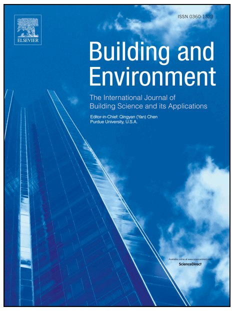

The significance of occupancy profiles in determining post retrofit indoor thermal comfort, overheating risk and building energy performance

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

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Abstract

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

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

1. Introduction

Abundant evidence exists that the climate change phenomenon is primarily exacerbated by greenhouse gas (GHG) concentrations in the atmosphere (IPCC, 2014a; Lowe *et al.*, 2019) . As a result, the rate of global warming has rapidly accelerated in the last few decades with a predicted 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 the high emission scenario (IPCC, 2014b; Lowe *et al.*, 2019). Notably, with surface and air temperatures continuing to rise, heatwaves are expected to occur more often and may well last for

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

Hence, to mitigate climate change, the UK has set a target to bring all its greenhouse gas (GHG) emissions to net zero by 2050 which is enshrined in law– (CCC, 2019; Gov.UK, 2019). Short-term action plans have already been implemented in the building sector to achieve the set targets, such as adopting a systematic approach to improve the energy efficiency of new and existing buildings, following the previously set target of reducing GHG emissions by 80% by 2050 compared to the 1990 levels (CCC, 2018a). Introducing effective energy-efficient retrofit programmes for existing buildings (Shen, Braham and Yunkyu, 2019) and developing long-term low energy building strategies for the new building stock would help achieve the national targets (Giesekam, Tingley and Cotton, 2018). Hence, enforcing key policies to deliver effective retrofit programmes with particular attention to meeting social housing minimum standards (i.e. Decent Homes Standard[2]) is vital where in 2019, 4.7 million homes (20% of England's domestic stock) failed to meet the Decent Homes Standard (DCLG, 2017; CCC, 2018b; Champ, 2019).

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

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[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 Comunities and Local Government, 2006).

potentially reduce the overall heating energy use, particularly in areas with high rates of fuel poverty. Current studies indicate that many people residing in London struggle to afford the energy demands of their properties, where around 34,000 households are considered to be in fuel poverty (Greater London Authority, 2018). The 'Progress in Preparing for Climate Change' report affirms that local authorities play crucial roles in delivering various aspects of the National Adaptation Programme[3] (CCC, 2017; Department for Environment Food & Rural Affairs (DEFRA), 2018). Hence, many retrofit programmes have been rolled out in the UK with multiple schemes introduced at local authority levels to improve the energy performance of dwellings, most of these schemes focus on reducing the heating energy demand (Baborska-Narozny and Grudzinska, 2017).

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

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[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.

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

Various studies have highlighted the issue of higher risk of overheating in UK flats compared with other housing types for many reasons, but mainly due to low wall to floor ratio, as well as little possibility for cross-ventilation (Gupta and Gregg, 2012a; Mavrogianni et al., 2015; Baborska-naro, 2017). Moreover, the risk of exposure to overheating hours in the top floors of a 1960's tower block is six times more than on the ground floor and nine times more than the case in Victorian terraced homes due to building characteristics, and construction age, as well as the association between the age of the building and morphology, glazing level, size of windows, the U-value, and the airtightness of the building (DCLG, 2011). The 1960's tower blocks usually have low solar thermal protection particularly on the top floor where poor thermal insulation increases the risk of being exposed to more solar radiation, whereas ground floor flats in the same building experience a considerable cooling impact because of the lack of floor insulation (DCLG, 2011). The study explores the risk of overheating in a 1960s tower block prototype[4] in future climate scenarios (2030, 2050, and 2080) following thermal performance improvement of the building envelope. To address the current research gap, the researchers argue that integrating real dominant occupancy profiles in the overheating prediction methodology considering the building typology, construction materials, and other building design factors helps predict more reliable building performance and thermal comfort for different building typologies as opposed to a generic one-size-fits-all model.

2. Research methodology

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

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

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

2.1 Case Study: 1960's tower block

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

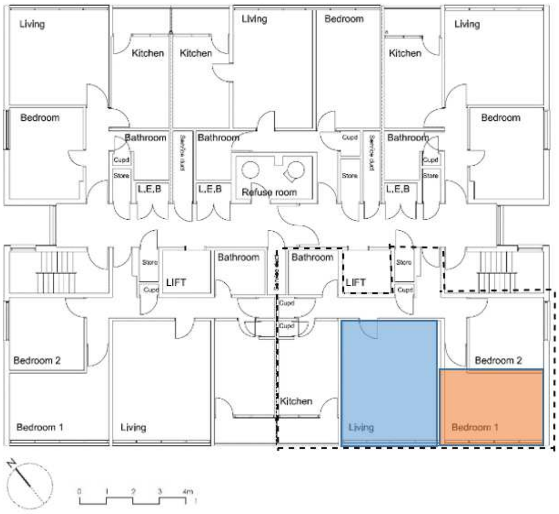

Figure 1: Typical floor plan of the case study building (Newham Council, 2007)

