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Occupants' adaptation and design parameters influencing behavioural actions of occupants in naturally ventilated sustainable timber buildings

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Abstract

Existing studies have examined occupants' adaptation and various parameters affecting thermal comfort of occupants in different buildings. However, there are limited studies that have examined occupants' adaptation and design parameters in naturally ventilated sustainable buildings, especially structural timber buildings. As a result, this study considers a comparative analysis of occupants' adaptation and examines various design parameters influencing behavioural actions of occupants in naturally ventilated structural timber buildings. The study evaluates indoor spaces of two dwelling units in each of the two sustainable timber case study buildings located in Western Europe. The research employed analysis of architectural design of the buildings, on-site measurements, and a thermal comfort survey. The parameters measured during the on-site survey include temperature and relative humidity at one hour intervals for twelve days during the summer period. The findings were compared with design parameters such as natural ventilation, size of opening, floor-to-ceiling height, and floor area of the spaces. The results showed more than 85% of the occupants in dwelling units with smaller floor area tend to adapt better to the thermal environment than those living in dwelling units with bigger floor area. It appears that at least 75% of the occupants in spaces with natural cross-ventilation tend to be more thermally satisfied than occupants in spaces with single-sided ventilation. The findings also revealed the risk of summertime overheating tends to be significantly reduced ($p<0.05$) when spaces have natural cross-ventilation, higher floor-to-ceiling height, and a larger floor area. Finally, the results showed the adaptation of occupants in naturally ventilated buildings and the ability to use control to adjust the thermal environment and reduce the overall annual energy consumption in sustainable buildings. Keywords: architectural design, comparative study, occupants' adaptation, design parameters, behavioural actions, naturally ventilated sustainable timber buildings

1. Introduction

This paper examines occupants' adaptation and different design parameters influencing behavioural actions of occupants in naturally ventilated structural timber buildings. Existing studies have addressed the issue of occupants' comfort [Peeters et al., 2009; Frontczak et al 2012; Adekunle and Nikolopoulou, 2014, 2016a] and adaptation [Nicol and Humphreys, 2002] in various buildings. Adaptation of occupants is a crucial issue that needs to be evaluated in order to understand thermal comfort of occupants in buildings [Adekunle, 2014]. A recent study highlighted that energy-efficient and sustainable buildings must be designed and built to reduce carbon emissions. Buildings must also be constructed to provide the expected level of comfort for occupants in different spaces [Adekunle and Nikolopoulou, 2016b]. Past studies highlighted that people in developed countries spend approximately 90% of their time indoors [Leech et al., 1997; Klepeis et al., 2001; Adekunle, 2014]. As a result, existing, refurbished, and newly constructed buildings must be able to provide the needed level of comfort, and support the well-being of occupants in order to perform various functions within the thermal environment. Previous investigations have considered the effects of environmental conditions such as the quality of air [Wargocki et al., 2002] and summertime temperatures [Adekunle and Nikolopoulou, 2016a] on thermal comfort of occupants in buildings. Other studies have considered parameters that are not generally linked to the thermal environment [Veitch, 2001, Adekunle and

