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The impact of refurbishment on thermal comfort in post-war office buildings

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Abstract

Post-war office buildings have been modelled using EnergyPlus to determine the effect on thermal comfort of a range of energy-saving refurbishment measures. The native buildings were found to be thermally uncomfortable in the winter due to low operative temperatures arising from their concrete construction and single glazing. When the building envelope was refurbished, the energy performance improved markedly and the buildings became thermally comfortable in the winter. However, in the summer they were prone to overheating, though the impact was mitigated by shading and night cooling. It is concluded that a wider range of refurbishment techniques needs to be investigated to achieve simultaneous energy reduction and year-round thermal comfort.

Keywords: Energy efficient refurbishment, Non-domestic buildings, Building energy simulation, Office building.

1. Introduction

The energy used in buildings accounts for 47% of the total energy use of the UK. Due to low-energy design and high-performance materials, new buildings can use much less energy. However, the replacement rate of existing buildings by new-build is only around 2% per annum [1] so the energy efficiency of the existing stock must be improved to achieve significant reductions in building energy consumption. Post-war non-domestic buildings, typically defined as those built between 1945 and 1985, represent a promising sector for studying energy demand

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reduction. They have disproportionately high energy consumption because many were built before the building regulations started to improve building thermal performance. In addition, because of the urgent need for new buildings, non-domestic buildings in particular were built rapidly and cheaply, leading to poor energy efficiency. Also, they were built in a specific, well-defined style (‘post-war architecture’), making it possible to represent large numbers of buildings using a limited number of forms. However, this should be seen against the backdrop of non-domestic buildings generally, which is notable for its diversity: not only are there many built forms, there are also many activities and modes of operation, making it difficult to generalize the results of studies. The present work has therefore focused on post-war office buildings, which are not only significant users of energy but also relatively uniform in architectural characteristics. In addition to the significant energy consumption, which is mainly due to lack of insulation and poor glazing, the urban heat island effect in cities and the internal heat gain due to the significant increase of the use of IT equipment, combine to make overheating one of the most important problems for this building type [2].

The work described in the present paper represents the initial stages of a PhD project that aims to define optimal refurbishment strategies for improving the energy performance of post-war office buildings using dynamic thermal modelling. The focus of the present paper is the impact of energy-saving refurbishments on thermal comfort.

2. Methodology

The approach adopted was to apply dynamic energy simulation to building models (‘exemplars’) representing post-war office buildings. In the literature various terms are used for the same approach such as ‘archetypal simulation model’ [3] which basically defines a simulation model with generalized characteristics of a particular building type in order to represent the stock by parameterizing modelling components. The base case exemplars, representing buildings before refurbishment, were created as EnergyPlus (E+) dynamic energy simulation program [4] models. The refurbishment options were implemented using JEPlus [5], a tool for managing parametric analysis in E+ simulations using multiple design parameters. The refurbishment variations were created using all possible combinations of the refurbishment options. The potential of a set of variations for improving the energy efficiency and thermal comfort of buildings of the chosen type was then analysed as described later. The analyses were repeated for current and 2050 weather conditions.

The first task was to form the exemplars which are representative of post-war office buildings. The typical characteristics which formed the parameters of the base case models were derived from surveys [6], regulations of the era [7], data analysis [8], previous studies [3, 9]**.** However, the literature data for non-domestic buildings is limited and relatively out of date. To increase the accuracy of the models, sensitivity analysis was carried out to identify the inputs with the most significant effect on the outputs of interest, namely energy demand and thermal comfort. As part of this process, the results were compared with national survey averages [6] and benchmarks [10], in order to ensure results were realistic. The base case results were also compared with the results of work [8] on the energy consumption of 2,600 buildings derived from their Energy Performance Certificates (EPCs). The built form of non-domestic buildings varies significantly and strongly affects the energy demand. Despite this diversity, detailed work by Steadman et al [11] suggests that six built forms adequately represent UK office buildings according to the layout of the space and the main lighting method (artificial or daylight). For the present study, the most common type, “cellular daylit 4 storeys”, which is of 34% of non-domestic UK buildings and 63.8% of the offices in 1994, was chosen as shown in Fig. 1(a). Supporting information was derived from the office benchmarks [10] which include a specific cellular daylit case. Room widths of 7 m separated by a 2 m corridor were used in the exemplar design, in line with the daylighting requirements described in [11]. As shown in Fig. 1(b), two office zones and a circulation zone were defined on each of the 32 m by16 m floors.

For each of the refurbishment alternatives, E+ was used to predict both the annual energy consumption and the thermal comfort of the whole building using its “Facility” output which is only available for the Simple ASHRAE Standard 55 [12]. This, in summary, states that the operative temperature should not be outside the comfort zone for more than 4% of the occupied hours.

