Thermal comfort, summertime temperatures and overheating in prefabricated timber housing

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Abstract

Timber is increasingly used in construction of buildings due to its green credentials and ability to reduce the overall construction period when compared with conventional materials. However, the lack of thermal mass along with the low U-values can be a risk factor in increasing overheating. This paper investigates the indoor thermal conditions and overheating risk in prefabricated timber buildings focusing on two buildings built in the last decade in the UK, Oxley Woods and Bridport. The study employs a combination of different methods: post-occupancy evaluation, thermal comfort surveys, monitoring and simulation. The results reveal high satisfaction rates in both buildings, with lower thermal sensation in Oxley Woods where monitored internal temperatures were higher, demonstrating higher adaptive capacity due to the increased use of controls. Overheating analysis through the use of the CIBSE comfort model revealed extreme summertime overheating in 67% of the spaces during the monitoring periods, while for the simulations in just 22% of the spaces. With the adaptive thermal comfort model (BSEN15251) overheating is more frequent at Oxley Woods with cold discomfort also becoming an issue in both buildings. Comparison of the two comfort models suggests that the CIBSE model is more sensitive predicting extreme occurrence of overheating, while the adaptive BSEN15251 model is closer to the results of the thermal comfort evaluations, with availability of controls enhancing adaptation further. Comparing the findings with those from previous studies, which were mostly built with heavyweight materials, indicate that high temperatures were more frequent in the current study, highlighting that the lack of thermal mass in prefabricated timber developments increases the overheating risk, even in mild summer weather conditions as occurring in the UK.

Keywords: Thermal comfort, prefabricated timber, overheating, summertime temperatures, monitoring, post-occupancy survey, simulation

1. Introduction

There has been a growing concern regarding the increase in summertime temperature in UK buildings, even as the climate is considered to be moderately warm, which is expected to occur regularly as global temperatures increase. Recent studies have highlighted the problem with increasing summertime temperatures on the occupants' comfort in the UK, as dwellings are built to meet improved building regulations with low U-values. As a result, they are likely to overheat and more sensitive to summertime high temperatures than older houses [1-2]. Similar issues have been identified in highly insulated passive houses in Europe, where occupants are likely to experience high temperatures when such buildings are located in a climatic region with hot summers [3]. Since the 2003 heat wave that led to many deaths across Europe [4-6], various researchers have addressed the issue of overheating in UK dwellings [7-13] but no study has solely focused on the performance of timber and particularly prefabricated timber houses.

Prefabricated timber housing is considered in this study due to modern methods of construction, which are increasingly used for development to save time and provide quick returns for investors, combined with timber's green credentials. However, internal spaces of lightweight buildings are predicted to be warmer than heavyweight houses for future years [14] due to low thermal mass of their envelopes and the expected increase in external temperatures [14-15]. This is an important concern in view of rising temperatures.

For these reasons an extensive study has been carried out to evaluate the thermal performance of two prefabricated timber housing developments in south-east of England, which is prone to summertime overheating and at higher risk, under the various climate change scenarios [7,10,16]. The principal aim of the study is to evaluate summer conditions in prefabricated timber housing, including occupants' comfort and summertime temperatures. Occupants' adaptive actions and design strategies for preventing thermal discomfort, especially when summer temperatures rise leading to overheating are important to minimise thermal discomfort. The study included post-occupancy evaluation surveys, comfort surveys with concurrent environmental monitoring and dynamic thermal simulations.

2. Description of the case study buildings

The case study buildings selected include Bridport, Oxley Woods and Stadthaus. This paper focuses, however, on the summer surveys, which were carried out only in two buildings (Bridport and Oxley Woods). Post-occupancy evaluation surveys were carried out at the three buildings while environmental monitoring and respective thermal comfort surveys during the summer were only conducted at Bridport and Oxley Woods. The buildings were selected based on their sustainability credentials, all being recipients of various awards for sustainable or low-energy design [17-21]. The relevant U-values for the different components of the buildings are presented in Table 1.

Table 1. U-values (W/m^{2}K) for the two buildings

	U-values for the different components (W/m^{2}K)		
Case study	Walls	Windows	Roof
Bridport House	0.14	1.37	0.12
Oxley Woods	0.12	1.7	0.17

Bridport House (51°53'50N, 0º08'61W), designed by Karakusevic Carson Architects, owned by the London Borough of Hackney, is a prefabricated timber block of flats built with cross-laminated timber (CLT). Completed in 2011, the total floor area of the building is 4,220m². It comprises of 41 flats (4 different prototypes). The prototypes include 8 four-bed maisonettes (125m^2/unit), 8 one-bed (58m^2/unit), 12 two-bed (80m^2/unit) and 13 three-bed flats (98m^2/unit). The building is built over two joint blocks, one 8-storey high with stair to access and the other 5-storey with separate stairs and lifts for the users to access the building. The floor-to-ceiling height is 2.65m.

Oxley Woods, designed by Rogers Stirk Harbour & Partners located in Milton Keynes (52°0′36N, 0°48′5W) is a prefabricated timber housing development built with Structural Insulated Panel (SIP). The construction of the development started in 2005 and is still ongoing. Oxley Woods has 10 different prototypes. It is a 145-unit development with an average density of 40 dwellings per hectare (dph) indicating a low-density development. At the time of the survey, 116 houses had been completed and 29 houses were yet to be built. The internal spaces of the houses have floor-to-ceiling height of 2.35m.

3. Methodology

The study included three different study methods. Post-occupancy surveys were carried out and supplemented by environmental monitoring and thermal comfort surveys over the summer period to evaluate the actual conditions in the buildings and occupants' responses to the conditions experienced. The questionnaires for the different surveys, i.e. POE, which were distributed to all residents, and the thermal comfort surveys, which were only distributed to the occupants of the houses monitored, are presented in Appendix 1 and 2 respectively. As the focus of the study was to evaluate the internal conditions through both objective and subjective parameters, it was crucial to address overheating analysis through the different methods available (the CIBSE and the BSEN15251). Focusing on both static and dynamic criteria, comparing the results from the different standards, highlighting potential limitations, was essential, particularly when compared with the results from the thermal comfort surveys.

3.1 Field surveys and monitoring

Post-occupancy surveys are critical to appreciating the thermal environment in buildings, while the comfort surveys help to understand as well as compare the nature and frequency of occupants' complaints of feeling warm or hot that cannot be obtained during surveys [22]. For the post-occupancy surveys, the respondents were asked to evaluate their overall thermal comfort and thermal satisfaction in different seasons, along with different aspects of control of the thermal environment. Basic information about age, gender, occupancy status and duration of occupancy was collected. The POE was carried out at the different buildings concurrently in June-July, 2012. Overall, 131 questionnaires were distributed to the residents of the three buildings and 65 completed questionnaires were returned.

The indoor monitoring was carried out at Bridport from 29/6/12 to 12/7/12 and at Oxley Woods from 20/7/12 to 31/7/12 due to access granted by the appropriate authorities to carry out the surveys at different periods during the summer. Temperature and relative humidity were recorded using HOBO and Tinytag sensors installed on the internal walls at the height of 1.1m above the floor level. The height was considered as the average height of the head-region of occupants seated and the mid-region of participants carrying out standing activities. The sensors were mounted on the internal walls to measure temperature experienced by the occupants [23]. The temperature and relative humidity were recorded every 15 minutes [24].

Four flats were monitored at Bridport and five houses at Oxley Woods. The spaces monitored were chosen as representative from different orientations and in agreement with the residents and facilities managers. All the spaces monitored have at least one side of the walls as an external wall to understand how the prefabricated timber walls regulate temperature swing in different seasons. In total, 17 spaces comprising of living areas and bedrooms were monitored. The households monitored at Bridport were selected from three flats on the ground and the first floors with different orientations (FL1, FL7 and FL8) and one flat on the second floor-FL35, while no access was allowed on the top floors. The houses monitored at Oxley Woods were also chosen from different orientations (A38ML- South facing, A6ML- South facing, A1WL- East facing, A142HA- West facing and A162HA- North facing). Table 2 below summarises the features of the spaces monitored at the two buildings.

The comfort surveys were carried out at Bridport from 29/06/12 to 12/07/12 and Oxley Woods from 20/07/12 to 31/07/12, and the participants were asked to complete the questionnaires three times per day enquiring their thermal comfort state (using the seven-point ASHRAE thermal sensation scale -where 1 is cold and 7 is hot- and a five-point preference scale -where 1 is much cooler, 2 is cooler, 3 is no change, 4 is warmer, 5 is much warmer). Additional information on clothing insulation and activity in the last 15 minutes was also collected. Overall, 141 questionnaires were collected. The information from the surveys and related environmental data was entered on the statistical programme SPSS for further analysis.

Table 2. Details of the internal spaces monitored at Bridport and Oxley Woods

Name	**Location**	**Floor area (m²)**	**Flat/ Housing type**	**Orientation**	**Floor level**
FL1GFL	BD	29.7	End-terraced flat	South-facing	GF
FL1FFB	BD	13.1	Mid-terraced flat	Southwest-facing	FF
FL7FFFB	BD	15.2	Mid-terraced flat	East-facing	FF
FL8FFSB	BD	7.7	End-terraced flat	Northeast-facing	FF
FL35SFL	BD	28.8	Mid-terraced flat	West-facing	SF
A1WLGFL	OX	20.9	End-terraced house	Southwest-facing	GF
A1WLFFFB	OX	12.2	End-terraced house	Southeast-facing	FF
A6MLSFBB	OX	8.7	Mid-terraced house	Northwest-facing	SF
A38MLGFL	OX	20.9	End-terraced house	Northeast-facing	GF
A38MLFFFB	OX	12.2	End-terraced house	Southeast-facing	FF
A38MLFFBB	OX	9.1	End-terraced house	Northeast-facing	FF
A142HAGFL	OX	18.3	End-terraced house	Southwest-facing	GF
A142HASFBB	OX	9.1	End-terraced house	Southeast-facing	SF
A162HAGFL	OX	20.9	Mid-terraced house	North-facing	GF
A162HAFFBB	OX	8.7	Mid-terraced house	Southeast-facing	FF

*GF- Ground floor, FF- First floor, SF- Second floor. *BD- Bridport, OX- Oxley Woods

The outdoor weather data for the monitoring period was collected from nearby meteorological stations. London City Airport was considered for Bridport and the weather data from Luton Airport for Oxley Woods.

3.2 Thermal simulations

Due to the limited monitoring dynamic thermal simulation was essential to investigate the thermal performance of the two case study buildings and compare the different dwellings on an equal basis, essential to ensure valid comparison and identification of overheating under similar conditions. This was carried out using the DesignBuilder software [25]. The Test Reference Year (TRY) weather data files (London Islington and St Albans) for the 2000s generated by the Prometheus Group at the Exeter University were used for the simulations [26], chosen due to the proximity to the case studies. The whole summer period (May-September) was considered for the simulation.