Nikolopoulou, 2016a]. The effects of various factors not connected to overall satisfaction of occupants within the thermal environment have also been evaluated [Frontczak and Wargocki, 2011; Frontczak et al 2012]. Existing research highlighted various parameters need to be evaluated to understand occupants' comfort and adaptation in buildings especially in naturally ventilated buildings, which require additional effort of occupants to adjust the thermal environment. Existing studies stated that thermal satisfaction of occupants can be influenced by environmental factors and building features, such as size, aesthetics and layout of buildings [Frontczak and Wargocki, 2011; Frontczak et al 2012]. Investigations on occupants' satisfaction in non-residential buildings linked to indoor environmental conditions, workspace, and building features have been documented in past studies [Humphreys, 2005; Frontczak et al 2012]. A few studies have focused on these aspects in residential and other sustainable buildings. Past studies reported that occupants are more productive when they are comfortable within the thermal environment; while those that are not productive are not comfortable [Leaman and Bordass, 2001, Adekunle and Nikolopoulou, 2016a]. Occupants' satisfaction in buildings is found to be determined by view, control, more than other parameters such as the indoor environment and level of privacy provided to the respondents [Frontczak et al 2012]. Also, design features such as arrangement of spaces within a floor, room size, furniture, and cleanliness can possibly contribute to occupants' satisfaction in buildings [Frontczak and Wargocki, 2011]. Floor area of indoor spaces and floor-to-ceiling height were mentioned as design features that could possibly contribute to occupants' comfort in buildings [Adekunle and Nikolopoulou, 2016a]. However, only brief discussions were presented in these studies to support the arguments. These further showed the importance of linking design features to occupants' adaptation to understand how these parameters influence thermal comfort of occupants in naturally ventilated buildings. Generally, buildings in Western Europe are expected to have mechanical heating and ventilation systems to enhance occupants' comfort in summer and winter. However, most buildings especially residential buildings are expected to be naturally ventilated in summer to reduce overall amount of carbon emissions generated in domestic buildings per year. These imply most residential buildings in Western Europe, especially in countries like UK, are not expected to use air-conditioners, but can use fans to supplement natural ventilation of spaces in summer [Adekunle and Nikolopoulou, 2016a]. Past studies have highlighted that residential buildings in Western Europe (in particular, UK) are becoming smaller in terms of floor area when compared to residential buildings in other European nations such as the Netherlands, Denmark, and Germany [Adekunle, 2014]. In addition, reduced floor-to-ceiling height and smaller area of openings are also common in sustainable buildings. Arguments are presented that the reduced floor area and floor-to-ceiling height are necessary to cut carbon emissions in residential buildings. However, existing studies explained that these reductions were actually done to increase the quantity of dwelling units provided. A recent study stated that while these reductions could help cut carbon emissions in buildings, occupants are likely to experience discomfort in summer due to high temperatures observed during the period [Adekunle, 2014]. As a result, this study intends to link the data obtained from the on-site measurements with the design features to understand occupants' comfort and adaptation in naturally ventilated buildings. It is also important to understand if these parameters (design features such as floor-to-ceiling height, floor area) could significantly influence adaptation and behavioural actions of occupants in sustainable buildings. The study aims to contribute to on-going discussions and findings on occupants' comfort and adaptation in naturally ventilated sustainable structural timber buildings.

2. Methods

The research considered a comparative analysis of occupants' adaptation and examined various design parameters influencing behavioural actions of occupants in naturally ventilated structural timber buildings. The study evaluated indoor spaces of two dwelling units in each of the two sustainable case study buildings located in Western Europe. The research employed analysis of architectural design of the buildings, on-site measurements of environmental parameters (such as temperature and relative humidity), and a thermal comfort survey. Existing studies [Rijal and Stevenson, 2010; Adekunle, 2014; Adekunle and Nikolopoulou, 2014, 2016a] in the field have explored all or part of the research methods considered in this study for investigations. For instance, some studies considered on-site measurements and thermal comfort surveys of respondents in different sustainable buildings [Rijal and Stevenson, 2010; Frontczak et al, 2012; Adekunle and Nikolopoulou 2014, 2016a]. A few studies focused mainly on environmental monitoring of parameters to

understand occupants' adaptation in buildings [Rijal et al, 2015]. Other studies combined two or more methods [Rijal and Stevenson, 2014; Adekunle and Nikolopoulou, 2014] and sometimes supplemented the methods with dynamic thermal building simulation to understand thermal comfort of occupants in buildings [Peeters et al., 2009; Adekunle and Nikolopoulou 2016a, 2016c]. For this study, it is important to understand the thermal environment, occupants' adaptation and various design parameters (building features) that can influence occupants' comfort in sustainable buildings. As a result, the study explored a combination of various methods to achieve the research goals.

The on-site measurements of two parameters (temperature and relative humidity) were considered to understand internal environmental conditions of the case study buildings. In order to measure the environmental parameters, the sensors shown in figure 1 were positioned at the height of 1.100m considered to be an average height of the head region of a man doing sedentary activities. Table 1 below summarises detailed features of the HOBO and Tinytag sensors used for the on-site measurements. The height (1.100m) was also considered as the mid-region of a man doing non-sedentary activities. The height of 1.100m is one of the three heights (0.600m, 1.100m, and 1.700m) recommended by ASHRAE at which various environmental parameters can be measured when evaluating occupants' comfort within the thermal environment [ASHRAE, 2013]. The parameters were measured for about twelve days each at the case study buildings during the summer period. The measurements were logged every sixty minutes (1 hour) throughout the period of the field investigation. The external weather data comprising of temperature and relative humidity measured at the same intervals (sixty-minute/1 hour) were collected from a meteorological station near each of the case study buildings.

