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Thermal Comfort in Zero Energy Buildings

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Abstract

This paper evaluates thermal comfort in domestic zero energy buildings. Dynamic simulations are used to assess a variation of scenarios including: construction types, natural ventilation strategies, solar shading, and occupancy periods in a low energy case study dwelling, within the United Kingdom. The Chartered Institution of Building Services Engineers Technical Memoranda 52 (CIBSE TM52) is used to evaluate the thermal comfort conditions, and the state of overheating within the case study dwelling. The results indicate that increasing the thermal mass of the external walls significantly reduces the risk of overheating within the case study dwelling. Additionally, the most beneficial window opening profile is night ventilation. The addition of solar shading on the South, East and West elevations considerably improved thermal comfort conditions. Increasing the effective openable glazing area to facilitate natural ventilation in zero energy buildings and further improve the indoor thermal comfort.

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Keywords: Overheating, Thermal Comfort, Zero Carbon, Zero Energy, Housing

1. Introduction

Sustainability has progressively become a pressing issue throughout the world, with many countries supporting policies to reduce carbon emissions. A large portion of domestic buildings are still dependant on fossil fuels as a source of energy [1], contributing to more than 30% of carbon emissions in the United Kingdom [2], therefore producing zero carbon homes would significantly decrease this. The UK has incorporated policies such as The Code for Sustainable Homes (CSFH) [3,4] to increase the energy performance of domestic dwellings, as well as assessment tools such as PassivHaus [5] and BREEAM [6] that are used to evaluate building design [1]. Furthermore, increasing the energy

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efficiency portrays increased air tightness, and therefore represents a negative impact on the indoor environment and health and wellbeing of occupants. Recently, the UK Government have withdrawn the CFSH [7]. Buildings have been idenfitied as providing the greatest opportunity to reduce carbon emissions [4]. Therefore, The Building Regulations, CIBSE Guide A [8] and additional policies are tightening the restrictions with the aim to provide increased efficiency and air tightness within domestic houses.

Studies have been conducted regarding methods to intergrate zero carbon in existing and new buildings [1,4,9] as well as assessing the carbon emission impact of buildings [10]. However, the negative impact on the indoor environment has not been fully assessed.

Yu and Kim [11] have previously conducted research in order to identify the health conditions related to indoor pollutants and poor indoor air quality. According to Yao and Yu [2], the correlation between the indoor environment and occupant satisfaction in low energy homes has not been previously researched. Therefore, it is unknown whether these types of dwellings are providing a satisfactory indoor environment for the user.

Ucci and Yu [12] have also voiced concerns related to the disregard of occupant health and wellbeing throughout energy related policies, due to the lack of evidence related to this topic. The NHBC Foundation [13] have stated concerns from both building occupants and builders with regards to the consequences related to increasing the air tightness within dwellings. Further to this, Ucci and Yu [12], Yu and Kim [11] and Howieson, Sharpe and Farren [14] have recommended the need for policies that evaluate the indoor environment and health and wellbeing of occupants prior to the construction stage. Yao and Yu [2] and Hashemi and Khatami [15] outline the need for additional research into whether low energy buildings are providing 'healthy indoor environments', this research will address the issue through assessing the collected simulation data.

To this end, the aim of this paper is to provide recommendations to improve thermal comfort conditions in low/zero energy homes. This study evaluates the conditions of a low energy case study building in order to assess alternative methods to reduce risk of overheating and thermal discomfort in zero energy buildings.

1.1. Zero Carbon Homes

Within previous years, increasingly airtight structures have been developed, along with the combination of improved thermal insulation, high performance windows, and additional U-value reductions throughout new buildings [16]. The requirement for lower carbon buildings and the development of knowledge and technologies resulted in the inclusion of policies to outline targets for the reduction of carbon emissions. Zero Carbon Hub [17] defines that a 'zero carbon home' must meet the following three criteria:

- The fabric performance must comply with the Fabric Energy Efficiency Standard (FEES).
- The total amount of carbon emissions ("after consideration of heating, cooling, fixed lighting and ventilation") must satisfy the Carbon Compliance limit, established for zero carbon homes.
- The fabric performance must comply with the Fabric Energy Efficiency Standard (FEES).