The buildings were considered as free-running in summer; therefore, no assumptions concerning temperature set-points were made on mechanical cooling and heating of the spaces during the set-up for the simulations. Assumptions concerning general lighting, task and display lighting, as well as the infiltration rate were calculated from CIBSE [27-28]. The infiltration rate was assumed at 0.12ach for Bridport (CLT panels) and at 0.15ach for Oxley Woods (SIPs) since the structural timber materials usually have low infiltration rates (0.1-0.5ach) compared to typical timber-framed buildings with an estimated value of 3.9ach [29]. Also, the buildings are airtight and built to meet the appropriate UK building regulations. The outside air change (ach) rate for indoor spaces in two storey dwellings with cross ventilation is recommended not to be more than 8ach. Dwellings with spaces that have no cross ventilation should not exceed 5ach [25]. The outside air change rate was assumed at 4ac/h for Oxley Woods and at 5ac/h for Bridport due to the additional floor area of spaces, larger size of windows and higher floor-to-ceiling heights at the latter.

The results from the simulations were calibrated and validated using the results obtained from the indoor monitoring of the spaces. The two-week period of the monitoring was considered for the calibration. The hourly simulated data was compared with hourly averages of the monitored data, which was recorded every 15 minutes during the survey, for consistency. The monitored temperatures were plotted on the same charts with the simulated results over the same period. Priority was set on the spaces that provided a close range and similar pattern between the monitored and simulated temperatures over 26ºC and 28ºC for the calibration, the CIBSE point of references for assessing internal temperature of bedrooms and living rooms respectively [27]. All the spaces monitored at Oxley Woods and three of the spaces (FL1GFL-BD, FL1FFB-BD, FL7FFFB-BD) at Bridport were thus calibrated. The two weather files were considered for the calibration to further validate the simulated results by checking the peak temperatures and the difference between the simulated data and the monitored data.

The case study buildings were modelled with the software (version 3.2.1), based on the architects' drawings. Forecast concerning window opening actions of occupants during night are important and cannot be easily determined [30]. However, priority must be given to reliable outcomes with precise window opening actions that produce a similar pattern of outcomes with monitored data. The window opening was modelled in accordance with the outcomes obtained from the accelerators (state loggers) used to monitor windows' open and close sessions. Summary of the parameters input is provided in the table below.

Table 3: Summary of parameters input for the modelling

Input parameters	**Value for Bridport**	**Value for Oxley Woods**
Heating	No heating required (free-running in summer)	No heating required (free-running in summer)
Heating setpoint/setback temperatures	No setpoint/setback temperatures required	No setpoint/setback temperatures required
Ventilation	Natural ventilation- no heating/cooling	Natural ventilation- no heating/cooling
Natural ventilation rate (per person)	9 l/s	10 l/s
Density (people/m^2)	0.03	0.05
Total floor area	4220m^2	Varied for different prototypes
Cooling setpoint/setback temperatures	No setpoint/setback temperatures	No setpoint/setback temperatures
Daytime period	08:00 – 22:00	08:00 – 22:00
Nightime period	23:00 – 07:00	23:00 – 07:00
General lighting	2.0W/m^2	2.0W/m^2
Task and display lighting	0.5W/m^2	0.5W/m^2
Metabolic (activity)	0.9	0.9
Metabolic (clothing)	0.5clo	0.5clo
Infiltration (ac/h)	0.12	0.15
Outside air change rate (ac/h)	5.0ach	4.0ach
Equipment such as computers)	3.9W/m^2	3.9W/m^2
Window to wall ratio	35%	Varied for different units
Window height	2.1m	1.35m
Floor-to-ceiling height	2.65m	2.35m
External wall (internal heat capacity)	81.61kJ/m^2-K	11.7kJ/m^2-K

Floor (internal heat capacity)	14.21kJ/m²-K	7.8kJ/m²-K
Roof (internal heat capacity)	12.67kJ/m²-K	10.37kJ/m²-K

Since the models were considered as free-running in summer, the simulated internal temperatures were mainly influenced by window opening sessions and envelope of the dwellings. The calibration of the simulated and monitored temperatures revealed the peak temperatures closely align with the data recorded during the monitoring. The difference between the maximum temperatures of the calculated and the monitored results was within a range of 2ºC most of the time [30], a requirement for the results to be considered credible especially for analysis of overheating [31].

4. Evaluation of thermal comfort using the static 'CIBSE' and the dynamic adaptive criteria

Overheating is considered as one of the major reasons causing occupants' discomfort and dissatisfaction in the thermal environment. According to CIBSE [27] 'overheating within a dwelling occurs when the actual indoor temperature for any given day is hot enough to make the majority of people feel uncomfortable'. This can also be experienced when the indoor temperature is exceeded long enough to make occupants feel uncomfortable.

Various indicators have been used for assessing overheating in dwellings. According to CIBSE [28], for overheating not to occur within a dwelling, the temperature threshold (25ºC/28ºC) should not be exceeded for more than a reasonable duration of hours (5%/1%) throughout the year. Furthermore, indoor temperature ranges 25°C-28°C during the summer can result in an increasing number of occupants feeling hot and uncomfortable, while the majority of the occupants will feel increasingly dissatisfied when the indoor temperatures stay at or above 25°C for long duration of hours in a day. Hence, the duration of hours at which the temperatures stay at or above 25°C should not be exceeded for more than 5% of the total occupied hours per year (usually 125 hours). For bedrooms, lower temperatures are considered, as thermal comfort and quality of sleep decrease with temperatures increasing over 24ºC, or exceed 26ºC with ceiling fans [28]. These static criteria have been used extensively to evaluate overheating risk in dwellings [8-9,11,13,32-34].

As people can adapt to changing temperatures [35], the adaptive comfort model is used for free-running buildings [36]. In the UK, most of the dwellings are considered free-running in the summer, i.e. not mechanically heated or cooled. In that case, thermal comfort is considered to drift with the outdoor temperature, rising at about 0.33K per K rate as the moving average of the outdoor temperature (T_{rm}) rises within the limit $10<T_{rm}<30$ºC [36]. The BSEN15251 [36] specifies different categories of comfort, depending on the temperature limits defining thermal comfort.

The current study uses both the static and dynamic criteria for evaluating overheating. The former use the number of occupied hours, 5%>25°C and 1%>28°C as indicators of moderately warm and extremely hot overheating risk for living areas, with 5%>24 and 1%>26ºC, used for bedrooms. For the BSEN15251 [35], Category II is employed for evaluating thermal comfort in buildings where rigorous tasks are not expected to be carried out and people are allowed to open or close windows and likely to adjust clothing insulation to meet the thermal conditions of their environment. Category II provides a temperature range of 6K. The BSEN15251 provides no restriction on the acceptable limits of the category markers and 5% of hours over (warm discomfort) or lower (cold discomfort) the category limit will be considered as an indicator in this study.

5. Data Analysis

Analysis of the data collected during the surveys is presented below.

5.1 Post-occupancy surveys

41 questionnaires were distributed at Bridport while 70 questionnaires were distributed at Oxley Woods. 26 questionnaires were returned from Bridport and 26 from Oxley Woods. There were 20 male (38.5%) and 32 female (61.5%) responses. Over 73% of the respondents were above the age of 30 (Table 4).

Table 4. Gender and age distribution of post-occupancy questionnaires for the the case studies

	Gender (frequency/ percentage distribution)		**Age (frequency/ percentage distribution)**					**Total number of the respondents (frequency/ percentage distribution)**
Case Study	Male	Female	Under 18	18-30	31-45	46-55	56 and above	
Bridport	9 (35%)	17 (65%)	-	-	7 (27%)	8 (31%)	11 (42%)	26 (50%)
Oxley Woods	13 (50%)	13 (50%)	2 (8%)	5 (19%)	15 (58%)	1 (3%)	3 (12%)	26 (50%)

The analysis of the thermal comfort showed an overwhelming response for the hot/warm part of the scale in the summer period across the buildings (Table 5), with at least 81% of the occupants feeling ‘warm’ or ‘hot’ at Bridport and Oxley. However, in the winter, there is a noticeable shift of thermal sensation with more than half of the responses at either ‘neutral’ or ‘slightly warm’ part of the scale, with the mean thermal sensation focusing around neutrality.

Table 5. Mean responses for thermal sensations (from 1= cold to 7= hot) and overall thermal comfort in the summer and the winter (from 1= very uncomfortable to 7= very comfortable) from the post-occupancy surveys

		Thermal sensation				**Overall thermal comfort**				**Thermal satisfaction**			
	N (%)	Summer		Winter		Summer		Winter		Summer		Winter	
		M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Bridport	26 (50%)	5.88	0.766	4.19	1.132	3.35	1.223	6.04	0.999	3.35	1.294	6.04	1.183
Oxley Woods	26 (50%)	5.65	1.325	4.46	1.174	3.85	1.461	4.58	1.880	4.85	1.255	5.62	1.098

*M- Mean, SD- Standard Deviation, N- number.

Overall, the occupants are satisfied with their thermal environment during the summer, with the lowest levels of satisfaction and overall thermal comfort at Bridport. On the contrary, in the winter, there is a noticeable shift in overall thermal comfort vote, with more than half of the responses at either ‘comfortable’ or ‘very comfortable’ (Table 4), and 65% of the occupants satisfied with the overall thermal comfort. Pearson correlation analysis indicated that the male occupants are less ‘comfortable’ with the thermal environment in the summer than the female at Bridport ($r=0.44$, $p<0.05$).

The residents in Oxley Woods interacted more with controls in the summer, which may have been influenced by the resulting internal conditions. They commented that the spaces on the upper floors can be very hot requiring windows to be open, with the use of windows influenced by their thermal sensation ($r=0.22$, $p<0.05$). Other actions included the use of doors for natural ventilation and a fan at night-time especially in the west facing bedrooms on the upper floors to reduce the impact of the late evening sun penetrating into the internal spaces and the use of internal blinds during the day-time to keep direct sunlight out.

Design related parameters found to influence thermal comfort include orientation and floor number. Occupants in the south-east and south-west facing spaces feel warmer than those in the north both in summer ($r=0.20$, $p<0.05$) and winter ($r=0.24$, $p<0.05$). Occupants on the lower floors were more satisfied with the thermal conditions in the summer than those on the upper floors at Bridport ($r=-0.41$, $p<0.05$), while the occupants on the upper floors feel warmer than those on the lower floors at Oxley Woods ($r=0.42$, $p<0.05$).

5.2 Environmental monitoring

Throughout the monitoring period, the external temperature at Bridport varied from the minimum of 11ºC on 12/7/12 to a maximum of 23.5ºC on 5/7/12 (Fig. 1a), with a wider range at Oxley Woods from 8ºC on 30/7/12 to a maximum of 27.5ºC on 24/7/12 (Fig. 1b). The beginning of the monitoring period for both case studies was considered to be wet and mild.