Variables HOBO Specifications Tinytag Specifications Product name HOBO U12 Temp/RH logger Tinytag Ultra 2 (TGU-4500) Temp/RH logger Range of measurement -20º to 70ºC (-4º to 158ºF) -25ºC to 85ºC (-13ºF to 185ºF) Accuracy ±0.35ºC from 0º to 50ºC (±0.63ºF from 32º to 122ºF) ±0.35ºC from 0º to 50ºC (±0.63ºF from 32º to 122ºF) Resolution of reading 0.03ºC at 25ºC (0.05ºF at 77ºF) 0.01ºC at 25ºC (0.03ºF at 77ºF) Drift 0.1ºC per year (0.2ºF per year) 0.1ºC per year (0.2ºF per year) Time of response in airflow of 1m/s 6 minutes, typical to 90% 20 minutes, typical to 90% Time accuracy ±1 minute per month at 25ºC (77ºF) ±1 minute per month at 25ºC (77ºF) Weight 46g (1.6oz) 55g (1.94oz) Dimensions 74x58x22mm (2.9x2.3x0.9inches) 72x60x33mm (2.83x2.36x1.3inches)

Table 1: Features of the HOBO and Tinytag data loggers used for the experiment (Adekunle, 2014)

Figure 1: HOBO and Tinytag sensors used for the on-site measurements

Thermal comfort surveys were also carried out at the case study buildings. The respondents were asked to fill a subjective questionnaire three times per day. The questions asked of the participants focused on thermal sensation, thermal acceptability, and satisfaction. Various questions on adaptive measures such as type of clothing currently worn, type of drinks consumed, level of control, and activities carried out in the last few minutes (15-minute and 30-minute) by the respondents were included in the questionnaire. Some of the crucial findings from the thermal comfort surveys of the buildings have been presented in existing studies [Adekunle and Nikolopoulou, 2014, 2016a]. In this study, the questions asked on thermal sensation, satisfaction, and control will be briefly discussed. The responses were compared with the environmental parameters, however, this paper will focus on responses of occupants in relation to adaptation and behavioural actions to adjust and improve the thermal environment of the case study buildings. The architectural drawings of the buildings were reviewed. Crucial building features such as floor area (size), floor-to-ceiling height, area of openings were highlighted as indicated in existing research [Frontczak et al, 2012]. The data from environmental monitoring of the spaces and thermal comfort surveys were linked with design parameters such as use of natural ventilation, size of opening, floor-to-ceiling height, and floor area of the spaces to find relationship between the variables. Appropriate statistical packages (Excel and SPSS) were employed for data analysis as highlighted in existing studies [Adekunle and Nikolopoulou, 2014, 2016a]. The statistical packages were also used to draw charts and find relationship between the parameters that will be presented and discussed in the latter part of the paper.

3. Description of the case study buildings

The study considered two case study buildings for the survey. One of the case study buildings is located in the Borough of Hackney, London. The second case study building is located in the county of Buckinghamshire in the southeast of England, UK (Figure 2). The two case study buildings are built with sustainable materials (i.e, structural timber panels) and completed in the 2000s. The case study buildings are housing developments for different size of households and income levels (low-income and middle-income earners). The case study buildings have been recognized by different reputable organizations as green buildings with low carbon footprints. Table 2 below summarises various features of the case study buildings.

Location of the case study building

Total number of floors

Year built

U-values of the building components (W/m2K)

Total number of dwelling units

Average floor-toceiling height

Walls Roof Windows

London, UK 8 2011 0.140 0.120 1.370 42 2.625m Buckinghamshire, UK 2 2005 0.120 0.170 1.700 145 2.365m

Table 2: Various features of the case study buildings

Figure 2: Floor plan (right) and cross-sectional view (left) of the case study building at Buckinghamshire, UK (RSHP Architects, London)

Two spaces in each of the case study building were selected for this study. The spaces were selected as representative spaces based on availability, approval of the residents to access and install the sensors in the spaces, and orientation of the spaces to understand occupants' adaptation and the effects of the building features. In each of the buildings, the spaces selected include a living area and bedroom. At both buildings, the living areas are located on the ground floors, while the bedrooms are on the upper floors. The window to wall ratios at the case study buildings in London and Buckinghamshire are 35% and 50% respectively. The features of each space including the floor area, floor level, orientation, window height, natural ventilation per person, type of ventilation, and density (person per m2) at the buildings are provided in table 3 below.

