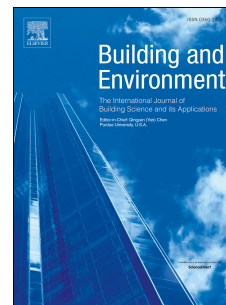


Journal Pre-proof

The significance of occupancy profiles in determining post retrofit indoor thermal comfort, overheating risk and building energy performance

Heba Elsharkawy, Sahar Zahiri



PII: S0360-1323(20)30034-2

DOI: <https://doi.org/10.1016/j.buildenv.2020.106676>

Reference: BAE 106676

To appear in: *Building and Environment*

Received Date: 5 October 2019

Revised Date: 6 January 2020

Accepted Date: 11 January 2020

Please cite this article as: Elsharkawy H, Zahiri S, The significance of occupancy profiles in determining post retrofit indoor thermal comfort, overheating risk and building energy performance, *Building and Environment*, <https://doi.org/10.1016/j.buildenv.2020.106676>.

This is a PDF file of an article that has undergone enhancements after acceptance, such as the addition of a cover page and metadata, and formatting for readability, but it is not yet the definitive version of record. This version will undergo additional copyediting, typesetting and review before it is published in its final form, but we are providing this version to give early visibility of the article. Please note that, during the production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

© 2020 Elsevier Ltd. All rights reserved.

1 **The significance of occupancy profiles in determining post retrofit indoor** 2 **thermal comfort, overheating risk and building energy performance**

3 **Heba Elsharkawy ^{a*}, Sahar Zahiri ^{a1}**

4 ^a Department of Architecture and Visual Arts, School of Architecture, Computing and Engineering,
5 University of East London, E162RD, London, UK

6 h.elsharkawy@uel.ac.uk

7 **Abstract**

8 Recently, retrofit of tower blocks has gained momentum particularly in the UK social housing sector due to the
9 increasing rate of fuel poverty coupled with deteriorating indoor living conditions. However, the process of
10 making improvements to the thermal performance of building envelopes can significantly impact on occupants'
11 thermal comfort, increasing overheating risks with the changing climate and associated heat waves. The first
12 phase of the study evaluated the building energy performance of a 1960s social housing tower block prototype in
13 London, pre-retrofit, where the building simulation model was created and calibrated with monitored indoor data
14 and occupants' interviews. The second research phase, the subject of this paper, uses the model to further
15 investigate the impact of improved thermal insulation of the building envelope, based on U-values prescribed by
16 the UK Building Regulations (Part L1B), on the potential risk of overheating. The study investigates the impact
17 of retrofitting on occupants' thermal comfort and building energy performance in the current and future climate
18 scenarios (2030, 2050 and 2080). Results confirm that improving the U-value of external walls will significantly
19 reduce the heating energy use by 70% under future climate scenarios while the T_o increases by 15-17% with U-
20 value of 0.5 W/m²K and 0.3 W/m²K in comparison to the base case. The overall results indicate that the different
21 occupancy patterns adopted in the simulation model have a significant impact on the predicted duration of
22 overheating which will, in turn, have an impact on determining appropriate retrofit strategies to reduce
23 overheating risks.

24 **Keywords:** retrofit, energy efficiency, overheating, thermal comfort, social housing, future climate

25 **1. Introduction**

26 Abundant evidence exists that the climate change phenomenon is primarily exacerbated by
27 greenhouse gas (GHG) concentrations in the atmosphere (IPCC, 2014a; Lowe *et al.*, 2019) . As a
28 result, the rate of global warming has rapidly accelerated in the last few decades with a predicted
29 increase in UK temperatures of 0.7°C to 4.2°C in winter, and 0.9°C to 5.4°C, in summer by 2070, in
30 the high emission scenario (IPCC, 2014b; Lowe *et al.*, 2019). Notably, with surface and air
31 temperatures continuing to rise, heatwaves are expected to occur more often and may well last for

¹ Low Carbon Building Research Group, School of Architecture, Oxford Brookes University, Oxford, UK
szahiri@brookes.ac.uk

32 longer periods (IPCC, 2014b). The UK Climate Change Projections 2018 (UKCP18) predicts that
33 Southern England may experience a rise in mean summer temperatures of up to 8°C by the end of the
34 century, relative to a 1981-2000 baseline at the 90th percentile (Lowe *et al.*, 2019). UK deaths related
35 to heat waves are also expected to rise from 2000 per year in 2015 to 7000 per year by 2050 (CCC,
36 2018). Moreover, due to its geographical location and urban density, it is predicted that London will
37 continue to have the highest heat-related mortality rates in the UK, where 30% of the related deaths in
38 the 2003 heat wave occurred in the capital (Hajat, Kovats and Lachowycz, 2007) and 40% of the
39 deaths related to the 2018 heat waves were in London (Public Health England, 2018).

40 Hence, to mitigate climate change, the UK has set a target to bring all its greenhouse gas (GHG)
41 emissions to net zero by 2050 which is enshrined in law– (CCC, 2019; Gov.UK, 2019). Short-term
42 action plans have already been implemented in the building sector to achieve the set targets, such as
43 adopting a systematic approach to improve the energy efficiency of new and existing buildings,
44 following the previously set target of reducing GHG emissions by 80% by 2050 compared to the 1990
45 levels (CCC, 2018a). Introducing effective energy-efficient retrofit programmes for existing buildings
46 (Shen, Braham and Yunky, 2019) and developing long-term low energy building strategies for the
47 new building stock would help achieve the national targets (Gieseckam, Tingley and Cotton, 2018).
48 Hence, enforcing key policies to deliver effective retrofit programmes with particular attention to
49 meeting social housing minimum standards (i.e. Decent Homes Standard²) is vital where in 2019, 4.7
50 million homes (20% of England's domestic stock) failed to meet the Decent Homes Standard (DCLG,
51 2017; CCC, 2018b; Champ, 2019).

52 In 2017, the domestic buildings in England comprised almost 24 million housing units of which
53 four million are social and affordable rented properties (MHCLG, 2018). The significant number of
54 social housing properties lends itself as the focus of energy-efficient retrofit interventions that can

² A Decent Home is defined thus: It meets the current statutory minimum standard for housing; it is in a reasonable state of repair; it has reasonably modern facilities and services; and it provides a reasonable degree of thermal comfort (Department for Communities and Local Government, 2006).

55 potentially reduce the overall heating energy use, particularly in areas with high rates of fuel poverty.
56 Current studies indicate that many people residing in London struggle to afford the energy demands of
57 their properties, where around 34,000 households are considered to be in fuel poverty (Greater London
58 Authority, 2018). The ‘Progress in Preparing for Climate Change’ report affirms that local authorities
59 play crucial roles in delivering various aspects of the National Adaptation Programme³ (CCC, 2017;
60 Department for Environment Food & Rural Affairs (DEFRA), 2018). Hence, many retrofit
61 programmes have been rolled out in the UK with multiple schemes introduced at local authority levels
62 to improve the energy performance of dwellings, most of these schemes focus on reducing the heating
63 energy demand (Baborska-Narozny and Grudzinska, 2017).

64 To reduce the overheating risk and adapt buildings to climate change, it is crucial to minimise
65 internal heat gain by considering orientation, shading, fenestration, insulation, green roof/wall,
66 exposed thermal mass, and passive ventilation supplemented with mechanical ventilation only when
67 needed (Greater London Authority, 2016). Moreover, scholars have acknowledged that indoor air
68 temperature may increase considerably during the warmer seasons post retrofit (Elsharkawy and
69 Rutherford, 2018) particularly under climate change scenarios where overheating is predicted, posing
70 significant risk to susceptible occupants (Mavrogianni *et al.*, 2015; Taylor *et al.*, 2015). Additionally,
71 studies found that the occupancy profile (i.e. family or elderly occupancy) has a significant impact on
72 overheating exposure; for example, the elderly may typically occupy their homes during the hottest
73 time of the day and hence are exposed to more overheating hours in comparison to family occupancy
74 with low attribution to occupancy during the daytime due to work or study commitments (S.M. Porritt
75 *et al.*, 2012; Mavrogianni *et al.*, 2015; Zero Carbon Hub, 2015). In a study in the UK, results reported
76 a general trend of window-opening patterns where the higher the indoor temperatures, the more
77 frequently the windows were opened (Yun and Steemers, 2008). Mavrogianni *et al.* (2014) reported
78 that predicting and estimating the overheating risk differ when the actual occupants’ patterns differ

³ National Adaptation Programme (NAP) sets the key actions that government and others will take to adapt to the challenges of climate change in the UK for the next five years.

79 from standard rules of occupancy used in simulation analysis. Moreover, Lomas and Porritt (2017)
80 stated that the overall building design and occupants' heat management in individual rooms are both
81 key contributors to overheating.

82 Various studies have highlighted the issue of higher risk of overheating in UK flats compared
83 with other housing types for many reasons, but mainly due to low wall to floor ratio, as well as little
84 possibility for cross-ventilation (Gupta and Gregg, 2012a; Mavrogianni et al., 2015; Baborska-naro,
85 2017). Moreover, the risk of exposure to overheating hours in the top floors of a 1960's tower block is
86 six times more than on the ground floor and nine times more than the case in Victorian terraced
87 homes due to building characteristics, and construction age, as well as the association between the age
88 of the building and morphology, glazing level, size of windows, the U-value, and the airtightness of
89 the building (DCLG, 2011). The 1960's tower blocks usually have low solar thermal protection
90 particularly on the top floor where poor thermal insulation increases the risk of being exposed to more
91 solar radiation, whereas ground floor flats in the same building experience a considerable cooling
92 impact because of the lack of floor insulation (DCLG, 2011). The study explores the risk of
93 overheating in a 1960s tower block prototype⁴ in future climate scenarios (2030, 2050, and 2080)
94 following thermal performance improvement of the building envelope. To address the current
95 research gap, the researchers argue that integrating real dominant occupancy profiles in the
96 overheating prediction methodology considering the building typology, construction materials, and
97 other building design factors helps predict more reliable building performance and thermal comfort for
98 different building typologies as opposed to a generic one-size-fits-all model.

99 **2. Research methodology**

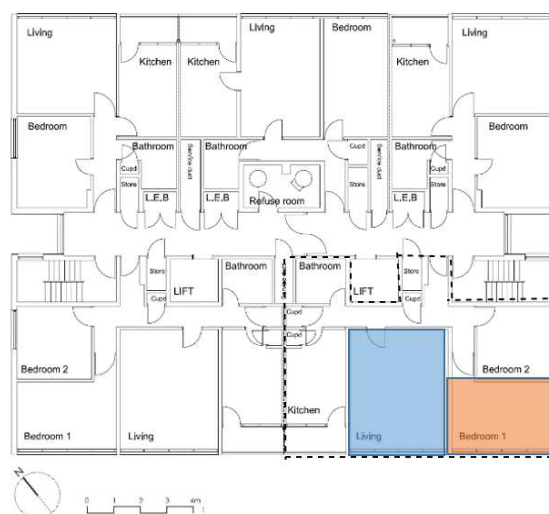
100 In London, 38% of housing types are categorised as purpose-built blocks of flats, the highest
101 compared to mid- and end-terraced houses (23%), semi-detached houses (19%), and detached houses
102 and bungalows (6%) (ONS, 2011). The study has been conducted over two phases; first, the

⁴ In London and South East England, almost 40% of purpose-built blocks were constructed in the 1960-1980 era (Greater London Authority, 2015).

