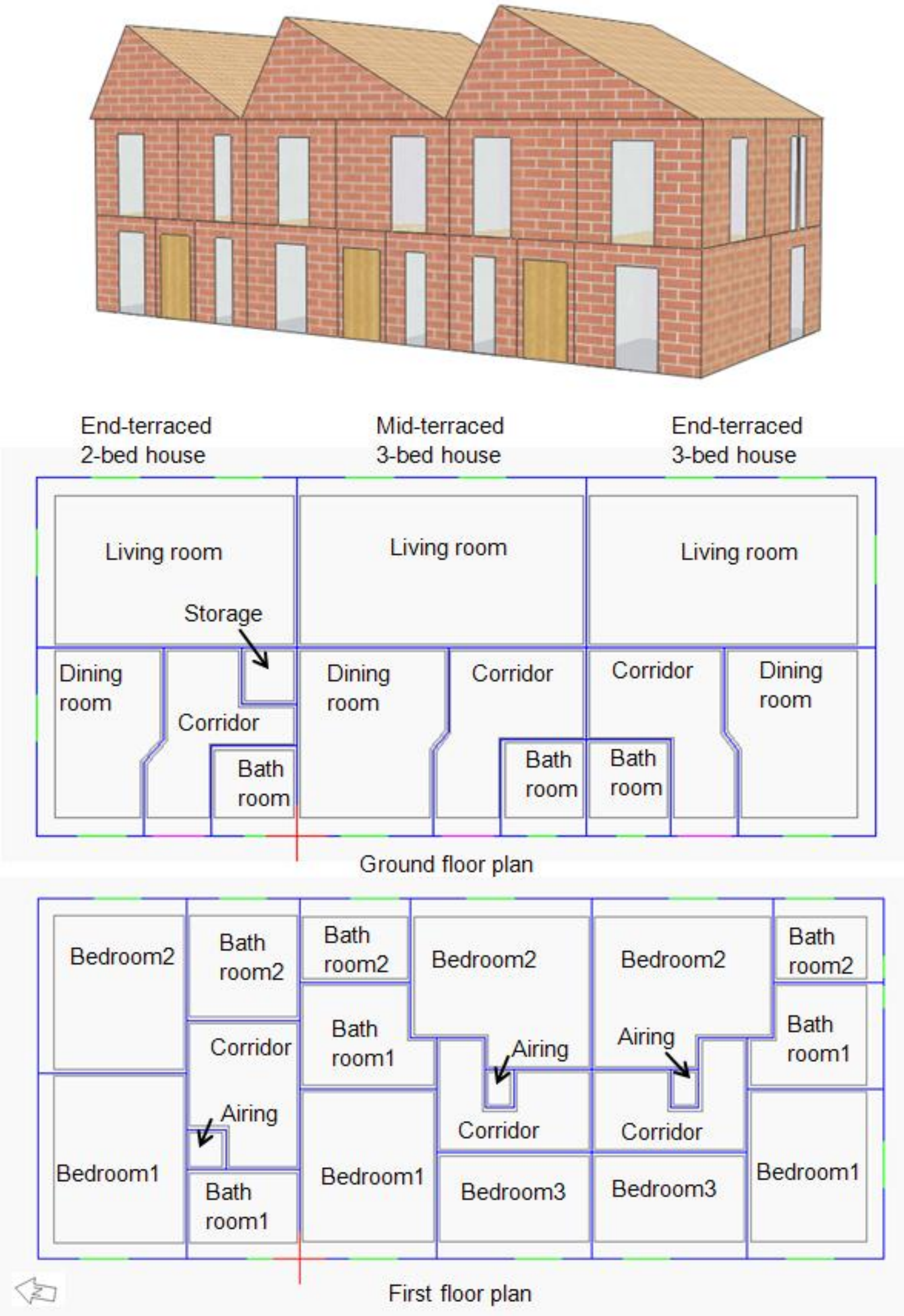

Figure 15 IES model of 3-bed mid-terraced and end-terraced house and their floor plans