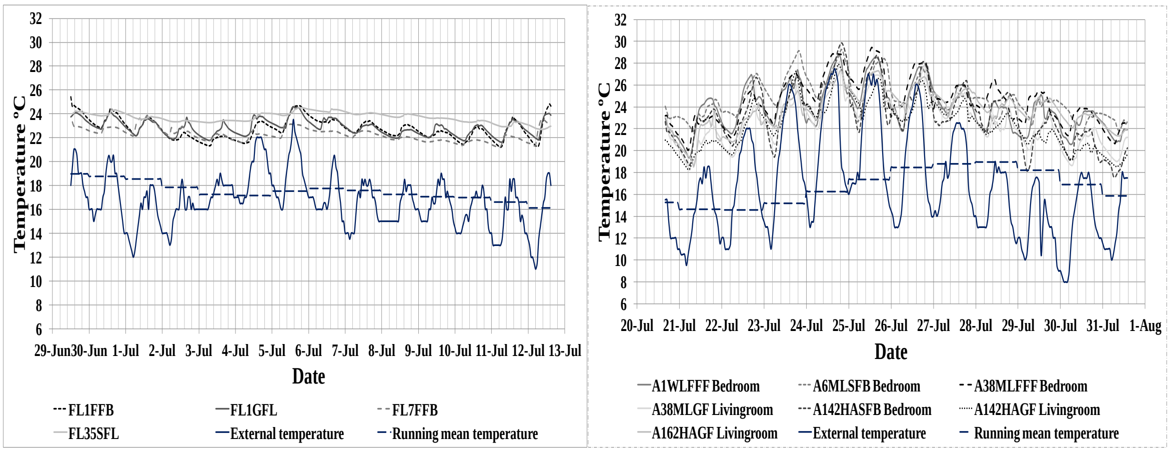

Fig. 1. The living rooms and the bedrooms monitored at Bridport (left) and Oxley Woods (right) in the summer

The running mean temperature[1] of the measured external temperature, T_{rm}, as defined in BSEN15251 [36] reached 19ºC on 29/6/12 at Bridport (Fig. 1a) and 19ºC on 28/7/12 at Oxley Woods (Fig. 1b). The average running mean temperature during the monitoring period was 17.5ºC at Bridport and 16.8ºC at Oxley Woods. The results suggest that the average weather conditions for the monitoring period were cooler than the average conditions for the survey month (July) in London (20.9ºC) and Luton (19ºC). Also, the average running mean temperature of the monitoring period was cooler than the hottest month (August) of the year with the average monthly running mean temperatures of 23ºC and 22.5ºC recorded in London and Luton respectively. T_{rm} throughout the monitoring period rose above 16ºC for 100% of the time and 18ºC for 19% of the time at Bridport compared with the T_{rm} value at Oxley Woods, which exceeded 16ºC for 64% and 18ºC for 37% respectively.

Table 6 summarises the findings of the monitored temperatures in the living areas at the buildings showing higher mean temperature at Oxley Woods for the periods from 08:00-22:00 and 18:00-22:00. Higher maximum and minimum day-time temperatures were also observed at Oxley Woods during these periods.

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[1] The running mean of external temperature (Trm) is described 'as an exponentially weighted running mean of the daily average outdoor temperature'. Θ_{ed} is the series. It is computed from the formula: $\Theta_{rm} = (1-\alpha).\{\Theta_{ed\,-1} + \alpha.\ \Theta_{ed\,-2} + \alpha^2\ \Theta_{ed\,-3} \ldots.\}$. Where, Θ_{rm}= Running mean temperature for today, Θ_{rm-1}= Running mean temperature for previous day, Θ_{ed-1}= daily mean external temperature for the previous day, $\Theta_{ed\,-2}$= daily mean external temperature for the day before and so on. α is a constant between 0 and 1 (usually, α=0.8) [35].

Table 6. Summary of the monitored temperatures in the living areas at Bridport and Oxley Woods in the summer

Name of space- Living areas	Max. day-time temp °C (08.00-22.00)	Min. day-time temp °C (08.00-22.00)	Mean day-time temp °C (08.00-22.00)	Max. day-time temp °C (18.00-22.00)	Min. day-time temp °C (18.00-22.00)	Mean day-time temp °C (18.00-22.00)	Max. temp °C	Min. temp °C	Mean temp °C
A1WLGFL- OW	30.0	20.4	24.2	29.6	21.6	24.5	30.0	19.8	23.5
A38MLGFL- OW	28.1	18.4	23.2	28.1	20.5	23.8	28.1	18.2	22.6
A142HAGFL- OW	27.9	18.5	22.8	27.9	19.8	23.2	28.0	18.3	22.4
A162HAGFL- OW	27.3	18.6	24.1	27.2	20.8	24.4	27.3	18.6	23.7
FL1GFL- BD	24.6	21.8	23.1	24.4	22.3	23.2	24.6	21.7	22.9
FL35SFL- BD	24.5	22.6	23.7	24.5	23.1	23.8	25.0	22.7	23.7
Bridport (Average living areas)	24.6	22.2	22.0	24.5	22.7	23.5	24.8	22.2	22.6
Oxley Woods (Average living areas)	28.3	18.9	23.7	28.2	20.7	24.0	28.4	18.7	23.9

*OW- Oxley Woods, BD- Bridport

Similar profiles are noticed for the bedrooms during the night-time period 23:00-07:00 (table 7) also showing higher mean temperatures at Oxley Woods.

It is difficult to compare the results for the two buildings, as the monitoring period at Oxley Woods was warmer than the survey period at Bridport where the weather conditions were mild and wet. However, the rooms of the two developments present noticeable differences, which will also be discussed in the modeling section. More specifically, the bedrooms at Bridport are larger in terms of size with a bigger height, while the bedrooms at Oxley Woods are on the upper floors. Additionally, the overall urban forms of the dwellings at Oxley Woods, arranged in a terrace, may contribute to the higher thermal load.

Table 7. Summary of the monitored temperatures in the bedrooms at Bridport and Oxley Woods in the summer

Name of space- Bedrooms	Max. night-time temp °C (23.00-07.00)	Min. night-time temp °C (23.00-07.00)	Mean night-time temp °C (23.00-07.00)	Max. temp °C	Min. temp °C	Mean temp °C
A1WLFFFB- OW	26.0	19.4	22.5	28.7	19.4	23.9
A6MLSFBB- OW	27.9	22.2	24.2	29.2	21.0	24.7
A38MLFFFB- OW	27.1	20.0	23.3	29.5	20.0	24.5
A38MLFFBB- OW	26.2	20.8	23.7	29.1	20.8	24.3
A142HASFBB- OW	28.3	18.0	21.7	29.8	18.0	23.2
A162HAFFBB- OW	27.7	20.8	23.8	30.5	20.8	25.7
FL1FFB- BD	24.0	21.3	22.3	24.7	21.3	22.8
FL7FFFB- BD	23.2	21.1	22.0	23.8	21.2	22.3
Bridport (Average bedrooms)	23.6	21.2	22.0	24.3	21.3	22.6
Oxley Woods (Average bedrooms)	27.2	20.2	23.2	29.4	20.0	24.4

5.3 *Thermal comfort surveys*

The analysis of thermal sensation shows a distribution clustered around the central categories with more than half of the responses feeling ‘comfortably warm’ with a moderately even distribution of votes varying between ‘neither cool or warm’ and ‘slightly warm’. Differentiating between the two developments, mean thermal sensation in Bridport is higher than in Oxley Woods (Table 8). Interestingly, only 38% of the respondents feel ‘warm’ at Oxley Woods while this category rises to 75% at Bridport, despite the fact that at the latter temperatures were significantly lower. These results suggest better adaptation of the occupants at Oxley Woods to the thermal environment than at Bridport (Table 8).

Table 8. Mean responses for thermal sensation (from 1=cold to 7=hot), thermal preference in the summer (from 1=much cooler to 5= much warmer), neutral and preferred temperatures from the comfort surveys

Case study	Thermal sensation			Thermal preference			Tn (ºC)	Tp (ºC)	Mean temp. (ºC)
	Mean	SD	N	Mean	SD	N			
Bridport	4.94	1.207	51	2.41	0.669	51	20.4	22.0	22.6
Oxley Woods	4.46	1.083	90	2.87	0.584	90	21.2	20.2	23.9

*Tn- Neutral temperature. Tp- Preferred temperature

Focusing on thermal preference, as expected the occupants preferred to be ‘cooler’ (Table). The mean distribution of votes indicates that more than half of the responses preferred to be ‘cooler’ at Bridport with a drift towards ‘no change’ at Oxley Woods, despite the higher temperatures experiencing at the latter, further strengthening the argument for thermal adaptation.

Linear regression analysis to calculate neutral (Fig. 2) and preferred temperatures further confirm the higher adaptation potential at Oxley Woods, with higher neutral and lower preferred temperature calculated for Oxley Woods (Table 8).

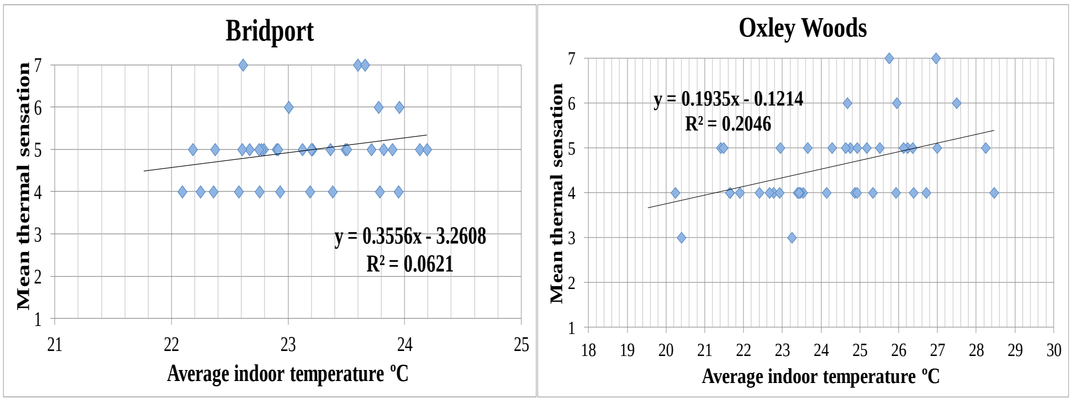

Fig. 2. Relationship between thermal sensation and the average indoor temperature at Bridport (left) and Oxley Woods (right)

Internal temperature is strongly related to external temperature, and the bedrooms are much warmer than the living rooms at Oxley Woods while the reverse occurs in the living rooms being warmer than the bedrooms at Bridport (Fig. 3). The bedrooms at Bridport have higher floor-to-ceiling height and larger floor areas than the bedrooms at Oxley Woods. In addition, the bedrooms at Oxley Woods are located on the upper floors of the houses with tendency for hot air to rise at a faster rate from the lower floors to the upper floors while most of the apartments at Bridport have the living areas and the bedrooms on the same floors.