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

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

2.2 Building simulation model settings

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

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

The main concern of the second phase is to assess heating energy use based on different occupancy and energy-use patterns, using dominant and real low and high occupancy, as well as prescribed patterns. To run the simulation analysis more efficiently, top, middle, ground and upper ground floors' plan are modelled in detail to include all flats and rooms comprising thermal zones. The focus of the analysis was on the middle floor to measure average energy use of middle floor and south-facing rooms including a main bedroom and a living room. The top, floor and upper ground floors are also included, which meant that the average T_o in these floors were also slightly different, caused by varying levels of heat transfer through internal building elements compared to typical floors. Overall, 55 thermal zones are created in each floor and simulation data are recorded with 4 time-steps per hour, to support the accuracy of the outputs. The heating is provided by individual gas-fired hot water boilers connected to radiators installed in thermal zones and the heating patterns are based on SAP 2012 recommendations for weekends and weekdays in all rooms. The heating system seasonal coefficient of performance (CoP) is also adjusted at 0.85, so the capacity of the zone heating system accounts for natural ventilation loads in the simulation model. The exhaust fans are included at the HVAC zone level to extract air from the bathroom and kitchen and are designed for use during scheduled patterns of occupancy in these rooms. The heating temperature set-point is 21°C for winter to provide a comfortable indoor air temperature for occupants.

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

Building simulation analysis is undertaken to predict heating energy use and overheating risks in the typical middle floor using each EWI option in the current climatic condition in comparison to the future climate scenarios (2030, 2050 and 2080). At this stage, the building simulation model settings, including occupancy and energy use patterns, are defined based on CIBSE Technical Memorandum 59 (TM59) (CIBSE, 2017) and Standard Assessment Procedure (SAP) 2012 (for winter heating schedules) (DECC, 2014). CIBSE's TM59 guideline is the recommended methodology for assessment of overheating risks in homes. The methodology predicts the level of risk of overheating for naturally ventilated domestic buildings if either of the two exceedance criteria fails[5]. This guideline does not include a pattern of heating energy use. Therefore, the model adopts the heating energy use of the UK Governments' Standard Assessment Procedure (SAP 2012) which was developed and approved for energy rating of domestic buildings (DECC, 2014). Following the initial analysis, the optimum wall U-value is selected for the consequent stage of building simulation to determine overheating risks in the bedroom and living room of a south-facing flat of a typical floor, as the worst-case scenario. The T_o of these zones is also assessed respectively in future climate scenarios. At this stage, the dominant low and high occupancy patterns within the tower block, obtained from the first phase, are applied to the simulation settings to compare the predicted results against TM59 methodology pre- and post-retrofit under climate change scenarios. This helps assess the effect of using dominant occupancy scenarios in predicting building energy performance and overheating risks in occupied rooms. However, it must be noted that heating patterns are expected to change post-retrofit.

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

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[5] The percentage of occupied hours, where _T = Top - Tmax 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]

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

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]	

[1] SAP2012 heating pattern-
Weekday: 0700-0900 and 1600-2300/ Weekend: 0700-2300
[2] TM59 occupancy pattern-
Bedroom: 2 people from 11pm to 8am 70% gain, 2people at full gain from 8am to 9am and from 10pm to11 pm, 1 person at full gain from 9 am to 10 pm
Living room: 2 people at 75% gain from 9am to 10 pm

It should be noted that natural ventilation schedules and window- and door-opening schedules are defined based on TM59 due to not having this detailed information from occupants. Windows are set to open when the room is occupied and indoor T_o rises above 22°C while internal doors are set to be open during the day time but closed when the occupants are asleep. Internal blinds are set to be in use when natural ventilation is provided, this is based on TM59 recommendations. Each window frame of the case study is 1.4 m height and 0.85-1 m width and window to wall ratio is approximately 20% in the tower block. In this study, only heat gain from occupants is included because the main focus is on the impact of occupancy and heating patterns on indoor T_o, overheating risk, and building energy use. The defined infiltration rate and air speed are obtained from TM59 and building regulation part L1B as a consequence of applying SAP 2012; 5 m^3/m^2h @ 50 Pa and 0.1 m/s, respectively. Table 2 summarises the input data of the building model.

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

BUILDING COMPONENTS	**MATERIALS**	**EXISTING**	**RETROFITTED**		
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 *et al.*,	0.28 W/m^{2}K		

	bitumen	2015)	
WINDOWS U-VALUE	Double glazing with UPVC panels	2 W/m² (Mavrogianni *et al.*, 2015)	2 W/m²K (Mavrogianni *et al.*, 2015)
AIR INFILTRATION	-	10 m3/m2h at 50 Pa (Mulville and Stravoravdis, 2016)	5.0 m3/m2h at 50 Pa (Building Regulation 2010, 2018)

To simulate the risk of overheating and the impact on occupants' thermal comfort, at the time of undertaking the simulation, weather data files for current and future climate are obtained from UK Climate Projections program[6] (UKCP09) PROMETHEUS project (University of Exeter, 2012). The weather files are exported in EnergyPlus format (epw) and used in DB simulation software. The files are also generated for the current climate condition based on the weather data of 1961-1990 as well as the three future climate scenarios (2030, 2050 and 2080). In this study, the 50th percentile central estimate weather files for London Heathrow are used to provide comparable outputs in relation to CIBSE's weather files, as suggested in TM59, to reduce extreme results.

3. Results and discussion

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

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[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).

