Journal of Building Engineering 42 (2021) 102746

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: http://www.elsevier.com/locate/jobe

Retrofitting post-war office buildings: Interventions for energy efficiency, improved comfort, productivity and cost reduction

Özlem Duran [a,*], Kevin J. Lomas [b]

[a] School of Architecture and Built Environment, College of Arts, University of Lincoln, Brayford Way, Brayford Pool, Lincoln, LN6 7TS, UK
[b] School of Architecture, Building and Civil Engineering, Loughborough University, Epinal Way, Loughborough, Leicestershire, LE11 3TU, UK

ARTICLE INFO

Keywords:
Retrofit
UK office Building
Energy demand
Comfort
Building performance simulation

ABSTRACT

Within the UK non-domestic building stock, offices built between 1940 and 1980, are especially in need of retrofit, they can suffer from high energy consumption and thermal discomfort. Many post-war offices will still be in use throughout the first half of this century. This paper evaluates retrofit strategies for post-war office buildings accounting for the improved energy efficiency, thermal comfort and hence productivity, and reduction of capital and running costs. The aim of the paper is seeking optimal, generic retrofit strategies to provide guidance to building owners, occupiers and other decision makers. Dynamic thermal modelling is used to compare retrofit outcomes for existing building standards (PartL2B) and higher standards (Passivhaus retrofit: EnerPHit). The effects of location and orientation and both current and future UK weather conditions (2050) are considered. Multiple combinations of heating and cooling strategies and retrofit measures are assessed. The analysis methodology uses a sophisticated comfort, productivity and cost assessment. An Overall Building Thermal Discomfort (OBTD) index is introduced which enriches the current CIBSE overheating criterion 1 by including the number of occupants. Productivity improvements as a result of better comfort are included in cost calculations. Cost benefits are calculated both for buildings used by the owner (CBO) and for buildings let to a tenant (CBT). On cost and energy grounds, UK building regulation compliant retrofit is optimal provided that passive summertime overheating controls, such as night ventilation, blinds and/or overhangs, are installed. The EnerPHit standard retrofit provides resilience as the climate warms provided summer cooling is available, for example through mixed-mode ventilation.

1. Introduction

1.1. Background and context

Buildings form a significant part of carbon reduction potential as they account for around 45% of total UK carbon emissions. Although, the commitment of the 2006 government that all new non-domestic buildings should be zero carbon from 2019 [1] was scrapped, The Climate Change Act, now requires the UK to achieve net-zero emissions "*at least %100*" by 2050 [2] is in force and legislations towards achieving this target is emerging.

The Energy Performance Certificate (EPC) is a European Union initiative which rates the energy efficiency of buildings (A to G) and is required in all non-domestic (and domestic in some counties) buildings over 500 m^2 whenever they are built, sold or rented. In response to The Energy Act 2011, from April 2018 private non-domestic landlords must ensure that the properties they rent out in England and Wales reach at least an (EPC) rating of E before granting a tenancy to new or existing tenants [3]. During the fourth quarter of 2019, 19% of UK non-domestic buildings were rated E or below [4], which could be classified as poorly performing and in the necessity of urgent retrofit.

Within the UK non-domestic building stock, post-war buildings built between 1940 and 1980, are especially in need of retrofit. They were built prior to the introduction of Building Regulations that regulate the thermal performance of buildings using pre-cast concrete with curtain wall systems for a speedy construction [5]. The insulation of the envelope is poor, and they have high infiltration rates through the poorly sealed facade [5]. Uncontrolled solar gains due to a lack of shading combined with high internal heat gains as a result of a significant increase in IT equipment and artificial lighting [6] can cause summertime overheating.

Many post-war offices have not completed their life span and will still be in use throughout the first half of this century. Considering that they represent 19% of the gross internal area of UK office buildings [7]

* Corresponding author.
E-mail address: oduran@lincoln.ac.uk (Ö. Duran).

https://doi.org/10.1016/j.jobe.2021.102746
Received 8 February 2021; Received in revised form 29 April 2021; Accepted 16 May 2021
Available online 24 May 2021

and an even higher proportion of the energy consumption, there is a significant national benefit to be had from retrofit. In so doing, running costs could be reduced and thermal comfort improved, so enhancing occupant productivity, and the buildings' aesthetics.

In the UK, the first mandatory requirements to include energy conservation measures in retrofit were published in 2006 in Approved Document L2B and was subsequently improved in 2010 and 2013 [8]. In line with concerns tackled in this paper, the upcoming version of the Regulations is expected to consider the mitigation of summertime overheating.

Technically and practically, it is feasible to achieve higher energy efficiency levels through building retrofit than the minimum levels set by the building regulations; PartL2B. This paper compares retrofit to Part L standard with retrofit to the EnerPHit standard, which is a Passivhaus standard created expressly for retrofit [9].

1.2. Previous research

Many retrofit studies have focused on office buildings, however most of these do not focus on buildings of the post-war era. They tend to consider only basic retrofit measures; but have concluded that advanced retrofit measures need to be evaluated [10,11]. Most studies have had limited objectives in terms of either costs or retrofit measures [12–16]. Some which evaluated advanced retrofit measures have not included advanced economic considerations [17]. Others have researched only the correlation of comfort with energy efficiency [18].

In 2009, Kolokotsa et al. [19] observed that studies of energy efficiency and building performance have focussed on specific actions or action categories rather than taking a global and holistic approach. This research seeks to fill this gap by evaluating both passive and active retrofit measures taking account of energy efficiency, costs and comfort and productivity.

1.3. Aim and structure

The aim of this paper is to evaluate different retrofit strategies for post-war UK office buildings, accounting for the improved energy efficiency, thermal comfort and hence productivity and the reduction of capital costs and running costs. Consideration is given to the effects of location and orientation and the current and 2050 UK weather conditions. Dynamic thermal modelling is used to predict annual energy demands and internal temperatures.

The methodology adopts a more sophisticated approach to thermal comfort assessment and cost estimation than the present literature: Overall Building Thermal Discomfort (OBTD) is calculated for both summer heat and winter cold, accounting for differences in the occupation of different spaces; productivity costs due to discomfort are calculated accounting for whether the building is occupied by the owner (CBO) or rented (CBT). The paper seeks to provide the optimal, generic retrofit strategies when using either current building standards (PartL2B) or the high, EnerPHit standard. The work aims to provide guidance to building owners, occupiers and other decision makers.

2. Methodology

Firstly, an exemplar building and its base-case models, which represents the typical post-war office building stock, were created based on a detailed literature review (Table 1). The buildings were simulated using the EnergyPlus (E+) [20] dynamic thermal model (DSM), with data input via the DesignBuilder [21] Graphical User Interface (DB). The retrofit options were implemented using JE Plus [22], a tool for managing parametric analysis in E+ simulations. After that, a series of retrofit measures were applied to the base-case models including envelope upgrades, and passive and active cooling strategies. Fig. 1 shows the parameter tree, which provides 256 possible combinations of retrofit options.

Initial optimisation simulations were undertaken to determine the best individual retrofit measures, and their detailed form. For instance, blinds have various characteristics, such as slat angle, reflectivity, operating schedule. Keeping other parameters constant, the optimal blind configuration was determined for each retrofit combination.

2.1. Energy reduction assessment

The energy demand output of the E+ simulations consisted of the annual electricity or gas use for each of the zones in the model: for lighting and equipment; for fans and automation (e.g. blinds and night ventilation); for space heating and for hot water; and for cooling (e.g. mixed-mode ventilation). Gas boilers were taken to be 90% efficient in

Table 1
Base-case, PartL2B and EnerPHit retrofit input summary.

		Base-case		PartL2B (2015)		EnerPHit		Source References
		Office	Circulation	Office	Circulation	Office	Circulation	
Weather Data								[46,47,59]
Occupancy	m^2/per	14	9[a]	14	9[a]	14	9[a]	[51,54,56,57,60]
Equipment	W/m^2	10	2	10	2	10	2	[43,61–63]
Lighting	W/m^2	12	3.4	8	3.4	8	3.5	[58,64–67]
Heating set-point	°C	22	20	22	20	2	20	[24,50,68]
Heating set-back	°C	14		14		14		
Heating season		1 October – 30 April		1 October – 30 April		1 Nov - 31 March		
Heating start time	hours	5:00		5:00		5:00		
Ventilation rate for fresh air	l/s/per	15		15		15		[55,69–71]
Nat. vent. cooling, window opening set-p't.	°C	Winter: 26 Summer:22		Winter: 26 Summer:22		Winter: 26 Summer:22		[72–75]
Natural ventilation cooling season		1 May –30 September		1 May –30 September		1 April - 31 October		
Mixed-mode/mechanical cooling set-point	°C	–		26		25		
Infiltration rate	ach	1		0.3		0.05		[50–53,76]
Hot water	L/day	2.8		2.8		2.8		
Wall U-value	W/m^2K	1.7		0.30[b]		0.15		[8,9,49]
Roof U-value	W/m^2K	1.42		0.18[b]		0.15		
Ground Floor U-value	W/m^2K	1.42		0.25[b]		0.15		
Glazing U-value	W/m^2K	5.87		1.8[b]		0.8		
Glazing SHGC		0.81		0.59[b]		0.47		
Glazing light transmission		0.88		0.77		0.66		

[a] When the density was coupled with the occupant frequency the actual density was lowered to approximately 1 or 2 people at a time in any corridor at any level.
[b] U-values when the area to be renovated is greater than 50% of the surface of the individual element or 25% of the total building envelope.