Once criteria one and two have been met, the remaining carbon emissions must be reduced to zero.

The Zero Carbon Hub [17] states that the zero carbon policy comprises of: fabric energy efficiency, on site low or zero carbon heat and power, as well as allowable solutions.

The UK Government proposed a 'Code for Sustainable Homes' policy in 2006, outlining the intention for new constructed dwellings to be zero carbon by 2016 [18]. The program to achieve zero this aim is shown in Table 1.

Table 1. Code Levels for Mandatory Minimum Standards in CO_2 Emissions [19]

Code Level	Minimum Percentage Improvement in Dwelling Emission Rate over Target Emission Rate
Level 1 (★)	0% (Compliance with Part L 2010 only is required)
Level 2 (★★)	0% (Compliance with Part L 2010 only is required)
Level 3 (★★★)	0% (Compliance with Part L 2010 only is required)
Level 4 (★★★★)	25%
Level 5 (★★★★★)	100%
Level 6 (★★★★★★)	Net Zero CO_2 Emissions

The final stage of the programme identified the integration of the ultimate zero carbon, level six by 2016 [19]. The Code for Sustainable Homes [3] was withdrawn, following a review of the technical housing standards [20]. Fell, Fell and Lukianova [18] recognises the confusion regarding the UK Government's current intentions concerning zero carbon policies, stating that the future of British homes is currently uncertain. Yet, CFSH remains the most appropriate and relevant document to this study considering its implementation within the UK building regulations until recently.

2. Case Study Building

The Sigma Home (Fig. 1) forms the initial prototype within the United Kingdom designed to achieve Code 5 (zero CO_2 for regulated energy) of the Code for Sustainable Homes [21]. The building consists of a semi-detached dwelling, with the adjacent dwelling forming a mirrored construction and design. The semi-detached construction consists of a four storey dwelling, to reduce the required footprint of the structure [22]. The home was constructed in 2007 by The Stewart Milne Group and is located within the BRE Innovation Park, Watford. The dwelling portrays a usable floor area of approximately 122m^2 with total of five occupied thermal zones corresponding to five simulated thermal zones. The thermal zones incorporating the following uses: ground floor open plan kitchen, dining, family area, first floor living room, first floor bedroom, second floor bedroom, third floor master bedroom. Table 2 portrays the as built constructions of the case study, as well as the associated U-values.

Table 2. The Sigma Home Construction Breakdown [21,23].

Case Study Component	Construction build up	U-Value
Foundations	Pre-case concrete pile and beam	-
External Walls	5mm External Render, 12mm Recycled Backing Board, 30mm Cavity and Battens, 75mm Celotex Insulation, 9mm OSB/3 Boards, 140mm Solid Timber Studwork and Glasswool Insulation, 9mm OSB/3 Boards, 25mm Battens, 12.5mm Plain Plasterboard, 12.5mm Internal Plain Plasterboard, 5mm Emulsion Paint.	0.15W/m^2
Internal Floors	10mm Faenza Clip Tiles, 18mm Chipboard, 15 OSB Decking, 300mm Deep Solid Timber Joists, 15mm Plain Plasterboard	0.18W/m^2
Ground Floor	10mm Faenza Clip Tiles, 18mm Chipboard, 15 OSB Decking, 300mm Deep Solid Timber Joists and Glasswool Insulation, 9mm OSB Boarding	0.18W/m^2
Roof	External Zinc Sheet System, Pre-fitted Weather-Proof Membrane, 15mm OSB Decking, 300mm Deep Solid Timber Joists and Glasswool Insulation, 9mm OSB Boarding, 25 x 38mm Service Zone Battens, 15mm Internal Plain Plasterboard	0.15W/m^2
Glazing	High Performance Triple Glazing: 14.52m^2 on the West elevation, 5.76m^2 shown on the South Elevation, 18.16m^2 incorporated on the East elevation, and 1m^2 on the North Elevation	0.68W/m^2

Fig. 1. The Sigma Home Case Study

3. Methodology

Throughout this research, the scenarios (identified in Table 3) were applied to the case study within Integrated Environmental Solutions software in order to evaluate the thermal comfort conditions. Overall, 184 combination scenarios were simulated to evaluate various conditions. The software facilitates the simulation of buildings and specific thermal zones in order to extract data such as: air temperatures, heating and cooling loads, or for CIBSE TM52 analysis. This study will specifically incorporate the use of CIBSE TM52 analysis using IES (VE) software.