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

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

Figure 2 (a, b, c, d) presents the mean T_o and the heating energy use of the typical middle floor of the case study under climate change scenarios by applying the U-values of 0.9 (base case), 0.7, 0.5 and 0.3 W/m²K using TM59-SAP 2012 occupancy and heating energy-use profiles. The figure shows that, in general, T_o increases steadily in 2030, 2050, and 2080 scenarios and, as expected, heating energy use reduces as a result. However, the changes are greater after improving building envelope thermal performance, as the building becomes more airtight with reduced air infiltration rate. As indicated earlier, the defined air permeability of the building post retrofit is based on Building 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 case which will have contributed to the significant heating energy use in colder seasons. The results demonstrate that, as the building becomes more thermally efficient and airtight, the indoor T_o rises while the heating energy use drops steadily.

Concerning the building performance of the typical middle floor (U-value 0.9 W/m²K); the indoor T_o is predicted to be within the comfort range by 2050 during the months of May-September with potential overheating risk in 2080 as the indoor T_o increases by around 10%, reaching 28°C. Notably, the base case uses significant heating energy to keep the occupants in a comfortable indoor environment during the colder months. However, the energy usage falls by 25% under future climate scenarios. For example, by improving the thermal performance of the external envelope from 0.9 to 0.7 W/m²K, heating energy use drops significantly by around 70% on average under the three future climate scenarios while annual mean indoor T_o increases by 13%. A possible reason for this is that by improving the thermal performance of external envelope from 0.9 to 0.7 W/m²K, indoor T_o moves closer to minimum thermal comfort boundaries or falls within the boundaries, so the occupants require less heating energy to keep the indoor temperature within the thermal comfort zone. In addition, as it consequently changes from 0.7 to 0.5 and 0.3 W/m²K; the indoor T_o increases accordingly, hence reducing the needs for heating energy use.

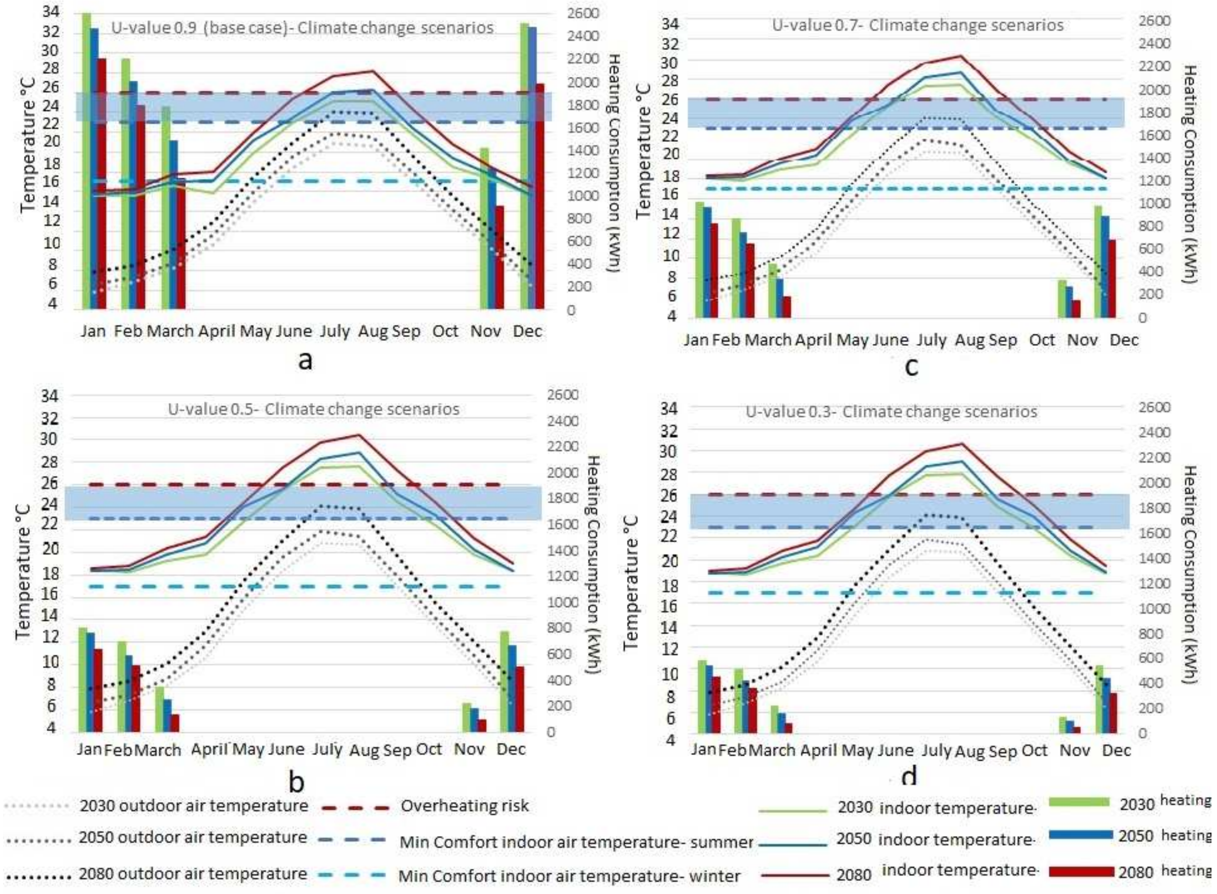


Figure 2 (a, b, c, d): Indoor T_o and heating energy use in a typical middle floor under the climate change scenarios (2030, 2050, 2080), using TM59-SAP patterns and U-values of a. 0.9 W/m²K , b. 0.7 W/m²K , c. 0.5 W/m²K and d. 0.3W/m²K.