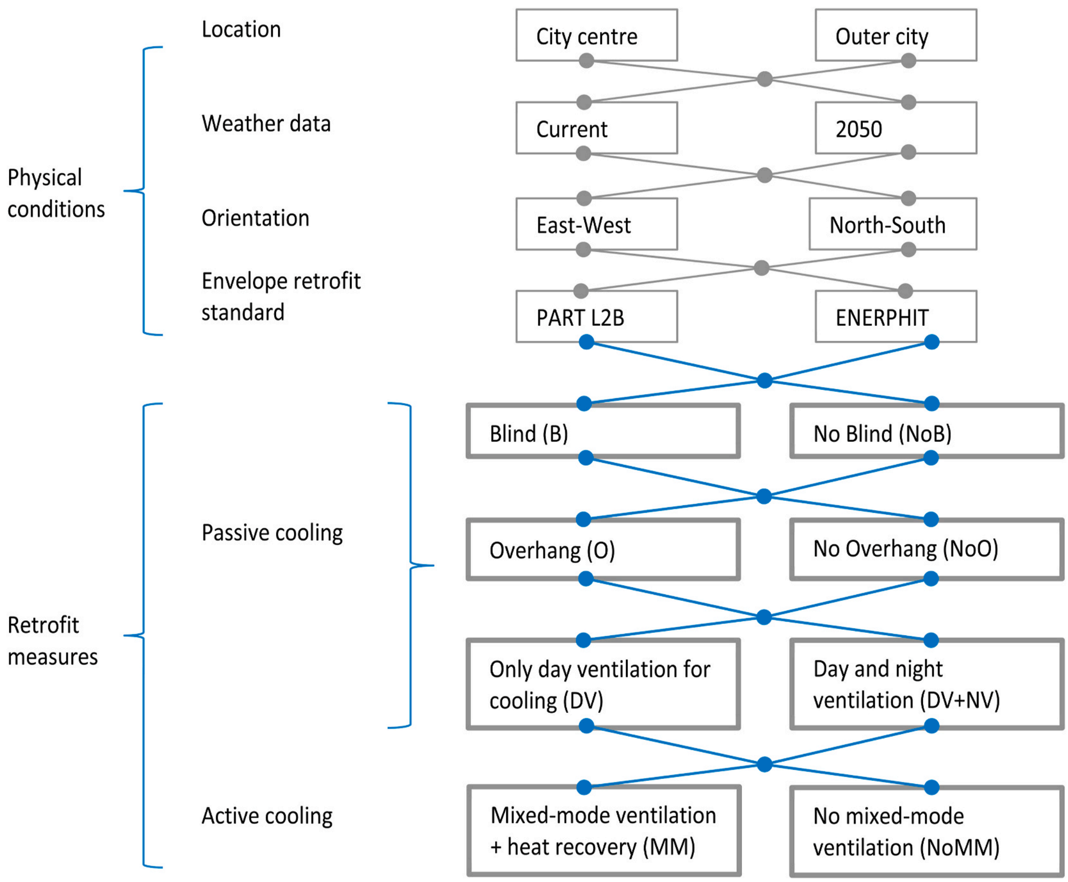


Fig. 1. Retrofit measures parameter tree.

retrofit cases and 70% efficient in the base-case, which assumes no recent heating upgrade in the base-case building [23]. A coefficient of performance of 2.5 was assumed for mechanical cooling. For each simulation, the total building energy consumption was calculated by summing up the annual consumption of primary electricity and gas in all the zones. The decrease in the total energy consumption between the retrofit case and the base-case provided the figure for the energy consumption reduction.

2.2. Thermal comfort assessment

The assessment of thermal comfort was split into two parts, namely winter (more likely to suffer from inadequate heating), and summer (discomfort likely to be due to overheating). It is possible that a retrofit measure could provide comfort in summer but cause winter discomfort or provide comfort in winter but lead to summer overheating. Because the UK has a heat-dominated climate, the initial aim was to eliminate winter discomfort by improvement to the building envelope and the provision of adequate heating. Then, measures to prevent overheating in summer were evaluated whilst also considering their effect in the winter.

The adaptive comfort standard, BSEN15251 [24], which has since been revised as BSEN16798–1:2019 [25], was used to assess summertime thermal comfort. In this standard, indoor temperature thresholds increase with the exponentially-weighted running mean of the daily mean ambient temperature. The thermal comfort threshold was taken as that for normal occupants, i.e. Category II.

Prevailing criteria that define overheating, e.g. those used by the Chartered Institution of Building Services Engineers (CIBSE) in the UK [26], do not take the number of occupants affected by overheating into consideration. Additionally, to compare retrofit combinations, the overall discomfort of a whole building, rather than a single zone, is needed and simulation programs can only produce zonal comfort outputs.

Ortiz et al. [27] used the Long-term Percentage Dissatisfied (LPD) index, which normalizes over the total number of people inside a household, over all the zones, and over all time periods. Inspired by Ortiz et al. here, a new approach to calculating the overall building thermal discomfort, OBTD, is proposed. This involves enriching CIBSE Criterion 1 [26] by including the number of occupants and calculating the occupant-weighted thermal discomfort in each zone of the building in each occupied hour and then totalling for all occupied hours:

$$OBTD = \frac{1}{T}\sum_{t=1}^{T} \frac{\sum_{z=1}^{Z} (NPz, t\ x\ Dz, t)}{NPt}\ x\ 100\ \% \quad (1)$$

Where: $NP_{z,t}$ = number of people in zone (z) at time (t), $D_{z,t}$ = whether the operative temperature exceeds the comfort threshold in zone (z) at time (t) or not, i.e. $D_{z,t} = 0$ if the threshold is not exceeded or 1 if it is, NP_t = total number of people in the building at the time (t), T = number of hours the building is occupied, Z = total number of zones in the building.

In all cases the occupied hours were from 07:00 to 19:00 on weekdays only. A building was taken to be overheated when the OBTD exceeded 1% of person-hours.

2.3. Costs estimation

The central cost dilemma with retrofit is that the occupier benefits from the energy cost savings whereas the investor pays the cost of the retrofit. Consequently, the investor, who is in most cases the building owner, is resistant to pay for actions which (s)he does not directly benefit from. This problem is one of reason for the sluggish penetration of energy efficiency technologies into the retrofit market [28]. Mimicking this real-life issue, Kumbaroglu & Madlener [29] suggested considering costs and benefits explicitly and for two groups; cost benefit for buildings used by the owner (CBO) and the cost benefit for buildings let to a tenant (CBT). This approach is adopted here, but while their work used dynamic net present value (NPV) analysis, here, additionally productivity costs were taken into consideration.

The cost calculations aim to enable realistic comparisons between retrofit options rather than to provide exact figures for each construction or retrofit. In this regard, although the overall cost figures are sensitive to uncertainties, such as in the rent increases or interest rates [30], the relative costs can be compared confidently.

The CBO was calculated by subtracting investment costs from the sum of the Net Present Value (NPV) of the energy cost benefit (ECB) and productivity benefit (PCB). In all the calculations, NPV was applied for the 35-year period from 2016 to 2050; the assumed lifespan of the retrofitted building as well as the average lifespan of the retrofit measures. In contrast, when office buildings are let to tenants (CBT), the owner only benefits from the potential rent increase (justified by the reduced energy cost, improved comfort, and aesthetics). Thus, the calculation was done by subtracting investment cost (IC) from the NPV of rent increase benefit (RIB) [30].

$$CBO = ECB + PCB - IC \tag{2}$$

$$CBT = RIB - IC \tag{3}$$

The costs and energy demands were normalised by the total floor area (TFA) of the office to enable scaling between the exemplar building used in this research and actual buildings that are being considered for retrofit [30].

2.3.1. Investment costs (IC)

To calculate the initial investment, the material and labour costs were based on UK national average best trade prices [31,32]. Overheads and profit were not included in the derived prices. An additional 40% was added on to capture fees and permits, taxes, client's internal costs, finance costs, inflation and contingencies based on the interviews with industrial practitioners (e.g. Ref. [33]).

The BCIS Alterations and Refurbishment Price Book [32] suggested that the cost of materials and labour varies regionally in the UK. Based on the figures given, an approximate addition of 15% was made to the costs for retrofitting the office located in the city centre (London).

2.3.2. Energy cost benefit (ECB)

ECB was calculated by subtracting the NPV of all the energy costs for a retrofitted case (E_{RC})from the NPV for base-case energy costs (E_{BC}) until the end of building life span (y = 1 to Y = 35). The real interest rate (IR) for NPV calculations was taken as 5% yearly.

$$ECB = \Sigma_{y=1}^{Y=35} \frac{E_{BC}}{(1+IR)^y} - \Sigma_y^Y \frac{E_{RC}}{(1+IR)^y} \tag{4}$$

2.3.3. Rent increase benefit (RIB)

To create profit and recuperate the financial outlay from retrofit, a potential rent increase becomes an important consideration for the building owner. Rent increase after retrofit could occur in two ways. One is market value increase as a result of improved service, aesthetics and prestige. The other is regulations which allow building owners to increase rents within special limits. For example, in Germany since 2011, landlords have been entitled to increase the rent by 11% of the retrofit investment costs [34]. In California, annual rent increase due "to major capital improvement" is limited to 10% of the yearly paid rent until the improvement has been paid off [35]. In the UK there is no regulation which entitles building owners to increase the rent of a retrofitted building. But when London is considered, which is one of the most desirable office building locations in the world, the potential for market-driven rent increase after retrofit becomes obvious.

$$RIB = \Sigma_{y=1}^{Y=35} \frac{R_{BC}}{(1+RI)^y} - \Sigma_y^Y \frac{R_{RC}}{(1+RI)^y} \tag{5}$$

In order to represent this situation, as well as to investigate the effect of a regulation which gives the right to increase rent, a 10% rent increase (RI) was applied in all calculations. RIB was calculated by subtracting the NPV of rent of retrofitted case (R_{RC}) from the NPV for base-case rent (R_{BC}) from y = 1 to Y = 35 to the average office building rents in both the London city centre and the outer city locations.