Table 3. Simulation Matrix

Variable	**Alternatives**
Types of Construction	As Built (Very lightweight), Masonry: brick and 100mm block (Heavyweight)
Window Opening Alternatives	Always Closed, Always Open, Night ventilation (Closed 07:00 – 18:00; Open 18:00 – 07:00)
Solar Shading Depth Alternatives Above Windows	None, 500mm, 750mm 1000mm
Openable Windows	No Openable Windows; As Built (7.76m^2 effective opening area); All openable (27.90m^{2}effective opening area)
Occupancy Periods	100% Occupied, BRE Occupancy (Lounge: 16:00 - 23:00; Circulation areas: 07:00 - 10:00 and 19:00 - 23:00; Bedrooms: 22:00 - 09:00)

Table 4 portrays the conditions applied throughout the IES(VE) simulations for data collection. According to CIBSE [24], when conducting overheating analysis, The Design Summer Year (DSY) is appropriate; therefore the London DSY weather data is used for these simulations. Due to the unoccupied status of the case study, occupancy profiles were not available and therefore the BRE estimates have been incorporated to allow for an evaluated source of occupancy profiles.

Table 4. Summary of Simulation Conditions

Condition Category	Simulation Conditions
Simulation Period	01May – 30 September
Location	Watford; England, GB
Wall construction	As Built External Wall Construction (Achieves a 'very lightweight' construction and U-value of 0.15W/m^2.K): 5mm External Render, 12mm Timber Board, 30mm Cavity, 75mm Insulation Board, 9mm Timber Board, 25mm Cavity, 25mm Plasterboard. Masonry External Wall Construction (To achieve a 'heavyweight' construction and U-value of 0.15W/m2.K.): 102.5mm Brickwork (Outer Leaf), 50mm Cavity, 153.3mm Polyurethane Board, 100mm Concrete Block (heavyweight), 0.1mm Plasterboard.
Total glazed area	South elevation: 5.76m^2, East elevation: 18.16m^2, West elevation: 14.54m^2
Additional Internal Gains	Fluorescent Lighting = 2 W/m^2/(100 lux)
Air Exchanges	Infiltration = 0.25ach
Heating	Set to 'Off Continuously'
Cooling	Set to 'Off Continuously'
Building surround	Free on the south, east & west; attached to another building on the north side

CIBSE TM52 has been used throughout the research in order to identify the state of thermal comfort and overheating within the case study building and applied scenarios. Three criteria are outlined for the definition of overheating in relation to free-running buildings in CIBSE TM52 [25]. Criterion 1 determines that the difference between the operative temperature (T_{op}) and the maximum acceptable temperature (T_{max}) must not be equal to or exceed 1 degree for more than 3% of occupied hours during the non-heating period of 1 May to the 30 September, this is shown within the equation below.

$$\Delta T = T_{op} - T_{max}$$

Number of hours (H_e) for which $\Delta T \geq 1°$ must be < 3% (during the period of 1 May to 30 September). Criterion 2 enables the measurement of overheating frequency within the period of a day. This criterion is determined using the formula below.

WF = 0 if $\Delta T \leq 0$

Where: W_e = The Weighted Exceedance, Σh_e = The total hours of exceedance, WF = The Weighting Factor, h_{ey} = the time (h) when WF = y, Otherwise WF = ΔT.