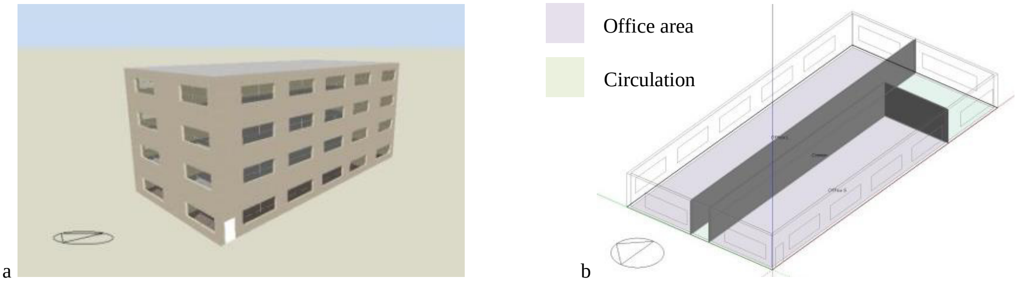

Fig. 1. (a) Cellular daylit office building exemplar (b) Office building exemplar zones.

2.1. Input Data

In the UK, the Building Regulations of 1965 [7] provided the first control of the thermal performance of the basic building envelope of all building types. Throughout the 1970s the regulations on the maximum allowable U-value of elements of the building fabric were gradually tightened but more stringently from 1985, Part L Conservation of Fuel and Power [13], to 2002. The regulations of 2006, introduced the first specific requirements on the energy conservation measures in refurbishment (Approved Document L2B Conservation of fuel and power in existing buildings other than dwellings [14]). As 1965 falls well within the period when post-war buildings were constructed, and the 1965 regulations were the first to specify building envelope properties, the specified U-values were used in the base case models as listed in Table 1.

Occupancy-related parameters were based on average behaviours for typical office workers and fixed for all computations; occupancy was from 9:00-18:00 on weekdays only, at a density of 14m^2 per person [15] and metabolic rate of 125 W [16]. The aim was to fix the occupancy characteristics so that the results of the refurbishments could be evaluated independently of user behaviour. As shown in Table 2, lighting, office equipment usage and heating set point were gathered from relevant regulations and surveys. The building was assumed to be naturally ventilated at 24 ˚C and above when it was occupied. Airtightness is one of the most uncertain values due to lack of relevant measurements. However, making use of [9], [10] and [17] and taking account of the known poor fabric properties of post-war buildings, the base case infiltration was taken as 1.2 ach. Following the findings of Gakovic [18], the proportion of glazed areas in the external walls was set at 30% of the wall area for the base case.

Table 1. Envelope properties:

Fabric U-values ($Wm^{-2}K^{-1}$) and infiltration (ach)	Base case [7] and Fixed Refurbishment	PartL 2010 [13]	Good Practice [10]	Passivhaus (EnerPHit) [20]
External wall	1.7	0.35	0.24	0.15
Roof	1.42	0.25	0.14	0.15
Ground floor	1.42	0.25	0.25	0.25
Glazing	5.87	2.2	1.8	0.8
Infiltration	1.2	0.5	0.3	0.05

Table 2. Model parameter variations

Model Parameters	Base case	All Refurbishment
Heating set point (C˚) [19,20]	23	22
Heating setback (C˚)	16	12
Ventilation (l/s/per person) [16]	10	20
Lighting (W/m^2) [10]	15	12
Daylight control	Off	On
Office equipment (W/m^2) [10]	12	10
HVAC efficiency	75%	95%

London was taken as the location because it contains 33% of the UK's office buildings. Islington weather data was chosen in order to represent the inner city and take account of the urban heat island effect. Both current and future weather were derived from the Prometheus Project of Exeter University. Future weather files were created by using a probabilistic approach at different percentiles. In this study, Test Reference Year (TRY) files for medium emission at the 50th percentile were used for the year 2050.

2.2. Refurbishment Options

In the present work, refurbishments were applied to reduce heating energy demand and provide shading and passive cooling, and the impact on thermal comfort was studied. Potential refurbishment features were evaluated at two levels. The first level was “fixed” refurbishments, consisting of building services and equipment efficiency. Post-war non-domestic buildings are typically concrete constructions and their structural lifespan is estimated at approximately 100 years, but building services such as heating and lighting systems have a lifespan of about 30 years. Thus, post-war offices currently in use are likely to have had minor refurbishments. To implement this assumption, the fixed refurbishments listed in Table 2, consisting of improvements in the efficiency of lighting, HVAC system and office equipment and addition of daylight control, were applied to all base cases.