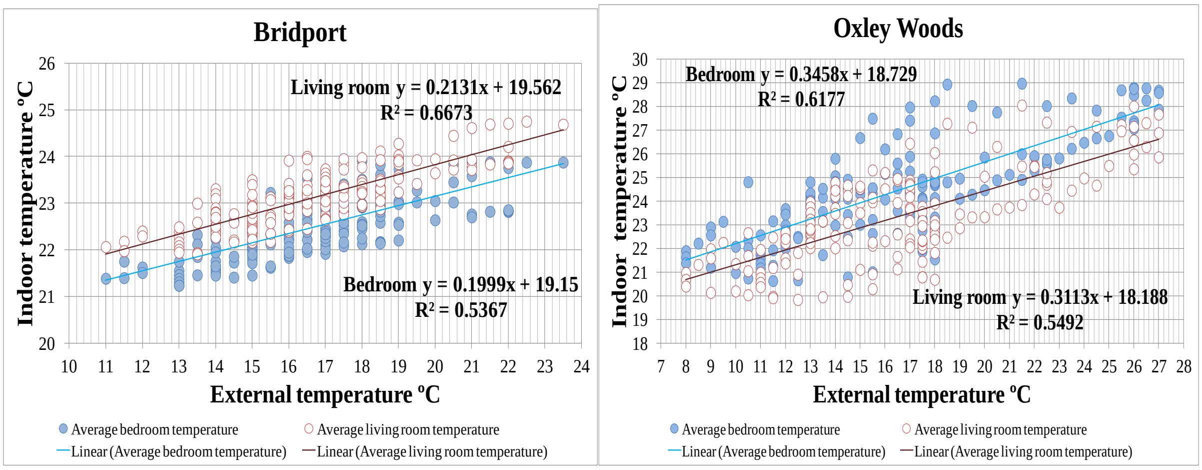

Fig. 3. Relationship between the mean internal temperature of the living areas and the bedrooms monitored at Bridport (left) and Oxley Woods (right) and the external temperature

5.4 *Dynamic thermal modelling and simulation*

The calculated results from the two weather files used for the simulations for the summer period show average external temperatures of 15.2ºC at London Islington TRY and 13.7ºC at St Albans TRY, which is lower than the average external temperature for the monitoring period, with 17.6ºC at London Islington and 15.7ºC at St Albans. Table 9 compares the outdoor weather data from the monitoring and the simulations.

Table 9. Summary of the calculated and the measured outdoor weather data used for analysis.

Outdoor weather	Hours above 25ºC	Hours above 28ºC	Maximum temp. (ºC)	Minimum temp. (ºC)	Average running mean (ºC)	Maximum running mean (ºC)	Minimum running mean (ºC)
London Islington TRY (May-September)	62	4	28.4	2.5	15.6	20.4	8.7
St Albans TRY (May-September)	84	2	28.3	1.0	14.1	18.4	6.7
London Islington TRY (June 29th – July 12th)	0	0	24.2	9.7	17.9	18.9	17.4
St Albans TRY (June 29th – July 12th)	1	0	25.1	6.6	15.7	17.0	14.2
London City Airport for Bridport (monitored)	0	0	23.5	11.0	17.5	19.0	15.4
London Islington TRY (July 20th – July 31st)	9	3	28.4	10.8	16.9	19.1	15.5
St Albans TRY (July 20th – July 31st)	5	0	26.1	9.5	17.0	18.3	14.7

Luton Airport for Oxley Woods (monitored)	25	0	27.5	8.0	16.8	19.0	14.6

The table considered different periods for the weather data files for comparison with the monitoring period at each case study building. The period from May 1st to September 30th was also considered for London Islington and St Albans TRYs for comparison.

Table 10 summarises various simulated indoor temperatures for the case study buildings. The results indicate higher internal temperatures in the bedrooms than the living rooms. Also, higher indoor temperatures are predicted at Oxley Woods than Bridport.

Table 10. Description of the calculated mean, minimum and maximum internal temperatures in the buildings

Case study/ Indoor temp.	Mean indoor temp (ºC)	Min. indoor temp (ºC)	Max. indoor temp. (ºC)	Mean indoor temp.-bedrooms (ºC)	Mean indoor temp-living rooms (ºC)	Max. temp.-hottest living room(ºC)	Min. temp.-hottest living room (ºC)	Mean temp.-hottest living room (ºC)	Max. temp.-hottest bedroom (ºC)	Min. temp.-hottest bedroom (ºC)	Mean temp.-hottest bedroom (ºC)
Bridport -London Islington TRY	20.1	13.0	27.2	22.2	20.7	28.3-FL35SFL	12.9-FL35SFL	19.2-FL35SFL	30.4-FL1FFB	18.7-FL1FFB	21.8-FL1FFB
Bridport - St Albans TRY	19.0	12.8	27.3	21.8	19.7	28.4-FL35SFL	13.3-FL35SFL	17.8-FL35SFL	28.9-FL1FFB	17.7-FL1FFB	21.4-FL1FFB
Oxley Woods-London Islington TRY	21.2	16.9	27.9	21.4	20.8	29.8-A142HAGFL	19.5-A142HAGFL	22.0-A142HAGFL	31.4-A142HASFBB	17.2-A142HASFBB	22.2-A142HASFBB
Oxley Woods-St Albans TRY	20.5	16.3	27.8	20.7	20.1	28.6-A142HAGFL	19.4-A142HAGFL	21.4-A142HAGFL	31.1-A142HASFBB	16.1-A142HASFBB	21.6-A142HASFBB

Fig. 4 shows the predicted internal temperatures across the buildings appear to be within the same range when the external temperature rises above 24ºC, while Bridport is predicted to be much cooler when the external temperature falls below 24ºC. This could be attributed to design related parameters such as higher floor-to-ceiling heights, allowing greater stratification for hot air internally. Additionally, Bridport is clad with bricks. It also has a larger space volume where there is shading from adjacent buildings at the west elevation minimising evening sun entering the building. Comparing the modelling of the whole buildings (Bridport and Oxley Woods), the findings suggest design related parameters especially larger floor areas and higher floor-to-ceiling heights at Bridport contribute to lower internal temperatures predicted in the spaces at Bridport.

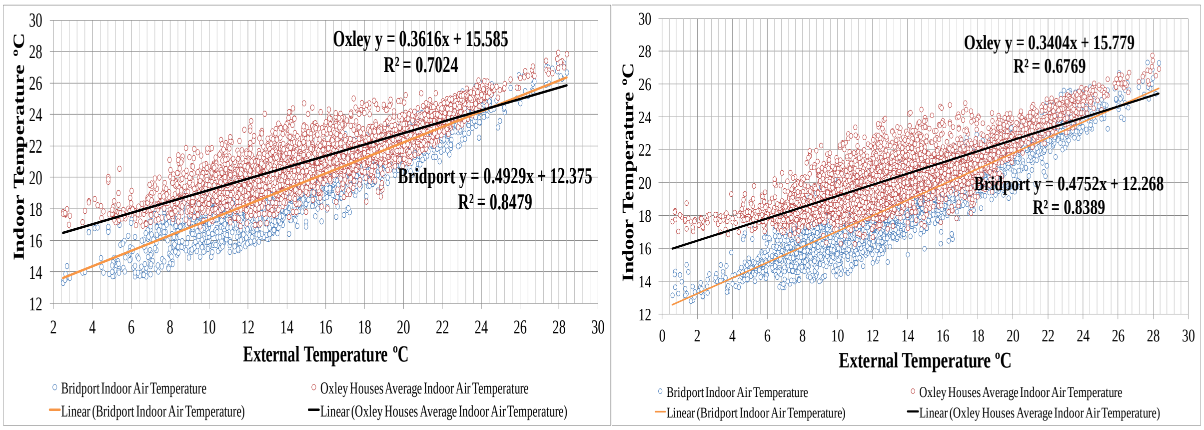

Fig. 4. Relationship between the calculated mean internal temperature of Bridport, Oxley Woods and the external temperature using London Islington TRY (left) and St Albans TRY (right)

6. Overheating analysis

6.1 *The static CIBSE comfort model*

Analysis of the overheating risk from monitoring at Oxley Woods illustrated the high percentage of hours that exceeded 25ºC and 28ºC for all the living areas (Fig. 5), and the percentage of hours above 24ºC and 26ºC for all the bedrooms (Fig. 6). Indoor conditions exceeded 25ºC for more than 10% of the time in all of the living areas (Fig. 5), for over 20% of the time in 50% of the living areas, and for more than 30% of the time in 25% of the living areas. At night-time, 24ºC was exceeded for over 10% of the time in 80% of the bedrooms (Fig. 6). In summary, the indoor temperatures exceeded the thresholds of moderately warm overheating risk.

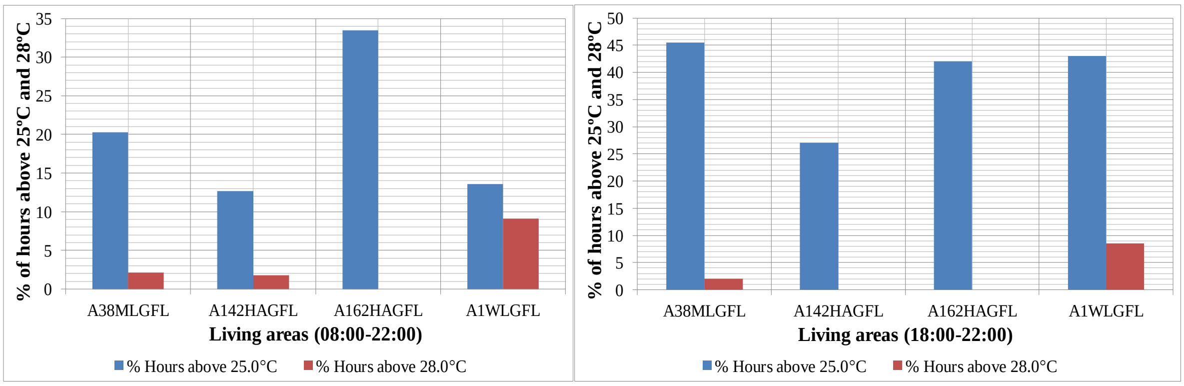

Fig. 5. Monitored temperatures and overheating risk criteria for living areas at Oxley Woods (08:00-22:00, left and 18:00-22:00, right)

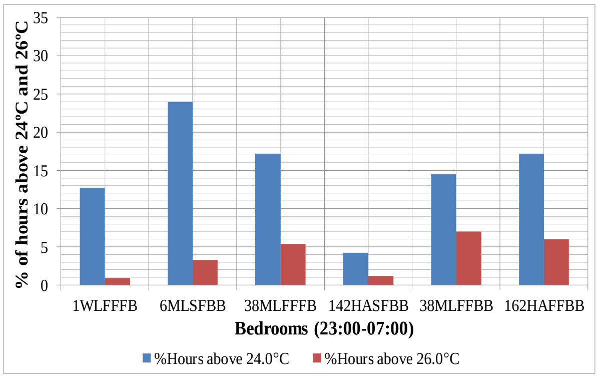

Fig. 6. Monitored temperatures and overheating risk criteria, bedrooms (23:00-07:00) at Oxley Woods

Considering all the eight living rooms monitored from 08:00-22:00, temperatures exceeded the 5%>25ºC mark of moderately warm overheating in four of the living areas (i.e, 50%). Focusing on the evenings from 18:00-22:00, temperatures were above the 5%>25ºC indicator in 70% of the living areas. Looking at the 1%>28ºC threshold of extremely hot summertime, temperatures were above the mark most of the time in three (i.e., 43%) of the houses (Fig. 5). At night-time, 23:00-07:00, temperatures recorded were above the 5%>24ºC mark in 56% of all the eight bedrooms monitored at the buildings and exceeded the 1%>26ºC indicator in 67% of the bedrooms (Fig. 6).