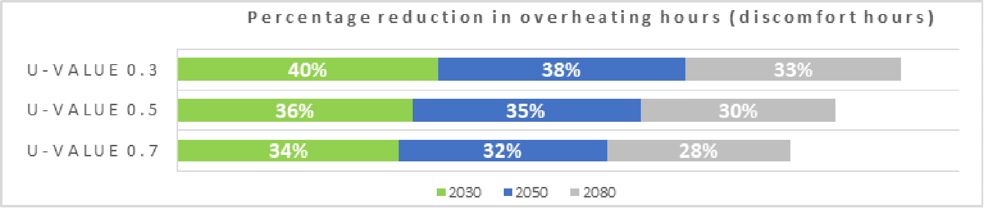
In addition, as the thermal performance of external walls improves, the indoor T_o increases slightly by a maximum of 15% with the U-value of 0.5 W/m²K and 17% with the U-value of 0.3 W/m²K in comparison to the base case. As can be seen, the difference between increases in indoor T_o using the values of 0.7, 0.5 and 0.3 W/m²K is not significant. The maximum average indoor T_o occurred in August ranging from around 28°C in 2030, 29°C in 2050, to 30°C in 2080 all of which already exceed the maximum comfort limit, magnifying the risk of overheating. However, heating energy-use falls significantly by between 65% and 75% in comparison to the base case. It must be noted, though, that the results discussed above are relevant to a typical floor including all thermal zones at all orientations; hence, the possibility for higher/lower hours of discomfort at south/north facing rooms is expected.

Table 3 presents the impact of climate change scenarios on minimum, maximum and mean annual operative temperatures and solar gains of exterior windows in the typical middle floor with U-values of 0.3, 0.5, 0.7 and 0.9 W/m^{2}K for external walls. It can be seen that indoor T_o increased steadily from 2030 to 2080 when applying improved U-values for external walls. In addition, as the U-value of external walls improved, the indoor T_o is predicted to rise. The improvement of building envelope results in a maximum mean annual temperature rise by around 3.5 °C by 2080 using the U-value of 0.3 W/m^{2}K, while the minimum mean temperature rise is predicted to be just below 3 °C.

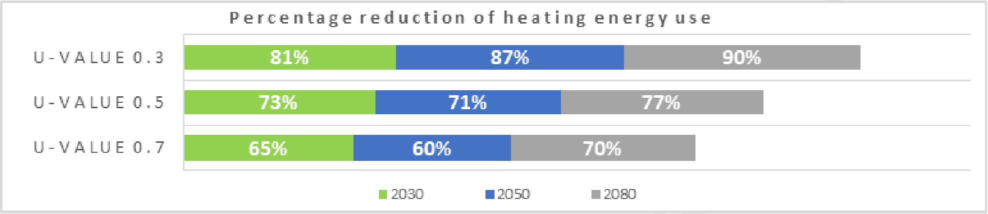
Table 3: Annual operative temperature in a typical middle floor using U-values of 0.3, 0.5, 0.7 and 0.9 W/m^{2}K in three climate change scenarios

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

Figure 3 (a and b) illustrates the predicted percentage of reduction in overheating hours (discomfort hours) in the warmer months (May-September), as well as the percentage of reduction of the heating energy use in the typical middle floor during the colder months (October-April) post-retrofit. The percentage of difference is the difference between the base case scenario and improved building performance obtained by dividing the absolute value of difference between the base case and the improved scenario divided by the average of two numbers and multiplied by 100. These data are calculated based on the discomfort hours and heating energy use obtained from the DB building simulation analysis that calculates discomfort hours based on ASHRAE 55 Standards (2004). It should be noted that TM59 methodology defines overheating risk solely based on indoor operative temperature, while discomfort hours include the impact of humidity levels on indoor thermal comfort using the ASHRAE 55 standard (ASHRAE, 2004) in naturally ventilated buildings. Although comfort criteria of ASHRAE and CIBSE TM59 are different, using both methodologies helps provide a clear indication of the impact of humidity on thermal comfort as extreme high and low humidity levels do contribute to levels of discomfort.



(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.

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

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

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

As one of this study's aims is to define the appropriate thermal performance of external walls that achieves a relative balance between heating energy use and hours of discomfort, besides findings that show a minor difference between the impact of the recommended U-values on overheating risk; the U-value of 0.5 W/m²K is selected for the second phase.. The focus of this phase is to study the impact of occupancy and energy-use patterns on overheating risk of the occupied zones of a south-facing flat on a typical floor, as the most at risk of overheating. To assess overheating risks in future climate scenarios, the results are compared using three patterns of occupancy – two real dominant patterns and the TM59 pattern.