Location of case study

Space Floor area (m2)

Level of floor

Orientation of the space

Types of ventilation in summer

Height of window

Natural ventilation per person

London, UK Living area

29.700 Ground floor

South orientation

Natural ventilation

2.200 m

9.000 l/s

Bedroom 13.100 First floor

Southwest orientation

Natural ventilation

Buckinghamshire , UK

Living area

20.900 Ground floor

Northeast orientation

Natural ventilation

1.400 m

10.000 l/s

Bedroom 12.200 First floor

Southeast orientation

Natural ventilation

Table 3: Summary of the features in each of the spaces at the case study buildings

4. Results and discussions

Table 3 shows that relationships exist between the internal temperature and the external temperature at each of the case study buildings. Significance is also found between the internal temperature and use of control for natural ventilation in the spaces. The study showed the bedroom tends to be warmer than the living area at the case study building in Buckinghamshire. On the other hand, the living area is slightly warmer than the bedroom at the case study building in London. The results showed the importance of ventilation, especially natural ventilation for cooling, which can enhance occupants' comfort in buildings. Lower temperatures are recorded in the spaces at the case study building in London due to provision of larger area of openings, which allow natural ventilation into the spaces in summertime. The findings revealed a possibility of higher cooling demands in the spaces at the building in Buckinghamshire than those spaces at the building in London. These may contribute to higher energy required per year at the building in Buckinghamshire, if the building is not naturally ventilated in summertime.

Location of the case study building

Internal temperature versus External temperature (R values)

Internal temperature versus Use of control for natural ventilation (*p value)

Temperature range of the linear regression (°C)

Living area Bedroom Living area Bedroom Living area Bedroom London, UK 0.371 0.559 $p<0.05$ $p<0.05$ 3.000 3.200 Buckinghamshire, UK 0.490 0.510 $p<0.05$ $p<0.05$ 6.400 6.000 *Significance level at $p<0.05$

Table 3: Summary of the relationships between the internal and the external temperatures at the case study buildings

Table 4 provides a summary of the measured temperatures, including average, maximum, and minimum temperatures in each space at the buildings. Higher average, maximum, and minimum temperatures are reported in the living area than the bedroom at the case study building in London. While higher average, maximum, and minimum temperatures are measured in the bedroom rather than the living area at the building in Buckinghamshire. The results revealed a tendency for a higher cooling demand by occupants in the living area than the bedroom at the building in London during summer period. On the contrary, higher cooling demand is likely to be reported by occupants in the bedroom than the living area at the building in Buckinghamshire. Also, occupants in the spaces with higher temperatures are likely to use various adaptive measures than the occupants in the cooler spaces at the case study buildings. At the case study buildings, the bedrooms are located on the upper floors while the living areas are located on the ground floors. The results suggested that location of the bedrooms might likely contribute to the higher temperatures observed in the bedrooms especially at the building in Buckinghamshire. The study also showed that bigger floor area of the spaces at the case study building in London possibly contribute to lower temperatures reported at the case study building than the spaces at the case study in Buckinghamshire.

Location of case study

Space Outside rate of air change (ac/h)

Average indoor temp (°C)

Max. indoor temp (°C)

Min. indoor temp (°C)

Average outdoor temp (°C)

Max. outdoor temp (°C)

Min. outdoor temp (°C)

London, UK Living area

5.000 22.900 24.600 21.700 16.700 23.500 11.000

Bedroom 22.800 24.700 21.300

Buckinghamshire , UK

Living area

4.000 22.600 28.100 18.200 16.800 27.500 8.000

Bedroom 24.300 29.100 20.800

Table 4: Summary of the finding in each of the spaces at the case study buildings

Linking the parameters (environmental variables and design features) to establish relationships between the variable, the results showed that higher temperatures are recorded in the south facing and east facing spaces of the buildings. The statistical analysis revealed significance is reported between most of the variables. For instance, the study showed the risk of summertime high temperatures tend to be significantly reduced ($p<0.05$) when spaces are cross-ventilated, and provided with higher floor-to-ceiling height, and bigger floor area. The statistical tests conducted between the variables (one-way ANOVA) revealed the occupants in south facing spaces feel warmer than those in other orientations, especially at the building in Buckinghamshire. The results also showed that the occupants in south facing and east facing spaces tend to have higher level of control than occupants in other locations. In terms of floor-to-ceiling height, the occupants living in the spaces with lowest floor-to-ceiling height feel warmer than the occupants in the spaces with medium and highest floor-to-ceiling height (Table 5).