The results at Oxley Woods show temperature rose above the 5%>25ºC marker in 20% of the living areas and above the 1%>28ºC marker in 3.3% from 18:00-22:00. At Bridport, however, the temperature did not exceed the 5%>25ºC marker and the 1%>28ºC indicator in any of the living areas as the weather conditions during the time of the survey were wet and mild.

The results of the simulations enable a better comparison between the two case study buildings (Figures 7-8). Combining the two buildings, the analysis shows that 57% of the living areas exceed the 5%>25ºC indicator and 14% the 10%>25ºC indicator considering London Islington TRY. For the same weather scenario, 50% of the bedrooms are predicted to exceed the 5%>24ºC marker (this reduces to 13% for the St Albans TRY). Focusing on the period 08:00-22:00, four of the living rooms (that is, 50%) exceeded the 5%>25ºC marker, while over 50% this for the evening period 18:00-22:00 considering the London Islington weather scenario (for St Albans this is reduced to three of the living rooms, i.e., is 38% for the 5%>25ºC from 08:00-22:00 and 50% for the 5%/25ºC from 18:00-22:00). Likewise, 33% and 22% of the households exceeded the 1%>28ºC indicator for most of the time when considering London Islington and St Albans respectively.

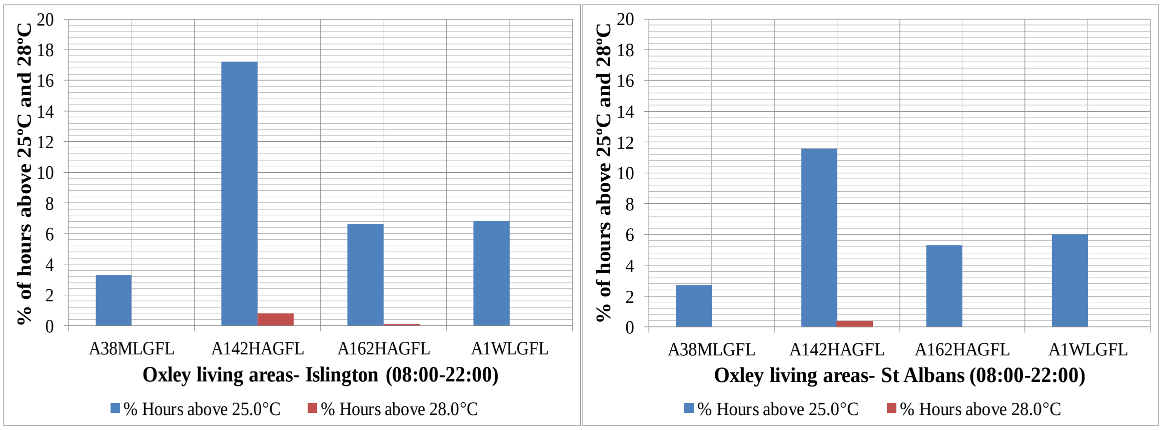

Fig. 7. Predicted temperatures and overheating risk model, living areas at Oxley Woods (08:00-22:00)

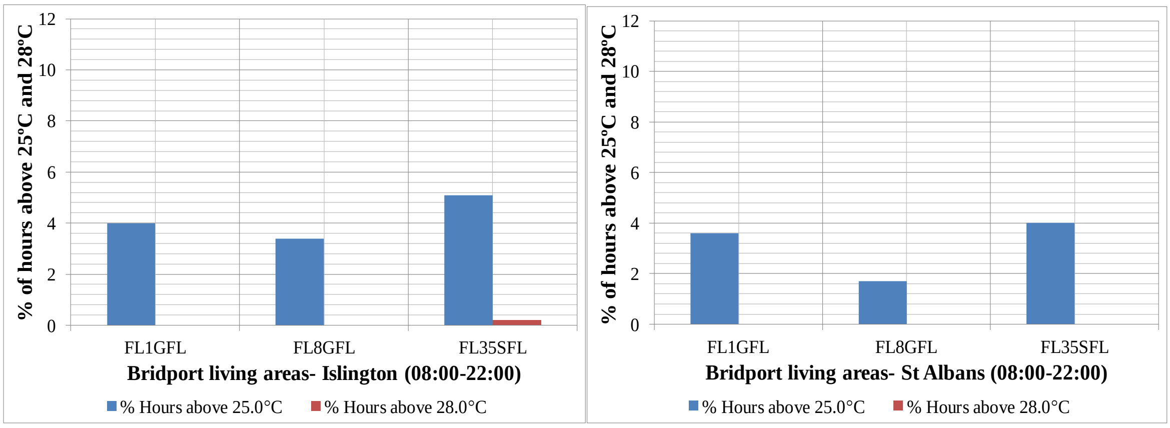

Fig. 8. Predicted temperatures and overheating risk model, living areas at Bridport (08:00-22:00)

The predicted overheating risk from 23:00-07:00 shows that 50% of the eight bedrooms evaluated exceeded the 5%>24ºC marker for London Islington and 13% for St Albans (Fig. 9). Interestingly, the modelling predictions did not exceed the 1%>26ºC indicator in any of the bedrooms.

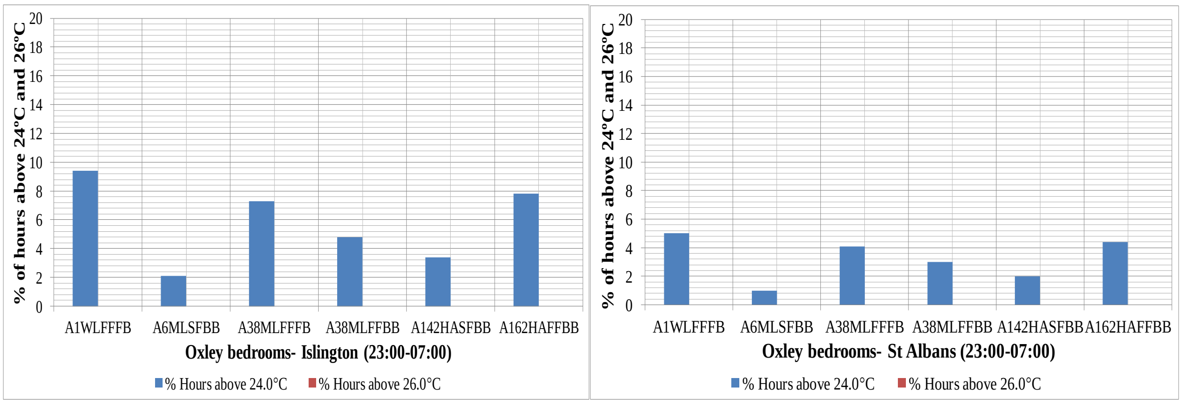

Fig. 9. Predicted temperatures and overheating risk model, bedrooms at Oxley Woods (23:00-07:00)

Comparing the results from the monitoring and the simulations show the spaces at Oxley Woods are warmer than Bridport.

Differentiating between the two buildings shows that indoor temperatures exceeded the 5%>25ºC indicator for 2% of the time at Bridport and 5% at Oxley Woods from 08:00-22:00 considering the London Islington weather scenario (for St Albans it was for 4% at Oxley Woods, while it did not exceed the 5%>25ºC threshold for more than 1% at Bridport). The overheating risk analysis at night-time shows temperatures did not exceed the 1%>26ºC marker at any of the case study buildings while 67% of the bedrooms exceeded the indicator during the monitoring.

The weather data used for the simulations had lower external temperatures than the actual temperatures during the monitoring period. The overall results for simulations (Figures 7-10) using the static comfort model show lower temperatures are predicted in the living areas and the bedrooms at Oxley Woods than the actual temperatures observed during the monitoring while the reverse cases occur within the spaces at Bridport for the simulations. The overall results further suggest extreme summertime temperatures in the spaces than expected.

6.2 The dynamic adaptive comfort model

Overheating was also examined using the adaptive comfort model, Cat. II 'normal level of expectation level'. Comparing the monitored hourly temperatures with the running mean of the daily mean outdoor temperature (T_{rm}) demonstrated a drift towards much warmer internal temperatures as T_{rm} increased (Figures 10-11). The variations in indoor temperatures for a certain T_{rm} value differ from one household to another. Some of the spaces monitored (A1WLFFFB, A6MLSFBB, A38MLFFFB, A142HASFBB, A1WLGFL, A38MLFFBB, A162HAFFBB) were above the Cat. III 'acceptable, moderate level of expectation' (T_{rm}>18ºC) mark which indicate extreme cases of high temperatures above the recommended Cat. II mark (Fig. 10). Other spaces monitored (A38MLGFL, A142HAGFL, A162HAGFL) in the houses at Oxley Woods were observed to be cooler with minimum difference in the everyday temperatures. Some houses were observed to be regularly lower than the Cat. II indicator, in mild weather (Fig. 10b). At Bridport, the adaptive comfort model showed that some of the monitored spaces (such as FL35SFL, FL1GFL) were within the Cat. II indicator (Fig. 11).