3.2 The effect of occupancy profiles on predicting overheating risks

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

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

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

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

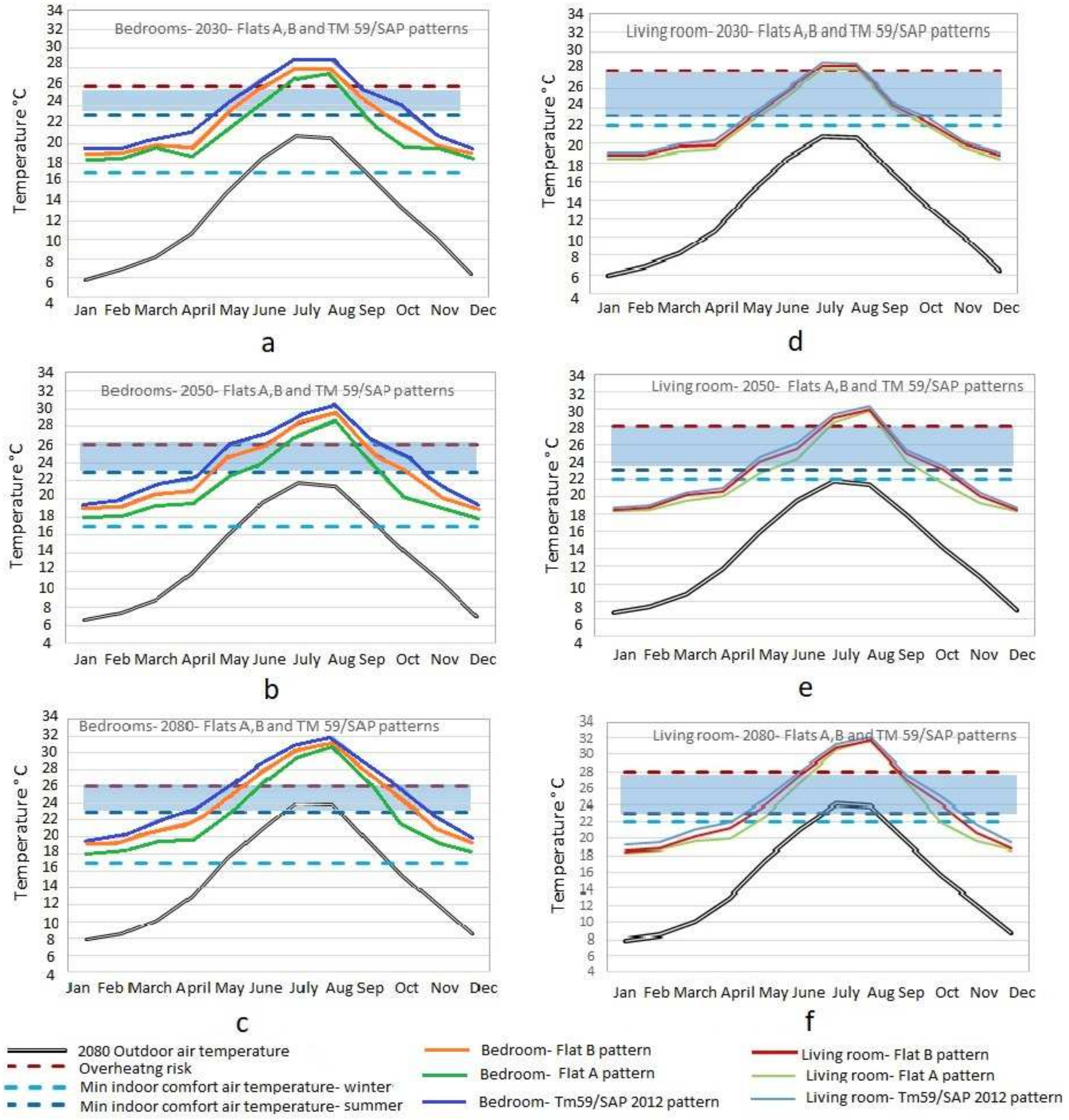


Figure 4 (a, b, c): Indoor T_o in the bedroom of the typical south-facing flat with the U-value of 0.5 W/m^2K and three occupancy profiles (Flat A, Flat B, and TM59) under the climate change scenarios (a) 2030, (b) 2050, and (c) 2080. Figure 4 (d, e, f): Indoor T_o in the living room of the typical south-facing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

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

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

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

ZONE	**HOURS EXCEEDING OVERHEATING RISK TEMPERATURE (TM59 CRITERIA: 26°C BEDROOM AND 28°C LIVING ROOM)**								
	2030			**2050**			**2080**		
OCCUPANCY SCHEDULE	**TM59**	**Flat A**	**Flat B**	**TM59**	**Flat A**	**Flat B**	**TM59**	**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

Moreover, results show that the impact of solar heat gain from windows incurs slight variance in mean annual solar gain in all three climate change scenarios. Table 5 presents the mean annual solar gain in the south-facing living room and bedroom in the typical middle floor using the U-value of 0.5 W/m^{2}K. It can be seen that solar gain is predicted to increase from 2030 to 2080 but the increase is not as significant as the increase in indoor operative temperature.

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

Climate projection	**2030**		**2050**		**2080**	
Room	**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

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

Several studies demonstrate that occupants' profiles have a tangible impact on predicting building performance (Mavrogianni *et al.*, 2014; University of Southampton, 2016; Ahmed *et al.*, 2017; Ahn *et al.*, 2017; Ben and Steemers, 2017; Yan *et al.*, 2017). A few studies even consider occupants' behaviour when evaluating building performance and assessing overheating risk (e.g., Steemers and Ben, 2014; Ben and Steemers, 2017). The research conducted by Porritt *et al.* (2012) on the impact of design interventions, including solar shading and ventilation on overheating risk, proved that the impact of occupancy profiles and behaviour is significant in predicting overheating risks. Other studies also asserted that the way that occupants operate their homes may contribute to thermal discomfort, which should be considered for future retrofit interventions (Elsharkawy and Rutherford, 2015, 2018; Mavrogianni *et al.*, 2015). Moreover, controlling natural ventilation to prevent warmer outdoor temperature from entering the building alongside night-time natural ventilation to cool down the surface temperature at night is an effective passive strategy alongside using externally fixed shading devices, shutters, and internal blinds and curtains, particularly for south-facing sides of dwellings. Studies also showed that the incentives for occupants may play an important role to reduce the risk of overheating and their response to improve the resilience is important (Murtagh, Gatersleben and Fife-Schaw, 2019). However, training is needed to improve occupants' knowledge and awareness of overheating risks to help reduce the risk by applying adaptive passive strategies according to their needs and based on their socio-demographic background and lifestyle.