Variables Classes of variable

Case study building in London

Case study building in Buckinghamshire

Mean Standard deviation

Mean Standard deviation

Thermal sensation in summer

Orientation North 4.000 0.707 4.000 0.707 West 5.170 0.753 3.000 1.000 South 5.780 0.972 6.420 0.515 East 5.670 0.516 5.170 1.169 Level of control Orientation North 3.600 0.894 4.400 1.673 West 4.500 0.548 5.330 0.577 South 4.560 1.236 4.080 1.881 East 5.170 0.753 4.330 1.211 Control satisfaction Orientation North 5.000 0.707 4.600 1.817 West 4.000 0.000 6.000 1.000 South 5.560 0.882 3.830 1.850 East 5.830 0.753 4.000 0.894 Frequency of control Orientation North 4.400 0.548 5.600 1.140 West 3.330 0.516 5.000 2.646 South 5.670 1.118 5.750 1.055 East 5.170 0.983 3.670 1.506 Thermal sensation in summer Height Low 6.250 0.957 6.090 0.944 Medium 5.940 0.680 NA* NA* High 5.500 0.837 5.330 1.496 Thermal satisfaction in summer Height Low 2.750 0.957 4.820 0.982 Medium 3.130 1.258 NA* NA* High 4.330 1.211 4.870 1.457 Level of control Height Low 3.750 0.957 4.000 1.789 Medium 4.440 1.031 NA* NA* High 5.170 0.753 4.600 1.404 Control satisfaction Height Low 5.250 0.957 4.000 1.612 Medium 4.940 1.063 NA* NA* High 5.670 0.516 4.470 1.727 Frequency of control Height Low 5.250 0.957 5.090 1.578 Medium 4.310 1.195 NA* NA* High 5.670 1.033 5.200 1.612 Thermal sensation in summer Floor area Small 5.500 0.707 6.000 0.000 Medium 6.100 0.738 5.650 1.461 Large 5.790 0.802 5.600 0.894 Level of control Floor area Small 5.500 0.707 4.000 0.000 Medium 4.000 0.816 4.300 1.780

Larger 4.710 1.069 4.600 0.548

Control satisfaction

Floor area Small 6.500 0.707 3.000 0.000 Medium 4.300 0.483 4.300 1.780 Large 5.570 0.756 4.400 1.342

Frequency of control

Floor area Small 5.000 1.414 5.000 0.000 Medium 3.700 0.675 5.400 1.569 Large 4.770 1.019 4.200 1.483 *Note: The case study building at Buckinghamshire has only two classes in terms of height (low and high)

Table 5: Summary of the statistical analysis showing relationship between different variables and design parameters

Considering the floor area of the spaces, the results showed the occupants living in smaller and medium sized spaces feel much warmer than those living in large spaces, especially at the building in Buckinghamshire. In addition, the occupants living in smaller spaces tend to develop a higher level of control than those living in medium sized and larger spaces. Higher frequency of control is also noted by the occupants living in smaller spaces than occupants living in the large spaces.

5. Conclusions

The study considered a comparative analysis of occupants' adaptation and examined various design parameters influencing behavioural actions of occupants in naturally ventilated structural timber buildings. The research employed analysis of architectural design of the buildings, on-site measurements, and thermal comfort survey as the research methods. The findings showed over 85% of the occupants in dwelling units with smaller floor area adapt better to the thermal environment than those living in dwelling units with bigger floor area. Additionally, more than 75% of the occupants in naturally cross-ventilated buildings are more satisfied than occupants in buildings with single-sided ventilation. The occupants residing in the smaller spaces tend to have higher level of control than those living in the bigger spaces. The study showed the occupants in naturally ventilated buildings use control to adjust the thermal environment thereby reducing overall annual energy consumption in sustainable buildings. Finally, the study showed design features can significantly influence occupants' adaptation in sustainable buildings and consideration of adequate natural ventilation can possibly contribute to occupants' satisfaction and reduce annual energy consumption in sustainable buildings.

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