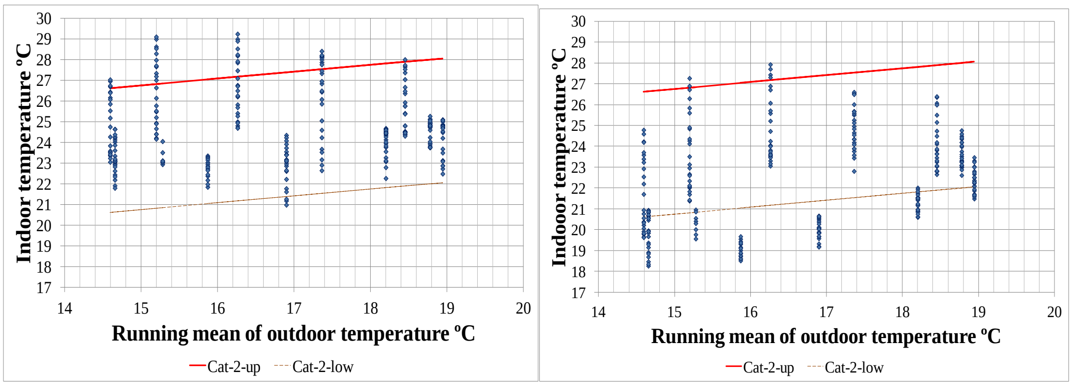

Fig. 10. Temperatures recorded in A6MLSFBB (left) suggesting warm discomfort and in A142HAGFL (right) suggesting cold discomfort, compared to the BSEN15251 thresholds

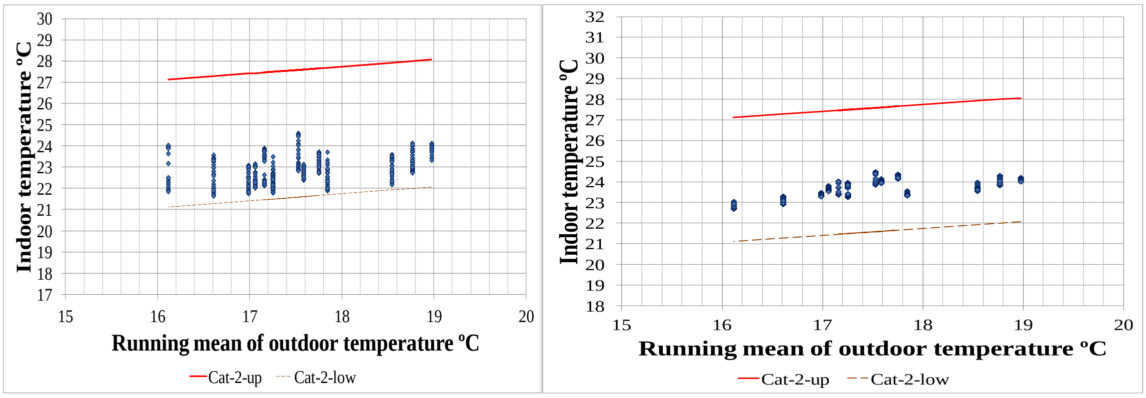

Fig. 11. Temperatures recorded in FL1GFL (left) and FL35SFL (right) suggesting no discomfort, compared to the BSEN15251 thresholds

Taking into consideration the Cat. II threshold ‘normal level of expectation’ for the period 08:00-22:00 for the living areas and 23:00-07:00 for the bedrooms, there was one living area and six bedrooms (42%) that exceeded 5% of hours above the Cat. II upper threshold. Also, six of the living rooms (35%) and four of the bedrooms (24%) exceeded 5% of hours below the Cat. II lower marker (Fig. 12). Combining all the spaces monitored at both developments, the results indicate 47% exceeded 5% of hours above the Cat. II upper indicator and 67% exceeded 5% of hours below the Cat. II lower threshold. The analysis suggests that there is significant overheating potential in the houses, along with cold discomfort when temperature drops.

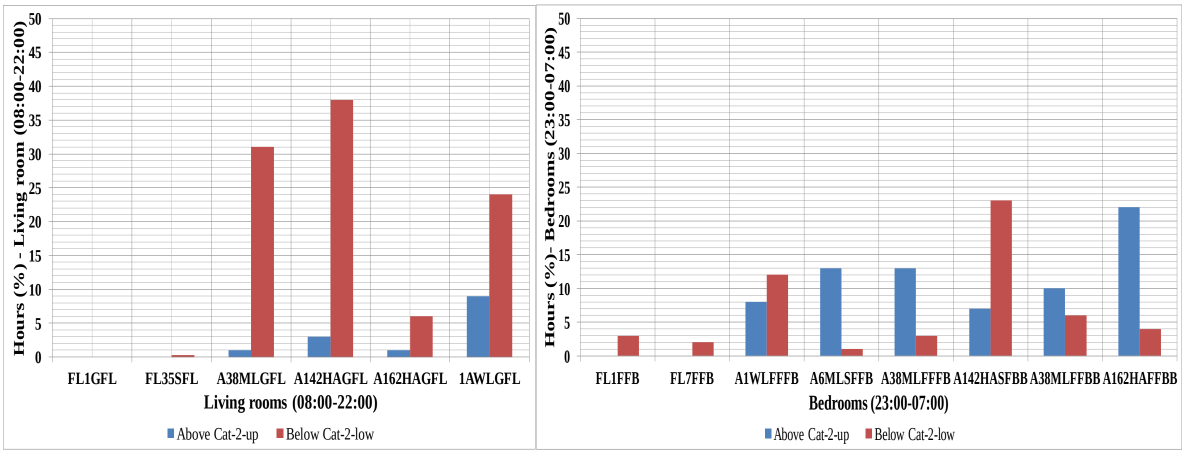

Fig. 12. Percentage of hours of the living room and the bedrooms temperatures in BSEN15251 Cat. II thermal comfort category

Further analysis of the overheating risk for the simulations shows that temperatures in some of the spaces simulated (A1WLFFFB, A6MLSFBB, A38MLFFFB, A142HASFBB, A38MLSFBB, A162HAFFBB) at Oxley Woods are above the Category III upper indicator for both weather scenarios. The findings also show an excessive occurence of high temperatures above the approved Category II upper indicator. At Oxley Woods, the spaces on the ground floor (living areas) are predicted to be cooler than the spaces on the upper floor as expected. The predicted temperature in some of the spaces (FL1FFB, FL35SFL) at Bridport exceeded the Category II upper marker contrary to the results obtained from the environmental monitoring. Also, predicted temperature in some of the spaces (such as FL7FFFB) exceeded the CategoryII upper and lower markers for most of the time.

Analysis of the simulation results from both developments suggest that none of the living areas and 13% of the bedrooms exceeded 5% of hours above the Category II upper marker, while they exceeded 5% of hours below the Category II lower maker in all spaces, highlighting that cold discomfort becomes prominent. At Bridport, temperature in 7% of the spaces exceeded 5% of hours above the Category II upper marker and 5% of hours below the Category II indicator, with the internal spaces being cooler than the results from the monitoring, where temperatures exceeded 5% of hours above the Category II upper marker in 47% and 67% of the spaces at Bridport and Oxley Woods respectively.

In order to classify and compare the internal temperatures in all the spaces monitored against the BSEN15251 thermal comfort standard, the bar charts (Figures 13-14) indicating percentage of hours that fall between the different categories were developed. Figure 13 shows the percentage of hours above the Cat. II upper and below the Cat. II lower boundaries for all the spaces monitored at Oxley Woods. Considering 5% of hours above the Cat. II upper threshold, the analysis suggests over 70% of all the spaces indicate warm discomfort (Fig. 13) while none of the spaces monitored at Bridport do. Some of the spaces monitored at Bridport and Oxley Woods suggest cold discomfort (that is, 5% of hours below the Cat. II lower marker) in the summer due to low temperatures observed in the spaces monitored at night-time when the external temperatures dropped. The results suggest cold discomfort above 5% in all the flat monitored at Bridport and the houses monitored at Oxley Woods (Fig. 14).

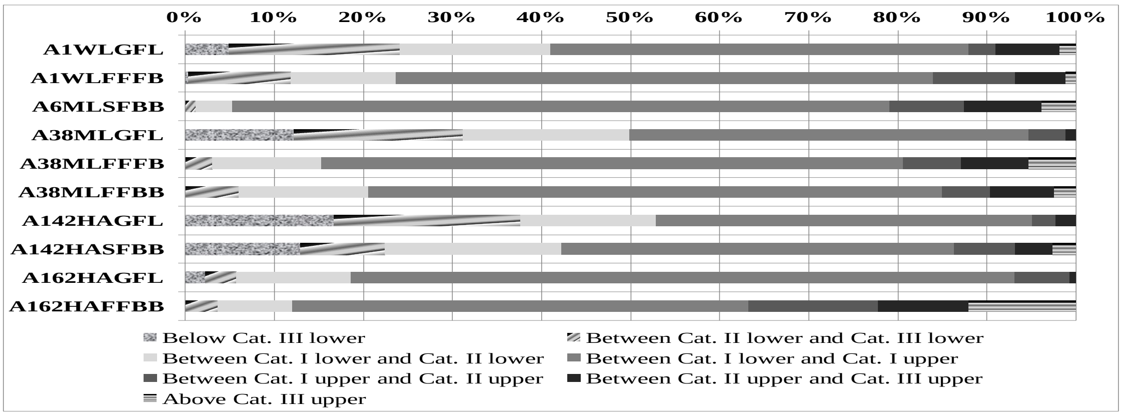

Fig. 13. Percentage of hours of temperatures recorded within the internal spaces monitored at Oxley Woods that fall between different BSEN15251 thermal comfort thresholds

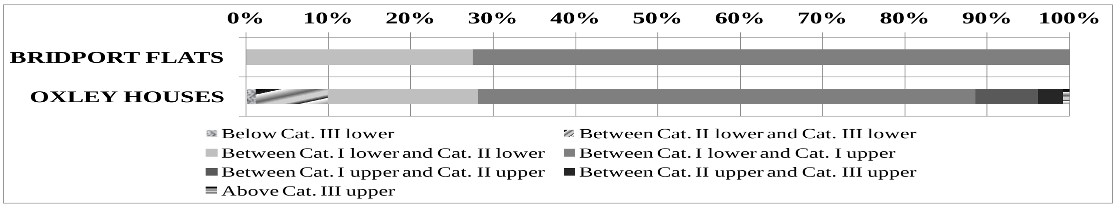

Fig. 14. Percentage of hours of temperatures recorded in the flats/houses monitored at Bridport and Oxley Woods that fall between different BSEN15251 thermal comfort thresholds

Focusing on the analysis from the simulations and the percentage of hours of the predicted temperatures that fall between the different BSEN15251 thermal comfort categories shows none of the living areas and 17% of the bedrooms at Oxley Woods exceeded 5% of hours above the Category II upper marker indicating warm discomfort when considering the London Islington and St Albans weather scenarios (Figures 15-16). At Bridport, none of the living areas and bedroms suggests warm discomfort. On the contrary, the percentage of hours exceeded 5% below the Category II lower marker for the period considered at Bridport. Analysis of the houses at Oxley Woods shows A142HA (west facing house with most of the indoor spaces facing southeast) is predicted as the warmest house. The finding also suggests cold discomfort above 5% of hours in all the case study buildings.

