EVALUATION OF REFURBISHMENT STRATEGIES FOR POST-WAR OFFICE BUILDINGS

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ABSTRACT

Multiple combinations of energy saving refurbishment measures were applied to representative models of post-war office buildings using EnergyPlus. Based on energy consumption, thermal comfort and costs, a range of heating and cooling refurbishment features were evaluated under a parameter study. The evaluation shows that although refurbished post-war offices with high insulation consume negligible amounts of heating energy, thermal comfort could only be provided by additional active cooling which results in higher costs and lower greenhouse gas reductions.

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 (UKGBC) 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 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 are notable for their 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 and user behaviour patterns.

In addition to the significant energy consumption, which is mainly due to poor glazing and lack of insulation, 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 (Gething, 2010).

The work described in the present paper is part 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 and costs.

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’ (Korolija et al., 2013) 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 (EnergyPlus, 2015) models. The refurbishment options were implemented using JEPlus (2015) a tool for managing parametric analysis in E+ simulations using multiple design parameters.

The aim of the refurbishments was to reduce energy consumption while providing thermal comfort. It was necessary to take the costs into account in order to be able to provide realistic guidance to the refurbishment designers and decision makers. Therefore, refurbishment variations were evaluated as energy reduction versus costs within the constraint of thermal comfort.

As the aim of the project is to provide real-world guidance, only refurbishments that would be applied together were considered. For saving heating energy, three envelope packages were designed, based on Part L of the current Building Regulations (ODPM 2012), Good Practice (ECON, 2003) and EnerPHit (2015), the Passivhaus standard for refurbishment, as described in Table 1.

It was known from earlier work (Duran et al 2015) that overheating was a likely result of envelope refurbishment of post-war office buildings, so a set of passive cooling measures and mixed mode ventilation were also considered to address this problem.

Using all possible combinations of the refurbishment options, the potential for improving the energy efficiency and thermal comfort of buildings of the chosen type was then analysed as described later. The costs of the refurbishment packages were taken into consideration and the results were evaluated to explore the possibilities for the refurbishment of such buildings.

Input data

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 (Pout, 2000), regulations of the era (HMG, 1965) data analysis (Armitage et al., 2015) and previous studies (Korolija et al., 2013, Smith, 2009). However, the literature data for non-domestic buildings is limited and rather 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 consumption and thermal comfort. As part of this process, the results were compared with national survey averages (Pout, 2000) and benchmarks (ECON, 2003), in order to ensure results were realistic. The base case results were also compared with the results of work (Armitage et al., 2015) 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 consumption. Despite this diversity, detailed work by Steadman et al. 2003 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 represents 34% of non-domestic UK buildings and 64% of the offices in 1994, was chosen as shown in Figure 1.

Figure 1 Cellular daylit office building exemplar

Supporting information was derived from the office benchmarks (ECON, 2003), 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 Steadman et al. (2003). As shown in Figure 2, two office zones and a circulation zone were defined on each of the 32 m by16 m floors.

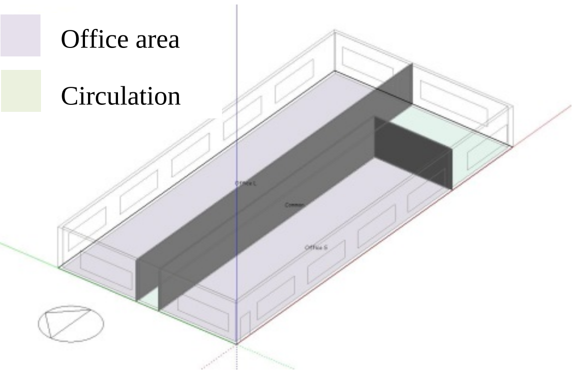

Figure 2 Zones in the office building exemplar

No dominant orientation could be derived from the literature so the short axis was oriented north-south.

In the UK, the Building Regulations of 1965 (HMG, 1965) 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 (HMG, 1985) to 2002. The regulations of 2006 introduced the first specific requirements on the energy conservation measures in refurbishment of non-domestic buildings (ODPM, 2010). 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.