103 researchers evaluated the building performance of a tower block, as one of the dominant social
 104 housing prototypes in London. Next, the risk of overheating in climate change scenarios is explored
 105 with a focus on the impact of thermal performance of external walls, as well as the role of occupancy
 106 profiles in predicting overheating. The overall research design adopted a quantitative methodology
 107 which incorporated a questionnaire-based survey, indoor monitoring, and dynamic thermal modelling.
 108 The first phase of the study was undertaken in 2017 when the data were collected through a
 109 questionnaire-based survey of the tower block tenants and structured interviews with sample
 110 households. Also, indoor environmental monitoring (operative temperature (T_o) and relative humidity
 111 (RH)), and building simulation modelling were undertaken concurrently to assess the building
 112 performance and the impacts of occupants' energy use and occupancy profiles on energy performance
 113 of the building. The outcome of the first phase was the development and calibration of a building
 114 simulation model of the case study (Zahiri and Elsharkawy, 2018), which is adopted in this second
 115 phase of the research. DesignBuilder (DB) (version 5.5) is used to create the building geometry,
 116 optimise the building performance and produce EnergyPlus calculations for further analysis.

117 *2.1 Case Study: 1960's tower block*

118 The case under study is a 22-storey council housing tower block built in 1966 and located in
 119 East London (Figure 1), consisting of 108 1-bedroom and 2-bedroom flats. Due to its site location, the
 120 building is mostly unshaded.



121

122 Figure 1: Typical floor plan of the case study building (Newham Council, 2007)

123 The tower block is constructed of an in-situ reinforced concrete frame with concrete floor slabs
124 spanning between shear walls and pre-cast concrete panels as external walls. The external building
125 envelope was refurbished in 2005 with asbestos cement over-cladding panels for aesthetic purposes
126 and all flats also received double-glazed windows with UPVC frames and trickle vents. The internal
127 partition walls consist of concrete blocks of 100 mm thickness. The wall layers from outside to inside
128 are 9 mm asbestos cement over-cladding, 80 mm air gap, 200 mm precast concrete panels, 20 mm
129 internal wall insulation and 13mm plaster finish. Internal floors consist of 150 mm reinforced concrete
130 slabs as well as ceiling plaster finishes. Heating is provided by natural gas-fired individual hot water
131 boilers and each flat has two extractor fans; one in the kitchen and another in the bathroom.

132 Following a building survey in 2016 (Medhurst, Turnham and Partners, 2016), results showed
133 that at least 25 flats experienced severe damp, mould and condensation issues, leading to the Council's
134 plan to retrofit the building in the short term. In the first research phase, to help evaluate building
135 performance and occupants' thermal comfort (Zahiri and Elsharkawy, 2017), structured interviews and
136 monitoring of indoor T_o and RH levels were undertaken in three sample flats presenting with indoor
137 environmental issues.

138 **2.2 Building simulation model settings**

139 Recent studies affirm that building components have a direct influence on indoor thermal
140 comfort as well as the related energy demands to keep indoor environment at acceptable comfort
141 levels (Lomas and Porritt, 2017; ZCH, 2016). The first phase of the study indicated that occupants'
142 socio-demographic characteristics and associated occupancy profiles and energy consumption
143 behaviour have a considerable impact on indoor environmental conditions and energy bills of
144 households (Zahiri and Elsharkawy, 2018; Zahiri, Elsharkawy and Shi, 2018). The study further
145 demonstrated the importance of adopting dominant occupancy and heating energy use patterns for
146 more accurate evaluation of the building performance.

147 In phase one, building simulation model was created using experimental data including
148 monitoring thermal comfort surveys and structured interviews to validate the model by implementing
149 outdoor weather data from the Met Office in Energy Plus (epw) format, as well as actual occupancy
150 and energy-use patterns. The results of the structured interviews and thermal comfort surveys also
151 revealed other information. This included heating set point, natural ventilation, domestic hot water
152 (DHW) and heating system schedules, exhaust fan and electrical lighting patterns for both sample flats
153 with low and high occupancy, which were applied to the dynamic simulation model. After applying
154 the required data including construction details, the hourly simulation analysis was run for the winter
155 season. The simulated hourly (T_o) was then compared to the measured results to evaluate the model
156 and create a test-bed for the second stage. In addition to T_o , the energy performance of the sample
157 properties was investigated to achieve a more in-depth understanding of correlation between heating
158 energy use of the building and the occupants' energy use patterns. The results of the initial phase
159 proved that the model is reliable for use in the second phase of building simulation as the variance
160 between the predicted and measured results was less than 15%.

161 The main concern of the second phase is to assess heating energy use based on different
162 occupancy and energy-use patterns, using dominant and real low and high occupancy, as well as
163 prescribed patterns. To run the simulation analysis more efficiently, top, middle, ground and upper
164 ground floors' plan are modelled in detail to include all flats and rooms comprising thermal zones. The
165 focus of the analysis was on the middle floor to measure average energy use of middle floor and south-
166 facing rooms including a main bedroom and a living room. The top, floor and upper ground floors are
167 also included, which meant that the average T_o in these floors were also slightly different, caused by
168 varying levels of heat transfer through internal building elements compared to typical floors. Overall,
169 55 thermal zones are created in each floor and simulation data are recorded with 4 time-steps per hour,
170 to support the accuracy of the outputs. The heating is provided by individual gas-fired hot water
171 boilers connected to radiators installed in thermal zones and the heating patterns are based on SAP
172 2012 recommendations for weekends and weekdays in all rooms. The heating system seasonal
173 coefficient of performance (CoP) is also adjusted at 0.85, so the capacity of the zone heating system

174 accounts for natural ventilation loads in the simulation model. The exhaust fans are included at the
175 HVAC zone level to extract air from the bathroom and kitchen and are designed for use during
176 scheduled patterns of occupancy in these rooms. The heating temperature set-point is 21°C for winter
177 to provide a comfortable indoor air temperature for occupants.

178 In the second phase, to optimise the building performance and heating energy use, a systematic
179 approach is applied to the model. The aim is to enhance the thermal performance of the building
180 envelope to investigate the building performance and occupants' thermal comfort under climate
181 change scenarios. The simulation analyses mainly aims to generate monthly and annual operative
182 temperatures and heating energy-use for the typical middle floor and south-facing living rooms and
183 bedrooms during the occupied hours under the three climate change scenarios. External Wall
184 Insulation (EWI) is chosen as one of the most effective methods to improve the thermal performance
185 of solid walls as it is much more effective than internal wall insulation in tower blocks (Cheng *et al.*,
186 2017). This involves fitting insulation boards to external wall surfaces covered by a protective coating
187 of render (Tink *et al.*, 2018). It should be noted that the improved thermal insulation levels are selected
188 to comply with current UK Building Regulations Approved Document Part L1B for existing
189 buildings; 0.3, and 0.7W/m²K (the lower and upper range values) (Department for Communities and
190 Local Government, 2018), and 0.5 W/m²K (as the middle value), compared to the base case of nearly
191 0.9 W/m²K.

192 Building simulation analysis is undertaken to predict heating energy use and overheating risks
193 in the typical middle floor using each EWI option in the current climatic condition in comparison to
194 the future climate scenarios (2030, 2050 and 2080). At this stage, the building simulation model
195 settings, including occupancy and energy use patterns, are defined based on CIBSE Technical
196 Memorandum 59 (TM59) (CIBSE, 2017) and Standard Assessment Procedure (SAP) 2012 (for winter
197 heating schedules) (DECC, 2014). CIBSE's TM59 guideline is the recommended methodology for
198 assessment of overheating risks in homes. The methodology predicts the level of risk of overheating

199 for naturally ventilated domestic buildings if either of the two exceedance criteria fails⁵. This guideline
200 does not include a pattern of heating energy use. Therefore, the model adopts the heating energy use of
201 the UK Governments' Standard Assessment Procedure (SAP 2012) which was developed and
202 approved for energy rating of domestic buildings (DECC, 2014). Following the initial analysis, the
203 optimum wall U-value is selected for the consequent stage of building simulation to determine
204 overheating risks in the bedroom and living room of a south-facing flat of a typical floor, as the worst-
205 case scenario. The T_o of these zones is also assessed respectively in future climate scenarios. At this
206 stage, the dominant low and high occupancy patterns within the tower block, obtained from the first
207 phase, are applied to the simulation settings to compare the predicted results against TM59
208 methodology pre- and post-retrofit under climate change scenarios. This helps assess the effect of
209 using dominant occupancy scenarios in predicting building energy performance and overheating risks
210 in occupied rooms. However, it must be noted that heating patterns are expected to change post-
211 retrofit.

212 To evaluate the influence of varying occupancy profiles and energy-use patterns on assessing
213 potential overheating, two dominant occupancy patterns extracted from the survey questionnaire
214 (undertaken in the first phase of the research) are adopted for modelling as well as TM59 and SAP
215 2012 methodology. Based on the survey results, 31% of the tower block has an almost identical profile
216 with low occupancy pattern (hereby labelled as Flat A) and 31% has an almost identical flat B profile
217 with high occupancy pattern (hereby labelled as Flat B) (Zahiri, Elsharkawy and Shi, 2018). This helps
218 demonstrate the importance of adopting actual high and low occupancy profiles to assess the extent of
219 overheating risks compared to TM59 methodology. Both occupancy profiles are applied to the DB
220 model, and the calculated building performance and overheating risks are compared to the TM59

⁵ The percentage of occupied hours, where $T = T_{top} - T_{max}$ is greater than or equal to 1 °C during the period May to September, inclusive, does not exceed 3% in living rooms, kitchens and bedrooms. Bedroom operative temperature does not exceed 26 °C for more than 1% of the assumed sleeping hours (22:00-07:00) annually (equivalent to 32 hours). [Recommendations by CIBSE Guide A: Environmental design recommends that peak bedroom temperatures should not exceed a threshold of 26 °C]

221 occupancy scenario in current and future climate scenarios (2030, 2050 and 2080). Table 1 presents
 222 the heating and occupancy patterns applied to the model in both phases.

223 Table 1: Energy-use and occupancy patterns applied at different stages of the simulation analysis

Room type		Flat A (single elderly)		Flat B (family of 2 adults and 3 children)		TM59-SAP2012	
		Winter	Summer	Winter	Summer	Winter	Summer
Bedroom	Heating	SAP2012 ¹	N/A	SAP2012 ¹	N/A	SAP2012 ¹	N/A
	Occupancy	10pm to 8am		7pm to 7am		TM59 ²	
Living room	Heating	SAP2012 ¹	N/A	SAP2012 ¹	N/A	SAP2012 ¹	N/A
	Occupancy	8am to 11pm		8am to 11pm		TM59 ²	

¹SAP2012 heating pattern-
 Weekday: 0700-0900 and 1600-2300/ Weekend: 0700-2300
²TM59 occupancy pattern-
 Bedroom: 2 people from 11pm to 8am 70% gain, 2 people at full gain from 8am to 9am and from 10pm to 11 pm, 1 person at full gain from 9 am to 10 pm
 Living room: 2 people at 75% gain from 9am to 10 pm

224 It should be noted that natural ventilation schedules and window- and door-opening schedules
 225 are defined based on TM59 due to not having this detailed information from occupants. Windows are
 226 set to open when the room is occupied and indoor T_o rises above 22°C while internal doors are set to
 227 be open during the day time but closed when the occupants are asleep. Internal blinds are set to be in
 228 use when natural ventilation is provided, this is based on TM59 recommendations. Each window
 229 frame of the case study is 1.4 m height and 0.85-1 m width and window to wall ratio is approximately
 230 20% in the tower block. In this study, only heat gain from occupants is included because the main
 231 focus is on the impact of occupancy and heating patterns on indoor T_o , overheating risk, and building
 232 energy use. The defined infiltration rate and air speed are obtained from TM59 and building regulation
 233 part L1B as a consequence of applying SAP 2012; 5 m³/m²h @ 50 Pa and 0.1 m/s, respectively. Table
 234 2 summarises the input data of the building model.