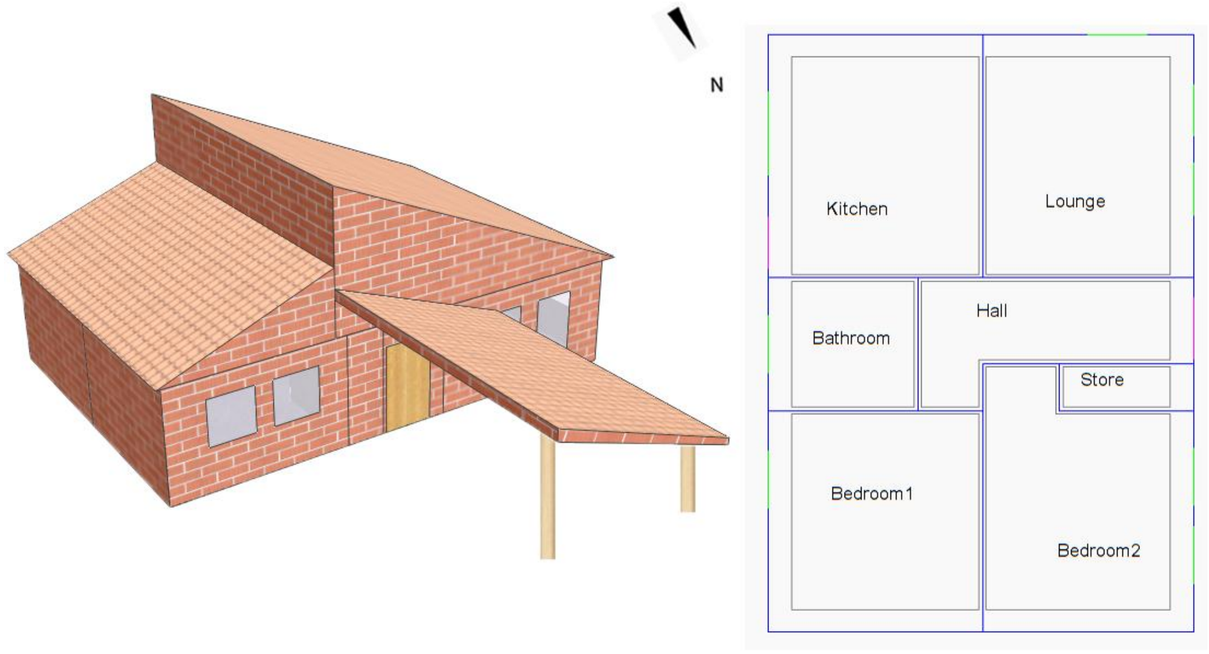

Figure 16 IES model of 2-bed bungalow and its floor plan

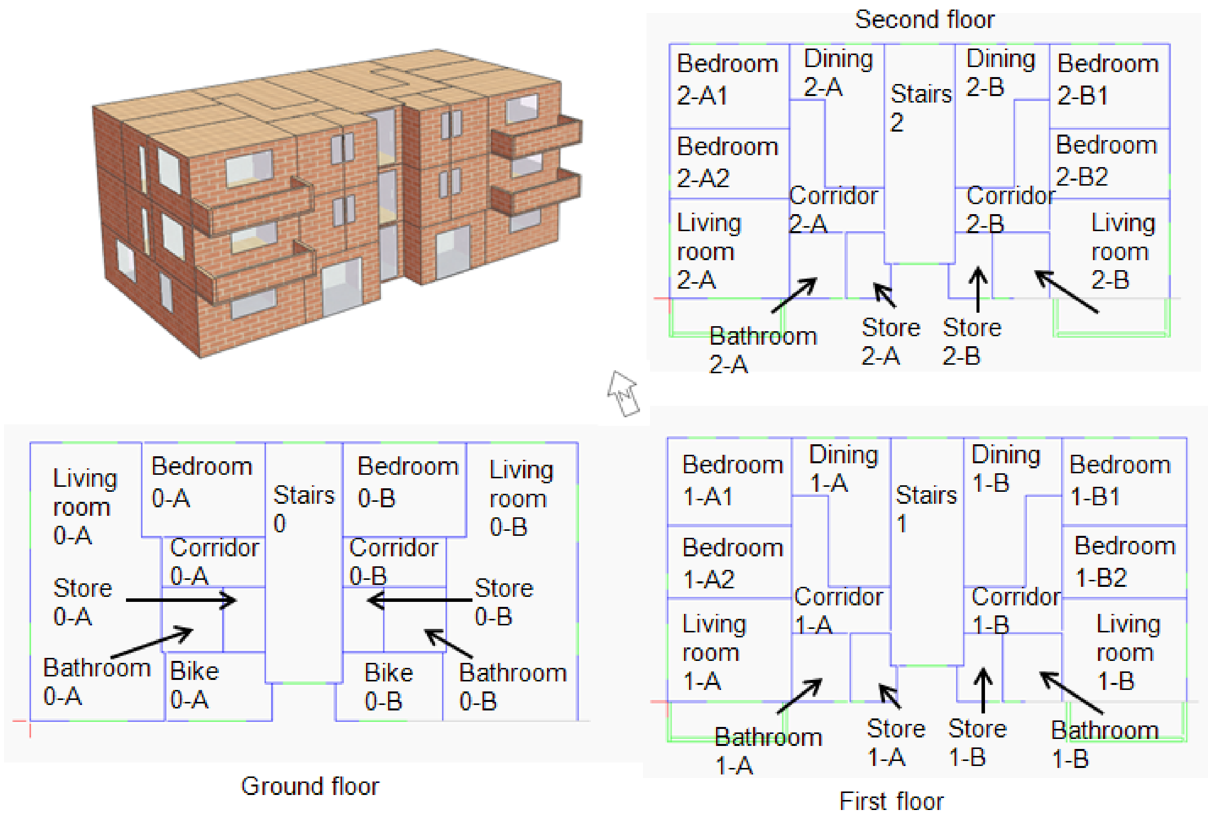

Figure 17 IES model of flat building block and its floor plans

Appendix B

Table 8 Building elements

	U-value (W/m^2K)
External wall	0.15
Roof	0.13
Ground	0.15
Partition	0.45
External door	0.80
Internal floor/ceiling	0.62
Glass	U-value: 0.84 G-value: 0.42

Table 9 Internal gain value

Gain type	Zone type	Value (W/m^2)	Schedule
Lighting Gain	Bathroom	7.8	Ligh+Equip
	Bedroom	5.2	Ligh+Equip
	DomCirculation area	5.2	Ligh+Equip
	DomDining area	7.8	Ligh+Equip
	DomLounge area	7.8	Ligh+Equip
	Unoccupied/Unconditioned	0	Off
Occupancy Sensible	Bathroom	1.2	Occupied
	Bedroom	1.35	Occupied
	DomCirculation area	1.8	Occupied
	DomDining area	1.34	Occupied
	DomLounge area	1.34	Occupied
	Unoccupied/Unconditioned	0	Off
Occupancy latent	Bathroom	1.2	Occupied
	Bedroom	0.45	Occupied
	DomCirculation area	1.8	Occupied
	DomDining area	0.86	Occupied
	DomLounge area	0.86	Occupied
	Unoccupied/Unconditioned	0	Off
Equipment Sensible	Bathroom	2	Ligh+Equip
	Bedroom	4.05	Ligh+Equip
	DomCirculation area	2	Ligh+Equip
	DomDining area	5	Ligh+Equip
	DomLounge area	5	Ligh+Equip
	Unoccupied/Unconditioned	0	Off
Equipment Latent	Bathroom	11.25	Ligh+Equip
	Bedroom	0.95	Ligh+Equip
	DomCirculation area	0	Off
	DomDining area	0	Off
	DomLounge area	0	Off
	Unoccupied/Unconditioned	0	Off

Table 10 daily schedules

Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Ligh+Equip	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0
Occupied Weekday	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
On	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Off	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 11 Ventilation and infiltration rate

Zone type	Infiltration (ACH)	Ventilation (ACH)	Schedule
Bathroom	0.155	1	on
Bedroom	0.155	1	on
DomCirculation area	0.155	1	on
DomDining area	0.155	1	on
DomLounge area	0.155	1	on
Unoccupied/Unconditioned	0.3	0	off

