Refurbishment options to decarbonise a 1960s public office building by 2050s

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Abstract

Climate change and the subsequent impact this has on carbon emissions for buildings has shown great concern for the industry. With over 1.35 million non-domestic buildings at least over 25 years old; the need for more practical refurbishment strategies in order to decarbonise and future-proof the old building stock against climate change is vital. The aim of this paper is to explore more sustainable, economic and less-disruptive refurbishment approaches for an air conditioned building as efficient future weather mitigation measures. Particular emphasis was placed on the evaluation of the carbon reductions associated with the best-suited approaches under two future climatic scenarios, 2030 & 2050.

A building simulation model of a public office building has been developed to assess the current energy performance as well as the predicted future energy performance for two refurbishment strategies. These strategies are adaptive thermal control and fabric modification. A reduction in carbon emissions, of 7.5%, results from applying adaptive heating and cooling set points to the model with a current weather data scenario. This reduces to 6.8% in 2030 and 5.3% in 2050. The potential savings are most significant for the current climate scenario and then reduce for the 2030 and 2050 scenarios largely because of an elevation in heating set points. In terms of cooling, an upper limit to the cooling set point of 26°C prevents meaningful differentiation between the 2030 and 2050 adaptive cooling set points but is necessary due to the lack of opportunities for building occupants to adapt their conditions. There is scope for research to be carried out into the application of adaptive set points for existing buildings. Some work has been carried out on the cooling scenario but little appears to have been done for heating as of yet. Given that this could be retrofitted into BMS systems, it is a potential option to reduce building carbon emissions with minimal cost for buildings with centralised systems. For the fabric modification, a significant reduction in carbon emissions was achieved by the use of composite panels to replace much of the glazing. This resulted in a significant improvement in building performance but at a significant investment cost.

Keywords: Adaptive thermal comfort, refurbishment, decarbonisation, future climate, office building

1.0 Introduction

The ‘fifth carbon budget’ announced by the UK government in 2016 (1) sets an ambitious new target of 57% carbon emission reduction by 2030 based on a 1990 baseline as well as maintaining the 80% reduction by 2050 (2). A reduction in climate change leading to temperature increase caused by carbon emissions is the driver for this strict and optimistic legislation (3, 4). The UKCP09 (5) indicates that the changes in summer mean temperatures are greatest in parts of southern England and will rise 4.2ºC by 2080. The far North will also see a rise, just over 2.5ºC with the rest of the UK in between the two.

There are over 1.8 million existing non-domestic buildings in the stock (6). Three quarters of them are over 25 years old and one third over 70 years old (7), it is predicted that 87% of these buildings will still be occupied by 2050 (8). The challenge of refurbishing our existing non-domestic building stock to adapt for the changing climate is huge, but the potential impact it will have on reducing carbon emissions is large.

Currently there is no legal framework to drive the decarbonisation of our existing building stock in the UK apart from when significant modifications or extensions are to be carried out. Most of the current guides, standards and policy (9, 10, 11, 28) for carbon reduction in the building industry is directed to new buildings at the construction stage to achieve air tight and thermally sound buildings. Part L2B (10) of the building regulations along with the BREEAM non-domestic manual (11) provide some guidance on refurbishment to meet higher energy ratings by reducing consumption. However, little thought is given to ‘future proofing’ non-domestic buildings against climate change or client incentives to uptake the measures set out. If the rate of building replacement is not radically increased or sustainable refurbishment is implemented extensively, new building design will have little impact on the threat of global warming (13).

Many pieces of literature discussing and investigating building future proof measures focus on the adaption to mixed mode non-domestic buildings (14, 15, 16, 17). This gives an indication that naturally ventilated buildings could be perceived as being the answer to the reduction in carbon emissions by reducing reliance on air conditioning. However, the resilience of naturally ventilated buildings in the future climate is questionable due to the continued rising global temperature (18), frequency of heat waves (19), change of internal gains (20) and air pollution issues (13).

ASHRAE 55 (21), CIBSE TM52 (22) and BS EN 15251 (23) provide current guidance on the application of the adaptive thermal comfort theory, including formulas and application descriptions. However, the focus is very much on mixed mode or naturally ventilated buildings (24) and little guidance is provided for its use in fully air conditioned buildings. One study (25) showed the benefits of applying an adaptive thermal comfort model to fully mechanically heated and cooled office buildings and concluded that an average of 6% reduction in daily HVAC (heating, ventilating and air conditioning) electricity consumption was observed by increasing the cooling set point by 1°C. However, an adverse effect was observed by an increase in complaints about ‘stuffiness’ which was attributed to the reduction in airflow demand associated with the use of variable air volume (VAV) systems in some of the case study buildings. There is still very little understanding of the implications on adaptive thermal control strategies in mechanically ventilated buildings.