235 Table 2: Building components modelling input data of the case study (existing and retrofitted)

BUILDING COMPONENTS	MATERIALS	EXISTING	RETROFITTED		
			0.7 W/m ² K	0.5 W/m ² K	0.3 W/m ² K
EXTERNAL WALL U-VALUE	External over-cladding & rendering, concrete panels, internal thermal insulation & plaster finish	0.9 W/m ² K	0.7 W/m ² K	0.5 W/m ² K	0.3 W/m ² K
FLOOR U-VALUE	Concrete slabs & rendering	2.7 W/m ² K	2.7 W/m ² K		
ROOF U-VALUE	Concrete slab & rendering,	2.3 W/m ² K (Mavrogianni <i>et al.</i> ,	0.28 W/m ² K		

	bitumen	2015)	
WINDOWS U-VALUE	Double glazing with UPVC panels	2 W/m ² (Mavrogianni <i>et al.</i> , 2015)	2 W/m ² K (Mavrogianni <i>et al.</i> , 2015)
AIR INFILTRATION	-	10 m ³ /m ² h at 50 Pa (Mulville and Stravoravdis, 2016)	5.0 m ³ /m ² h at 50 Pa (Building Regulation 2010, 2018)

236

237 To simulate the risk of overheating and the impact on occupants' thermal comfort, at the time of
 238 undertaking the simulation, weather data files for current and future climate are obtained from UK
 239 Climate Projections program⁶ (UKCP09) PROMETHEUS project (University of Exeter, 2012). The
 240 weather files are exported in EnergyPlus format (epw) and used in DB simulation software. The files
 241 are also generated for the current climate condition based on the weather data of 1961-1990 as well as
 242 the three future climate scenarios (2030, 2050 and 2080). In this study, the 50th percentile central
 243 estimate weather files for London Heathrow are used to provide comparable outputs in relation to
 244 CIBSE's weather files, as suggested in TM59, to reduce extreme results.

245 3. Results and discussion

246 Once the building simulation model was developed and calibrated in the first phase of the
 247 research, the existing over-cladding system is then replaced with three EWI options to explore the
 248 impact of improved thermal performance on the overall building energy performance and indoor
 249 thermal comfort. Building performance of the typical middle floor is assessed where TM59 occupancy
 250 profile (CIBSE, 2017) and SAP 2012 heating profile (DECC, 2014) are adopted. The results of the
 251 analysis are later compared against improved building envelope performance applying three U-values
 252 (0.3, 0.5 and 0.7 W/m²K) under three future climate scenarios to determine the optimum U-value that
 253 may help achieve a relative balance between heating energy use and hours of discomfort. At this stage,
 254 the only variables are the U-value of external walls and the future weather data for 2030, 2050 and
 255 2080. It is expected that improved thermal performance of external walls will reduce annual heating

⁶ There is considerable overlap between UKCP09 and UKCP18 data sets. The significant advances of UKCP18 over previous probabilistic projections provided in UKCP09 are: the inclusion of simulated natural interannual variability; the inclusion of models from the most recently completed IPCC assessment report; a more comprehensive sampling of Earth System modelling uncertainty; and more up-to-date observational constraints. UKCP18 also includes improvements to the detailed methodological approach, including the statistical aspects of the methodology (Lowe *et al.*, 2019).

256 energy. However, the outcomes may provide evidence for whether improving the building envelope
257 performance influences overheating risk in future climate conditions and if so, to what extent.

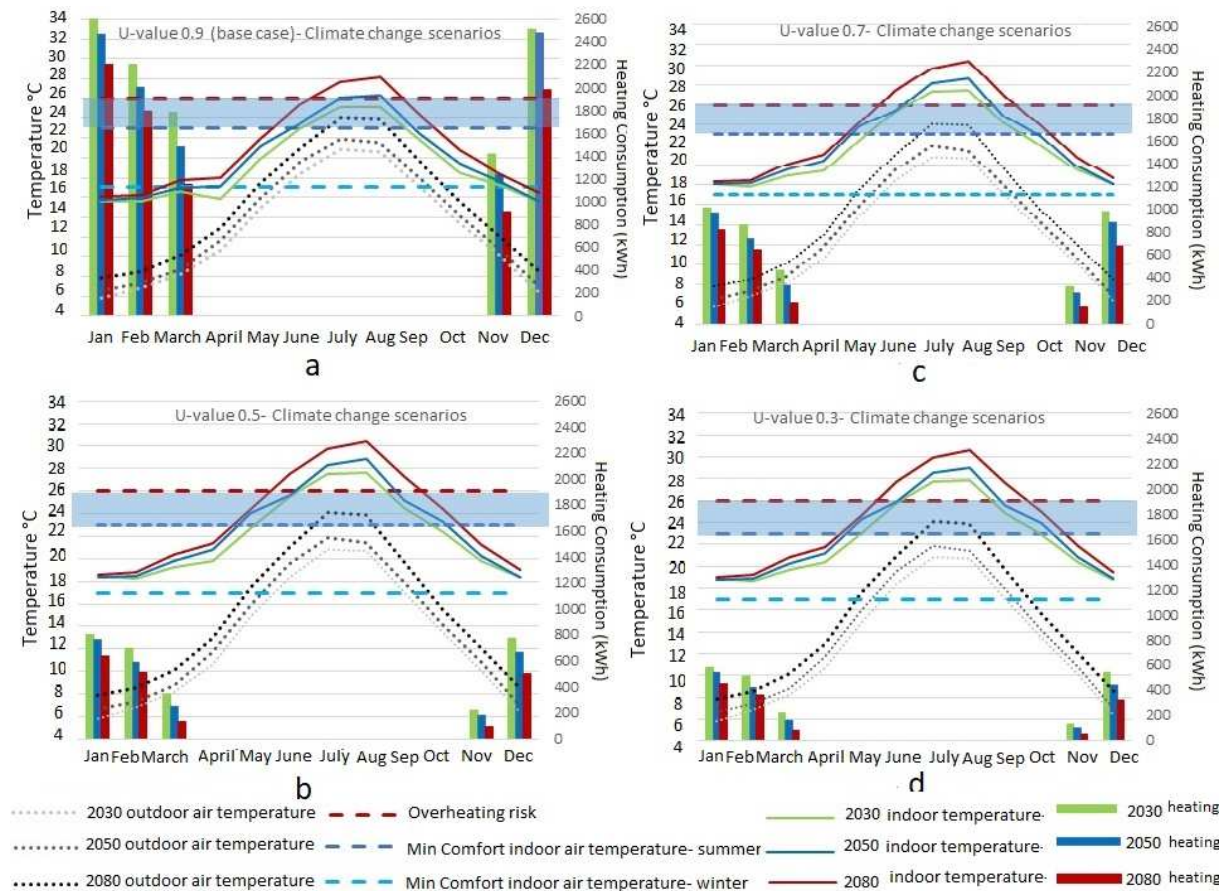
258 ***3.1 The impact of building envelope thermal performance on thermal comfort and building energy*** 259 ***performance***

260 Figure 2 (a, b, c, d) presents the mean T_o and the heating energy use of the typical middle floor
261 of the case study under climate change scenarios by applying the U-values of 0.9 (base case), 0.7, 0.5
262 and 0.3 W/m^2K using TM59-SAP 2012 occupancy and heating energy-use profiles. The figure shows
263 that, in general, T_o increases steadily in 2030, 2050, and 2080 scenarios and, as expected, heating
264 energy use reduces as a result. However, the changes are greater after improving building envelope
265 thermal performance, as the building becomes more airtight with reduced air infiltration rate. As
266 indicated earlier, the defined air permeability of the building post retrofit is based on Building
267 Regulation Part L1B; $5 m^3/hr/m^2 @ 50 Pa$ while it is estimated to be $10 m^3/hr/m^2 @ 50 Pa$ in the base
268 case which will have contributed to the significant heating energy use in colder seasons. The results
269 demonstrate that, as the building becomes more thermally efficient and airtight, the indoor T_o rises
270 while the heating energy use drops steadily.

271 Concerning the building performance of the typical middle floor (U-value $0.9 W/m^2K$); the
272 indoor T_o is predicted to be within the comfort range by 2050 during the months of May-September
273 with potential overheating risk in 2080 as the indoor T_o increases by around 10%, reaching $28^\circ C$.
274 Notably, the base case uses significant heating energy to keep the occupants in a comfortable indoor
275 environment during the colder months. However, the energy usage falls by 25% under future climate
276 scenarios. For example, by improving the thermal performance of the external envelope from 0.9 to
277 $0.7 W/m^2K$, heating energy use drops significantly by around 70% on average under the three future
278 climate scenarios while annual mean indoor T_o increases by 13%. A possible reason for this is that by
279 improving the thermal performance of external envelope from 0.9 to $0.7 W/m^2K$, indoor T_o moves
280 closer to minimum thermal comfort boundaries or falls within the boundaries, so the occupants require
281 less heating energy to keep the indoor temperature within the thermal comfort zone. In addition, as it

282 consequently changes from 0.7 to 0.5 and 0.3 W/m²K; the indoor T_o increases accordingly, hence
 283 reducing the needs for heating energy use.

284



285

286 Figure 2 (a, b, c, d): Indoor T_o and heating energy use in a typical middle floor under the climate change
 287 scenarios (2030, 2050, 2080), using TM59-SAP patterns and U-values of a. 0.9 W/m²K , b. 0.7 W/m²K , c. 0.5
 288 W/m²K and d. 0.3W/m²K.

289 In addition, as the thermal performance of external walls improves, the indoor T_o increases
 290 slightly by a maximum of 15% with the U-value of 0.5 W/m²K and 17% with the U-value of 0.3
 291 W/m²K in comparison to the base case. As can be seen, the difference between increases in indoor T_o.
 292 using the values of 0.7, 0.5 and 0.3 W/m²K is not significant. The maximum average indoor T_o.
 293 occurred in August ranging from around 28°C in 2030, 29°C in 2050, to 30°C in 2080 all of which
 294 already exceed the maximum comfort limit, magnifying the risk of overheating. However, heating
 295 energy-use falls significantly by between 65% and 75% in comparison to the base case. It must be
 296 noted, though, that the results discussed above are relevant to a typical floor including all thermal

297 zones at all orientations; hence, the possibility for higher/lower hours of discomfort at south/north
 298 facing rooms is expected.

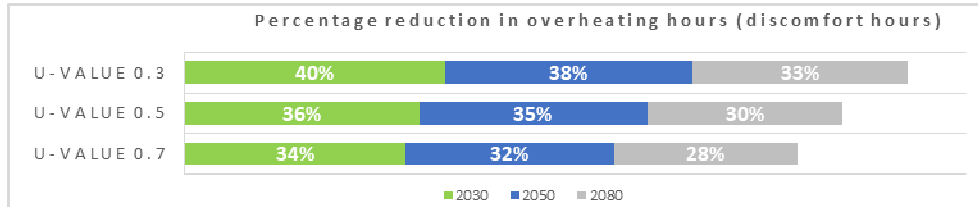
299 Table 3 presents the impact of climate change scenarios on minimum, maximum and mean
 300 annual operative temperatures and solar gains of exterior windows in the typical middle floor with U-
 301 values of 0.3, 0.5, 0.7 and 0.9 W/m²K for external walls. It can be seen that indoor T_o increased
 302 steadily from 2030 to 2080 when applying improved U-values for external walls. In addition, as the U-
 303 value of external walls improved, the indoor T_o is predicted to rise. The improvement of building
 304 envelope results in a maximum mean annual temperature rise by around 3.5 °C by 2080 using the U-
 305 value of 0.3 W/m²K, while the minimum mean temperature rise is predicted to be just below 3 °C.