2.3.4. Productivity cost benefits (PCB)

There are studies showing that improved indoor climate and comfort improve health (e.g. sick leave [36]: and productivity, and therefore offers cost benefits [37–39]. Petersen and Knudsen [40] suggest "*Using productivity to articulate the relationship between humans and indoor climate would be a paradigm shift in general design practice*". Such an approach prioritises optimisation of the relation between indoor climate and productivity instead of comfort-based acceptance criteria. Although studies have shown that high ventilation rates can increase productivity [36,38], a universally-applicable ventilation/health relationship was not evidenced [41] and quantification studies are limited. Therefore, while setting a higher ventilation rate than the standards in retrofit cases, the focus of this research was the relation between thermal comfort and productivity.

Placing a value on productivity is, perhaps, the most difficult part of the cost/benefit estimation. This because of the inherent subjectivity of comfort as well as the limited empirical work was undertaken in the area. However, Seppanen et al. [38] reviewed 22 studies which measured performance when undertaking office-type work, such as text processing, simple calculations, the length of telephone customer service times, and total handling time per customer for call-centre workers. Their work indicated that an increase of indoor air temperature (T_a) up to 21 °C and 22 °C was associated with a statistically significant improvement in performance but an increase of (T_a) above 24 °C with a statistically significant decrease in performance. Their relationship between (T_a) and relative productivity (Fig. 2) is given by:

$$RP = 0.1647524T_a - 0.0058274T_a^2 + 0.0000623T_a^3 - 0.4685328 \tag{6}$$

Where:RP = productivity relative to that at an optimum indoor air temperature (T_a) of 21-22°C.

The relative productivity cost (RPC) in zone, z, at time, t, was found by multiplying the productivity decrease by the number of people in the zone at that time ($NP_{z,t}$) and their average hourly rate of pay (HPR). The total RPC was the sum of these costs for all times and all zones:

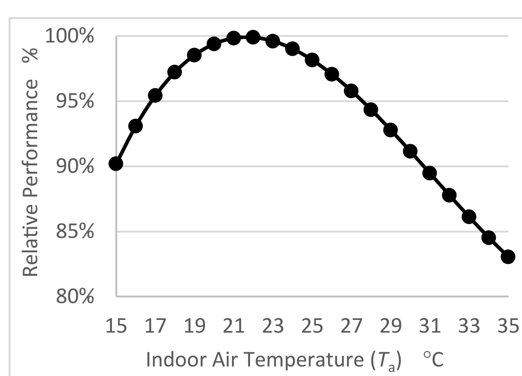


Fig. 2. Percentage productivity as indoor air temperature changes: after Seppanen et al. (2006) [38].

$$\text{RPC} = \sum_{z=1}^{Z}\sum_{t=1}^{T}(1-RP)\ x\ NPz, t\ x\ HPR \tag{7}$$

In these equations, *HRP* is especially uncertain because there is a very wide range of hourly pay rates depending on the region, employee age group, type of work and gender. Here the national average figure, derived from the UK Office of National Statistics (ONS 2015), was used, 13£/h.

The productivity cost benefit (*PCB*) of the retrofit is given by the change in *NPV* of *RPC* relative to the base-case from y = 1 to Y = 35:

$$PCB = \Sigma_y^Y \frac{RPC_{BC}}{(1+IR)^y} - \Sigma_y^Y \frac{RPC_{RC}}{(1+IR)^y} \tag{8}$$

3. Exemplar building

3.1. Built form

Built form can have a significant impact on building energy demand. Despite its significant diversity, a detailed study of UK non-domestic building forms by Steadman et al. [42] identified six basic built forms according to space layout and whether spaces were predominantly daylit or artificially lit. The most common built form, 34%, had a side-lit cellular plan and up to four storeys. This built form is also in line with the naturally ventilated cellular office building benchmark defined ECON 19 [43,44].

The four storey office adopted in this study (Fig. 3), represents UK offices built between the 1940s and 1980s. The long axis was oriented East-West (E-W). It has a concrete frame structure with uninsulated solid brick walling, natural side-lighting through windows and occupant-controlled, one-sided, natural ventilation [42]. There is a high infiltration rate through the poorly sealed façade.

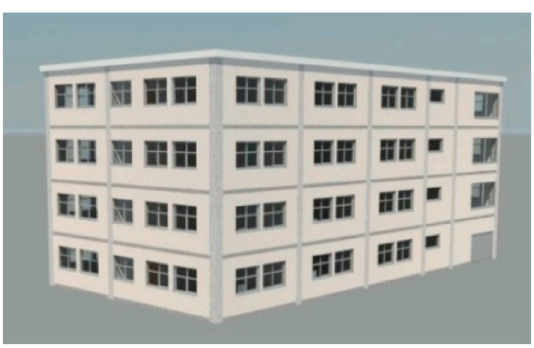


Fig. 3. Three-dimensional visualisation of the exemplar building.

It was assumed that there had been no previous fabric retrofit but that minor refurbishments to lighting and equipment had been made in recent years.

The cellular offices are arranged in 7 m deep perimeter zones with a 2 m circulation zone between (Fig. 4). The internal walls were defined as separators within the zones. Common spaces included reception areas, toilets, tea kitchens, circulation, etc. The floor-to-floor height was taken as 3.5 m and the glazing to wall ratio (G/W) 30%.

3.2. Weather and urban context

To examine the effect of the surrounding buildings and the urban heat island effect, two variations of the base-case model were used: City Centre (Islington) and Outer City (Heathrow). City centre models included neighbouring buildings which were modelled surrounding the exemplar at a 10 m distance and with the same dimensions.

Weather data for these two sites, for both the present day and the 2050s, when the UK is to be zero-carbon, was used. Retrofit decisions need to be robust to both current and future weather conditions. The hourly weather data typical of these years was derived from the Prometheus web portal [45] of Exeter University [46]. These data are based on the UKCP09 weather generator [47] using the method described by Eames et al. [46] to produce the 50th percentile weather data under a medium emissions scenario which, overall, might be the most likely weather condition. TRY weather data was assumed to reflect the heat island effect because it is compiled by averaging the temperature and wind speed over many years.

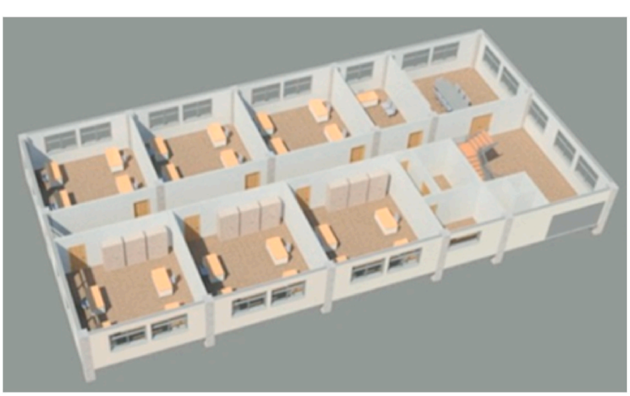
The mean wintertime (December to February) temperature of 2050 weather data was 7.4 ˚C whereas current weather mean temperature was 5.2 ˚C. The increment in wintertime outdoor temperature could have positive effect on the heating demand reduction. The mean summertime (June to August) temperature of 2050 weather data was 19.8 ˚C, 3 ˚C higher than the current weather data, which suggests an elevated risk of summertime overheating.

Overheating in summer and the design of shading are affected by the building's orientation [48]. An E-W orientation (the long-axis orientated East-West) and a N–S orientation (the long-axis orientated North-South) were evaluated for all retrofit cases.

3.3. Envelope parameters

The U-values of the envelope components of the exemplar building were set based on the regulations; base-case [49], PartL2B [8] and EnerPHit [9]. Considering the limited published information and the high level of uncertainty, an infiltration level of 0.8–1.4ach is likely for post-war office buildings [50,51] the infiltration of the base-case building was taken as 1ach.

The PartL2B requirement of maximum air permeability of 10 $m^3/s{\cdot}m^2$ at 50Pa is approximately equal to 0.5ach at ambient pres-



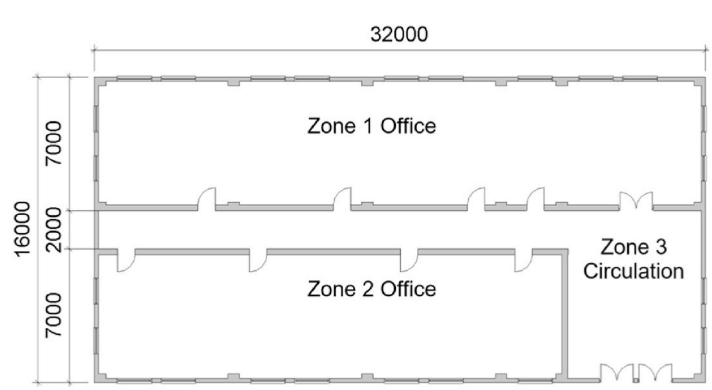


Fig. 4. Exemplar building floor plan.

sure. However, Korolija et al. [52] suggested 0.3ach for an office building archetype as it both complies with the existing regulations and "*represents a crude approximation across the non-domestic building stock due to vast differences in reported measurements*". Similarly, Attma standard [53] recommends 3–7 $m^3/s{\cdot}m^2$ at 50Pa giving 0.15 to 0.35ach for best practice and typical buildings respectively. Thus, in this research, 0.3ach was taken for the building retrofitted to the PartL2B standard. The permitted maximum infiltration rate of 0.05 ach [9] was used for the EnerPHit retrofit.