Table 1
Envelope properties

Fabric U-values (Wm^{-2}K^{-1}) infiltration (ach)	Base case and Minor Refurb.	PartL 2010	Good Practice	EnerPHit
External wall	1.7	0.35	0.25	0.15
Roof	1.42	0.25	0.14	0.15
Ground floor	1.42	0.25	0.15	0.15
Glazing	5.87	2.0	1.8	0.8
Infiltration	1.2	0.5	0.3	0.05

Occupancy-related parameters were based on average behaviours for typical office workers and fixed for all computations; occupancy was solely on weekdays from 8:00 - 18:00 at a density of 14m² per person (BCO, 2009). 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 were gathered from relevant regulations and surveys. The building was assumed to be naturally ventilated at internal temperatures above 24.0 ˚C when it was occupied. Airtightness is one of the most uncertain values due to lack of relevant measurements. However, making use of Smith (2009), ECON (2003) and CIBSE TM53, (CIBSE 2013b) 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 (2000), the proportion of glazed areas in the external walls was set at 30, 40 and 50 percent of the wall area for the base case in order to capture all possibilities.

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. Current weather was derived from the Prometheus Project of Exeter University (Eames et al., 2011) which also provides future weather data to be used in later work.

Energy reduction

Post-war non-domestic buildings are typically concrete constructions with a structural lifespan of about 100 years, but building services such as heating and lighting systems are typically upgraded every 30 years or so. The minor refurbishments likely to have been applied to post-war offices currently in use are listed in Table 2. They consist of improvements in the efficiency of lighting, HVAC system and office equipment and addition of daylight control, and were applied to the three base cases defined by the glazing ratios.

Table 2
Model parameter variations

Model Parameters	Base case	After Minor Refurbishment
Heating set point (˚C) (CEN 2007b, CIBSE 2006a)	23	22
Heating setback (˚C)	16	12
Ventilation (l/s/person) (CEN 2007a)	10	20
Lighting (W/m²) (ECON, 2003)	15	12
Daylight control	Off	On
Office equipment (W/m²) (ECON, 2003)	12	10
Boiler efficiency	70%	90%

Two groups of refurbishments were then applied. First, heating energy reduction was achieved by envelope modifications consisting of various fabric modifications based on Part L 2010, Good Practice and EnerPHit standards such as addition of insulation, changing glazing type and assigning better airtightness and U-values as defined in Table 1.

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, along with mixed mode cooling to address the problem of potential summer overheating.

The blinds were external, operating only during occupied hours when the internal temperature was over 24.0˚C.

The ratio of the projection of the overhang to the height of the window determines the solar control of the overhangs. Although a ratio of 1:1 gives good protection in summer, it would cause overshading of the north facade. TM37 (CIBSE 2006) suggests that an overhang projecting by only half the window height is adequate, particularly on south facing windows so a 1:2 ratio overhang was used.

Thus, overhangs were medium reflective slats, which were set at 1.0m depth according to the sunlit angle in London and attached to the top of the windows.

Especially for heavyweight constructions, night ventilation can be beneficial. Increased night time ventilation increases the daytime cooling capacity of the building fabric, although there are diminishing returns with increasing air change rates (CIBSE 2000). Night ventilation was defined as the ventilation in unoccupied hours and implemented from 1 April to 30 September when the internal temperature was above 24.0˚C.

Mixed mode, also known as hybrid, ventilation consists in turning on the mechanical ventilation when natural ventilation cannot provide required cooling. In order to identify whether passive cooling methods alone could provide an acceptable level of thermal comfort and to evaluate the potential of mixed mode ventilation, this partial mechanical cooling was included as a refurbishment option. Different combinations of period and set-point temperature were investigated to determine when the mechanical ventilation should turn on (and natural ventilation turn off). It was found that the period 1 March to 30 October and a set-point temperature of 24.0˚C were needed to ensure overheating was addressed. The aim was to reduce the thermal discomfort due to summer overheating. An unshaded case was studied to observe the level of overheating in the absence of this second group of refurbishments.