Criterion 3 uses the method of assessing an upper limit temperature (T_{upp}) that is identified by stating that the value of ΔT as described in criterion 1 should never exceed 4K. Therefore, T_{op} should never exceed $T_{max} + 4$. The three criteria previously mentioned are used by IES(VE) to analyse the simulated scenarios against CIBSE TM52 and to determine if the thermal zones overheat.

4. Results of simulation

Simulations were conducted for 184 combination scenarios based on alternative conditions explained in Table 4. This section explains the results of the simulations and data collected through IES (VE) simulations.

4.1. Worst Case

The worst case scenario is portrayed with the following attributes: construction portrayed as built, windows are always closed, no solar shading above windows, and one hundred percent occupancy. Although unrealistic, this was simulated to evaluate the conditions for the worst case scenario in relation to the case study dwelling. The worst-case scenario is predictable due to the conditions projected by the attributes. As shown in Table 5, the temperature in the first floor living room reaches 51.39°C, which is extremely high in comparison to the maximum comfortable temperature.

Table 5. Worst Case Scenario Simulated Conditions

Thermal Zone	Criteria Failed	Pass/Fail	Maximum Temperature
Ground Floor Living/Dining/Kitchen	1 & 2 & 3	Fail	35.77
First Floor Living Room	1 & 2 & 3	Fail	51.39
First Floor Bedroom	1 & 2 & 3	Fail	49.81
Second Floor Bedroom	1 & 2 & 3	Fail	46.41
Staircase Void/Light Tower	1 & 2 & 3	Fail	44.26

4.2. Best Case

All thermal zones in ‘As Built’ simulated scenarios (32, 50, 53, 56, 87, 88, 89, 90 and 91) pass the three CIBSE TM52 criteria. When compared against the baseline study, the best case scenario was signified as number 56. The scenario consists of windows open at night, 1000mm of solar shading above the windows on all elevations, all windows can be openable, and occupancy period profiles. The resultant scenario classified as the ‘best case’ is as anticipated. The strategy of opening the windows at night allows for a large amount of ventilation when the building is at peak occupancy. However, during night hours there will be no solar gain and therefore this may adjust the results regarding only opening windows at night. The solar gain will not hinder this scenario in comparison to the extreme in which it may affect alternative scenarios with no solar shading. Additionally, all windows are openable within this scenario, which considerably increases the ventilation rate.

Scenario 32 portrays a more appropriate alternative, as this scenario reduces the effective openable area of the windows by 20.14m^2. This alternative is more feasible as the occupants are less likely to open all of the windows at night due to possible security issues draft or noise. Compared to scenario 56; Scenario 88 portrays an appropriate substitute due to the reduced depth of solar shading (1000mm to 500mm) which may reduce the costs.

4.3. Thermal Mass

The effects of thermal mass on thermal comfort for all 184 combination scenarios are evaluated in this section.

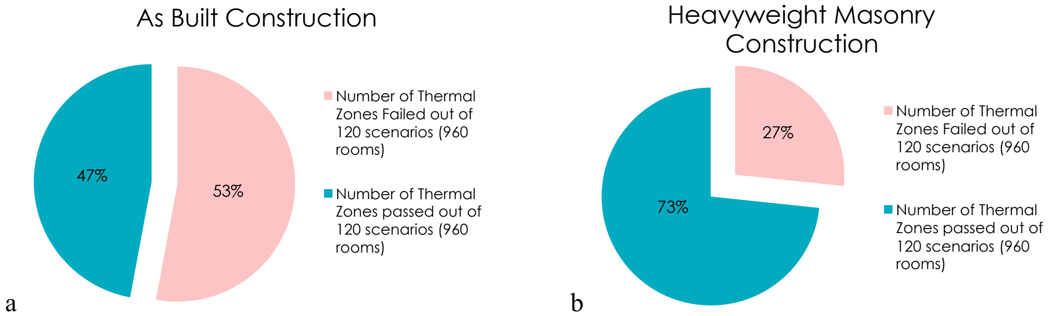

Fig. 2. (a) As Built Construction Analysis; (b) Heavyweight Masonry Construction Analysis.