3.4. Heating schedule & internal gains

For the base-case and retrofit cases, an air temperature set-point of 22 °C was taken. The heating was set to come on from 05:00 until 19:00 during weekdays only, with the set-back temperature of 14 °C outside these hours [52].

The percentage of the maximum possible occupancy of the offices, 65% [54–57] and circulation areas at each hour of the day is shown in Fig. 5. Office working hours were set as 7:00 to 19:00 (Weekdays) with a 2-h lunch period between noon and 14:00.

The maximum occupancy density was $14m^2$/person for the office area and $9m^2$/person for circulation for in all cases. The metabolic rate was averaged to 125W/person for light office work.

Equipment is independent of building age. Taking the average internal equipment heat gain associated with each person and occupancy schedule as 140W [55] this equates to $10W/m^2$ ($1.85W/m^2$ in circulation areas). Artificial lighting levels were set 500lux for workstations and 200lux in circulations areas operating according to the occupant schedule. Base-case lighting internal gain was $12W/m^2$ based on surveys [43,51] and for the retrofit cases 8–12 W/m^2 [58]. To capture the wasted energy, 10% of the lighting and equipment were assumed to be on during unoccupied hours on the weekdays and the weekends. In retrofit cases, linear daylighting control was adapted which works with two sensors located in the middle of each zone. Glare control was also achieved by limiting the maximum allowable glare rating (UGR) to 19. The hot water consumption was set as 2.8l/person/day considering the mixed use of cold and hot water evenly because the supply water temperature was 65 °C. Table 1 summarises the base-case and retrofit inputs.

4. Active and passive cooling retrofit

An early problem discovered with the base-case building simulations was the very high heating energy consumption and the winter discomfort due to the low radiant temperature of the cold, poorly-insulated fabric components; a phenomenon observed in actual buildings of this type.

In contrast, the initial retrofit simulations showed that the total energy consumption was reduced significantly and the insulated envelope overcame the winter discomfort problem. However, these interventions caused a new problem; summertime overheating [77]. The energy consumption reduction from the base-case of the PartL2B and EnerPHit retrofit cases with no cooling measures, E-W orientation and located in the city centre, was 62% and 81% respectively and both cases resulted in overheating and failed to provide thermal comfort [30].

Overheating in the EnerPHit cases was more significant than for the PartL2B cases. This result is not unexpected as the Passivhaus standard suggests applying mechanical ventilation with heat recovery (MVHR) to prevent overheating and to provide adequate ventilation [9].

Consequently, both passive and active cooling strategies are explored to provide thermal comfort in summer. Passive cooling involved automated window opening to enable night-time ventilation and the use of shading. In addition to these measures, active cooling necessitated mixed-mode mechanical ventilation and cooling approach.

Nevertheless, the simulations for EnerPHit cases with no cooling measures were important to identify the extent and severity of the overheating and to determine the season during which cooling interventions are necessary. The PartL2B retrofit resulted in overheating from June to September but with the EnerPHit retrofit, overheating occurred for a longer period and the cooling season was set from April to October.

4.1. Ventilation and passive cooling

To solve the summer overheating problem, firstly, passive cooling measures were evaluated. In addition to the minimum ventilation rate of 15 l/s/per, higher day and night-time ventilation (DV and NV) single-sided ventilation was enabled through the windows. Wind pressure was assumed to be the dominant ventilation driver.

To prevent the wind blowing directly onto the occupants, and to provide rain protection, a top hung window of height 1.5 m was assumed and the total window area was retained as 30% (as for the glazing to wall ratio of the exemplar building). Following the work of Raja et al. [74] and Yun & Steemers [75], it was assumed that occupants opened the windows when the indoor temperature was over 22 °C (which is also the temperature at which productivity is maximum, Fig. 2). In winter, a window opening set point of 26 °C was set for cooling purposes because in the EnerPHit cases without passive or active cooling, overheating occurred very occasionally on mild days in the heating season.

In the UK, night ventilation, which takes advantage of the temperature decrease during the night, is an effective passive cooling strategy for office buildings [78]. The cool air reduces the temperature of the exposed structural mass in the building, especially of the exposed concrete ceilings (which were presumed in the retrofit cases) [79]. However, attention has to be paid not to over cool in the morning before the occupants first arrive.

To prevent over-cooling and yet provide effective night ventilation, natural ventilation was assumed to operate when [80]:

- Zone temperature is greater than outside air temperature;
- Zone temperature is greater than heating set-point; and
- Outside air temperature >12 °C.

To avoid draughts, automatically controlled windows, 1.7 m above the floor were assumed for night venting in the retrofit cases [81]. This automation also accounted for the wind speed. The additional cost of the ventilation automation was included in the cost-benefit analysis.

For both day and night ventilation, it was assumed that the windows opened 50% when the internal temperature was above 22 °C and the local wind speed was below 0.8 m/s and 10% when the local wind speed

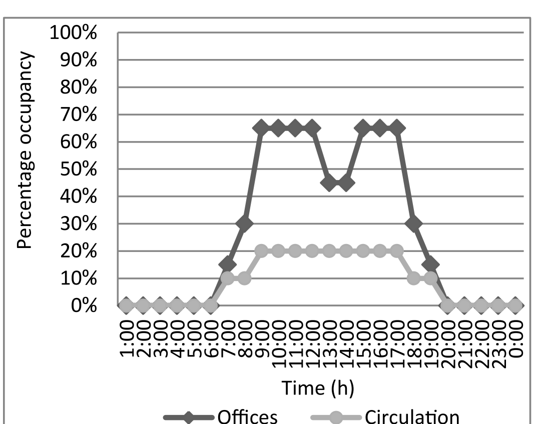


Fig. 5. Variation of occupancy with time for a typical day expressed as fraction of total possible occupancy.

was above 0.8 m/s [82]. The limit was raised to 1.5 m/s, as suggested by Gratia et al. [83], for night ventilation.

The hourly air-change rate was reported by E+ and these results were averaged for each hour throughout the cooling season and set as that particular hour's air-change rate. This was calculated and applied in the simulations in two cases, when there was only day ventilation and when there were both day and night ventilation.

4.2. Shading

The initial simulations to optimise the external blinds and their operation showed that an operation schedule activated by internal operative temperature was more effective than a schedule using the solar gain on the window. A greater slat angle or reflectivity decreased discomfort, but in order to benefit from daylight, yet prevent glare, blind slats with high reflectivity (0.8) and an angle of 45° were used. These were operated when the internal operative temperature exceeded either 22 °C or 24 °C for EnerPHit and PartL2B retrofits respectively.

The main challenge of passive cooling optimisation, for determining the length of the overhang, was the question of which weather data was used, current or future (Fig. 6 shows an illustration of overhang and Table 2 shows the length of the optimal overhangs and side-fins determined from the initial simulations.). The initial results showed that, for the PartL2B retrofit, city centre cases, an overhang, no matter how deep, failed to provide comfort unless night ventilation was used. However, when the night ventilation and blinds were combined adding an overhang created overcooling for the current weather but not for the future climate. As a solution, the optimisation was run using 2050 weather data but for the PartL2B retrofit, the overhang was installed as an alternative to external blinds instead of in combination.

For the EnerPHit retrofit, both an overhang and external blinds had to be used to provide comfort. For the outer city, as there were no external obstacles, the necessity of shading was greater than in the city centre. Moreover, because, for structural reasons, the length of the overhang was limited to 1.5 m, side-fins (vertical overhangs) had to be added to ensure comfort.

Contrary to expectations based on the literature, the E, W and S overhang lengths were taken to be the same in order to simplify the simulation models because the results for the different orientations were fairly similar. This was due to limiting the overhang length to 1.5 m to avoid structural problems which also provides for simpler construction and reduced costs.

Fig. 6. Illustration of overhang.

Table 2
Length of the overhangs and side-fins.

	Overhang E-W-S	Overhang N
City centre PartL2B	0.5 m	None
Outer city PartL2B	1.0 m	0.5 m
City centre EnerPHit	1.5 m	1.0 m
Outer city EnerPHit	1.5 m + (0.5 m side fin)	1.5 m + (0.5 m side fin)

4.3. Active cooling

The initial results for passive cooling retrofit showed that, especially in most of the EnerPHit cases and some PartL2B future climate cases, passive cooling alone was not adequate to provide the required thermal comfort. Thus, energy efficient active cooling measures were investigated.

To minimise energy consumption while ensuring thermal comfort in all zones, mixed-mode (hybrid) ventilation with the change-over strategy (same space, different times) was adopted. Active cooling operates during occuied hours. By this approach, night ventilation was used for cooling as much as possible, with active cooling when passive (day and night) ventilation could not provide the required cooling setpoints. The night ventilation involved the automatic opening of windows if the internal temperature was above 22 °C. The active cooling set-points were 26 °C and 25 °C for PartL2B and EnerPHit respectively.

5. Results

The total energy demand and discomfort levels, for the current and then the future climate are discussed and illustrated (Figs. 7 and 8) for all the PartL2B and EnerPHit retrofit options. The overall evaluation, which includes the cost analysis, follows.