The JEPlus software used in this work requires a "parameter tree", shown in Figure 3, to describe the option variations it creates. Three base case combinations were formed based on the input parameters mentioned earlier and differing only in glazing ratio. To achieve this workflow, the E+ base case files were modified in JEPlus in order to prepare 144 simulations that capture all possible combinations. “No” symbolises the cases which defined refurbishment was not applied. By this, individual effects of refurbishment features could be also identified.

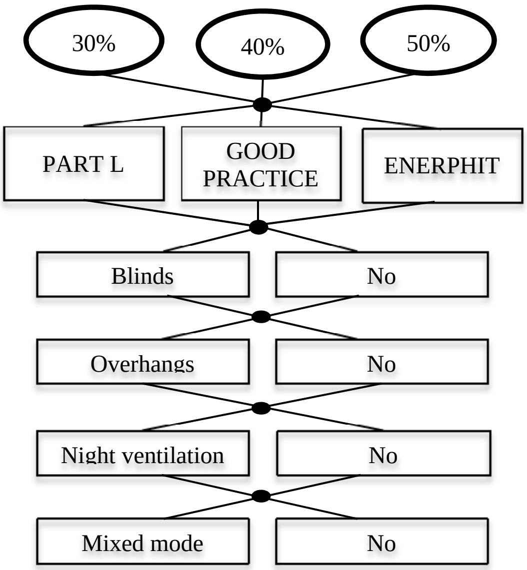

Figure 3 Parameter tree

Thermal comfort

The thermal comfort of the building occupants represents an important constraint on the results. Only those packages that achieve a reasonable level of thermal comfort are considered to be potential solutions. Several methods of assessing thermal comfort were available in E+, including ANSI/ASHRAE Standard 55 (ASHRAE 2004) and variants of the CEN standard (CEN 2007b). The one chosen was CEN level 2 (CEN2 hereafter) which applies to both new and refurbished buildings. This is an adaptive method making it suitable for the naturally ventilated buildings being considered and which, being European, is appropriate for UK buildings.

The approach adopted requires a level of thermal comfort to be assigned to the whole building. E+ calculates a ‘Facility’ figure for one specific thermal comfort measure Simplified ASHRAE 55, and. software was written to perform a similar calculation for CEN2. But the Facility method can be misleading because the whole building is deemed uncomfortable when there is thermal discomfort in one or more zones. A zonal average measure of hours of thermal discomfort was therefore used instead.

Comparison of summer and annual results showed that the thermal discomfort is mainly the result of summer overheating.

The summer overheating definition of CIBSE (2013a) criterion one was used in the present work in order to determine the thermal comfort of the various refurbishment cases. Cases, which have thermal discomfort above 3% of the occupied hours (86 hours for the present work) are taken to be uncomfortable.

Cost estimations

Cost estimation has significant uncertainty due to calculation methods, the ratio of the assumptions to be made and the choosing figures out of wide price ranges. Two specialised price books are chosen to calculate the costs; Spon's architects' and builders' price book 2015 and BCIS Alterations and Refurbishment Price Book 2015. Both books provide estimates including material and labour costs based on UK national average best trade prices. Overheads and profit are not included in the calculations. Therefore, the given figures do not represent the actual budget for the refurbishment but do provide values suitable for comparison.

Also, refurbishments such as mixed mode ventilation can be complex to model and have widely varying costs and performance. For these sorts of cases, average figures have been used.

Additionally, refurbishment standards such as EnerPHit require experienced workmanship and careful implementation, which could increase the working hours. However, this phenomenon was not implemented to the calculations due to uncertainty of the estimation.