Appendix C

Adaptation measures	Implementation of these adaptation measures in IES model
Base model	Outside surface emissivity: 0.9 Outside surface solar absorptance: 0.7 for external wall; 0.4 for roof Inside surface emissivity:0.9 Visible light normal transmittance:0.76 Transmittance of internal layer:0.44 Outside/inside reflectance:0.23 Setup timber frame construction layers in IES model SBEM Thermal capacity of external wall: 8.37 kJ/m^2K SBEM Thermal capacity of internal wall partition: 4.19 kJ/m^2K SBEM Thermal capacity of internal floor partition: 39.38 kJ/m^2K
1. White paint	Outside surface emissivity: 0.9 Outside surface solar absorptance: 0.2 for external wall and roof
2. Cream paint	Outside surface emissivity: 0.87 Outside surface solar absorptance: 0.4 for external wall and roof
3. Light film	Inside surface emissivity:0.74 Visible light normal transmittance:0.36 Transmittance of internal layer:0.176 Outside/inside reflectance:0.0713
4. Dark film	Inside surface emissivity:0.7 Visible light normal transmittance:0.137 Transmittance of internal layer:0.0528 Outside/inside reflectance:0.1265
5. Masonry wall (medium weight external wall)	Setup masonry wall construction layers in IES model SBEM Thermal capacity of external wall: 85.04 kJ/m^2K SBEM Thermal capacity of internal wall partition: 4.19 kJ/m^2K SBEM Thermal capacity of internal floor partition: 39.38 kJ/m^2K
6. Heavy weight external wall	Setup heavy weight external wall construction layers in IES model SBEM Thermal capacity of external wall: 191.34 kJ/m^2K SBEM Thermal capacity of internal wall partition: 4.19 kJ/m^2K SBEM Thermal capacity of internal floor partition: 39.38 kJ/m^2K

7. Heavy weight external wall and heavy weight internal partition	Setup heavy weight external wall and heavy weight internal partition construction layers in IES model SBEM Thermal capacity of external wall: 191.34 kJ/m^{2}K SBEM Thermal capacity of internal wall partition: 149.09 kJ/m^{2}K SBEM Thermal capacity of internal floor partition: 126.31 kJ/m^{2}K
8. Two air change rate	Set natural ventilation rate as 2 ACH, and set its profile as continuously
9. Three air change rate	Set natural ventilation rate as 3 ACH, and set its profile as continuously
10. Nigh time ventilation (three air change rate at nigh time)	Set natural ventilation rate as 3 ACH, and set its profile active during 18.00-08.00
11. Conditional windows opening	Set windows opening type in MarcoFlo as follows, Opening category: Window-top hung Opening Category: 10% Max Angle Open: 10^0 Proportions: Length/Height<0.5 Crack Flow Coefficient: 0.15 Opening threshold temperature: 23^{0}C Opening profile: On when indoor air temperature >23^{0}C and > external air temperature
12. Internal curtain with control	Set curtains as internal shading devices Incident radiation to lower device: 100 W/m^2 Incident radiation to raise device: 100 W/m^2
13. Internal curtain without control	Set curtains as internal shading devices Percentage profile group: Active during 10:00-18:00
14. Internal blinds with control	Set blinds as internal shading devices Incident radiation to lower device: 100 W/m^2 Incident radiation to raise device: 100 W/m^2
15. Internal blinds without control	Set blinds as internal shading devices Percentage profile group: Active during 10:00-18:00
16. Fixed shading	Set Projections as local shading devices Windows width: 1.1m Window height: 0.8m Overhang projection: 0.8m Left fin projection: 0.8m Right fin projection: 0.8m
17. External shutter with control	Set shutter as external shading devices Incident radiation to lower device: 100 W/m^2 Incident radiation to raise device: 100 W/m^2
18. External shutter without control	Set shutter as external shading devices Percentage profile group: Active during 10:00-18:00
19. External louver with control	Set louver as external shading devices Incident radiation to lower device: 100 W/m^2 Incident radiation to raise device: 100 W/m^2
20. External louver without control	Set louver as external shading devices Percentage profile group: Off during 10:00-18:00
21-27. Orientations	Set site rotation angle in IES as 79, 124, 169, 214, 259, 304, 349, 34

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