5.1. Current weather conditions

The base-case simulations (no retrofit) in the city centre and outer city locations resulted in very high energy consumptions; 199 kWh/m^2 and 208 kWh/m^2 respectively. The effect of orientation on the energy consumption of base-case models was minimal; >0.5%. The effect of location was small and provided with a similar pattern in bases-cases and retrofit cases; decrease in heating energy loads and increase in cooling loads due to the change in microclimate and the lack of surrounding buildings and so lack of site shading. Therefore, the “typical retrofit case” was defined as E-W orientation and located in the city centre. Outer city and N–S orientation results were presented as comparison to this typical case. When calculating energy reduction, each and every retrofit case was compared to the base-case with the same orientation and location combination.

The energy consumption of the PartL2B typical retrofit case with no cooling measures, E-W orientation and located in the city centre, was 74 kWh/m^2; a 62% reduction from its base-case. For this retrofit, the lowest energy consumption and costs with better comfort were achieved in the cases with only day ventilation and either of the shading devices (external blinds (B) or an overhang (O), or both (B–O)).

Although night ventilation (NV) decreased the overheating (for natural ventilation during the day only (DV), OBTD = 1.9%; natural ventilation during the day and night (DV-NV), OBTD = 1.3%), its overall effect was not significant because overheating occurred in specific zones over a limited time period. In other words, when no active cooling was provided, overheating occurred even in the current weather conditions unless shading was incorporated.

In the outer city PartL2B retrofit case (E-W orientation with no cooling measures), the total energy consumption was 68 kWh/m^2; a 67% decrease from its base-case. The energy demand was lower than for the city centre retrofit case because surrounding buildings did not prevent the solar gains in the winter (Fig. 7). This effect was observed in all retrofit cases. As with the city centre PartL2B retrofit-cases, overheating occurred also in the two outer city cases that had no shading: OBTD = 4.7% with day ventilation only (DV) and OBTD = 3.4% with both day and night (DV-NV).

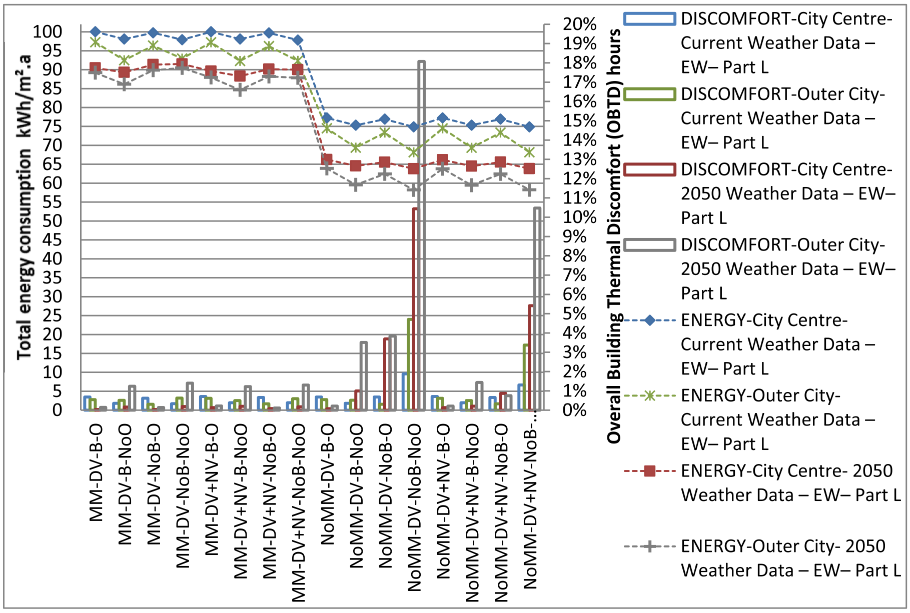


Fig. 7. The comparison of total energy consumption and OBTD for PartL2B retrofit cases.

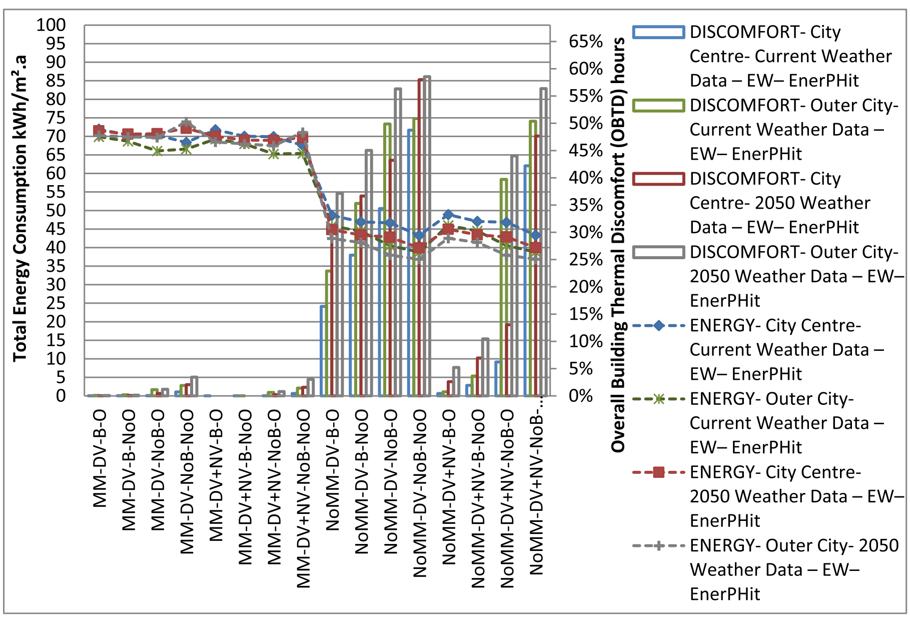


Fig. 8. The comparison of total energy consumption and OBTD for EnerPHit retrofit cases.

The E-W and N–S orientation cases resulted in similar energy consumption and cost figures for both city centre and outer city locations. The same cases with no shading (NoMM-DV-NoB-NoO and NoMM-DV + NV-NoB-NoO), failed to provide summer comfort although overheating was more severe in N–S combinations.

In EnerPHit cases, heating energy consumption was significantly low (6–8 kWh/m^2), therefore electricity consumption dominated the total consumption; this was significantly higher in MM cases. The typical EnerPHit retrofit-case, E-W orientation and located in the city centre, with no cooling resulted in total energy consumption of 37 kWh/m^2 which is an 81% reduction from the base-case. Energy consumption of the MM combination without any passive cooling was 68 kWh/m^2 (Fig. 8). Energy consumption of all MM cases (68-72 kWh/m^2) was within a similar range to the PartL2B naturally ventilated cases (75-77 kWh/m^2).

The current weather results of the EnerPHit retrofit showed that it may be possible to provide comfort with careful passive cooling design; but only when all the passive cooling measures are applied. In the MM combinations, all of which passed the comfort criteria, the passive cooling measures reduced the discomfort hours and improved productivity in comparison with no-passive-cooling MM combinations. Additionally, the positive effect of night ventilation was more noticeable in the EnerPHit cases than the PartL2B cases.

The results of N–S orientation and outer city location combinations were very similar to the typical EnerPHit retrofit-case. Apart from NoMM-DV + NV-B-O, all the natural ventilation cases failed the comfort criteria. In this case, energy consumption was 46 kWh/m^2 in outer city (E-W); 6% lower than the city centre case.

In the EnerPHit cases with MM ventilation and cooling, productivity loss was limited, especially in the NV cases, because the indoor temperatures tended to be closer to 22 °C, at which the highest productivity occurs whereas in the NoNV cases, indoor temperatures were likely to be closer to the cooling set point: 25 °C. In the outer city cases, the application of shading devices was critically important even in the MM cases because there is no site shading; MM-DV-NoB-NoO case failed to provide comfort with OBTD: 1.9% because the capacity of active cooling was not adequate to provide the desired temperature rapidly enough. With the EnerPHit retrofit combinations, the effect of orientation on energy consumption and comfort was very small.

5.2. Future weather conditions

The major outcome of investigating the effect of the 2050 weather conditions for both PartL2B and EnerPHit retrofit cases was the significant discomfort due to overheating, more so in outer city cases.

For the typical PartL2B case, E-W orientation and city centre location, three naturally ventilated cases provided acceptable comfort, NoMM-DV-B-O (both of the shading devices were applied and no night ventilation), NoMM-DV + NV-B-NoO (night ventilation and blinds were applied) and NoMM-DV + NV-B-O (all passive cooling measures were applied). In outer city cases (E-W orientation) however, the NoMM-DV-B-O and NoMM-DV + NV-B-O cases clearly passed the comfort criterion whereas the NoMM-DV + NV cases with either of the shading devices failed the OBTD criterion because of lack of additional shading of surrounding buildings. The same combinations failed to provide comfort in N–S oriented cases both in city centre and outer city with 1-3% higher OBTD.

The results do though suggest that in both the current and future weather conditions passive cooling measures can provide thermally comfortable buildings when PartL2B retrofit is applied.

For the 2050 EnerPHit cases, comfort was only achievable with MM ventilation but the lack of passive cooling measures increased discomfort and energy consumption, thus, the optimal solution is to apply the passive cooling measures with the mixed-mode ventilation; shading devices were more effective in the outer city conditions and the night ventilation was more effective in city centre.

In 2050, when the objective is energy reduction, both PartL2B naturally ventilated cases with the passive cooling measures and EnerPHit mixed-mode cases, provided the required thermal comfort and resulted in similar energy consumption.