Greenhouse gas emissions

The main output of the simulations consisted of the annual electricity, heating and cooling load for each of the zones in the model. This was post-processed to determine consumption of electricity and gas. 100% efficiency was assumed for electricity, while gas boilers were taken to be 90% efficient and a coefficient of performance of 2.5 was assumed for mechanical cooling. Carbon dioxide equivalent emissions were then obtained by multiplying by the emissions factors of DEFRA (2013): 0.184 kg CO_2e/kWh (based on gross CV) for natural gas and the long-term marginal factor of 0.406 kg CO_2e/kWh for grid electricity.

RESULTS AND DISCUSSION

Figures 4 and 5 are sample graphs of 50% and 30% glazing ratio alternatives sorted according to energy consumption. The given name of each case (e.g. G30_GP_Bx_O_NV_MM) indicates, in order, glazing ratio (G30, G40, G50), envelope standard (PL-Part L, GP-Good Practice, EPH-EnerPHit), blind (B), overhang (O), night ventilation (NV), mixed mode (MM) and lack of these are indicated by an additional x.

Heating

For heating as expected the dominant effect is the result of providing better U-values for the envelope. EnerPHit, Good Practice and Part L envelope levels reduce annual heating energy to less than 1, around 7 and around 20 kWh/m^2 respectively, from the base case with minor refurbishments heating consumption of 128 kWh/m^2. For all envelopes, the increase of the glazing ratio increases heating consumption, as does the existence of an overhang. For instance, options with 40% glazing ratio and overhang require higher heating energy than those with 50% glazing ratio and no overhang.

Cooling

Cooling consumption is calculated for the cases to which mixed mode ventilation is applied as a refurbishment option to take the operational energy into consideration. With a few exceptions, the existence of night ventilation is the dominant feature, which provides lower cooling consumption. Additionally, lack of blinds and overhangs also cause higher cooling consumption. Improvement of the envelope with no shading devices increases the need for cooling. EnerPHit envelope 50% glazing with no passive cooling requires 57.3 kWh/m^2 while Part L envelope 30% glazing with shading devices consumes less than a quarter of this figure at 13.4 kWh/m^2.

Lighting and appliances

Lighting energy consumption is dominated by glazing ratio and the existence of shading devices, especially blinds. A higher glazing ratio provides lower artificial lighting while shading devices increase it. An EnerPHit option with 30% glazing and shading devices requires 23.1 kWh/m^2 lighting energy while 50% glazing ratio option without shading devices requires 7.4 kWh/m^2.

Equipment energy is 29.6 kWh/m^2 for all the cases because no alteration was made for the equipment.

Overall energy consumption

Total energy consumption is the sum of heating, cooling, lighting and equipment energy, which is varied between 40.9 kWh/m^2 (50% glazing without any cooling, EnerPHit envelope) and 98.2 kWh/m^2 (50% glazing with no passive cooling but only mixed mode ventilation, EnerPHit envelope). Total energy consumption significantly increases for the cases with mixed mode ventilation because of additional cooling consumption. Separate evaluation of the cases according to the presence or otherwise of mixed mode shows that higher energy reduction is provided by EnerPHit envelope cases when there is no mixed mode ventilation while the cases with the Part L envelope envelope and shading devices have highest energy consumption. However, when mixed mode is used, EnerPHit envelope cases are the highest consumers.

Emissions

It is worth to highlight that higher energy reduction and GHG emissions reduction is not always provided by similar refurbishment feature combinations. The cases, which have their energy consumption dominated by electricity, cause more GHG emissions although they are lower energy consumer. Similar to total energy consumption, GHG emissions could be evaluated in two groups according to existence of mixed mode. For the cases without mixed mode so that cooling consumption, highest GHG emissions are the result of higher lighting energy, which is due to shading devices and heating energy as a result of envelope standard. For instance, the case with 30% glazing, EnerPHit level and passive cooling, consumes 54.9 kWh and release 20.98 kg CO2e/kWh while the case with 50% glazing, Part L standard and passive cooling, consumes 65.1 kWh and release 21.07 kg CO2e/kWh.