306 Table 3: Annual operative temperature in a typical middle floor using U-values of 0.3, 0.5, 0.7 and 0.9 W/m²K in
 307 three climate change scenarios

<i>Climate projection</i>		2030				2050				2080			
<i>U-Value W/m²K</i>		0.3	0.5	0.7	0.9	0.3	0.5	0.7	0.9	0.3	0.5	0.7	0.9
<i>Annual operative temperature °C</i>	Min	18.60	18.21	17.90	15.54	18.79	18.38	18.03	15.62	18.99	18.62	18.32	16.08
	Mean	22.10	21.71	21.39	18.98	22.67	22.30	22.00	19.51	23.96	23.22	22.93	20.57
	Max	27.90	27.63	27.40	25.13	29.04	28.83	28.65	26.33	30.65	30.46	30.31	28.19

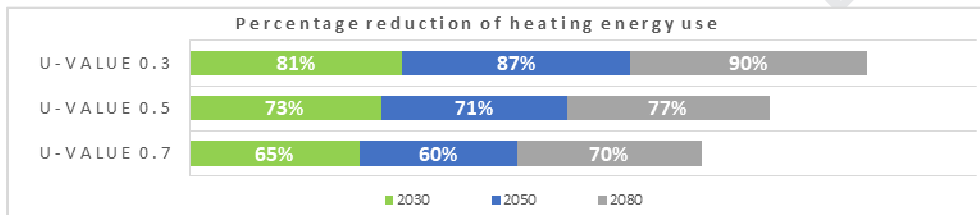
308 Figure 3 (a and b) illustrates the predicted percentage of reduction in overheating hours
 309 (discomfort hours) in the warmer months (May-September), as well as the percentage of reduction of
 310 the heating energy use in the typical middle floor during the colder months (October-April) post-
 311 retrofit. The percentage of difference is the difference between the base case scenario and improved
 312 building performance obtained by dividing the absolute value of difference between the base case and
 313 the improved scenario divided by the average of two numbers and multiplied by 100. These data are
 314 calculated based on the discomfort hours and heating energy use obtained from the DB building
 315 simulation analysis that calculates discomfort hours based on ASHRAE 55 Standards (2004). It should
 316 be noted that TM59 methodology defines overheating risk solely based on indoor operative
 317 temperature, while discomfort hours include the impact of humidity levels on indoor thermal comfort
 318 using the ASHRAE 55 standard (ASHRAE, 2004) in naturally ventilated buildings. Although comfort

319 criteria of ASHRAE and CIBSE TM59 are different, using both methodologies helps provide a clear
 320 indication of the impact of humidity on thermal comfort as extreme high and low humidity levels do
 321 contribute to levels of discomfort.



322
323

(a)



324

325

(b)

326 Figure 3: Percentage of difference between the reduction of discomfort hours (a) and the reduction of energy use
 327 (b) in the base case (U-value 0.9 W/m²K for external walls) compared to the upgraded thermal performance of
 328 the building envelope (U-values of 0.3, 0.5 and 0.7 W/m²K) in a typical middle floor.

329 The results (Figure 3a) show a significant difference between the discomfort hours of the base
 330 case compared to the improved thermal performance following upgrade to the external walls. These
 331 changes to discomfort hours are 28% (U-value of 0.7 W/m²K in 2080), reaching 40% (U-value of 0.3
 332 W/m²K in 2030). However, the changes in indoor T_o are not as significant when comparing 0.3, 0.5
 333 and 0.7 W/m²K. Typically, the U-value of 0.3 W/m²K results in a notable increase in indoor T_o and
 334 hence a rise in discomfort hours compared to 0.5 and 0.7 W/m²K, but the maximum difference ranges
 335 between 5 and 6% under the three climate change scenarios.

336 Moreover, the heating energy use improves significantly in the typical middle floor using
 337 improved U-values in comparison to the base case (Figure 3b). Overall, improving the thermal
 338 conductivity of the building envelope improves the building performance and reduces heating energy
 339 demand. However, with the improved thermal performance of the building envelope, indoor T_o rises in
 340 the warmer seasons and, as a result, the risk of overheating is clearly identified.

341 Studies show that improving the thermal performance of the building envelope by improving
342 the thermal insulation may lead to a reduction in the building energy consumption of between 50%
343 and 90% depending on the building type (Aditya *et al.*, 2017; Ozarisoy and Elsharkawy, 2019).
344 According to Jie *et al.* (2018), the improved thermal performance of the insulation material in the
345 external building envelope has a minimum impact on reducing the cooling energy consumption while
346 its effect on reducing heating energy consumption is significant. A study conducted by Fosas *et al.*
347 (2018) also investigates the impact of improving the building performance on overheating risk by
348 upgrading thermal insulation materials. Their study shows that if sufficient air circulation is delivered
349 by purge ventilation, improving the building performance by improved thermal insulation does not
350 significantly affect the overheating risk and the difference of risk of overheating between the un-
351 insulated building and super-insulated building is 5% (Fosas *et al.*, 2018). However, the lack of indoor
352 air infiltration may increase the overheating risk as the building becomes more impermeable. Tink *et*
353 *al.* (2018) also state that improving the building performance by improving thermal insulation may
354 increase the indoor air temperature during the warmer seasons. Other studies indicate that using
355 appropriate mitigation approaches such as shading devices and suitable ventilation strategies including
356 night-time cooling may reduce the impact in the future climate conditions to a certain extent (Gupta
357 and Gregg, 2012b; S. M. Porritt *et al.*, 2012; Porritt *et al.*, 2013; Mavrogianni *et al.*, 2014, 2015;
358 Baborska-naro, 2017; Pathan *et al.*, 2017). These studies show that passive cooling strategies may
359 have a comparable influence on improving the building performance in warmer seasons in super-
360 insulated and low-insulated buildings. However, if there is a lack of indoor ventilation, the level of
361 external wall insulation becomes an important factor in determining overheating. Therefore, it is
362 necessary to investigate the optimum U-value for the building envelope, which helps provide a
363 comfortable indoor environment all year round, particularly in future climate scenarios.

364 As one of this study's aims is to define the appropriate thermal performance of external walls
365 that achieves a relative balance between heating energy use and hours of discomfort, besides findings
366 that show a minor difference between the impact of the recommended U-values on overheating risk;
367 the U-value of 0.5 W/m²K is selected for the second phase.. The focus of this phase is to study the

368 impact of occupancy and energy-use patterns on overheating risk of the occupied zones of a south-
369 facing flat on a typical floor, as the most at risk of overheating. To assess overheating risks in future
370 climate scenarios, the results are compared using three patterns of occupancy – two real dominant
371 patterns and the TM59 pattern.

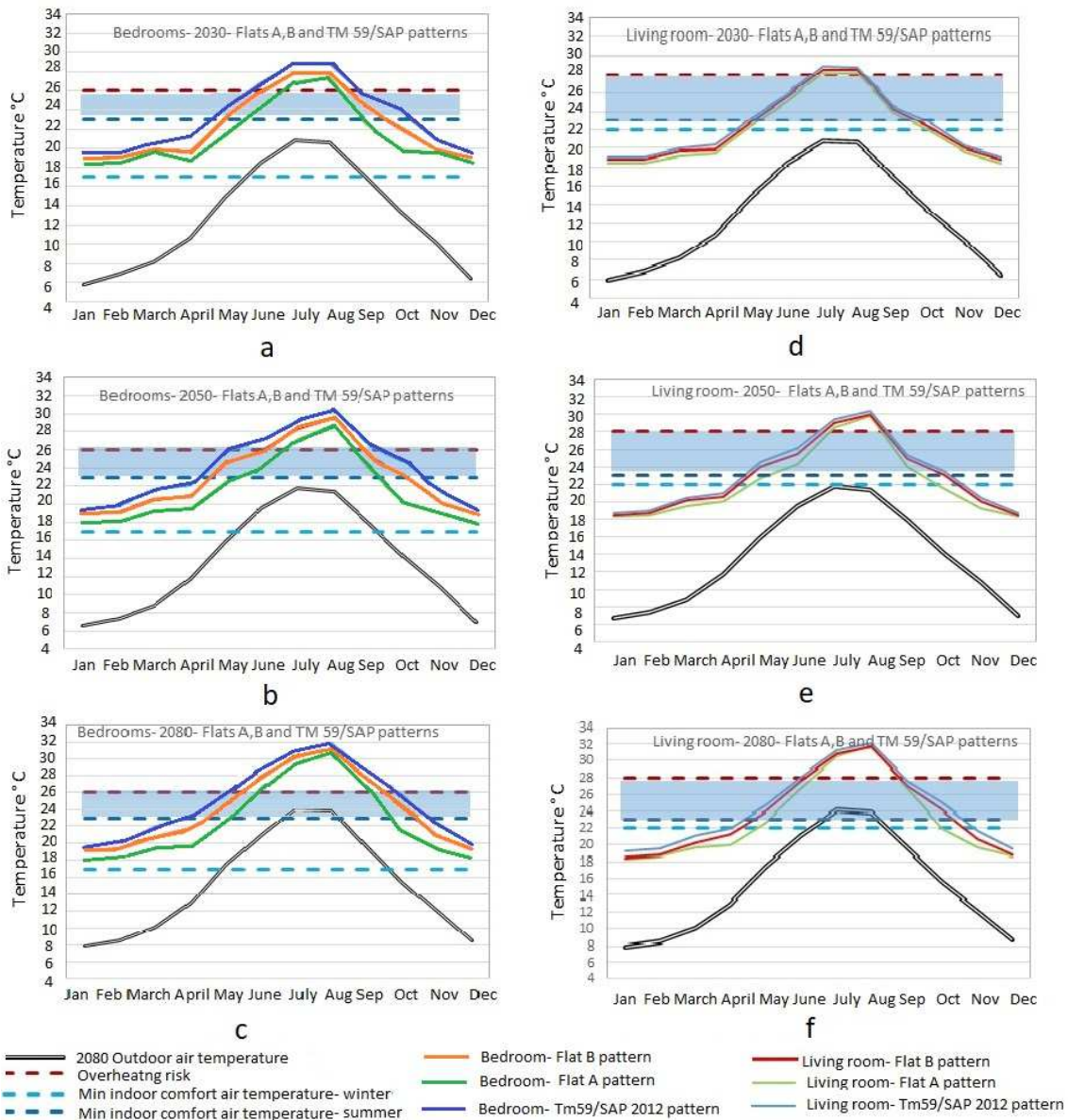
372 *3.2 The effect of occupancy profiles on predicting overheating risks*

373 At this phase, the focus is on the role of occupancy patterns in predicting the building
374 performance and thermal comfort in the future climate scenarios. It should be noted that the TM59
375 methodology prescribes a limited pattern of occupancy, which varies by the number of bedrooms with
376 no variance between weekend and weekday occupancy patterns. To evaluate the impact of the actual
377 occupancy patterns on building performance against TM59 occupancy profile to assess overheating
378 risk, two dominant occupancy profiles (explained in section 2.2) are deployed to the model whilst
379 retaining improved external wall U-value at a constant of 0.5 W/m²K. The indoor T_o of the main
380 occupied zones – namely the bedroom and living room – are assessed and the results are compared
381 against the CIBSE TM59 occupancy pattern.

382 Figures 4 (a, b, c) and 4 (d, e, f) present predicted indoor T_o in the bedroom and living room of
383 the typical south-facing 2-bedroom flat in 2030, 2050 and 2080 climate scenarios using three different
384 occupancy profiles: Flat A, Flat B, and TM59. The results demonstrate that indoor T_o rises above
385 maximum comfort level, exceeding 26°C in bedrooms during most of summer months. However, the
386 extent of the increase mostly depends on occupancy patterns of rooms as well as the outdoor climate
387 conditions.