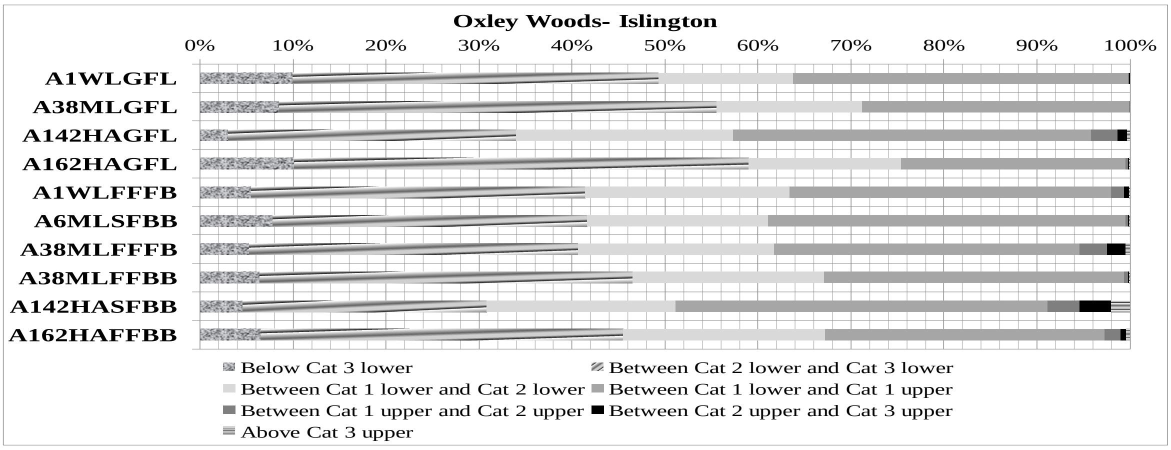

Fig. 15. Percentage of hours of temperatures predicted within the spaces at Oxley Woods that fall between different BSEN15251 thermal comfort thresholds for the Islington TRY.

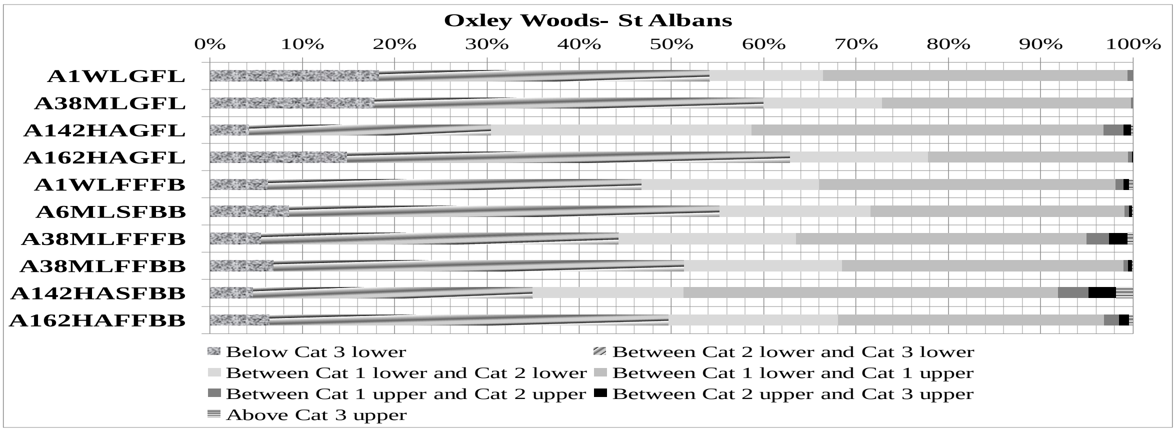

Fig. 16. Percentage of hours of temperatures predicted within the spaces at Oxley Woods that fall between different BSEN15251 thermal comfort thresholds for the St Albans TRY.

7.0 Comparison with previous studies on overheating in dwellings

Table 11 summarises the internal temperatures in all the spaces monitored at Bridport and Oxley Woods. The analysis shows the maximum temperature recorded at Bridport is lower than at Oxley Woods. The mean temperatures recorded in Oxley Woods are slightly higher than at Bridport, with more frequent occurence of high temperatures at Oxley Woods. The simulation results confirm higher temperatures predicted at Oxley Woods, with the spaces being much warmer than those at Bridport.

Table 11. Comparison between the monitored and the calculated internal temperatures at the case study buildings in the summer periods

Year	**Monitored (Summer 2012)**					**London Islington TRY- 2000s**					**St Albans TRY- 2000s**				
Name of space- Living areas	**Max. temp °C**	**Min. Temp °C**	**Mean temp °C**	**CIBSE: Total hours above 28°C**	**Hours above BSEN15251 Cat II upper**	**Max. temp °C**	**Min. Temp °C**	**Mean temp °C**	**CIBSE: Hours above 28°C**	**Hours above BSEN15251 Cat II upper**	**Max. temp °C**	**Min. Temp °C**	**Mean temp °C**	**CIBSE: Hours above 28°C**	**Hours above BSEN15251 Cat II upper**
A1WLGFL-OW	30.0	19.8	23.5	15	15	27.1	14.9	20.5	0	4	25.7	15.0	19.7	0	0
A38MLGFL-OW	28.1	18.2	22.6	4	3	27.3	15.0	20.2	0	0	25.9	15.1	19.4	0	0
A142HAGFL-OW	28.0	18.3	22.4	3	6	29.8	19.5	22.0	28	48	28.6	19.4	21.4	8	34
A162HAGFL-OW	27.3	18.6	23.7	0	2	28.2	15.1	20.6	1	2	27.0	15.4	19.8	0	1
FL1GFL-BD	24.6	21.7	22.9	0	0	26.8	14.8	18.6	0	0	26.7	15.3	20.6	0	0
FL35SFL-BD	25.0	22.7	23.7	0	0	28.3	12.9	19.2	5	6	28.4	13.3	17.8	2	8
Name of space- Bedrooms	**Max. temp °C**	**Min. Temp °C**	**Mean temp °C**	**CIBSE: Total hours above 26°C**	**Hours above BSEN15251 Cat II upper**	**Max. temp °C**	**Min. Temp °C**	**Mean temp °C**	**CIBSE: Hours above 26°C**	**Hours above BSEN15251 Cat II upper**	**Max. temp °C**	**Min. Temp °C**	**Mean temp °C**	**CIBSE: Hours above 26°C**	**Hours above BSEN15251 Cat II upper**
A1WLFFFB-OW	28.7	19.4	23.9	14	18	29.8	16.0	21.5	0	18	29.6	15.0	20.8	0	36
A6MLSFBB-OW	29.2	21.0	24.7	18	33	28.7	16.7	20.8	0	6	28.4	15.6	20.1	0	12
A38MLFFFB-OW	29.5	20.0	24.5	25	34	30.6	16.3	21.8	0	93	30.4	15.2	21.1	0	91
A38MLFFBB-OW	29.1	20.8	24.3	18	16	28.6	16.1	20.9	0	6	28.5	15.0	20.2	0	13
A142HASFBB-OW	29.8	18.0	23.2	16	18	31.4	17.2	22.2	0	197	31.1	16.1	21.6	0	173
A162HAFFBB-OW	30.5	20.8	25.7	40	37	29.6	16.3	21.4	0	37	29.3	15.1	20.8	0	53
FL1FFB-BD	24.7	21.3	22.8	0	0	30.4	18.7	21.8	0	38	28.9	17.7	21.4	0	48
FL7FFFB-BD	23.8	21.2	22.3	0	0	27.5	20.1	21.6	0	0	27.3	19.4	21.3	0	3
Case study building	**Monitored (Summer 2012)**					**London Islington TRY- 2000s**					**St Albans TRY- 2000s**				
Bridport	24.2	21.7	22.6	0	0	27.3	13.3	20.1	0	0	27.3	12.8	19.0	0	1
Oxley Woods	28.5	19.5	23.9	3	10	27.9	16.9	21.2	0	3	27.8	16.3	20.5	0	9

The CIBSE total hours above 28ºC considered for the case study buildings *Threshold values for the hours of monitored temperatures in the spaces at Bridport and Oxley Woods: 1% of 316 hours (FL1GFL, FL35SFL, FL1FFB, FL7FFFB)- about 3.25 hours, 1% of 263 hours (A38MLGFL, A142HAGFL, A162HAGFL, A1WLFFFB, A6MLSFBB, A38MLFFFB, A142HASFBB)- about 2.75 hours and 1% of 166 hours (A1WLGFL, A38MLFFBB, A162HAFFBB) - about 1.75 hours.

It is interesting, however, to compare the findings from this study, which is the first one focusing on prefabricated timber houses, with previous studies that have investigated summertime temperatures and occupants' comfort in the UK [8-9,11-13,23]. Table 12 shows that the external conditions for the monitoring periods were comparable in the various studies. Nevertheless, higher mean internal temperatures were observed within the spaces monitored in the current study. However, there is consistently frequent occurrence of overheating when compared to previous studies, particularly increased for the adaptive thermal comfort model (BSEN15251). The results highlight that under similar weather condition, extreme summertime overheating is likely to be more frequent in timber houses than those built with conventional materials.

Table 12. Comparison between findings from this study and previous studies for the summer periods

Findings	**This Study**		**Lomas & Kane (2012, 2013)**	**Beizaee et al (2013)**	**Firth & Wright (2008)**
	Bridport	*Oxley Woods*			
Mean internal temperature- living areas	22°C	23.7°C	22.2°C	21.8°C	21.4°C
Mean internal temperature- bedrooms	21.8°C	23.1°C	22.4 °C	21.6°C	21.5°C
Mean seasonal external temperature	16.7°C	16.8°C	16.4°C	15.3°C	15.5°C
Overheating Analysis	**This Study**		**Lomas & Kane (2012, 2013)**	**Beizaee et al (2013)**	**Wright & Firth (2008)**
1%>28°C from 08.00-22.00 (living areas)	43%		27%	4%	-
5%>25°C from 08.00-22.00- (living areas)	50%		58%	27%	-
5%>25°C from 18.00-22.00- (living areas)	70%		63%	-	-
Above 5% of the Cat. II upper indicator (living areas)	17%		0.5%	-	-
Above 5% of the Cat. II upper indicator (bedrooms)	42%		2%	-	-

Focusing on the different thermal properties of the building components, which could influence how the envelopes perform in different seasons especially in terms of overheating risk, highlights the low heat capacity and thermal mass of prefabricated timber materials (CLT and SIPs) when compared to traditional materials such as bricks (1360kJm^3/K), earth wall (1800kJm^3/K), rammed earth (1673kJm^3/K) [37], limiting the ability of timber materials to regulate temperature swings at different seasons.