Thermal comfort

Thermal discomfort hours are calculated for zonal averaged values as described above. Prior to refurbishment, the major reason for the thermal discomfort of post-war office buildings was due to low radiant temperatures, which is the result of poor envelope properties. Improvement of the envelope provides a solution for this phenomenon However, the cases which any cooling refurbishment was not applied did result in significant discomfort due to summer overheating (Duran et al. 2015).

Thermal comfort is also has to be evaluated according to existence of mixed mode because only in a few cases, which have other cooling options, a reasonable thermal comfort could be provided without mixed mode ventilation and none of which was EnerPHit level. EnerPHit level cases without night ventilation and mixed mode ventilation, no matter shading devices exist or not, have excessive thermal discomfort varying between 1419-1585 hours. Of the cases which have shading devices but no night ventilation and mixed mode, a significant improvement observed for Part L and Good Practice but not for EnerPHit standard. Smallest discomfort provided for EnerPHit standard is 109 hours as a result of 30% glazing and including all cooling features. The higher the envelope standard, the more discomfort hours calculated in the lack of cooling strategy.

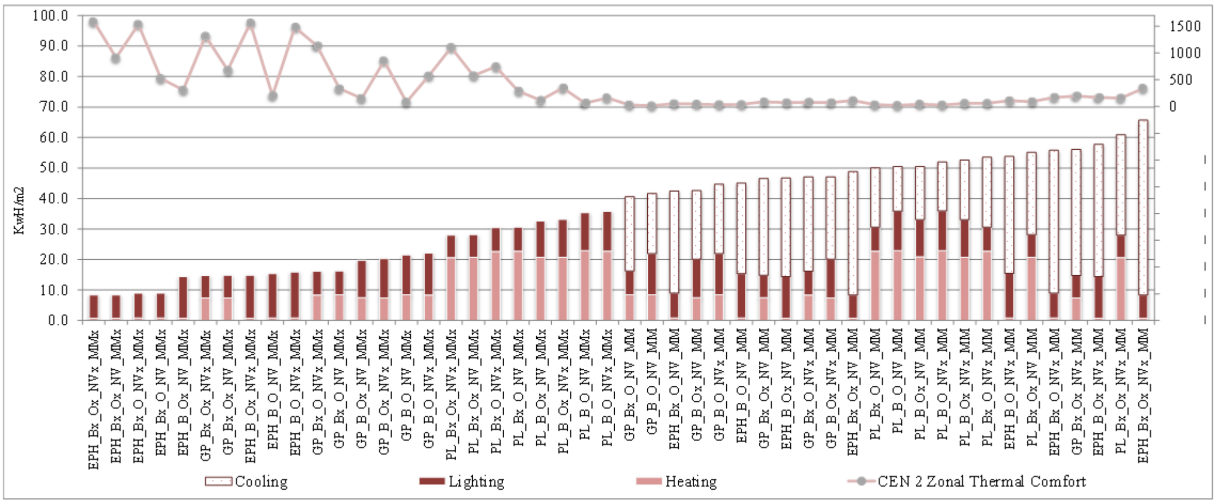

Figure 4 Energy demand and thermal discomfort hours of all cases with glazing ratio 50%