388 The results show that the average predicted indoor T_o using TM59 pattern is 1-1.6°C higher
389 than the Flat B pattern in the bedroom in all future climate scenarios. This variance has an impact on
390 exaggerated prediction of the overheating period in summer as the duration of discomfort extends as a
391 result. It can be seen (Figure 4 a) that in 2030, the overheating period expands from [May to Sep]
392 using TM59 while it reduces from [June to September] using Flat B pattern and from [July to Aug]
393 using Flat A scenario. While predicted temperatures continue to rise, the duration of overheating
394 continue to expand up until 2080 and its parameters are expected to change to [May to October] using

395 TM59 pattern, [June to October] using Flat B and [June to September] using Flat A pattern. The
 396 overall results show that different occupancy patterns in the simulation model significantly impact on
 397 predicted overheating period which might, in turn, influence decisions to implement appropriate
 398 strategies to reduce the overheating risk in the future.
 399



400

401 Figure 4 (a, b, c): Indoor T_o in the bedroom of the typical south-facing flat with the U-value of $0.5 \text{ W/m}^2\text{K}$ and
 402 three occupancy profiles (Flat A, Flat B, and TM59) under the climate change scenarios (a) 2030, (b) 2050, and
 403 (c) 2080. Figure 4 (d, e, f): Indoor T_o in the living room of the typical south-facing flat with the U-value of 0.5
 404 $\text{W/m}^2\text{K}$ and three occupancy profiles (Flat A, Flat B, and TM59) under the climate change scenarios (a) 2030,
 405 (b) 2050, and (c) 2080.

406 Figure 4 (d) illustrates the slight overheating risk in the living room in 2030. However, the T_o
407 rise is expected to increase steadily up to 2080, rising above 31°C. Similarly, in the bedroom, the
408 predicted overheating period increases steadily until 2080. It can also be noted that indoor T_o is highest
409 using TM59 patterns in comparison to Flat A and Flat B occupancy profiles. However, the percentage
410 of difference is less than that in the bedroom, varying between 0.4°C and 0.9°C under all climate
411 change scenarios. As the bedrooms are occupied over a greater number of hours in both flats using the
412 occupancy patterns of Flats A and B, as well as the TM59 pattern, the mean indoor T_o is generally
413 higher in bedrooms than in living rooms.

414 Noticeably, Flat A occupancy pattern results in the lowest predicted indoor T_o as it has the
415 lowest occupancy pattern of the case study based on one elderly occupant. For example, the results
416 indicate that the average predicted indoor T_o using TM59 pattern is almost 7% more than using Flat B
417 profile in bedrooms in all climate change scenarios while it is 11% more than the Flat A profile. This
418 difference has an impact on the increase of predicted overheating hours as the discomfort periods
419 extend. Table 4 presents the total occupied hours that exceed the maximum comfort temperature in the
420 bedroom and the living room of the south-facing flat under climate change scenarios using the three
421 occupancy profiles. Overall, in the living room, the total hours of discomfort is less than in the
422 bedroom and this may be attributed to the different thresholds in TM59 for overheating, which is 28°C
423 for living rooms and 26°C for bedrooms. In addition, the number of the occupied hours falling within
424 the overheating risk temperature increases gradually under climate change scenarios in all occupied
425 zones. It can also be seen that the TM59 occupancy pattern results in considerably more hours above
426 the maximum comfort temperature than Flat A and Flat B profiles. For instance, the total hours above
427 26°C in the bedroom using the TM59 pattern is almost 57% more than the Flat B profile in 2030, 61%
428 more in 2050, and 58% in 2080 (Table 4). Overall, the differences between the total hours of
429 discomfort using different occupancy schedules are significant particularly between standardised and
430 dominant schedules.

431 Table 4: Hours above overheating risk temperature in bedroom and living rooms of a typical south-facing flat
432 with the U-value of 0.5 W/m²K in the future climate change scenarios

ZONE	HOURS EXCEEDING OVERHEATING RISK TEMPERATURE (TM59 CRITERIA: 26°C BEDROOM AND 28°C LIVING ROOM)								
	2030			2050			2080		
	TM59	Flat A	Flat B	TM59	Flat A	Flat B	TM59	Flat A	Flat B
OCCUPANCY SCHEDULE									
LIVING ROOM	521	468	449	748	492	719	1200	967	1161
BEDROOM	2207	394	952	3051	717	1178	3495	913	1492

433 Moreover, results show that the impact of solar heat gain from windows incurs slight variance in
 434 mean annual solar gain in all three climate change scenarios. Table 5 presents the mean annual solar
 435 gain in the south-facing living room and bedroom in the typical middle floor using the U-value of 0.5
 436 W/m²K. It can be seen that solar gain is predicted to increase from 2030 to 2080 but the increase is not
 437 as significant as the increase in indoor operative temperature.

438 Table 5: Solar heat gain in south-facing living room and bedroom of a typical middle floor

Climate projection	2030		2050		2080	
	Bedroom	Living room	Bedroom	Living room	Bedroom	Living room
Mean annual solar gain in kWh	24.31	16.54	25.84	16.65	25.89	16.89

439 The significant gap between the results using the three occupancy patterns indicates that sole
 440 reliance on the standardised profile may affect the design and implementation of retrofit strategies,
 441 which may not be as cost-effective nor as energy-efficient as expected and may not provide a
 442 comfortable indoor environment for the occupants due to potential overheating. It is important to
 443 identify realistic occupancy patterns as a variable to help predict appropriate retrofit strategies that
 444 would reduce both; heating energy and thermal discomfort.

445 Several studies demonstrate that occupants' profiles have a tangible impact on predicting
 446 building performance (Mavrogianni *et al.*, 2014; University of Southampton, 2016; Ahmed *et al.*,
 447 2017; Ahn *et al.*, 2017; Ben and Steemers, 2017; Yan *et al.*, 2017). A few studies even consider
 448 occupants' behaviour when evaluating building performance and assessing overheating risk (e.g.,

449 Steemers and Ben, 2014; Ben and Steemers, 2017). The research conducted by Porritt *et al.* (2012) on
450 the impact of design interventions, including solar shading and ventilation on overheating risk, proved
451 that the impact of occupancy profiles and behaviour is significant in predicting overheating risks.
452 Other studies also asserted that the way that occupants operate their homes may contribute to thermal
453 discomfort, which should be considered for future retrofit interventions (Elsharkawy and Rutherford,
454 2015, 2018; Mavrogianni *et al.*, 2015). Moreover, controlling natural ventilation to prevent warmer
455 outdoor temperature from entering the building alongside night-time natural ventilation to cool down
456 the surface temperature at night is an effective passive strategy alongside using externally fixed
457 shading devices, shutters, and internal blinds and curtains, particularly for south-facing sides of
458 dwellings. Studies also showed that the incentives for occupants may play an important role to reduce
459 the risk of overheating and their response to improve the resilience is important (Murtagh, Gatersleben
460 and Fife-Schaw, 2019). However, training is needed to improve occupants' knowledge and awareness
461 of overheating risks to help reduce the risk by applying adaptive passive strategies according to their
462 needs and based on their socio-demographic background and lifestyle.

463 The socio-demographic characteristics of occupants is another significant variable in predicting
464 overheating as confirmed in the first phase of this study (Zahiri and Elsharkawy, 2017). Porritt *et al.*
465 (2012) and Mavrogianni *et al.* (2014) focused on vulnerable occupants including children and elderly
466 people where the studies adopted the profiles of a family of two adults with children who spent the day
467 outdoors and would be indoors in the evenings, and a couple of elderly people who spent most of their
468 days at home. The studies found that as the elderly and other vulnerable people spend much of their
469 day-time at home, and as the highest temperature during the warm seasons and heat wave is normally
470 in the afternoon, they are exposed to more overheating hours particularly in the living room. This
471 proves that the overheating experience is more than a family occupancy issue (DCLG, 2011;
472 Mavrogianni *et al.*, 2014; Porritt *et al.*, 2012).

473 **3.3 Limitations of the study**

474 Various studies have affirmed that relying solely on dynamic thermal modelling for predicting
475 overheating may not be effective, as results may vary by 50-100% (Lomas and Porritt, 2017; Tink *et*

476 *al.*, 2018). In fact, models derived from onsite measurements may produce more reliable results
477 (Lomas and Porritt, 2017). Hence, onsite measurements and occupants' profiles have been collected in
478 the case study. Also, the standard TM59 was utilised, as well as two of the dominant occupancy
479 profiles concluded from an earlier survey questionnaire, to investigate the variance between
480 occupancy patterns as a critical parameter in predicting overheating risks. However, as the occupants'
481 interviews were undertaken during the winter of 2017; the summer window and door opening patterns
482 were not collected from occupants, so TM59 schedules were applied instead.

483 Furthermore, it was not feasible to run the simulation for all 108 flats of the case study due to
484 recognized limited capability of software simulations. The modelling and simulation focused on south-
485 facing flats, as the orientation most prone to overheating. The variable under study was internal heat
486 gain from occupants demonstrated by the low and high occupancy profiles. Another limitation of the
487 study is that heating patterns have been kept constant pre- and post-retrofit due to the difficulty to
488 predict occupants' heating patterns post-retrofit. However, it must be acknowledged that heating
489 patterns may probably change post-retrofit due to better heat retention of the improved building
490 envelope. Finally, as the research is undertaken in collaboration with the local council the cost for
491 retrofit interventions affected the decision not to replace all existing windows with energy efficient
492 units. However, the council has been made aware of the potential benefits of deep retrofit
493 interventions.

494 **4. Conclusion**

495 The paper presents the second phase of a study which investigates the impact of retrofitting
496 a 1960's tower block prototype on occupants' thermal comfort and building energy performance in the
497 current and future climate scenarios (2030, 2050 and 2080). The first phase of the study evaluated the
498 building performance and validated the building simulation model adopted in this second phase. This
499 model was employed to explore the risk of overheating in the case study under climate change
500 scenarios as a result of improving building envelope performance using EWI. The results from the first
501 phase of the study indicated that the occupants' socio-demographic backgrounds and occupancy
502 profiles had a significant influence on energy use (Zahiri and Elsharkawy, 2018).

503 Research indicates that improved building performance may result in over-insulated and airtight
504 building envelopes which can potentially increase the overheating risk during warmer seasons
505 particularly when building components are exposed to direct solar radiation (van Hooff *et al.*, 2015;
506 Mulville and Stravoravdis, 2016b; Fosas *et al.*, 2018). The study expands on previous published work
507 exploring the effectiveness and impact of improved thermal performance of the building envelope to
508 reduce, if not prevent, overheating and improve indoor thermal comfort in the summer whilst
509 minimising annual heating energy use. First, building performance of a typical floor of the tower block
510 is assessed by comparing the effect of existing over-cladding and improved EWI on energy-use and
511 overheating risk using TM59 and SAP 2012 occupancy and energy-use profiles in the simulation
512 model in the current and future climate scenarios (2030, 2050 and 2080). To ensure the building's
513 airtightness and to explore the impact of the EWI thermal properties in facilitating a comfortable
514 indoor environment and reduced heating energy, three defined U-values (0.3, 0.5 and 0.7 W/m²K) are
515 then applied. The results confirm that improving the U-value of the external walls will reduce the
516 heating energy use during the winter season in future climate scenarios.