Two groups of refurbishments were then applied. First were envelope modifications consisting of various fabric refurbishments based on Part L 2010, Good Practice and Passivhaus Standards such as addition of insulation, changing glazing type, increasing glazing-to-wall ratio and assigning better airtightness and U-values as defined in Table 1. The glazing-to-wall ratio was increased to 80% as a refurbishment option to capture variations with higher solar gain. No dominant orientation could be derived from the literature so the short axis was oriented north-south. The second group is a set of “cooling” refurbishments consisting of shading and passive cooling methods including the addition of blinds, overhangs and night ventilation to address the problem of potential summer overheating. The blinds were external, operating only at occupied hours when the internal temperature was over 24 ˚C. Overhangs were set at 1.5 m width according to the sunlit angle in London and attached to the top of the windows. Night ventilation was implemented from 1st April to 30th September when the internal temperature was above 24 ˚C. An unshaded case was studied to observe the level of overheating in the absence of this second group of refurbishments.

3. Results

Simulation results are presented in Fig. 3 for total annual energy consumption and thermal comfort, both for the present day and the 2050 weather, and for all refurbishment combinations with both 30% and 80% glazing ratios. The base case model had total annual energy consumption of 250 kWh, in good agreement with the average energy consumption of office buildings, 252 kWh, as reported in a national survey [6]. In the base case model, because of low radiant temperature caused by the poor thermal properties of the fabric, acceptable operative temperatures could not be achieved unless the heating set point exceeded 24 ˚C. This is consistent with previous work [22] which found that wintertime discomfort due to low radiant temperature led the occupants to adjust the heaters to raise the air temperature to a level providing an acceptable operative temperature. In the summer, however, the low operative temperature and poor airtightness lead to reasonable thermal comfort.

Significant heating consumption reduction is identified as a result of all refurbishment variations. Only applying fixed refurbishments reduced energy consumption to 175.1 kWh. Among the envelope refurbishments, the variation with the lowest energy consumption, 42.7 kWh, was the Passivhaus standard envelope with 80% glazing and no shading, while the highest energy consumption was 63.7 kWh from the variation consisting of the Part L standard and 30% glazing. For all cases, the Passivhaus standard envelope provided the lowest heating demand and therefore the lowest energy consumption. Also, the higher glazing ratio provided higher solar gain and daylight availability resulting in lower heating and electricity demand. Similar results were obtained for the future weather data but with lower heating demand due to increased ambient temperature. As a result of thermal comfort analyses, an inverse correlation between energy reduction and thermal comfort was observed. The low radiant temperature problem is mitigated in the refurbished variations. However, alternatives with no shading are likely to have higher discomfort due to summer overheating. This was addressed using the “cooling” refurbishments. For the 80% glazing alternatives, the effect of these measures is shown in Figure 3. Although the ‘No shading’ alternative has the lowest energy consumption, it provides the highest discomfort which decreases in turn as blind (B), blind + overhang (B+OH) and blind + overhang + night ventilation (B+OH+NV) are added. For the 30% glazing versions, the same pattern arises except for the Good Practice standard envelope with (B+OH) because of additional solar protection causes discomfort in the winter. So the “cooling” refurbishments have a positive effect on the discomfort, which is mainly due to summer overheating, but do not entirely solve the problem. Due to reduction of heating energy as a result of the high performance envelope, the proportion of the electricity increases within the total energy consumption. Despite the positive effect of shading on thermal comfort, it increases electricity demand because of the reduced daylight, so that total consumption likely to increase.