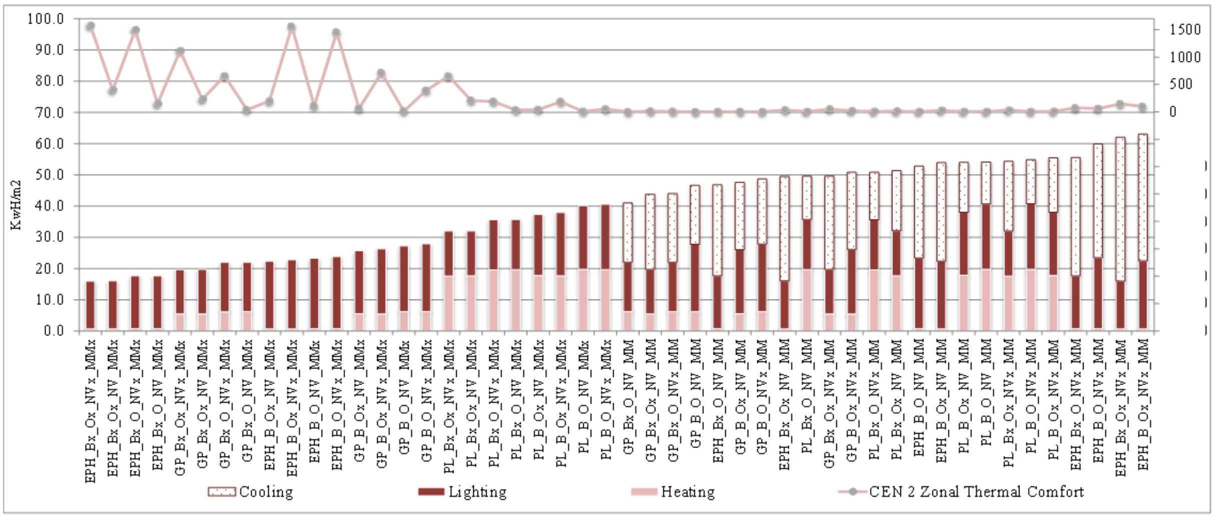

Figure 5 Energy demand and thermal discomfort hours of all cases with glazing ratio 30%

Larger glazing causes worse thermal comfort in the lack of cooling refurbishment. This is obvious for Part L and Good practice, for instance 30% glazing ratio Part L standard case with no cooling has thermal discomfort of 653 hours while same case with 50% cause 1103 hour discomfort. However, in EnerPHit level discomfort is already excessively high for uncooled cases so that the difference is negligible. When mixed mode ventilation is applied, all cases result in reasonable thermal comfort except the EnerPHit level with no other cooling features.

Impact of costs

In addition to the costs of refurbishment features, the impact of cost savings due to reduced operational energy consumption was evaluated. This allows a comparison of the efficacy of the different refurbishment packages for reducing greenhouse gas emissions by calculating a cost-effectiveness in £/kg CO2e for each.

By considering the operational energy consumption for 35 years, a rough estimate of the lifetime of the measures, along with the cost of the refurbishment itself, it is possible to estimate the overall benefit of each package. Energy costs and the emissions factor for gas were kept at current values, while the emissions factor for electricity was assumed to decrease linearly to zero over the time period, to take account of grid decarbonisation. The net present values of the operational energy costs were calculated using a discount rate of 5% and the cost-effectiveness calculated according to the methods described by Taylor (2012). Note that all values were positive, thus avoiding the problems discussed in that work. Results for the cases with 30% and 50% glazing which provided thermal comfort are shown in Tables 3 and 4.

It is noticeable that the best figures for cost-effectiveness are provided by the more modest envelope refurbishments offered by Part L and Good Practice, with use of the EnerPHit envelopes leading to at least three times the cost of the leading package to achieve the same emissions reduction. The reasons are the higher initial cost of the EnerPHit envelope refurbishment and the additional electricity use required by extensive mixed mode operation to deal with the amount of cooling required.

While the approximate nature of the cost-effectiveness calculation and the uncertainty in the many assumptions underlying it mean that it should be seen as indicative only, it is interesting that the modest level of refurbishment represented by Part L standards represents much better value in emissions saving than the much higher specification EnerPHit. In reality, the difference is probably even greater because the costs associated with the higher quality work were not included in the analysis.