517 In addition, the results show that as thermal performance of external walls improves from 0.9
518 W/m²K to 0.7, 0.5 and 0.3 W/m²K, indoor T_o increases gradually under the three climate change
519 scenarios. The changes fluctuate between 15% with the U-value of 0.5 W/m²K and 17% with the U-
520 value of 0.3 W/m²K in comparison to the base case with the U-value of 0.9 W/m²K. The results also
521 show that a significant difference between discomfort hours of the base case in comparison to the
522 improved thermal conductivity of external walls. These changes vary from 28% with the U-value of
523 0.7 W/m²K in 2080 to 40% with the U-value of 0.3 W/m²K in 2030. The second phase studies indoor
524 thermal comfort of a south-facing living room and bedroom on a typical floor flat with improved
525 building envelope (U-value 0.5 W/m²K) using two dominant occupancy and energy-use profiles, as
526 well as the TM59 and SAP 2012 methodology. The results demonstrate that it is necessary to consider
527 dominant profiles in simulation modelling to achieve more accurate building energy performance as
528 well as realistic predictions of overheating risks post retrofit. The results demonstrate that indoor T_o is
529 above the maximum operative temperature that indicates overheating risk in bedrooms during the

530 warm seasons, exceeding 26°C in all bedrooms. The results also show that the average predicted
531 indoor T_o using TM59 pattern is almost 7% more than using Flat B pattern in bedrooms (with high
532 occupancy profile) in all climate change scenarios while it is 11% more than Flat A pattern (with low
533 occupancy profile). This difference has an impact on the upsurge of the predicted overheating duration
534 in summer as the discomfort periods extend consequently.

535 The study indicates that the occupancy profiles may vary significantly for every household that
536 has different age groups, number of occupants, and associated lifestyles. It has emerged that a young
537 family of five, which represents households with high occupancy and energy-use profiles, has a higher
538 risk of overheating during the warm season than a single elderly occupant, which represents a low
539 occupancy profile. However, the study confirms that both cases are at lower risk of overheating
540 compared to the projected overheating risk using the TM59 patterns, which exceeds the worst-case
541 scenario in occupancy and energy-use patterns. There are also notable variances in overheating risk
542 predictions when applying dominant occupancy profiles and standard profile, also confirmed by
543 Buttitta *et al.* (2019) and Ozarisoy and Elsharkawy (2019).

544 Neither Approved Document Part L nor CIBSE TM59 uses a method that is based on the
545 multiple occupancy profiles or building characteristics that can be adopted for different types of
546 domestic buildings. Integrating real dominant occupancy profiles in the overheating prediction
547 methodology considering the building typology, construction materials and age of the building, among
548 other factors, helps predict more reliable building performance for each type of household as opposed
549 to a generic one-size fits all. The occupancy profile and building characteristics have a significant
550 effect on mean indoor T_o and consequently on energy use. Hence, using multiple occupancy scenarios
551 allows researchers to improve predictions for various family types with different socio-demographics
552 that may not be possible using an equation based on the number of rooms per household. Moreover,
553 modelling appropriate occupancy and energy-use profiles in addition to evidence-based adaptive
554 strategies may reduce overheating risk. However, thermal comfort is variable for diverse groups of
555 people; depending on gender, age, ethnicity, health condition, and others. To improve occupants'

556 thermal comfort and energy-efficiency of buildings as well as to reduce the gap between predicted and
557 actual performance of buildings, it is imperative to consider real and dominant occupancy patterns
558 when evaluating risks of overheating in different building typologies.

559 As indicated by CIBSE (2018a) and also concluded by this study, currently, overheating risk is
560 not sufficiently addressed in the Building Regulations Approved Documents. Notably, a consultation
561 on Parts L and F for new dwellings is currently underway in the lead up to the Future Homes Standard
562 set to be introduced in 2025 (MHCLG, 2019). Hence, it is imperative to consider thermal conductivity
563 benchmarks for existing buildings in the Approved Documents Part L1B (and all associated guidance
564 documents) to address the increasing risk of overheating in existing domestic buildings. Overall, the
565 study demonstrates the significance of occupancy patterns in predicting building energy performance,
566 and hence overheating risks and heating energy demand. The findings show that if thermal
567 performance of the building fabric and airtightness level of the building improves without considering
568 multiple occupancy scenarios for different households, this may lead to inaccurate predictions of
569 overheating risks in climate change scenarios, and hence retrofit interventions that may potentially
570 cause complications in the future.

571 **Acknowledgements**

572 The authors would like to acknowledge the support of Newham Council in London for facilitating the
573 survey and monitoring the case study.

574 **Funding**

575 This work was supported by the British Council under the Newton Institutional Links project fund
576 [grant number 2015EGY01].

577 **Declaration of Interest**

578 None

579 **References**

580 Aditya, L. *et al.* (2017) 'A review on insulation materials for energy conservation in buildings', *Renewable and*

- 581 *Sustainable Energy Reviews*, pp. 1352–1365. doi: 10.1016/j.rser.2017.02.034.
- 582 Ahmed, K. *et al.* (2017) ‘Occupancy schedules for energy simulation in new prEN16798-1 and ISO/FDIS
583 17772-1 standard’, *Sustainable Cities and Societies*, 35, pp. 134–144.
- 584 Ahn, K. U. *et al.* (2017) ‘Predictability of occupant presence and performance gap in building energy
585 simulation’, *Applied Energy*, 208, pp. 1639–1652. doi: 10.1016/j.apenergy.2017.04.083.
- 586 ASHRAE (2004) *ANSI/ASHRAE 55-2004: Thermal Environmental Conditions for Human Occupancy*,
587 *ASHRAE*. doi: 10.1007/s11926-011-0203-9.
- 588 Baborska-naro, M. (2017) ‘Overheating in retrofitted flats : occupant practices , learning and interventions’, 45,
589 pp. 40–59.
- 590 Baborska-Narozny, M. and Grudzinska, M. (2017) ‘Overheating in a UK High-rise Retrofit Apartment Block -
591 Ranking of Measures Available to Case Study Occupants Based on Modelling’, in *Energy Procedia*, pp. 568–
592 577. doi: 10.1016/j.egypro.2017.03.219.
- 593 Ben, H. and Steemers, K. (2017) ‘Tailoring domestic retrofit by incorporating occupant behaviour’, in *Energy
594 Procedia*, pp. 427–432. doi: 10.1016/j.egypro.2017.07.421.
- 595 Building Regulation 2010 (2018) ‘Conservation of Fuel and Power- L1B, Incorporating 2010, 2011, 2013, 2016
596 and 2018 amendments’. HM Government.
- 597 Buttitta, G. *et al.* (2019) ‘Development of occupancy-integrated archetypes: Use of data mining clustering
598 techniques to embed occupant behaviour profiles in archetypes’, *Energy and Buildings*, 198(1), pp. 84–99.
- 599 CCC (2017) *Progress in preparing for climate change, 2017 Report to Parliament*. Available at:
600 [https://www.theccc.org.uk/wp-content/uploads/2017/06/2017-Report-to-Parliament-Progress-in-preparing-for-](https://www.theccc.org.uk/wp-content/uploads/2017/06/2017-Report-to-Parliament-Progress-in-preparing-for-climate-change.pdf)
601 [climate-change.pdf](https://www.theccc.org.uk/wp-content/uploads/2017/06/2017-Report-to-Parliament-Progress-in-preparing-for-climate-change.pdf).
- 602 CCC (2018a) *Reducing UK emissions- 2018 Progress Report to Parliament*.
- 603 CCC (2018b) ‘Reducing UK emissions - 2018 Progress Report to Parliament - Committee on Climate Change’,
604 *Committee on Climate Change*, (June). doi: 10.1111/j.1530-0277.1986.tb05619.x.
- 605 CCC (2019) *Net Zero: The UK’s contribution to stopping global warming*.
- 606 Champ, H. (2019) ‘Nearly a fifth of homes fail Decent Homes Standard’, *Housing Today*, 19 July. Available at:
607 <https://www.housingtoday.co.uk/news/nearly-a-fifth-of-homes-fail-decent-homes-standard/5100686.article>.
- 608 CIBSE (2017) ‘TM59: Design methodology for the assessment of overheating risk in homes’. London: The
609 Chartered Institution of Building Services Engineers.
- 610 CIBSE (2018) *Building Regulations Part L & F Briefing*. Available at:
611 [https://www.cibse.org/getmedia/4a601f5c-a866-41a2-8cf7-1bab17f4f57e/Position-Paper-on-Building-](https://www.cibse.org/getmedia/4a601f5c-a866-41a2-8cf7-1bab17f4f57e/Position-Paper-on-Building-Regulations-Part-L-F.pdf.aspx)
612 [Regulations-Part-L-F.pdf.aspx](https://www.cibse.org/getmedia/4a601f5c-a866-41a2-8cf7-1bab17f4f57e/Position-Paper-on-Building-Regulations-Part-L-F.pdf.aspx).
- 613 DCLG (2011) *Investigation into Overheating in Homes*. London. Available at:
614 [https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/7604/2185850.](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/7604/2185850.pdf)
615 [pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/7604/2185850.pdf).
- 616 DCLG (2017) ‘English Housing Survey 2017’, *Department for Communities and Local Government*. doi:
617 10.1017/CBO9781107415324.004.
- 618 DECC (2014) ‘SAP 2012- The Government’s Standard Assessment Procedure for Energy Rating of Dwellings’.
619 Watford: BRE.
- 620 Department for Communities and Local Government (2018) ‘Approved Document L1B Conservation of Fuel
621 and Power in Existing Dwellings, HMSO’. doi: 10.1017/S0010417500001705.
- 622 Department for communities and local government (2006) ‘A Decent Home: Definition and guidance for

- 623 implementation', (June), p. 35. doi: 10.1016/j.ifacol.2016.07.369.
- 624 Department for Environment Food & Rural Affairs (DEFRA) (2018) *The National Adaptation Programme and*
625 *the Third Strategy for Climate Adaptation Reporting*.
- 626 Elsharkawy, H. and Rutherford, P. (2015) 'Retrofitting social housing in the UK: Home energy use and
627 performance in a pre-Community Energy Saving Programme (CESP)', *Energy and Buildings*, 88. doi:
628 10.1016/j.enbuild.2014.11.045.
- 629 Elsharkawy, H. and Rutherford, P. (2018) 'Energy-efficient retrofit of social housing in the UK: Lessons learned
630 from a Community Energy Saving Programme (CESP) in Nottingham', *Energy and Buildings*, 172. doi:
631 10.1016/j.enbuild.2018.04.067.
- 632 Fosas, D. *et al.* (2018) 'Mitigation versus adaptation: Does insulating dwellings increase overheating risk?',
633 *Building and Environment*, 143, pp. 740–759. doi: 10.1016/j.buildenv.2018.07.033.
- 634 Giesekam, J., Tingley, D. D. and Cotton, I. (2018) 'Aligning carbon targets for construction with (inter)national
635 climate change mitigation commitments', *Energy and Buildings*, 165, pp. 106–117. doi:
636 10.1016/j.enbuild.2018.01.023.
- 637 Gov.UK (2019) 'UK becomes first major economy to pass net zero emissions law', 27 June. Available at:
638 <https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law>.
- 639 Greater London Authority. (2016) *The London Plan the Spatial Development Strategy for London Consolidated*
640 *with Alterations Since 2011*. London.
- 641 Greater London Authority. (2018) *Fuel Poverty Action Plan for London*. London.
- 642 Greater London Authority (2015) *Housing in London 2015*. London. Available at:
643 https://www.london.gov.uk/sites/default/files/housing_in_london_2015.pdf.
- 644 Gupta, R. and Gregg, M. (2012a) 'Using UK climate change projections to adapt existing English homes for a
645 warming climate', *Building and Environment*. doi: 10.1016/j.buildenv.2012.01.014.
- 646 Gupta, R. and Gregg, M. (2012b) 'Using UK climate change projections to adapt existing English homes for a
647 warming climate', *Building and Environment*. Elsevier Ltd, 55, pp. 20–42. doi: 10.1016/j.buildenv.2012.01.014.
- 648 Hajat, S., Kovats, R. S. and Lachowycz, K. (2007) 'Heat-related and cold-related deaths in England and Wales:
649 Who is at risk?', *Occupational and Environmental Medicine*, 64(2), pp. 93–100. doi: 10.1136/oem.2006.029017.
- 650 van Hooff, T. *et al.* (2015) 'On the predicted effectiveness of climate adaptation measures for residential
651 buildings (Reprinted from vol 82, pg 300-316, 2014)', *Building and Environment*, 83, pp. 142–158. doi:
652 10.1016/j.buildenv.2014.10.006.
- 653 IPCC (2014a) *5th Assessment Report on Climate Change 2014: Mitigation of Climate Change*.
654 Intergovernmental Panel on Climate Change.
- 655 IPCC (2014b) *Climate Change 2014: Synthesis Report*. Geneva.
- 656 Jie, P. *et al.* (2018) 'Optimizing the insulation thickness of walls and roofs of existing buildings based on
657 primary energy consumption, global cost and pollutant emissions', *Energy*. Elsevier Ltd, 159, pp. 1132–1147.
658 doi: 10.1016/j.energy.2018.06.179.
- 659 Lomas, K. J. and Porritt, S. M. (2017) 'Overheating in buildings: lessons from research', *Building Research and*
660 *Information*. Taylor & Francis, 45(1–2), pp. 1–18. doi: 10.1080/09613218.2017.1256136.
- 661 Lowe, J. A. *et al.* (2019) *UKCP18 Science Overview Report*, Met Office. Available at:
662 <https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP18-Overview-report.pdf>.
- 663 Mavrogianni, A. *et al.* (2014) 'The impact of occupancy patterns, occupant-controlled ventilation and shading on
664 indoor overheating risk in domestic environments', *Building and Environment*, 78, pp. 183–198. doi:
665 10.1016/j.buildenv.2014.04.008.