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

3.3 Limitations of the study

Various studies have affirmed that relying solely on dynamic thermal modelling for predicting overheating may not be effective, as results may vary by 50-100% (Lomas and Porritt, 2017; Tink *et* *al.*, 2018). In fact, models derived from onsite measurements may produce more reliable results (Lomas and Porritt, 2017). Hence, onsite measurements and occupants' profiles have been collected in the case study. Also, the standard TM59 was utilised, as well as two of the dominant occupancy profiles concluded from an earlier survey questionnaire, to investigate the variance between occupancy patterns as a critical parameter in predicting overheating risks. However, as the occupants' interviews were undertaken during the winter of 2017; the summer window and door opening patterns were not collected from occupants, so TM59 schedules were applied instead.

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

4. Conclusion

The paper presents the second phase of a study which investigates the impact of retrofitting a1960's tower block prototype on occupants' thermal comfort and building energy performance in the current and future climate scenarios (2030, 2050 and 2080). The first phase of the study evaluated the building performance and validated the building simulation model adopted in this second phase. This model was employed to explore the risk of overheating in the case study under climate change scenarios as a result of improving building envelope performance using EWI. The results from the first phase of the study indicated that the occupants' socio-demographic backgrounds and occupancy profiles had a significant influence on energy use (Zahiri and Elsharkawy, 2018).

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

In addition, the results show that as thermal performance of external walls improves from 0.9 W/m²K to 0.7, 0.5 and 0.3 W/m²K, indoor T_o increases gradually under the three climate change scenarios. The changes fluctuate between 15% with the U-value of 0.5 W/m²K and 17% with the U-value of 0.3 W/m²K in comparison to the base case with the U-value of 0.9 W/m²K. The results also show that a significant difference between discomfort hours of the base case in comparison to the improved thermal conductivity of external walls. These changes vary from 28% with the U-value of 0.7 W/m²K in 2080 to 40% with the U-value of 0.3 W/m²K in 2030. The second phase studies indoor thermal comfort of a south-facing living room and bedroom on a typical floor flat with improved building envelope (U-value 0.5 W/m²K) using two dominant occupancy and energy-use profiles, as well as the TM59 and SAP 2012 methodology. The results demonstrate that it is necessary to consider dominant profiles in simulation modelling to achieve more accurate building energy performance as well as realistic predictions of overheating risks post retrofit. The results demonstrate that indoor T_o is above the maximum operative temperature that indicates overheating risk in bedrooms during the warm seasons, exceeding 26°C in all bedrooms. The results also show that the average predicted indoor T_o using TM59 pattern is almost 7% more than using Flat B pattern in bedrooms (with high occupancy profile) in all climate change scenarios while it is 11% more than Flat A pattern (with low occupancy profile). This difference has an impact on the upsurge of the predicted overheating duration in summer as the discomfort periods extend consequently.

The study indicates that the occupancy profiles may vary significantly for every household that has different age groups, number of occupants, and associated lifestyles. It has emerged that a young family of five, which represents households with high occupancy and energy-use profiles, has a higher risk of overheating during the warm season than a single elderly occupant, which represents a low occupancy profile. However, the study confirms that both cases are at lower risk of overheating compared to the projected overheating risk using theTM59 patterns, which exceeds the worst-case scenario in occupancy and energy-use patterns. There are also notable variances in overheating risk predictions when applying dominant occupancy profiles and standard profile, also confirmed by Buttitta *et al.* (2019) and Ozarisoy and Elsharkawy (2019).

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

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

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Declaration of Interest

None

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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]	

[1] SAP2012 heating pattern-
Weekday: 0700-0900 and 1600-2300/ Weekend: 0700-2300

[2] TM59 occupancy pattern-
Bedroom: 2 people from 11pm to 8am 70% gain, 2people at full gain from 8am to 9am and from 10pm to11 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**		
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 *et al.*, 2015)	0.28 W/m^{2}K		
WINDOWS U-VALUE	Double glazing with UPVC panels	2 W/m^{2} (Mavrogianni *et al.*, 2015)	2 W/m^{2}K (Mavrogianni *et al.*, 2015)		
AIR INFILTRATION	-	10 m3/m2h at 50 Pa (Mulville and Stravoravdis, 2016)	5.0 m3/m2h 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/m2K		**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

ZONE	**HOURS EXCEEDING OVERHEATING RISK TEMPERATURE (TM 59 CRITERIA: 26°C BEDROOM AND 28°C LIVING ROOM)**								
	2030			**2050**			**2080**		
OCCUPANCY SCHEDULE	**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

Climate projection	**2030**		**2050**		**2080**	
Room	**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