Table 13: Comparison of various thermal properties of the buildings' components

Case study	Components	Estimated values			
		U-value (W/m^2-K)	Thermal mass (Wh/m^{2o}C)	Amount of heat store/cm^3 (kWh)	Volumetric heat capacity Cp (Thermal mass- (kJm^3/K)*
Bridport	External wall	0.14	13.0	8-15	600
	Floor	0.16	15.0		
	Roof	0.12	10.0		
Oxley Woods	External wall	0.12	11.0	8-10	550
	Floor	0.10	10.0		
	Roof	0.17	9.0		
*Typical concrete buildings	External wall (150mm)	0.26	45	80	2060
	Floor (100mm)	0.22	56		
	Roof (50mm)	0.18	28		

*Data extracted from the simulation and the information presented in [37]

8. Conclusions

This paper focused on summertime overheating and occupants' comfort in two prefabricated timber houses, Bridport and Oxley Woods, in the southeast of England. The methodology involved post-occupancy evaluation (POE) surveys, thermal comfort surveys supplemented by environmental monitoring and dynamic thermal simulations.

Overall, the POE revealed high satisfaction rates during the summer despite the fact that 81% of the occupants feel warm. The comfort surveys reported similar results for Bridport with 75% of the occupants feeling warm, but this was significantly lower for Oxley Woods with 38%, although internal temperatures were higher at Oxley Woods during the monitoring period. Similarly, 30% of the respondents at Oxley Woods and 50% at Bridport preferred to be cooler. This suggests a higher adaptation potential for the residents of Oxley Woods, confirmed by the higher neutral and lower preferred temperature. This could be due to the fact that the residents in Oxley Woods interacted more with controls during the summer-period, particularly for ventilation operating windows, doors and fans, as well as blinds for shading.

Other design related parameters found to influence comfort include orientation and floor level with southern orientation and upper floors experiencing warmer conditions. Floor-to-ceiling height appears to influence the occurrence of high internal temperatures contributing to summer overheating.

Regarding indoor temperatures, although mean values were within the comfort range for both monitoring and modelling in both case studies, overheating analysis showed a very different picture. Considering the CIBSE comfort model, extreme summertime overheating occurs in 67% of the spaces during the monitoring periods, while for the simulations overheating occurs in just 22% of the spaces. These differences may be attributed to the fact that the monitoring conditions were warmer than the weather files used for the simulations.

With the adaptive thermal comfort model (BSEN15251) overheating appears to be more frequent at Oxley Wood than Bridport. More specifically, 25% of the living areas and 100% of the bedrooms monitored at Oxley Woods exceeded 5% of the hours above the Cat. II upper marker, while none of the spaces at Bridport were above the marker. For the simulations, none of the living areas and 17% of the bedrooms at Oxley Woods exceeded 5% of hours above the Cat. II upper indicator showing warm discomfort. At Bridport, none of spaces experience warm discomfort. Both the monitoring and modelling also highlights that cold discomfort could become an issue., exceeding 5% of the time below Cat II lower marker in all spaces.

Categorising and comparing the percentage of hours that fall between the different thermal comfort categories, it is apparent that over 70% of all the spaces monitored at Oxley Woods exceeded 5% of the hours above the Cat. II upper threshold indicating warm discomfort, while none of the spaces monitored at Bridport suggest warm discomfort. However, for the simulations, only 10% of all the spaces at Oxley Woods exceeded 5% of the hours above the Cat. II marker and none of the spaces at Bridport. These, although in line with the outcomes of the monitoring surveys,that indicate Bridport is cooler than Oxley Woods, greatly underestimate the occurrence of overheating, highlighting the limitations of modelling.

Regarding the two comfort models considered for evaluating the risk of overheating, it is apparent the CIBSE comfort model is more sensitive predicting extreme occurrence of overheating, with the adaptive BSEN15251 model showing only moderate overheating. This would be closer to the thermal comfort evaluations.

Comparing the findings obtained from this study with those from previous studies [8-9,11-13,23] as summarised in table 12, the results revealed that summertime overheating risks were more frequent in buildings built with lightweight materials such as prefabricated timber than the buildings investigated in the previous studies, which were mostly built with heavyweight materials. Despite the green credential of timber for construction over other building materials such as bricks, the lack of thermal mass in timber developments suggests that overheating risk is much higher which can lead to discomfort, even in mild summer weather conditions as occurring in the UK. It is thus essential to provide special attention to the design of timber houses with appropriate strategies for internal heat to be dissipated effectively. Additionally, provision of controls carefully incorporated in the design of buildings can increase occupants' adaptive capacity reducing feelings of warm discomfort, essential in buildings where increased internal temperatures can be expected.

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Appendix 1

This appendix presents structure of the post-occupancy questionnaire discussed in the paper. The results of the data gathered from the surveys were presented in Section 5.1.

Kent School of Architecture | Centre for Architecture & Sustainable Environment (CASE)

UNIVERSITY OF KENT, CANTERBURY
POST-OCCUPANCY QUESTIONNAIRE FOR EVALUATION OF INDOOR ENVIRONMENT OF LOW-CARBON PREFABRICATED TIMBER HOUSING

This survey is part of a study to evaluate the thermal conditions of low-carbon prefabricated timber housing developments in the UK. We appreciate your feedback in this evaluation.

A. General Information

Building name: ....

Date: .... Time: .... Floor/Flat number: …………………………………........

1. Age (i) Under 18 (please state..........) ☐ (ii) 18-30 ☐ (iii) 30-45 ☐ (iv) 46-55 ☐
(v) 56 and above ☐

2. Sex (i) Male ☐ (ii) Female ☐

3. Employment status. (i) Retired ☐ (ii) Full-time ☐ (iii) Part-time ☐
(iv) Currently not in employment ☐

3b. Please state type of occupancy. (i) Rented ☐ (ii) Owned ☐

4. How long have you lived in the building? Years............................... Months.................................

5. On the average, how many hours per day do you spend in the building? ....

6. How many people live in your flat? (i) 1-2 ☐ (ii) 3-4 ☐ (iii) 4 and above ☐

7. What are the factors that influence your decision to live in the building? Please tick as many that apply
(i) Cost ☐ (ii) Building type ☐ (iii) Materials ☐ (iv) Location ☐
(v) Others (please state).......................

B. Thermal Comfort

8a. How would you describe the thermal conditions in your flat in **summer** season?

Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

8b. How would you describe the thermal conditions in your flat in **winter** season?

Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

9a. How do you rate the overall thermal comfort of your flat in **summer** season based on the following scale? (Please tick one)

Very Comfortable ☐☐☐☐☐☐☐ Very uncomfortable

9b. How do you rate the overall thermal comfort of your flat in **winter** season based on the following scale? (Please tick one)

Very Comfortable ☐☐☐☐☐☐☐ Very uncomfortable

C. Satisfaction

10a. How do you rate the overall thermal environment of your flat in **summer** season based on the following scale?

Very satisfied ☐☐☐☐☐☐☐ Very dissatisfied

10b. How do you rate the overall thermal environment of your flat in **winter** season based on the following scale?

Very satisfied ☐☐☐☐☐☐☐ Very dissatisfied

D. Control

11. Please tick any item listed below you use to improve thermal environment of your indoor spaces?

Door open	Window open	Blind/curtain open	Light on	Central heating on	Fan on	Portable heater on	Others (specify)

12. Do you use any of the items listed in question 11 to improve thermal conditions of your flat often?
(i) Yes ☐ (ii) No ☐

13. Do you use any shading device to reduce sunlight into your flat? (i) Yes ☐ (ii) No ☐

14. How much control do you feel you have over the thermal environment of your indoor space?
High Control ☐☐☐☐☐☐☐ No control

15. How satisfied are you with this level of control?
Very satisfied ☐☐☐☐☐☐☐ Very dissatisfied

16. In general, how often do you use any of the controls provided in the building to adjust the thermal environment at your indoor space?
Regularly ☐☐☐☐☐☐☐ Never

17. How does your thermal comfort in your indoor space enhance or interfere with your ability to carry out activities?
Enhances ☐☐☐☐☐☐☐ Interferes

E. Others

18a. Please state the space you spent most of your time within your flat. (i) Lounge ☐ (ii) bedroom ☐

(iii) Dining/Kitchen ☐ (iv) Others (please specify)…………………………

18b. Is there any space in your apartment you consider to be much warmer than the other spaces? ....

19. How would you describe your experience as an occupant of the building you are living at this moment?
Pleasant ☐☐☐☐☐☐☐ Unpleasant

20. Is there any aspect of the indoor environment of the modern house you would like to comment on?..
....
....

Appendix 2

This appendix presents structure of the comfort survey questionnaire discussed in the paper. The results of the data gathered from the survey were presented in Section 5.3.

Kent School of Architecture | Centre for Architecture & Sustainable Environment (CASE)

UNIVERSITY OF KENT, CANTERBURY

COMFORT SURVEY QUESTIONNAIRE FOR EVALUATION OF LOW-CARBON PREFABRICATED TIMBER HOUSING

This survey is part of a study to evaluate the thermal conditions of low-carbon prefabricated timber housing developments in the UK. Please tick or select as appropriate. We appreciate your feedback in this evaluation. Thank you for your participation

A. General Information

Date: .... Building name: ....

1. Age (please tick) (i) Under 18 (please state........) ☐ (ii) 18-30 ☐ (iii) 30-45 ☐

(iv) 46-55 ☐ (v) 56 and above ☐

2. Sex (please tick) (i) Male ☐ (ii) Female ☐

3. Location of apartment in the building (floor/ flat number/ orientation): ....

Time: Morning……………………………. Afternoon…………………………..

Evening…………………………………

4. **Feeling-** At present I feel

Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

5. **Preference-** I would prefer to be

Much cooler	Cooler	No change	Warmer	Much warmer

6. Is the thermal environment within your flat at this moment acceptable to you? (i) Yes ☐ (ii) No ☐

7. Have you used any of the options below in the last half hour?

Door open	Window open	Blind/curtain open	Light on	Central heating on	Fan on	Portable heater on	Others (specify)

8. Which items of clothing below are you currently wearing?

Short sleeve shirt/blouse	Long sleeve shirt/blouse	Trousers/ Long skirt	Shorts/ Short skirt	Dress	Pullover	Jacket	Long socks
Short socks	Tights	Tie	Slippers	Sandals	Shoes	Boots	Others (specify)

9. At this moment are you wearing more clothing than you prefer? (i) Yes ☐ (ii) No ☐

10. What has been your activity in the last 15 minutes?

Sitting (passive work)	Sitting (active work)	Standing relaxed	Standing working	Walking indoors	Walking outdoors	Others (specify)

11. Have you consumed any of the following items within the last 10mins? (i) Hot drink ☐ (ii) Cold drink ☐

B. Response on Thermal Comfort Parameters

12. I would like higher air movement into my present space. (i) Yes ☐ (ii) No ☐

13. Have you experienced any overheating in your flat today? (i) Yes ☐ (ii) No ☐

14. Do you like to add anything? ....