5.3. Overall evaluation

The results were plotted to evaluate the costs versus the energy consumption while the thermal discomfort was taken as the constraint. The results for the cost benefits when the building is let to a tenant (CBT) are presented in Fig. 9 and the costs benefits for buildings used by the owner (CBO) in Fig. 10. In both graphs, the cases which failed to provide thermal comfort in current climate are marked with the black circles, and the 2050 cases in red. The dashed line circles indicate the mixed-mode ventilation cases. The optimum solution had to fulfil the comfort criteria in both climate conditions.

For all cases, the CBT resulted in positive figures which indicated a profit predominantly due to the rent increase. The profit for the EnerPHit cases was lower than for the PartL2B cases because of the higher investment costs of the EnerPHit retrofit (the MM ventilation, NV and overhang) and higher running costs (the operational electricity costs for the MM system, NV controls and additional artificial lighting caused by permanent overhang).

It is worth highlighting that the CBT evaluation is only valid when the rent increase is possible, and the significant difference between rents in the city centre and the outer city caused a clear separation in Fig. 9; the higher values are for the city centre cases and the lower group for the outer city cases.

The overall evaluation of the CBT showed that the PartL2B natural ventilation cases which pass the comfort criteria now and in 2050 (NoMM-DV + NV-B-O, NoMM-DV + NV-NoB-O, NoMM-DV + NV-B-NoO) -resulted in the optimum energy and the cost results for both locations. This result suggests that current building regulations; PartL2B, requires passive cooling to provide comfort in the future climate and highlights the importance of giving priority to natural ventilation in retrofit.

Comfort in the PartL2B natural ventilation cases is less assured than when using a MM approach, especially if the 2050 weather becomes warmer than the assumption of this study.

In the current climate, the lowest energy consumption and highest profit for both locations were as a result of EnerPHit-NoMM combinations but these cases failed to provide comfort except for one case; the combination in which all the passive cooling measures were applied. However, this case failed the comfort criteria in 2050.

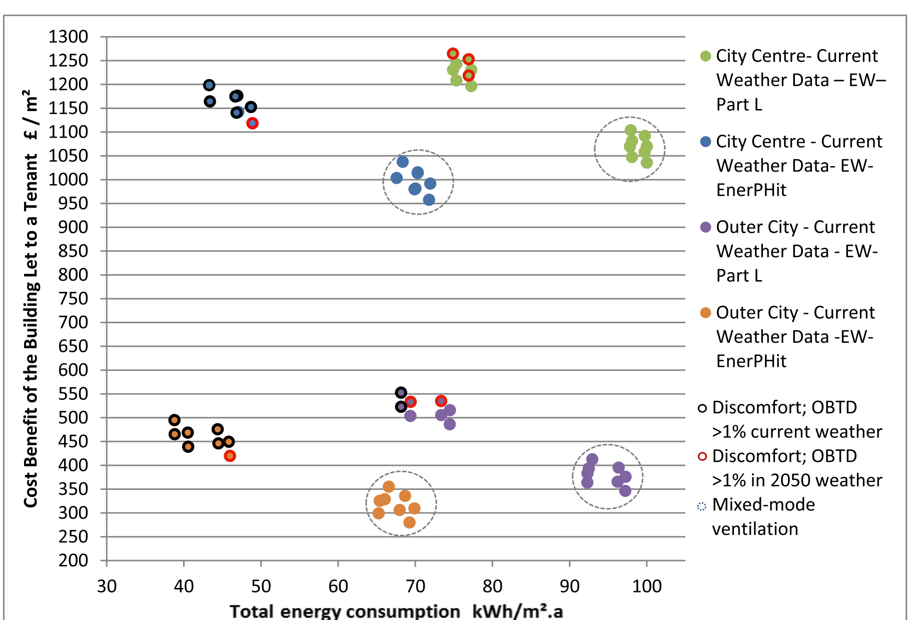


Fig. 9. Comparison of costs, energy consumption and comfort for the building is let to a tenant (CBT).

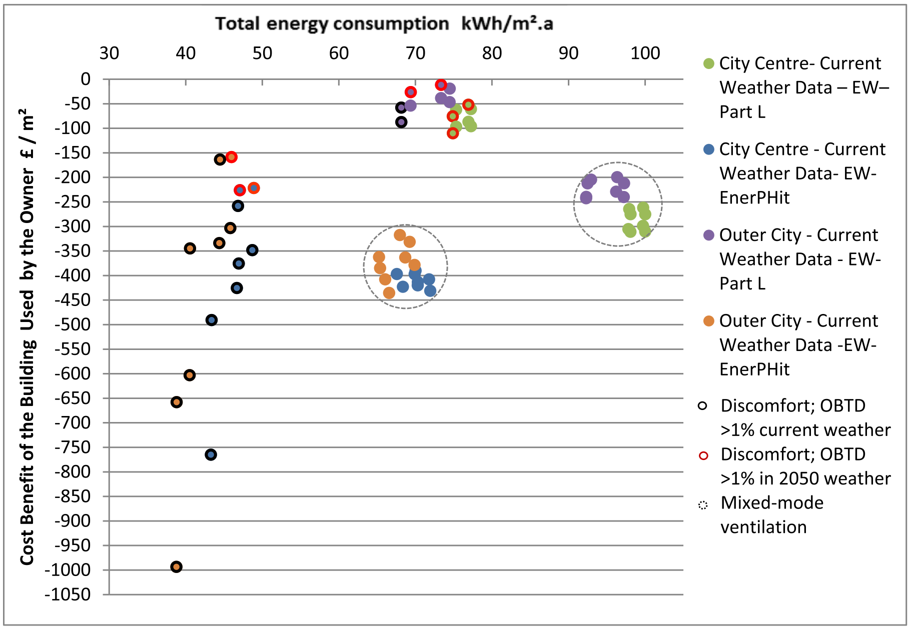


Fig. 10. Comparison of costs, energy consumption and comfort for the buildings used by the owner (CBO).

EnerPHit mixed-mode cases provided a similar range of energy consumption to the PartL2B naturally ventilation cases but with lower cost benefit. For example, the EnerPHit-MM strategy results in a 20% CBT reduction compared to the PartL2B-NoMM (e.g. £1197£/m^2 to 958£/m^2). However, in comparison to the PartL2B mixed-mode cases, the EnerPHit mixed-mode combinations reduced energy demand by 28% (e.g. MM-DV + NV-B-O cases).

In contrast, the CBO was negative for all retrofit cases. The CBO costs were dominated by the investment costs. Thus, the EnerPHit retrofit was more costly than the PartL2B retrofit. Also, in many non-MM cases, there were higher productivity costs as a result of discomfort.

The major difference between the CBO and CBT cost benefits are the productivity costs; these are most significant in the EnerPHit-NoM cases which do not provide thermal comfort, but also in the EnerPHit-MM cases without any passive cooling measures; for instance the MM-DV + NV-B-O case resulted in a profit of 84£/m^2 (outnumbered by investment costs towards negative) whereas MM-DV-NoB-NoO case productivity cost was - 20£/m^2. Fig. 8 shows significant levels of discomfort of these cases and Fig. 10 indicates the negative impact of discomfort on productivity hence costs.

The total costs of the EnerPHit retrofit (investment and running) was much higher than the PartL2B retrofit. However, PartL2B-MM cases, despite the better CBO figures, resulted in higher energy consumption than the EnerPHit-MM cases.

The overall CBO evaluation showed that the PartL2B natural ventilation cases which pass the comfort criteria (NoMM-DV + NV-B-O, NoMM-DV-B-O and NoMM-DV + NV-B-NoO resulted in the optimum energy and cost results for both locations.

6. Discussion

By applying the retrofit assessment method adopted in this research, it was possible to create generic retrofit solutions which could be applied to post-war office buildings. Conventional retrofit decision-making is rather simplified, comparing energy reduction versus payback period of investments [84–86] which is most of the time prioritised by the budget. Adopting a more comprehensive evaluation strategy, such as the one used in this research, could highlight the hidden costs, such as the cost of lost productivity, which are absent in current approaches. Literature suggests [38] that "*there is an obvious need to develop tools so that economic outcomes of health and productivity can be integrated into cost-benefit calculations with initial, energy and maintenance costs*".

The results of the analysis show that in current weather conditions, post-war office retrofit to Building Regulations PartL2B standard without any passive cooling risks summer-time overheating [77]. Other the studies which investigated overheating risk in future climate conditions also highlights the necessity of passive and active cooling interventions [87–89]. The risk can be mitigated by passive cooling measures. In 2050, both PartL2B retrofit naturally ventilated cases with the passive cooling measures, and the EnerPHit retrofit with mixed-mode ventilation provide the required thermal comfort and result in the similar range of energy consumption; although PartL2B retrofit cost-benefits are higher. Thus, the optimal retrofit solution for post-war office buildings seems to be to use a PartL2B standard retrofit with passive cooling measures, these are essential. However, if the 2050's are warmer than anticipated (tested using 90th percentile future weather data, see Eames et al., 2010), mixed-mode ventilation becomes a more secure option. Although the EnerPHit retrofit provides less cost benefit than the PartL2B cases, to provide a future-proof retrofit, EnerPHit with MM ventilation (and with passive cooling) is an alternative, lower energy demand, solution. The study of Kerdan et al. [90], which investigates energy efficient and costly optimal retrofit using exergy-based building simulation tool, also suggests that Passivhaus retrofit provides good energy performance but that the approach is not economically viable. They concluded that their study "*neglected the quantification of other non-energy related benefits, such as indoor air quality, thermal comfort and building aesthetics improvement; if appropriately quantified, it could enhance the financial viability of the actual retrofit design*". This conclusion supports the necessity of multicriteria optimisation and the methodology applied in this paper.