Most of the literature tackling the retrofit measures of occupied non-domestic buildings showed two distinct routes, the ‘wait and see’ and ‘act now’ approach (13, 26). However, cost was found to be the most critical driver in any retrofit project (9, 14). Clients/ Building owners need to be persuaded into ‘future-proofing’ measures that are relatively inexpensive and non-disruptive whilst showing tangible results. Even though the UK government provides a range of economic incentives and financing instruments such as the enhanced capital allowance (ECA), low-cost loans from the Carbon Trust, feed-in tariffs (FIT) and the Renewable Heat Incentive (RHI); these schemes mainly focus on the use and installation of the low carbon and renewable technologies. No funding or grants are available for non-domestic building owners to improve the thermal performance of their building façades.

More research effort is required to provide practical guidance for the 'old' building owner in terms making an informed and cost effective decision when it comes to decarbonising and future-proofing their stock. Applications and implications of implementing adaptive thermal control strategies in mechanical ventilated buildings deserve more a lot attention as well; it could be one of least disruptive and economical refurbishment strategies that could be easily adopted for most centrally controlled non-domestic buildings.

The present study is to explore and examine the refurbishment options for a 1960s public office building by 2050s.

2.0 Background

A typical 1960's public office building, located in the heart of Portsmouth, is chosen as the case study building for this research. It is a post-war, pre-fabricated office building, very common for the UK building stock with poorly insulated fabric and high levels of glazing. Single glazing was the original feature; however, in subsequent years since its construction, secondary glazing has been added internally to improve the thermal performance. The glazing is tinted, which is assumed to be a high-reflective glass. The estimated thermal transmittance (U- value) of the building fabric based on a previous energy analysis carried out by a third party (29) are shown in the table 1 below.

Table 1. The estimated thermal transmittance value of the case study building

Element name	**U Value (W/m^{2}K)**
External Wall	1.6
Floor	1.3
Roof	1.3
Glazing	3.9

The building has a typical office workday pattern of 08:00-18:00 and conduct civic duties. Significant disruption from refurbishment measures therefore, would be more than a mild annoyance, it would cause disruption to important civic work.

The building is mechanically heated and cooled by centralised all air systems through air handling units (AHUs). The building is separated into six vertical cores and each core has its own plantroom located on the roof (see figure 1). An underfloor air distribution strategy is used to supply conditioned air through the raised floor with floor plenum located along the windows. In the initial design, all the AHUs were run on 100% fresh air supply (with no re-circulation). In 2013, all the AHUs were adapted to allow re-circulation of room air and free cooling and at the same time the old chiller plant was replaced. An 18% reduction in

Figure 1: Portsmouth Civic Centre – (51)

the total electrical energy consumption was achieved in the subsequent year in 2014 (figure 2). In order to further improve energy efficiency, the building has undergone a series of refurbishment and retrofitting works (figure 3) including boiler plant replacement, PV installation and a LED lighting upgrade between 2012 and 2017. These measures have effectively reduced the building total energy consumption by almost 36% compared to the 2012 energy consumption.

Figure 2. Annual energy consumption of the case study building over the past 6 years