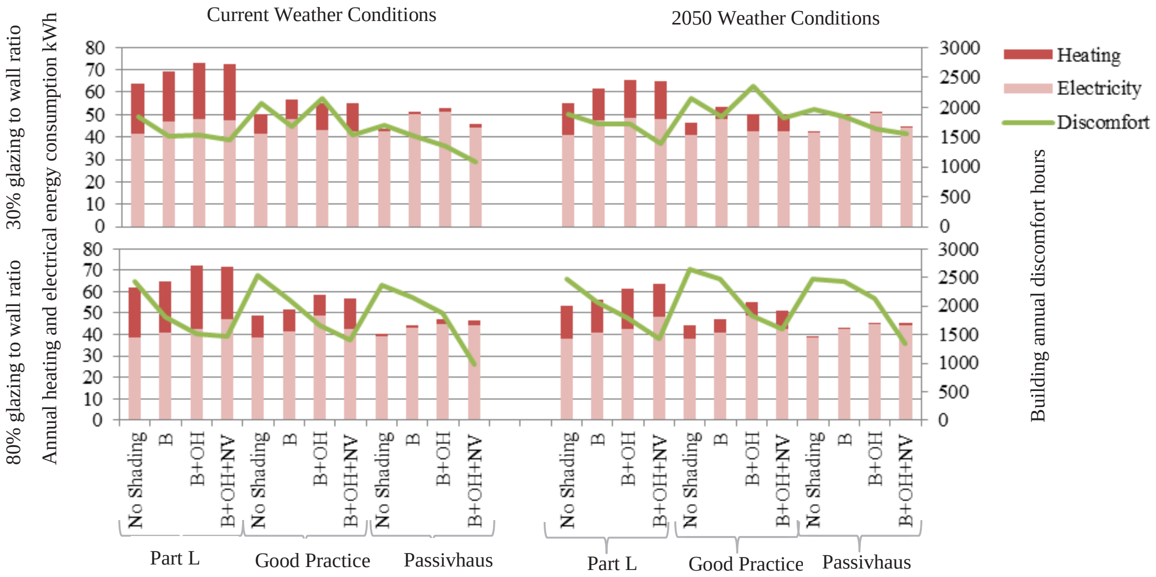

Fig.3. Heating energy and electricity consumption and thermal discomfort

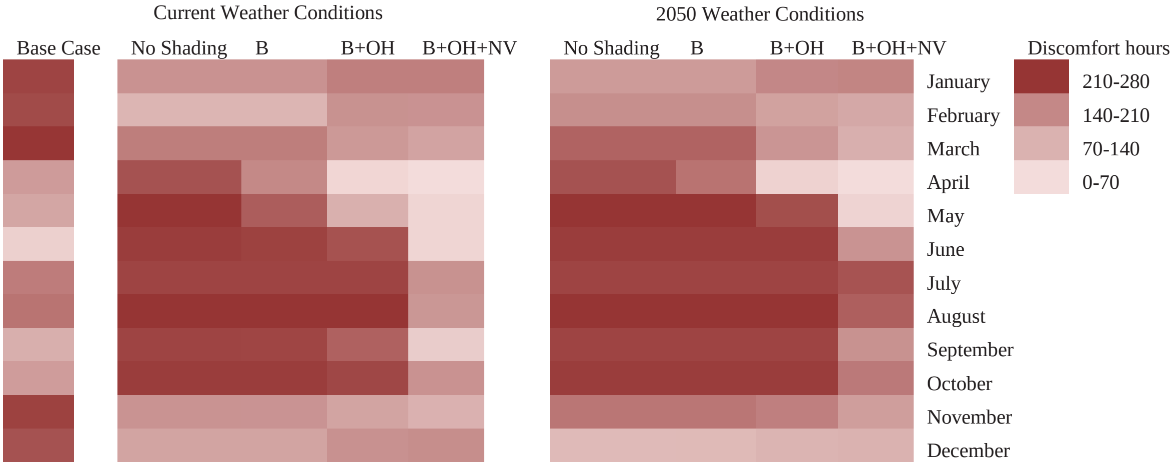

Fig.4. Comparison of discomfort hours of base case, current and 2050 weather conditions for Passivhaus envelope with 80% glazing ratio

The pattern of discomfort through the year for the Passivhaus envelope with 80% glazing is illustrated in Fig. 4. The key comparison is between the base case on the left and all other cases, which represent the impact of the “cooling” measures in the present day and 2050. In the base case, the dark shades, which indicate high overheating, are in the winter and reflect the thermal discomfort due to low operative temperature. In all other cases the dark shades are in the summer showing that thermal discomfort is now due to overheating. Its mitigation by introducing gradually more passive “cooling” measures is clearly visible, as is the slight worsening in 2050 due to the warmer weather.

4. Conclusions

Thermal discomfort leads to lower productivity in the workplace and so represents an important driver for refurbishment decisions in non-domestic buildings. However, post-war office buildings are not only high energy consumers but also cause thermal discomfort in winter due to low radiant temperatures. Although commonly applied refurbishment solutions yield significant reductions in energy consumption in these types of buildings, the present work shows that they fail to deliver the required thermal comfort in summer due to overheating, and warmer weather in the future will make this situation worse. As a solution, greater attention needs to be given to providing a wider range of summertime cooling measures as part of whole-building refurbishment packages.

Future work

Future work will include a study of more advanced refurbishment packages for heating and cooling energy reductions. In addition costs will be attributed to the refurbishment packages, allowing optimization to be carried out along with a study of the possible trade-offs. Finally, the study will be extended to outer city zones.

Acknowledgements

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