Figures 2a and 2b show the percentage of thermal zones, which pass and/or fail CIBSE TM52 criteria, when modelled with two different external wall constructions (as built: lightweight; and masonry: heavyweight). According to the results, increasing thermal mass of the external walls significantly decreases the risk of overheating within the case study dwelling. Figures 2a and 2b portray the substantial difference between the construction alternatives. Moreover, 53% of Zones failed when simulated using the as built construction, whereas only 27% failed when using a masonry construction, with a higher thermal mass.

This indicates a direct relation between overheating and thermal mass. It could be deduced that increasing the thermal mass of external walls, would considerably decrease the risk of overheating and thermal discomfort in low energy buildings.

4.4. Window Opening Alternatives

This section analyses the effects of window opening scheduled (always open, always closed, and open at night) on thermal comfort.

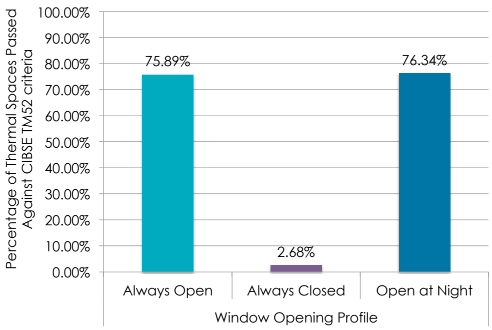

Fig. 3. Graph Analysis of the Window Opening Alternatives, 'As Built' Construction

The data collected enables the evaluation of the most efficient window opening profile. Figure 3 portrays the percentage of thermal zones that pass the thermal comfort requirements for the window opening profiles. Figure 3 represents that opening the windows at night is the most effective method of natural ventilation.

The 'always open' profile is almost as effective as having the windows open at night, however this would not be appropriate in most occupancy patterns and therefore opening the windows at night would also be more suitable to typical occupancy periods. The ‘always closed’ profile portrays a significant risk to overheating, as only 2.68% of room scenarios pass during simulation.

4.5. Solar Shading

Simulations were conducted for various depths including: no shading, 500mm, 750mm and 1000mm on all elevations. Figure 4 represents a comparison between four solar shading alternatives. Assessing the difference between ‘no solar shading’ and ‘500mm solar shading’ on all elevations can identify the effectiveness solar shading.

By adding 500mm of solar shading to all elevations, a reduction of 0.6813MWh (Megawatt hours) solar gain is portrayed. The difference is reduced between 500mm, 750mm and 1000mm solar shading depth alternatives. Comparing the 500mm and 750mm solar shading alternatives portrays a further decrease of 0.2308MWh, and an additional 0.1762MWh reduction when 750mm and 1000mm are compared. This outlines the positive outcome that solar shading has in regards to reducing the amount solar gain, risk of overheating and further improving the thermal comfort of the simulated dwelling.

According to the results, compared to no solar shading, 500mm, 750mm and 1000mm shadings portray nearly 16%%, 21.4% and 25.5% solar gain reduction, respectively. As expected, 1000mm shading provides the highest benefit in comparison to the other three alternatives. However, the efficiency and effectiveness of using solar shading may not be thoroughly analysed by using the depth alternatives alone. The elevation alternatives provide a better picture in relation to the most efficient elevation or combination of elevations to prevent overheating.

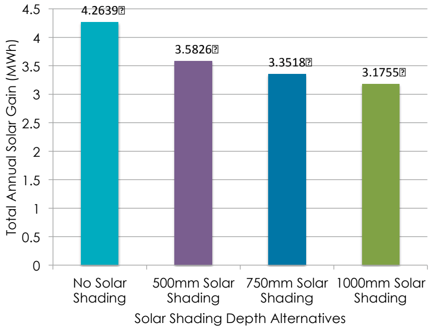

Fig. 4. Graph Analysis of the Solar Depth Alternatives, ‘As Built’ Construction

The following elevation alternatives have been simulated for the analysis: ‘South’, ‘East’, ‘South and East’, ‘West,’ ‘West and East’, ‘South and West’ and ‘South, West and East’. The North elevation has been excluded from the solar shading analysis due to limited solar gains from this elevation. As stated in table 5, total glazing areas of south east and west elevations are 5.76m^2, 18.16m^2 and 14.54m^2, respectively.