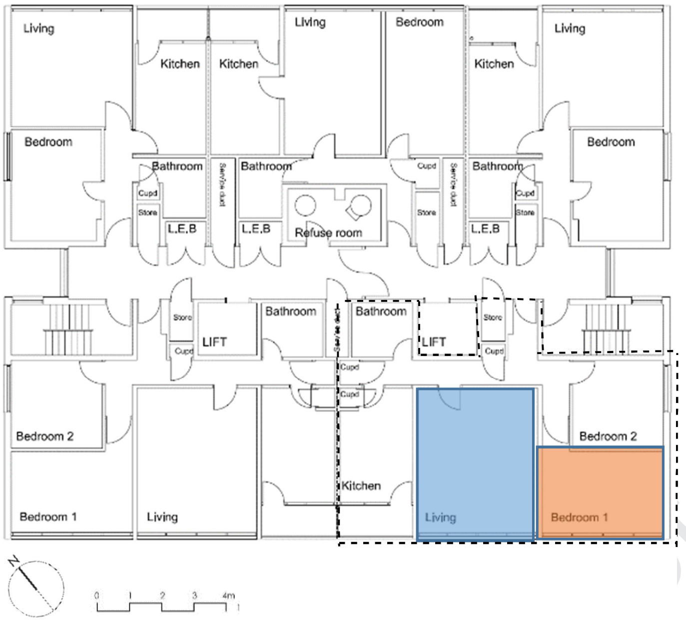


Figure 1: Typical floor plan of the case study building (Newham Council, 2007)

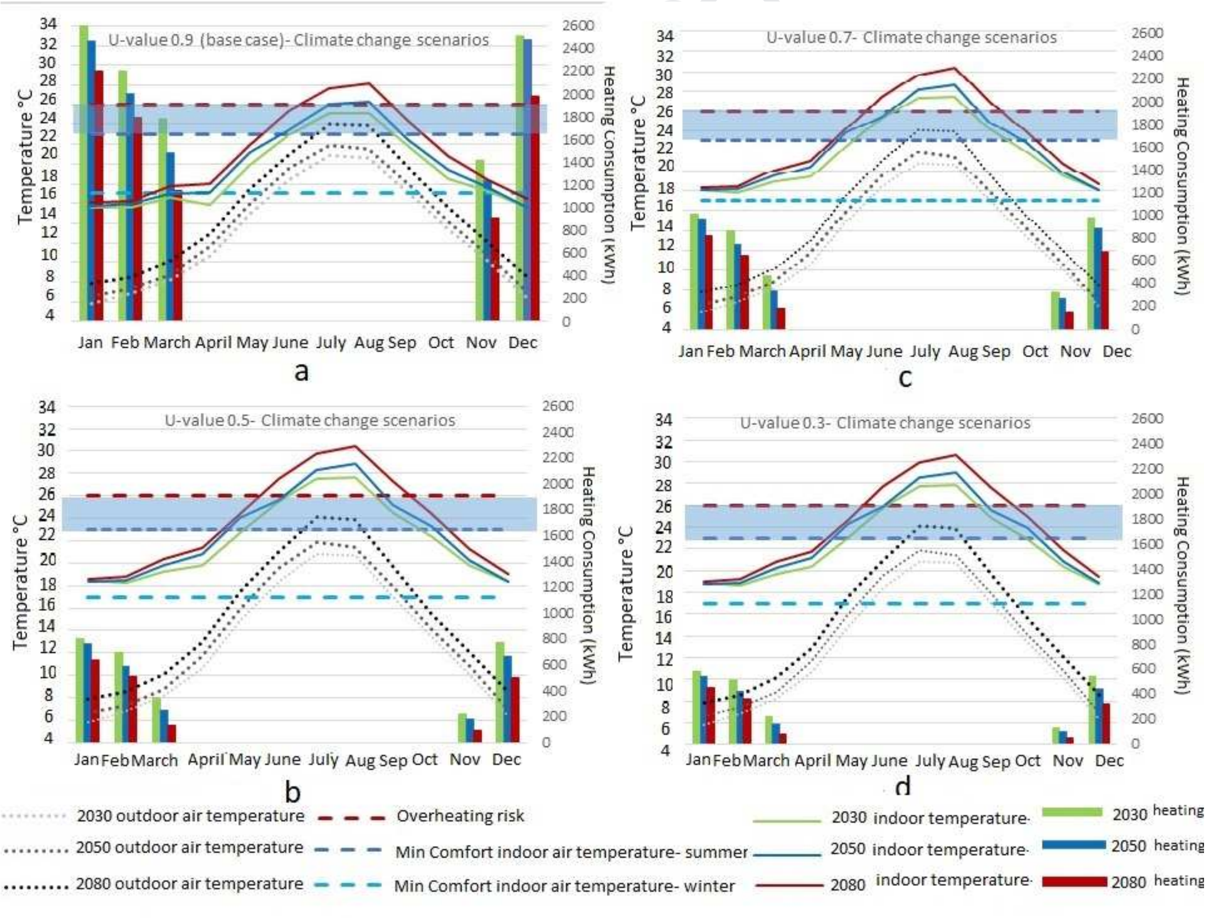
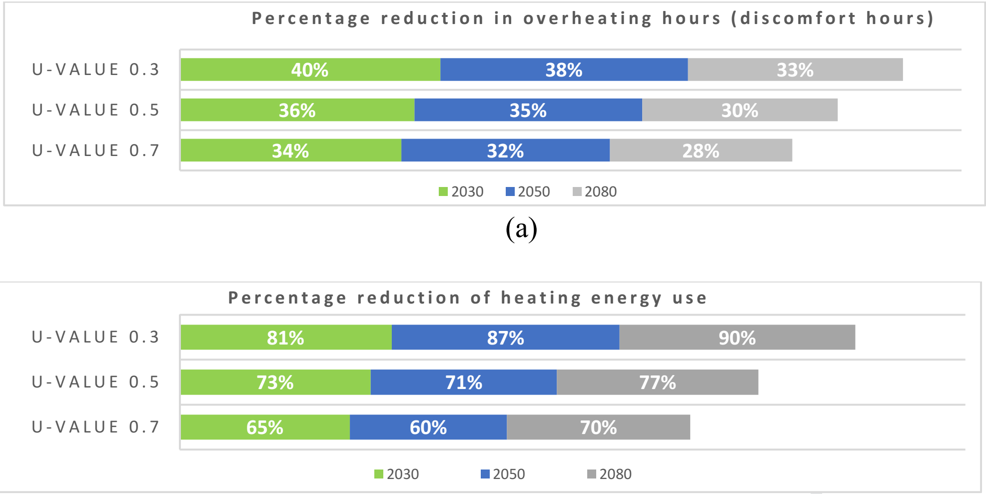