The results indicate the importance of evaluating the performance of retrofit buildings not only now, but also in a warmer future; the retrofit combinations which provided comfort in the current climate but fails in 2050 weather, demonstrate the necessity of future-proofing retrofit designs.

The results suggest that PartL2B of the building regulations could be updated by requiring lower U-values and infiltration than the current version. With control of solar gains and sufficient natural ventilation, a higher envelope standard would result in lower energy consumption. Such an approach would also help ensure lower energy demands if climate warming results in the need for mechanical cooling. Further research is needed to determine the higher envelope standards that would be optimal on energy, comfort and cost grounds, and which is applicable to all post-war office types.

Cost calculations highlighted the potential benefits of rent increase as a result of retrofit. The central cost dilemma of retrofit - the occupier benefits from the energy cost savings whereas the investor pays the cost of the retrofit - could be resolved by allowing building owners a regulated rent increase after retrofit.

In the UK, the drive for energy efficiency has been achieved in recent years through energy efficient retrofit. In order to avoid costs, thermal discomfort to occupants is sometimes ignored. Other, such as Larsen [91] also notes that "*the large focus on energy performance has reduced the focus on indoor environment*". In effect, the developers increased cost benefit is achieved at the expense of the occupants' comfort. Perhaps the building regulations should be changed to prevent this practice.

7. Conclusion

This paper has reported on the application of a methodology to evaluate retrofit of UK post-war office buildings. The work considers the effect of building location and orientation. The methodology accounts for the improvement in energy efficiency, as well as the thermal comfort and hence productivity benefits. These are encapsulated in the calculated capital and running costs. Retrofit to UK building regulations standard PartL2B, and the higher retrofit standard EnerPHit, using current and future weather conditions, were evaluated. The aim was to determine the optimal generic retrofit strategies, which could form the basis for guidelines about post-war office building retrofit for the decision-makers.

The research considers the costs benefits for buildings used by the owner (CBO) and for buildings let to a tenant (CBT). With the assumptions made in this work, CBT resulted in considerable profit, which could be a driver for accelerating the retrofit of the office building stock. Both CBO and CBT, calculations also showed that EnerPHit retrofit costs are higher than PartL2B retrofit costs.

On cost and energy grounds, PartL2B retrofit with passive summertime overheating interventions is optimal provided that the overheating controls (night ventilation, blinds and/or overhangs) are installed. The EnerPHit standard retrofit becomes an alternative for achieving resilience to climate warming, provided mixed mode ventilation with passive cooling is adopted. This will provide summertime thermal comfort with significant heating demand reduction and similar total energy consumption to a PartL2B retrofit.

Currently, the UK building regulations do not require any overheating analysis, our results suggest that this is an omission that should be rectified so that both current and future overheating risk is regulated.

CRediT authorship contribution statement

Özlem Duran: Conceptualization, Methodology, Validation, Investigation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Kevin J. Lomas:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This research was made possible by Engineering and Physical Sciences Research Council (EPSRC) support for the London-Loughborough Centre for Doctoral Training in Energy Consumption (Grant EP/H009612/1).

References

[1] D. Buildings, Zero carbon non-domestic buildings Available at: 2017. https://www.designingbuildings.co.uk/wiki/Zero_carbon_non-domestic_buildings. (Accessed 1 February 2017).
[2] Hm Government, Climate change Act. The stationery office, London Available at: 2008. http://www.legislation.gov.uk.
[3] MHCLG, Domestic private rented property: minimum energy efficiency standard - landlord guidance Available at: 2017. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/824018/Non-Dom_Private_Rented_Property_Minimum_Standard_-_Landlord_Guidance.pdf. (Accessed December 2020).
[4] MHCLG, Energy performance of buildings certificates statistical release: q4 2019: England and Wales Available at: 2019. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/861840/EPB_Cert_Statistics_Release_Q4_2019.pdf. (Accessed December 2020).
[5] N. Baker, The Handbook of Sustainable Refurbishment: Non-domestic Buildings, Taylor & Francis, 2009.
[6] CIBSE 2010. How to manage overheating in buildings, knowldge series 6, chartered institution of building services Engineers, London, UK pg:14-21. Available at: http://www.cibse.org/knowledge/cibse-ks/ks16-how-to-manage-overheating-in-buildings. (Accessed April 2021).
[7] BEIS, Building Energy Efficiency Survey, Department for Business, Energy & Industrial Strategy, London, 2016.
[8] HMG, The building regulations 2010 :, 2015. Approved Document L2B Conservation of Fuel and Power in Existing Buildings Other than Dwellings, 2015.
[9] PHI, Passivhaus institute, passive house planning package (PHPP) 9 Available at: 2020. http://passivehouse.com/04_phpp/04_phpp.htm. (Accessed December 2020).
[10] A. Boyano, P. Hernandez, O. Wolf, Energy demands and potential savings in European office buildings: case studies based on EnergyPlus simulations, Energy Build. 65 (2013) 19–28.
[11] S.E. Chidiac, E.J.C. Catania, E. Morofsky, S. Foo, Effectiveness of single and multiple energy retrofit measures on the energy consumption of office buildings, Energy 36 (8) (2011) 5037–5052.
[12] T. Ebbert, Integrated refurbishment planning for sustainable office buildings, Struct. Build. 166 (2) (2013) 100–107.
[13] G. Hillebrand, G. Arends, R. Streblow, R. Madlener, D. Müller, Development and design of a retrofit matrix for office buildings, Energy Build. 70 (2014) 516–522.
[14] E. Dascalaki, M. Santamouris, On the potential of retrofitting scenarios for offices, Build. Environ. 37 (6) (2002) 557–567.
[15] E. Rey, Office building retrofitting strategies: multicriteria approach of an architectural and technical issue, Energy Build. 36 (4) (2004) 367–372.
[16] Y. Juan, P. Gao, J. Wang, A hybrid decision support system for sustainable office building renovation and energy performance improvement, Energy Build. 42 (3) (2010) 290–297.
[17] A.G. Hestnes, N.U. Kofoed, Effective retroftting scenarios for energy effciency and comfort: results of the design and evaluation activities within the OFFICE project, Build. Environ. 37 (2002) 569–574.
[18] S. Barlow, D. Fiala, Occupant comfort in UK offices-How adaptive comfort theories might influence future low energy office refurbishment strategies, Energy Build. 39 (7) (2007) 837–846.
[19] D. Kolokotsa, C. Diakaki, E. Grigoroudis, G. Stavrakakis, K. Kalaitzakis, Decision support methodologies on the energy efficiency and energy management in buildings, Adv. Build. Energy Res. 3 (2009) 121–146.
[20] E. Plus, Energy Plus website Available at: 2020. https://energyplus.net/. (Accessed December 2020).
[21] D. Builder, Design builder website Available at: 2017. http://www.designbuilder.co.uk/. (Accessed December 2020).
[22] J.E. Plus, JE Plus website Available at: 2020. http://www.jeplus.org/wiki/doku.php. (Accessed December 2020).
[23] The Heating Hub, Boiler efficiency calculator Available at: 2020. https://www.theheatinghub.co.uk/boiler-efficiency-guide-and-energy-saving-tips. (Accessed December 2020).
[24] BSI, BS EN 15251, Ventilation for Buildings - Calculation Methods for Energy Losses Due to Ventilation and Infiltration Inbuildings, The British Standards Institution, London, UK, 2007.
[25] BSI, BS EN 16798-1:2019 Energy Performance of Buildings - Ventilation for Buildings. Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics - Module M1-6, The British Standards Institution, London, UK, 2019.
[26] CIBSE, TM52: the Limits of Thermal Comfort:avoiding Overheating in European Buildings, Chartered Institution of Building Services Engineers, London, UK, 2013, p. 13 London, UK..
[27] J. Ortiz, A. Fonseca, J. Salom, N. Garrido, P. Fonseca, V. Russo, Comfort and