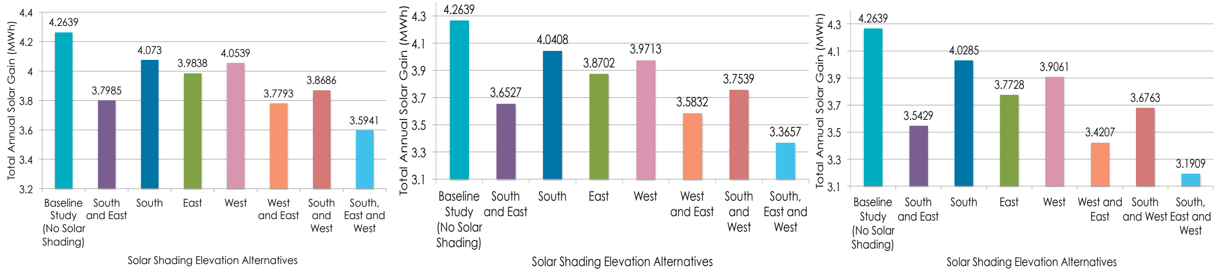

Fig. 5. (a) 500mm; (b) 750mm; (c) 1000mm Solar Shading Elevation Alternatives

Figures 5a, b and c outline the benefit associated with incorporating solar shading against the baseline study without solar shading. According to the results, the ‘South, East and West’ solar shading alternative is significantly beneficial to reduce solar gain. Figure 5a portrays that 500mm; 750mm and 1000mm on the South, East and West elevations respectively reduce the amount of solar gain by around 670kWh, 898kWh and 1073 kWh in comparison to the baseline study. The most effective solar shading seems to be on the West and East elevations due to the orientation of the case study and the location of the majority of glazing.

4.6. Openable Windows

The following openable window alternatives have been analysed as follows: 'as built' (7.76m^2), all windows openable (27.90m^2).

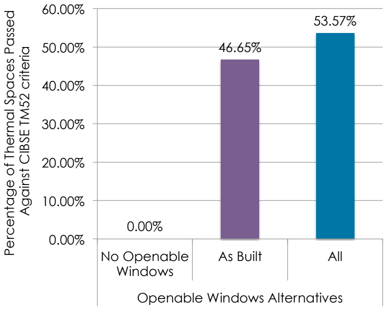

Fig. 6. Graph Analysis of the Openable Window Alternatives, 'As Built' Construction

Figure 6 signifies that around 47% of the evaluated thermal zones pass CIBSE TM52 criteria when the openable windows are set 'as built'. This figure increases to 54% showing an improvement of around 7% when all windows are considered as openable. It is to be expected that the thermal comfort will be increased and the risk of overheating decreased by designing a dwelling to incorporate an increased number of openable windows. However, allowing for all the windows to be operational may not be feasible. Overall, the risk of overheating within low energy case study dwelling is decreased when the number of openable windows is increased.

4.7. Occupancy Periods

This section will compare the application of BRE defined occupancy against a 100% occupancy profile (Figure 7). As shown in Figure 7, 63.67% of evaluated thermal zones pass CIBSE TM52 criteria when BRE occupancy periods are simulated. When the occupancy increased to 100% of the time, this percentage falls to only 22.27% and therefore a large number of scenarios would be at risk of overheating. It should be noted that it is unlikely that people will occupy the building 100% of the time, however this could be a possibility for more vulnerable people such as the elderly and mothers with young children.

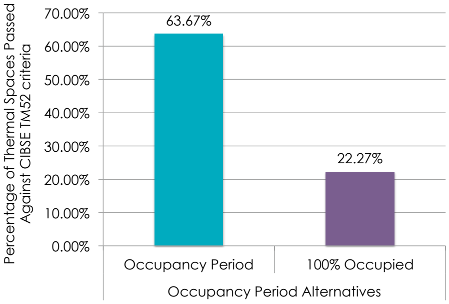

Fig. 7. Graph Analysis of the Occupancy Period Alternatives, 'As Built' Construction

5. Summary and Discussion

Table 6 summarises the recommended solutions based on the results of the simulations explained above.