Table 3
Cost effectiveness for 30% glazing

Cost effectiveness of refurb package £/tCO2	Heating	Cooling			
	Enevelope	Blind	Overhang	Night Ventilation	Mixed Mode
£72.75	Part L	No	Yes	Yes	No
£74.00	Part L	No	No	No	Yes
£76.21	Part L	No	Yes	No	Yes
£84.93	Part L	Yes	Yes	No	No
£88.11	Good Practice	No	Yes	Yes	No
£89.78	Part L	Yes	No	Yes	No
£98.49	Part L	Yes	Yes	Yes	No
£99.63	Part L	Yes	No	No	Yes
£100.14	Good Practice	No	Yes	No	Yes
£100.97	Good Practice	No	No	No	Yes
£104.58	Part L	Yes	Yes	No	Yes
£107.30	Good Practice	Yes	No	Yes	No
£108.20	Part L	No	No	Yes	Yes
£112.97	Part L	No	Yes	Yes	Yes
£113.73	Good Practice	Yes	Yes	Yes	No
£126.57	Good Practice	Yes	No	No	Yes
£128.06	Good Practice	No	No	Yes	Yes
£128.98	Good Practice	Yes	Yes	No	Yes
£130.70	Good Practice	No	Yes	Yes	Yes
£137.15	Part L	Yes	No	Yes	Yes
£141.84	EnerPHit	No	Yes	No	Yes
£143.68	Part L	Yes	Yes	Yes	Yes
£157.84	Good Practice	Yes	No	Yes	Yes
£161.71	EnerPHit	No	No	Yes	Yes
£162.07	Good Practice	Yes	Yes	Yes	Yes
£164.12	EnerPHit	No	Yes	Yes	Yes
£173.16	EnerPHit	Yes	Yes	No	Yes
£194.37	EnerPHit	Yes	No	Yes	Yes
£197.81	EnerPHit	Yes	Yes	Yes	Yes

Table 4
Cost effectiveness for 50% glazing

Cost effectiveness of refurb package £/tCO2	Heating	Cooling			
	Enevelope	Blind	Overhang	Night Ventilation	Mixed Mode
£86.72	Part L	No	Yes	No	Yes
£106.50	Part L	Yes	Yes	Yes	No
£107.86	Part L	Yes	No	No	Yes
£115.52	Part L	Yes	Yes	No	Yes
£115.57	Good Practice	No	Yes	No	Yes
£119.24	Part L	No	Yes	Yes	Yes
£124.41	Good Practice	Yes	Yes	Yes	No
£137.38	Good Practice	Yes	No	No	Yes
£140.51	Good Practice	No	Yes	Yes	Yes
£141.66	Good Practice	No	No	Yes	Yes
£142.04	Good Practice	Yes	Yes	No	Yes
£142.27	Part L	Yes	No	Yes	Yes
£151.25	Part L	Yes	Yes	Yes	Yes
£164.89	Good Practice	Yes	No	Yes	Yes
£171.69	Good Practice	Yes	Yes	Yes	Yes
£175.39	EnerPHit	No	Yes	Yes	Yes
£205.94	EnerPHit	Yes	No	Yes	Yes
£210.79	EnerPHit	Yes	Yes	Yes	Yes

CONCLUSIONS

Post-war office buildings are not only high energy consumers but also cause thermal discomfort in winter due to low radiant temperatures. Additionally, because of their large proportion in building stock and ongoing life span they have significant potential for refurbishment. However, refurbishment decisions are affected by complex parameters; in this paper three parameters are evaluated: energy saving, thermal comfort and costs.

The overall evaluation shows that applying the highest practical standard of envelope refurbishment, the EnerPHit envelope, to a postwar office results in additional energy for cooling and even higher costs.

Although this envelope reduces heating energy to values close to zero, the required active cooling consumption to provide thermal comfort is high enough in many cases to outweigh the energy reduction due to heating. Moreover, the application, running and maintenance of the additional active cooling system causes higher costs.

On the other hand, although existing standards such as Part L require little or no cooling energy to provide thermal comfort, their heating consumption is clearly higher and by this way, they consume higher energy in operational costs.

The use of cost-effectiveness to assess the balance between these cases suggests that, as far as the reduction of emissions is concerned, better value is obtained by applying the more modest level of refurbishment represented by Part L than the very high specification Passivhaus-level EnerPHit.

FUTURE WORK

Future work will include the attribution of costs to the other more advanced refurbishment packages for heating and cooling energy reductions, allowing optimization to be carried out along with a study of the possible trade-offs. In addition, the study will be extended to outer city zones and future weather. Later, the whole process will be repeated for “Exemplar II” which is representative of open plan deep office types.

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