economic criteria for selecting passive measures for the energy refurbishment of residential buildings in Catalonia, Energy Build. 110 (2016) 195–210.
[28] A.B. Jaffe, R.N. Stavins, The energy-efficiency gap what does it mean?, Energy Pol. 22 (10) (1994) 804–810.
[29] G. Kumbaroglu, R. Madlener, Evaluation of economically optimal retrofit investment options for energy savings in buildings, Energy Build. 49 (2012) 327–334.
[30] Ö. Duran, Evaluation of Retrofitting Strategies for Modernist Office Buildings, PhD Thesis, Loughborough University, UK, 2018.
[31] V. Johnson (Ed.), Laxton's SMM Building Price Book, Laxton's Publising Limited, Watford, 2015.
[32] N. Barnett (Ed.), BCIS Alterations and Refurbishment Price Book 20th ed., BCIS, 2015.
[33] Jofeh, Personal Communications with Cris Jofeh, Head of Global Buildings Retrofit Team from Arup Cardiff Office, 2015.
[34] BGB, German Civil Code Section 559. Bundesministerium der Justiz und fuer Verbraucherschutz Available at: 2017. https://www.gesetze-im-internet.de/englisch_bgb/englisch_bgb.html#p2152. (Accessed December 2020).
[35] SFTU, San francisco tenants union, rent control – coverage and rent increases Available at: https://www.sftu.org/rentcontrol/ 2017. https://www.sftu.org/rentcontrol/. (Accessed December 2018).
[36] D. Milton, P. Glencross, M. Walters, Risk of sick leave associated with outdoor air supply frequency humidification, and occupant complaints, Indoor Air 10 (2000) 212–221.
[37] W.J. Fisk, D. Black, G. Brunner, Benefits and costs of improved IEQ in U.S. offices, Indoor Air 21 (2011) 357–367.
[38] O. Seppanen, W.J. Fisk, Q.H. Lei, Effect of Temperature on Task Performance. Lawrence Berkeley National Laboratory, 2006.
[39] D.P. Wyon, The effects of indoor air quality on performance and productivity, Indoor Air 14 (2004) 92–101.
[40] S. Petersen, M. Knudsen, Method for including the economic value of indoor climate as design criterion in optimisation of office building design, Build. Environ. 122 (2017) 15–22.
[41] P. Carrer, P. Wargocki, A. Fanetti, W. Bischof, E.O. Fernandes, T. Hartmann, S. Kephalopoulos, S. Palkonen, O. Seppanen, What does the scientific literature tell us about the ventilation-health relationship in public and residential buildings?, Build. Environ. 94 (2015) 273–286.
[42] P. Steadman, H. Bruhns, S. Holtier, B. Gakovic, B. Rickaby, F. Brown, A classification of built forms, Environ. Plann. Plann. Des. 27 (1) (2000) 73–91.
[43] DETR, Energy Use in Offices ECON 19, Energy Efficiency Best Practice Programme Energy Consumption Guide ECG19, Department of the Environment, Transport and the Regions, 2000.
[44] CIBSE, Energy Efficiency in Buildings: Guide F, The Chartered Institution of Building Services Engineers, London, UK, 2013.
[45] Prometheus web portal, Prometheus the use of probabilistic climate change data to futureproof design decisions in the building sector. Centre for energy and the environment, exeter university Available at: 2017. http://emps.exeter.ac.uk/engineering/research/cee/research/prometheus/. (Accessed December 2020).
[46] M. Eames, T. Kershaw, D. Coley, On the Creation of Future Probabilistic Design Weather Years from UKCP09. Building Services Engineering Research and Technology, 2010, pp. 1–16.
[47] UKCP09, UKCP09 UK climate projections Available at: http://ukclimateprojections.metoffice.gov.uk/21684 2009. http://ukclimateprojections.metoffice.gov.uk/21684. (Accessed August 2018).
[48] H. Poirazis, A. Blomsterberg, M. Wall, Energy simulations for glazed office buildings in Sweden, Energy Build. 40 (7) (2008) 1161–1170.
[49] HMG, The Building Regulations, Her Majesty's Stationery Office, London, UK, 1965.
[50] CIBSE, Environmental Design: Guide A, seventh ed., The Chartered Institution of Building Services Engineers, London, UK, 2006.
[51] CIBSE, Environmental Design: Guide A, The Chartered Institution of Building Services Engineers, London, UK, 2015.
[52] I. Korolija, L. Marjanovic-Halburd, Y. Zhang, V. Hanby, UK office buildings archetypal model as methodological approach in development of regression models for predicting building energy consumption from heating and cooling demands, Energy Build. 60 (2013) 152–162.
[53] Attma, Technical Standard L2 Measuring Air Permeability of Dwellings, The Air Tightness Testing & Measurement Association, Northampton, UK, 2010.
[54] BCO, Guide to Specification, The British Council for Offices, London, UK, 2009.
[55] BCO, Guide to Specification, British Council for Offices, London, UK, 2014.
[56] C. Duarte, K. Van Den Wymelenberg, C. Rieger, Revealing occupancy patterns in an office building through the use of occupancy sensor data, Energy Build. 67 (2013) 587–595.
[57] J. Zhao, B. Lasternas, K.P. Lam, R. Yun, V. Loftness, Occupant behavior and schedule modeling for building energy simulation through office appliance power consumption data mining, Energy Build. 82 (2014) 341–355.
[58] SLL, The SLL Code for Lighting, The Society of Light and Lighting, London, UK, 2012.
[59] T. Kershaw, M. Sanderson, D. Coley, M. Eames, Estimation of the urban heat island for UK climate change projections, Build. Serv. Eng. Technol. 31 (3) (2010) 251–263.
[60] I. Knight, G. Dunn, Evaluation of heat gains in UK office environments, CIBSE/ASHRAE Conference. Edinburgh, UK, 2003.
[61] Stanhope, A Review of Small Power Provision and Occupation Densities in Office Buildings, Stanhope Position Paper, London, UK, 2001.
[62] P. Komor, Space cooling demands from office plug loads, ASHRAE J. 39 (12) (1997) 41–44.
[63] C.A. Webber, J. Roberson, M. McWhinney, R. Brown, M. Pinckard, J. Busch, After-hours power status of office equipment in the USA, Energy 31 (14) (2006) 2487–2502.
[64] M.S. Horgan, The Feasibility of LED Lighting for Commercial Use. Project Report, Worcester Polytechnic Institute, 2014.
[65] BSI, BS EN 12464-1 Light and Lighting - Lighting of Work Places. Indoor Work Places, The British Standards Institution, London, UK, 2011.
[66] CIBSE, Lighting Guide 7 : Office Lighting, The Chartered Institution of Building Services Engineers, London, UK, 2005.
[67] H.R. Bruhns, P. Steadman, H. Herring, S. Moss, P. Rickaby, Types, numbers, and floor areas of nondomestic premises in England and Wales, classified by activity, Environ. Plann. Plann. Des. 27 (5) (2000) 641–665.
[68] ASHRAE, Handbook 2007: HVAC Applications, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA, 2007.
[69] ANSI/ASHRAE, Standard 62. 1-2007 Ventilation for Acceptable Indoor Air Quality, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA, 2007.
[70] BSI, BS EN 13779 Ventilation for Non-residential Buildings - Performance Requirements for Ventilation and Room-Conditioning Systems, The British Standards Institution, London, UK, 2007.
[71] HMG, The Building Regulations 2010 : Approved Document F: Ventilation, 2010.
[72] J. Wu, Thermal Comfort and Occupant Behaviour in Office Buildings in South-East China. PhD Thesis, the University of Nottingham, 2015.
[73] J.F. Nicol, Characterising occupant behavior in buildings: towards a stochastic model of occupant use of windows, lights, blinds heaters and fans, 7th International IBPSA Conference. Rio de Janeiro, Brazil, 2001, pp. 1073–1078.
[74] I. Raja, F. Nicol, K. McCartney, M. Humphreys, Thermal comfort: use of controls in naturally ventilated buildings, Energy Build. 33 (3) (2001) 235–244.
[75] G.Y. Yun, K. Steemers, Time-dependent occupant behaviour models of window control in summer, Build. Environ. 43 (9) (2008) 1471–1482.
[76] CIBSE, TM53 Refurbishment of Non-domestic Buildings, The Chartered Institution of Building Services Engineers, London, 2014.
[77] Ö. Duran, S. Taylor, K. Lomas, The impact of refurbishment on thermal comfort in post-war office buildings, Energy Procedia 78 (2015) 877–882.
[78] M. Kolokotroni, B.C. Webb, S.D. Hayes, Summer cooling with night ventilation for office buildings in moderate climates, Energy Build. 27 (3) (1998) 231–237.
[79] B. Givoni, Indoor temperature reduction by passive cooling systems, Sol. Energy 85 (8) (2011) 1692–1726.
[80] M. Kolokotroni, Information Paper IP 4/98 Night Ventilation for Cooling Office Buildings, BRE, London, UK, 1998.
[81] CIBSE, Applications Manual AM 10 Natural Ventilation in Non-domestic Buildings, The Chartered Institution of Building Services Engineers, London, UK, 2005.
[82] D. Rennie, F. Parand, Environmental Design Guide for Naturally Ventilated and Daylit Offices, BRE, London, UK, 1998.
[83] E. Gratia, I. Bruyère, A. De Herde, How to use natural ventilation to cool narrow office buildings, Build. Environ. 39 (10) (2004) 1157–1170.
[84] S.E. Chidiac, E.J.C. Catania, E. Morofsky, S. Foo, A screening methodology for implementing cost effective energy retrofit measures in Canadian office buildings, Energy Build. 43 (2–3) (2011) 614–620.
[85] Y. Fan, X. Xia, Energy-efficiency building retrofit planning for green building compliance, Build. Environ. 136 (2018) 312–321.
[86] E. Cascio, Z. Ma, D. Borelli, C. Schenone, Residential building retrofit through numerical simulation: a case study, Energy Procedia 111 (2017) 91–100.
[87] D. Jenkins, A.D. Peacock, P.F.G. Banfill, Will future low-carbon schools in the UK have an overheating problem?, Build. Environ. 44 (3) (2009) 490–501.
[88] M.F. Jentsch, A.S. Bahaj, P.A.B. James, Climate change future proofing of buildings—generation and assessment of building simulation weather files, Energy Build. 40 (12) (2008) 2148–2168.
[89] D. Jenkins, Y. Liu, A.D. Peacock, Climatic and internal factors affecting future UK office heating and cooling energy consumptions, Energy Build. 40 (5) (2008) 874–881.
[90] I.G. Kerdan, R. Raslan, P. Ruyssevelt, S. Vaiciulyte, D.M. Gálvez, Thermodynamic and exergoeconomic analysis of a non-domestic Passivhaus retrofit, Build. Environ. 117 (2017) 100–117.
[91] T.S. Larsen, R.L. Jensen, Comparison of Measured and Calculated Values for the Indoor Environment in One of the First Danish Passive Houses Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association, Sydney, Australia, 2011.