Table 6. Summary of Recommendations

Matrix Variable	Assessed Alternatives	Recommended Alternative
Types of Construction	As Built, Masonry	Masonry (high thermal mass)
Window Opening	Always Open, Always Closed, Open at Night	Night Ventilation
Solar Shading Depth	None, 500mm, 750mm, 1000mm	500mm
Solar Shading Elevations	South, South and East, West and East, West, East, South and West, and South, East and West	East and West
Openable Windows	No Openable Windows, As Built, All	Increase the percentage of openable windows
Occupancy Periods	Occupancy Periods, 100% Occupied	Occupancy Periods

According to the results, increasing the thermal mass reduced the risk of overheating and improved indoor thermal comfort. Overall, increasing thermal mass can provide significant benefits in terms of thermal comfort in low energy buildings.

Night ventilation portrayed the highest benefit in relation to improving indoor thermal comfort in the case study dwelling. Opening the windows at night will improve indoor conditions as well as prevent overheating, as this is typically when a dwelling is at peak occupancy. However, this may not be feasible on the ground floor and in noisy urban environments due to security and sound pollution issues.

As to solar shading, the data analysis portrayed a benefit in relation to the thermal comfort in domestic dwellings. Including 1000mm solar shading would portray a significant reduction of solar gain; however, a 500mm solar shading would be more applicable due to the higher costs associated the increased depth of shading. According to the results, as expected, inclusion of shading on all elevations (South, East and West) would provide the most appropriate recommendation. However, a more feasible recommendation to incorporate solar shading would be on the West and East elevations due to the building orientation and the location of the majority of glazing.

The simulations provided conclusive evidence that increasing the percentage of openable windows would improve the thermal comfort and reduce the risk of overheating. Increasing the percentage of openable windows within the dwelling is therefore recommended; however, more investigation is required to assess the optimum ratio of opening to total glazing area.

100% occupancy portrays a significant risk for overheating throughout the simulated data. This may apply to more vulnerable people such as the elderly and mothers with young children. Therefore, some additional passive design strategies would be required in order to provide comfortable environment for the 100% occupancy scenarios.

5.1. Recommendations for Future Works

Poor indoor air quality can generate occupant illness such as sick building syndrome. Future research into the effects of low energy dwellings on the indoor air quality is recommended. The following attributes were disregarded for this specific study, but could be included in future research: internal shading, future weather data and the building orientation. Throughout the data collection, alternative window opening profiles were utilised to determine the effects of altering the window opening profile on thermal comfort. Development of a control strategy would enhance the associated improvement on the indoor environment and also may become more beneficial. Finally, future research could consider using physical tests, post occupancy evaluation and interviews as substitute data collection methods, this would allow for an assessment of thermal comfort in situ, or from alternative perspectives.

6. Conclusion

This paper provides advances in the field regarding the issues related with low energy buildings. Previous research has incorporated methods to achieve zero carbon in existing buildings through retrofitting, the potential of incorporating renewable sources in existing buildings, system boundaries surrounding zero carbon buildings, and assessments of carbon emission generation related to buildings. This paper progresses from previous literature due to the focus on the effects of zero carbon dwellings on the occupied indoor environment, rather than concentrating on strategies to incorporate low carbon in existing buildings.

Thermal comfort in domestic zero energy buildings was evaluated. Dynamic simulations were conducted for 184 combination scenarios to assess thermal comfort in a low energy case study dwelling, within the UK. This research has identified the risk of overheating and the compromise on the indoor thermal comfort associated with low energy dwellings. Following recommendations may be considered to improve the thermal comfort in low energy dwellings:

- Increase the thermal mass of external walls;
- Night ventilation;
- Incorporate external solar shading devices on the elevations most prone to risk of solar gain; and
- Increase the effective openable glazing area to facilitate natural ventilation.

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