- 666 Mavrogianni, A. *et al.* (2015) 'Urban social housing resilience to excess summer heat', 43(3), pp. 316–333.
- 667 Medhurst, J., Turnham, C. and Partners, J. R. and (2016) *Damp Survey for London Borough of Newham*.
668 London.
- 669 MHCLG (2018) *Dwelling Stock Estimates: 2017, England*.
- 670 MHCLG (2019) *The Future Homes Standard*. Available at:
671 [https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/835536/Future](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/835536/Future_Homes_Standard_Consultation_Oct_2019.pdf)
672 [_Homes_Standard_Consultation_Oct_2019.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/835536/Future_Homes_Standard_Consultation_Oct_2019.pdf).
- 673 Mulville, M. and Stravoravdis, S. (2016a) 'The impact of regulations on overheating risk in dwellings', *Building*
674 *Research and Information*. doi: 10.1080/09613218.2016.1153355.
- 675 Mulville, M. and Stravoravdis, S. (2016b) 'The impact of regulations on overheating risk in dwellings', *Building*
676 *Research and Information*, 44(5–6), pp. 520–534. doi: 10.1080/09613218.2016.1153355.
- 677 Murtagh, N., Gatersleben, B. and Fife-Schaw, C. (2019) 'Occupants' motivation to protect residential building
678 stock from climate-related overheating: A study in southern England', *Journal of Cleaner Production*. doi:
679 10.1016/j.jclepro.2019.04.080.
- 680 Newham Council (2007) *Typical floor plans of Newham Homes*.
- 681 Ozarisoy, B. and Elsharkawy, H. (2019) 'Assessing overheating risk and thermal comfort in state-of-the-art
682 prototype houses that combat exacerbated climate change in UK', *Energy and Buildings*, 187, pp. 201–217. doi:
683 10.1016/j.enbuild.2019.01.030.
- 684 Pathan, A. *et al.* (2017) 'Monitoring summer indoor overheating in the London housing stock', *Energy and*
685 *Buildings*, 141, pp. 361–378. doi: 10.1016/j.enbuild.2017.02.049.
- 686 Porritt, S.M. *et al.* (2012) 'Ranking of interventions to reduce dwelling overheating during heat waves', *Energy*
687 *and Buildings*. Elsevier, 55, pp. 16–27. doi: 10.1016/J.ENBUILD.2012.01.043.
- 688 Porritt, S. M. *et al.* (2012) 'Ranking of interventions to reduce dwelling overheating during heat waves', in
689 *Energy and Buildings*, pp. 16–27. doi: 10.1016/j.enbuild.2012.01.043.
- 690 Porritt, S. M. *et al.* (2013) 'Heat wave adaptations for UK dwellings and development of a retrofit toolkit',
691 *International Journal of Disaster Resilience in the Built Environment*, 4(3), pp. 269–286. doi: 10.1108/IJDRBE-
692 08-2012-0026.
- 693 Public Health England (2018) *Heatwave mortality monitoring - Summer 2018*.
- 694 Shen, P., Braham, W. and Yunky, Y. (2019) 'The feasibility and importance of considering climate change
695 impacts in building retrofit analysis', *Applied Energy*, 233–234(1), pp. 254–270.
- 696 Steemers, K. and Ben, H. (2014) 'Energy retrofit and occupant behaviour in protected housing: A case study of
697 the Brunswick Centre in London', *Energy and Buildings*, 80, pp. 120–130.
- 698 Taylor, J. *et al.* (2015) 'Mapping the effects of urban heat island, housing, and age on excess heat-related
699 mortality in London', *Urban Climate*. Elsevier B.V., 14, pp. 517–528. doi: 10.1016/j.uclim.2015.08.001.
- 700 Tink, V. *et al.* (2018) 'Measuring and mitigating overheating risk in solid wall dwellings retro fitted with
701 internal wall insulation', *Building and Environment*. Elsevier, 141(February), pp. 247–261. doi:
702 10.1016/j.buildenv.2018.05.062.
- 703 University of Exeter (2012) *Future weather files, Centre for Energy and the Environment*.
- 704 University of Southampton (2016) *Occupancy Patterns Scoping Review Project*. Southampton.
- 705 Yan, D. *et al.* (2017) 'IEA EBC Annex 66: Definition and simulation of occupant behavior in buildings', *Energy*
706 *and Buildings*, 156, pp. 258–270.

- 707 Yun, G. Y. and Steemers, K. (2008) 'Time-dependent occupant behaviour models of window control in
708 summer', *Building and Environment*, 43(9), pp. 1471–1482. doi: 10.1016/j.buildenv.2007.08.001.
- 709 Zahiri, S. and Elsharkawy, H. (2017) 'Building Performance Evaluation for the Retrofit of Council Housing in
710 the UK: A case study of a tower block in London', *PLEA 2017, Passive Low Energy Architecture- Design to
711 Thrive*. Edinburgh: NCEUB 2017, pp. 941–947.
- 712 Zahiri, S. and Elsharkawy, H. (2018) 'Towards energy-efficient retrofit of council housing in London: Assessing
713 the impact of occupancy and energy-use patterns on building performance', *Energy and Buildings*, 174, pp. 672–
714 681. doi: 10.1016/j.enbuild.2018.07.010.
- 715 Zahiri, S., Elsharkawy, H. and Shi, W. (2018) 'The Importance of Occupancy and Energy Use Patterns on
716 Predicting Building Energy Performance: A Case Study of a Residential Building in London', *BSO2018 papers*,
717 (September), pp. 11–12.
- 718

Table 1: Energy-use and occupancy patterns applied at different stages of the simulation analysis

Room type		<i>Flat A (single elderly)</i>		<i>Flat B (family of 2 adults and 3 children)</i>		<i>TM59-SAP2012</i>	
		Winter	Summer	Winter	Summer	Winter	Summer
Bedroom	Heating	SAP2012 ¹	N/A	SAP2012 ¹	N/A	SAP2012 ¹	N/A
	Occupancy	10pm to 8am		7pm to 7am		TM59 ²	
Living room	Heating	SAP2012 ¹	N/A	SAP2012 ¹	N/A	SAP2012 ¹	N/A
	Occupancy	8am to 11pm		8am to 11pm		TM59 ²	

¹SAP2012 heating pattern-
Weekday: 0700-0900 and 1600-2300/ Weekend: 0700-2300
²TM59 occupancy pattern-
Bedroom: 2 people from 11pm to 8am 70% gain, 2people at full gain from 8am to 9am and from 10pm to 11 pm, 1 person at full gain from 9 am to 10 pm
Living room: 2 people at 75% gain from 9am to 10 pm

Table 2: Building fabric modelling input data of the case study (existing and retrofitted)

BUILDING COMPONENTS	MATERIALS	EXISTING	RETROFITTED		
			0.3 W/m ² K	0.5 W/m ² K	0.7 W/m ² K
EXTERNAL WALL U-VALUE	External over-cladding & rendering, concrete panels, internal thermal insulation & plaster finish	0.9 W/m ² K	0.7 W/m ² K	0.5 W/m ² K	0.3 W/m ² K
FLOOR U-VALUE	Concrete slabs & rendering	2.7 W/m ² K	2.7 W/m ² K		
ROOF U-VALUE	Concrete slab & rendering, bitumen	2.3 W/m ² K (Mavrogianni <i>et al.</i> , 2015)	0.28 W/m ² K		
WINDOWS U-VALUE	Double glazing with UPVC panels	2 W/m ² (Mavrogianni <i>et al.</i> , 2015)	2 W/m ² K (Mavrogianni <i>et al.</i> , 2015)		
AIR INFILTRATION	-	10 m ³ /m ² h at 50 Pa (Mulville and Stravoravdis, 2016)	5.0 m ³ /m ² h at 50 Pa (Building Regulation 2010, 2018)		

Table 3: Annual operative temperature in a typical middle floor using U-values of 0.3, 0.5, 0.7 and 0.9 W/m²K in three climate change scenarios

Climate projection		2030				2050				2080			
U-Value W/m ² K		0.3	0.5	0.7	0.9	0.3	0.5	0.7	0.9	0.3	0.5	0.7	0.9
Annual operative temperature °C	Min	18.60	18.21	17.90	15.54	18.79	18.38	18.03	15.62	18.99	18.62	18.32	16.08
	Mean	22.10	21.71	21.39	18.98	22.67	22.30	22.00	19.51	23.96	23.22	22.93	20.57
	Max	27.90	27.63	27.40	25.13	29.04	28.83	28.65	26.33	30.65	30.46	30.31	28.19

Table 4: Hours above overheating risk temperature in bedroom and living rooms of a typical south-facing flat with the U-value of 0.5 W/m²K in the future climate change scenarios

<i>ZONE</i>	HOURS EXCEEDING OVERHEATING RISK TEMPERATURE								
	(TM 59 CRITERIA: 26°C BEDROOM AND 28°C LIVING ROOM)								
	2030			2050			2080		
<i>OCCUPANCY SCHEDULE</i>	TM59-SAP	Flat A	Flat B	TM59-SAP	Flat A	Flat B	TM59-SAP	Flat A	Flat B
LIVING ROOM	521	468	449	748	492	719	1200	967	1161
BEDROOM	2207	394	952	3051	717	1178	3495	913	1492

Table 5: Solar heat gain in south-facing living room and bedroom of a typical middle floor

<i>Climate projection</i>	2030		2050		2080	
<i>Room</i>	Bedroom	Living room	Bedroom	Living room	Bedroom	Living room
<i>Mean Annual solar gain in kWh</i>	24.31	16.54	25.84	16.65	25.89	16.89