Figure 2 (a, b, c, d): Indoor T_o and heating energy use in a typical middle floor under the climate change scenarios (2030, 2050, 2080), using TM59-SAP patterns and U-values of a. 0.9 W/m²K , b. 0.7 W/m²K , c. 0.5 W/m²K and d. 0.3W/m²K.



(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.

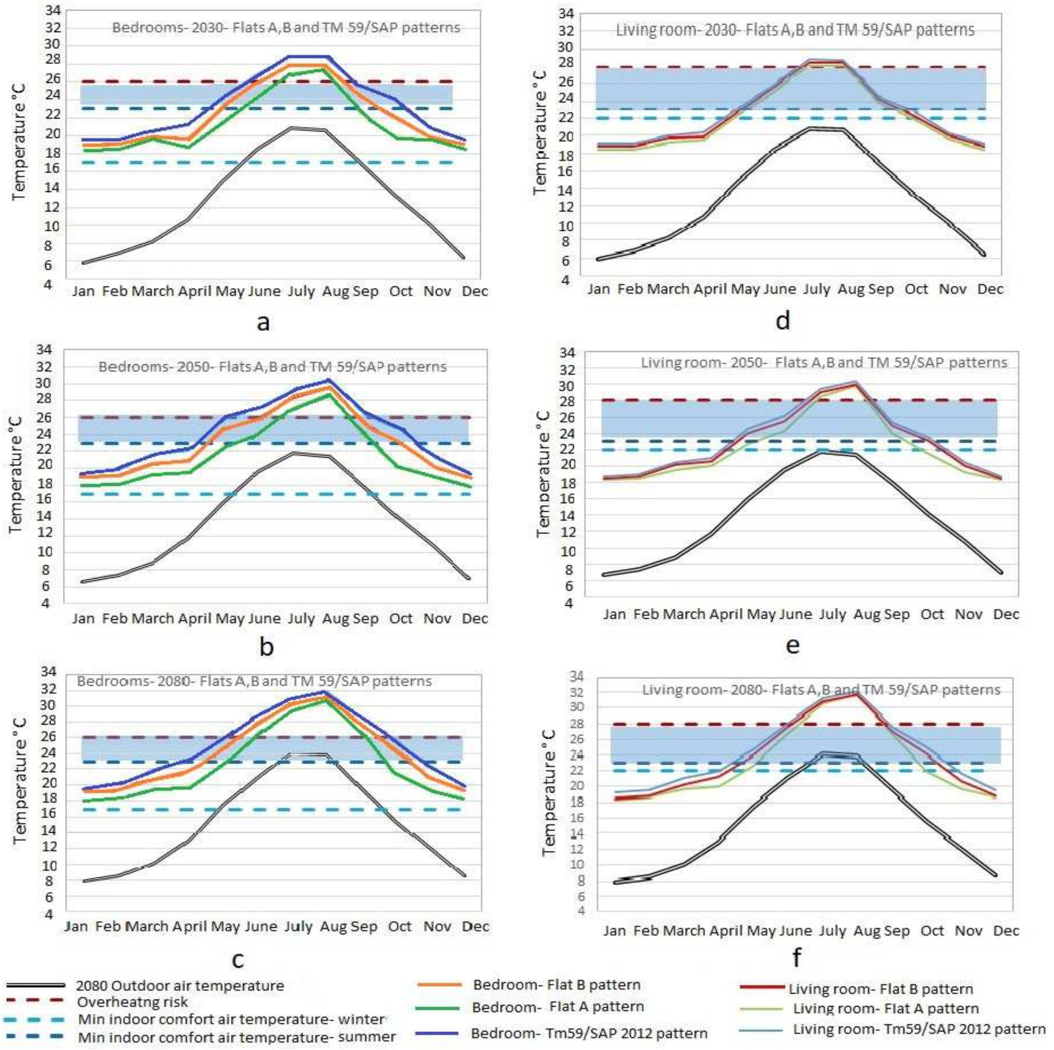


Figure 4 (a, b, c): Indoor T_o in the bedroom of the typical south-facing flat with the U-value of 0.5 W/m²K and three occupancy profiles (Flat A, Flat B, and TM 59) under the climate change scenarios (a) 2030, (b) 2050, and (c) 2080. Figure 4 (d, e, f): Indoor T_o in the living room of the typical south-facing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

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