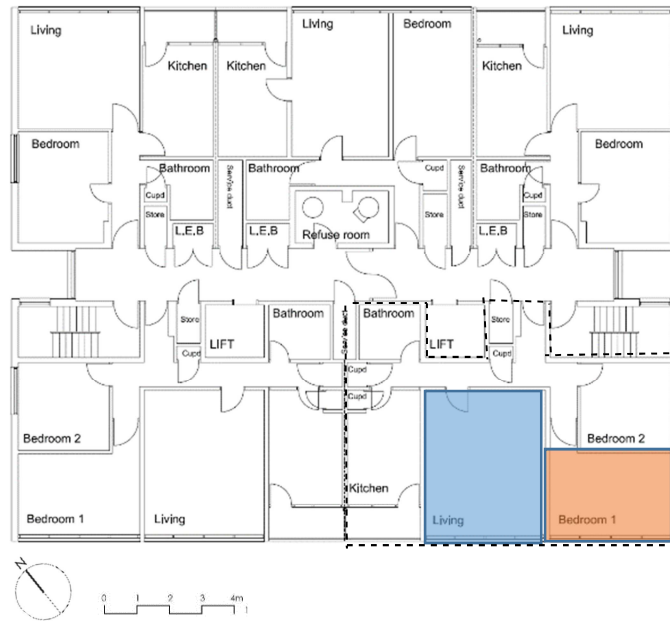


Figure 1: Typical floor plan of the case study building (Newham Council, 2007)

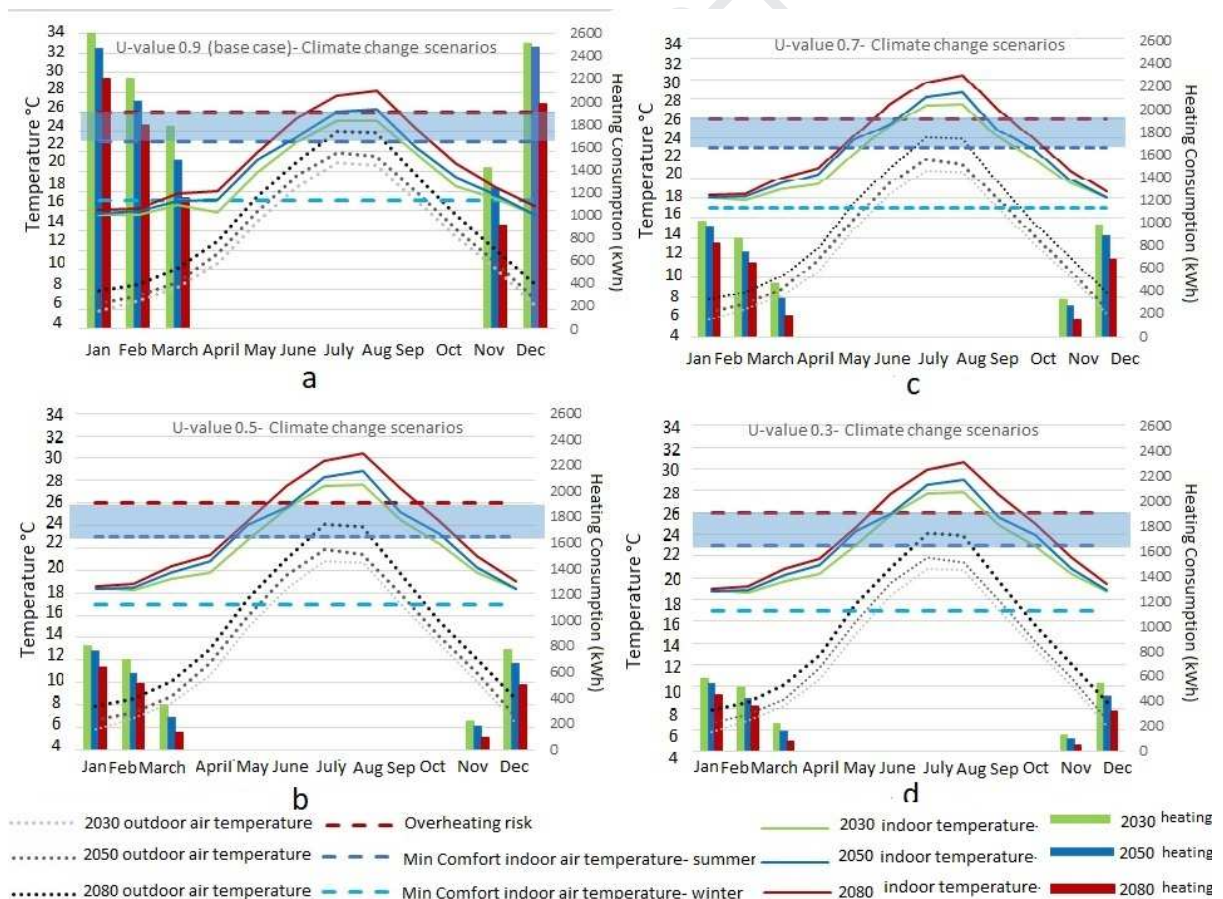
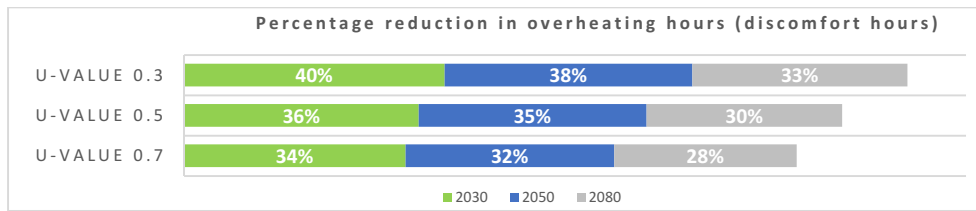
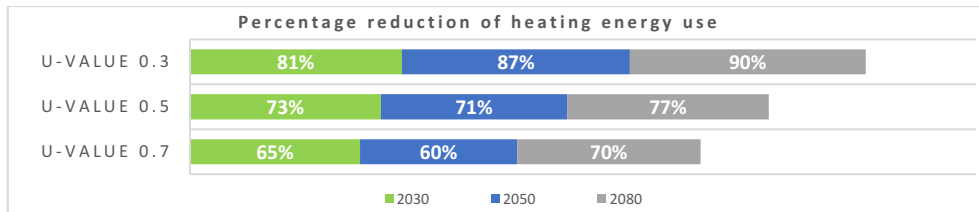


Figure 2 (a, b, c, d): Indoor T_o and heating energy use in a typical middle floor under the climate change scenarios (2030, 2050, 2080), using TM59-SAP patterns and U-values of a. 0.9 W/m²K , b. 0.7 W/m²K , c. 0.5 W/m²K and d. 0.3W/m²K.



(a)



(b)

Figure 3: Percentage of difference between the reduction of discomfort hours (a) and the reduction of energy use (b) in the base case (U-value 0.9 W/m²K for external walls) compared to the upgraded thermal performance of the building envelope (U-values of 0.3, 0.5 and 0.7 W/m²K) in a typical middle floor.

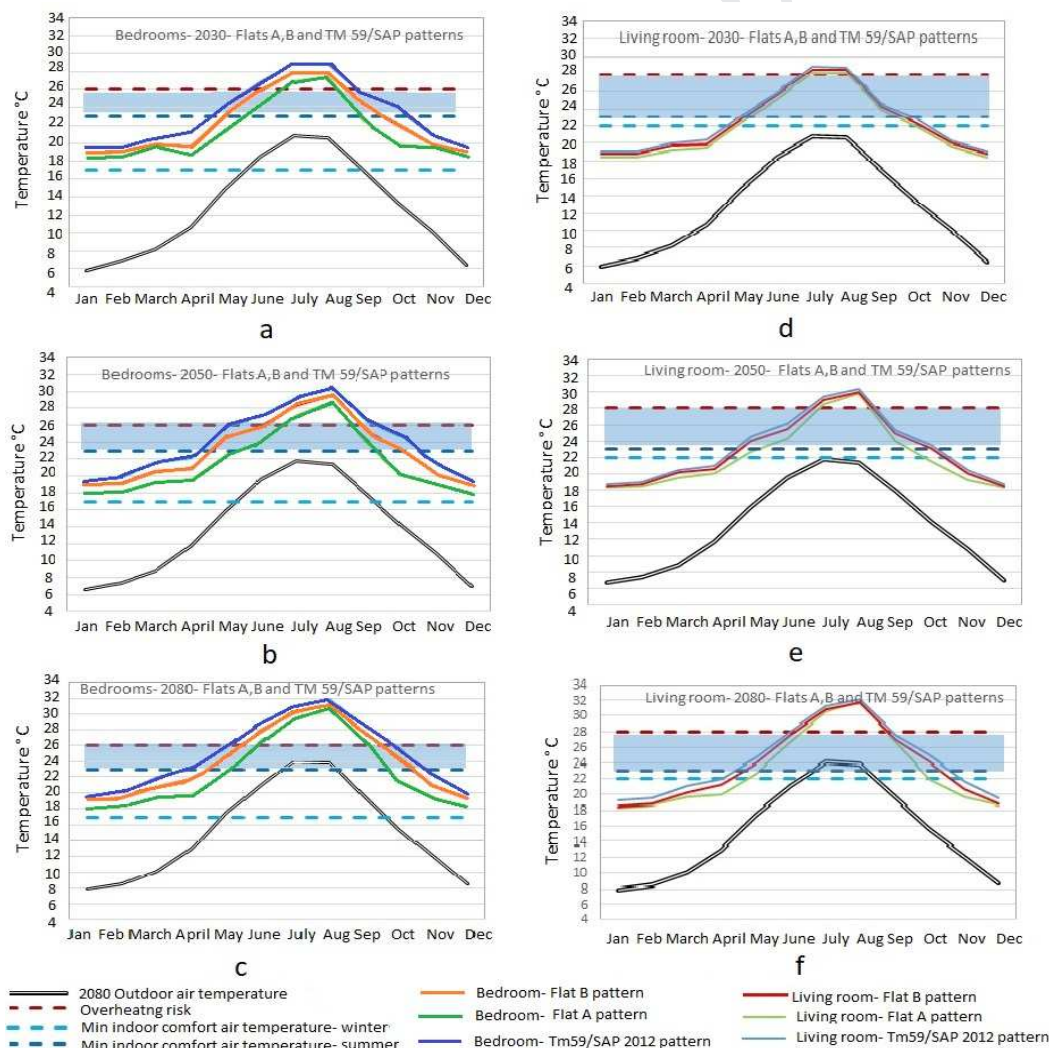


Figure 4 (a, b, c): Indoor T_o in the bedroom of the typical south-facing flat with the U-value of 0.5 W/m²K and three occupancy profiles (Flat A, Flat B, and TM 59) under the climate change scenarios (a) 2030, (b) 2050, and (c) 2080. Figure 4 (d, e, f): Indoor T_o in the living room of the typical south-facing flat with the U-value of 0.5

W/m²K and three occupancy profiles (Flat A, Flat B, and TM 59) under the climate change scenarios (a) 2030, (b) 2050, and (c) 2080.

Journal Pre-proof

The significance of occupancy profiles in determining post retrofit indoor thermal comfort, overheating risk and building energy performance

Highlights:

- The overheating risk is not sufficiently addressed in the UK Building Regulations Approved Documents
- The study demonstrates the importance of real occupancy patterns in predicting overheating risks and heating energy demand
- The focus is on the impact of retrofitting 1960s tower blocks on occupants' thermal comfort and building energy performance in future climate scenarios
- Improving the U-value of external walls will significantly reduce the heating energy use by 70% under future climate scenarios
- Operative temperature increases by 15-17% with U-value of 0.5 and 0.3 W/m²K in comparison to the base case (0.9 W/m²K)

The significance of occupancy profiles in determining post retrofit indoor thermal comfort, overheating risk and building energy performance

Declaration of interest: None

Journal Pre-proof