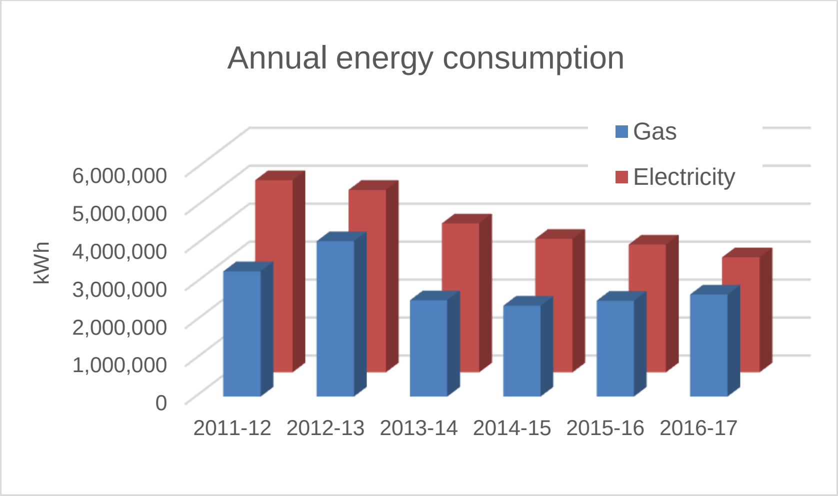
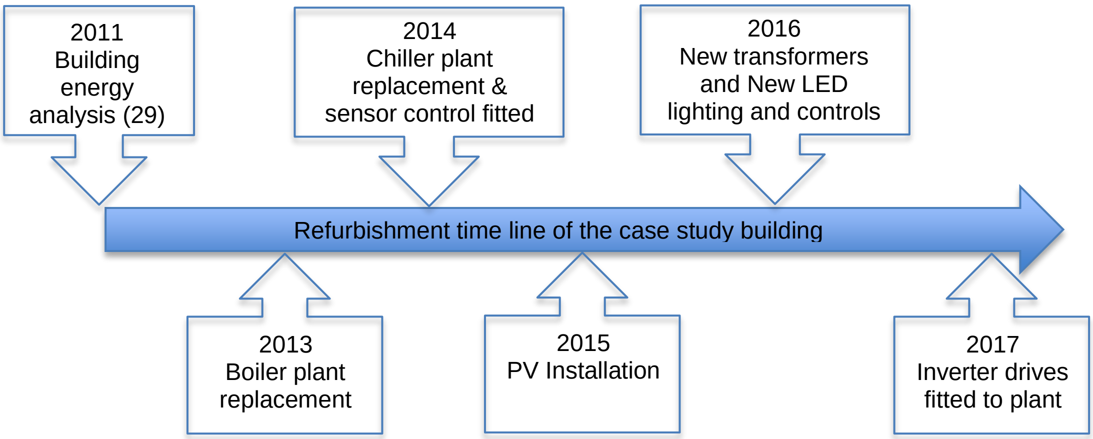


Figure 3 Refurbishment time line of the case study building



3.0 Objectives

The aim of this paper is to explore the most sustainable, economic and least disruptive refurbishment approaches for a mechanically ventilated building to efficiently mitigate future weather implications, with particular emphasis placed on the evaluation of carbon reduction.

A mechanical and electrical services survey of the case study building was conducted through site visits and the use of existing technical drawings and specifications.

A building simulation model was developed based on current mechanical and electrical services and plant and the model was validated using existing building energy consumption data.

The effectiveness of two refurbishment strategies (façade adaptation and thermal adaptation) was evaluated by building simulation based on current climate and two future climate scenarios.

The potential and implication of applying thermal adaptive control in a mechanically ventilated building was evaluated.

4.0 Methodology

Model development and validation

A 3D building simulation model is developed in the IES VE environment (27) based on the actual building geometry, the estimated construction (table 1) and the installed HVAC plant. A slightly edited National Calculation Methodology (NCM) (28) profile is used to configure the internal heat gains in all the occupied zones based on the reported general occupancy pattern from the client.

The predicted annual energy consumption from the IES models are validated against the: 1) energy benchmark ECON 19 guide for typical office building (29), 2) the reported average energy consumption in 2008 - 2010 from the preliminary energy analysis (29), and 3) the actual measured building energy consumptions in 2017 as shown in table 2.

Table 2. Comparison of the building simulation and benchmark values

		Gas (MWh/yr)	**Electricity (MWh/yr)**
1	Energy benchmark ECON 19 Guide	4837	5652
2	Average energy consumption between 2008 - 2010	4292	5876
3	Actual measured energy consumption in 2016 – 2017	2600	4000
4	IES base model from this work	2586	3575

As explained previously, the building has undergone a series of refurbishment and retrofitting works between 2011 and 2016, and therefore significant reductions in energy consumption over the past 10 years is expected as shown in table 2.

There is a small difference between the actual energy measurement (in 2016-2017) and the IES predictions as expected; the IES model is set up based upon a number of assumptions about the building. The model could be tailored to more closely match the actual energy data if the usage profiles and internal gains are provided on a room by room basis.

Future weather data

The COPSE-Northumbria weather data tool (30), which was developed at Northumbria University from 2008-2011 through a EPSRC funded project, was used to generate the two future weather data sets, i.e. the Design Reference Year (DRY) files in 2030s and 2050s for the medium carbon emission scenarios. The benefit of the COPSE weather data is that it localises the general CIBSE provided data from nationwide measurements to regional 5km x 5km grids, providing a more accurate prediction for a specific geographical location based on the case study building.

Simulation scenarios

Taking into consideration the recent renovation works, the current building conditions and the nature of the building, the 3 appropriate changes in each of the refurbishment areas of: A) **thermal adaptation** and B) **fabric modification** were identified and applied in the IES model and examined for 3 weather scenarios - current, 2030s and 2050s.

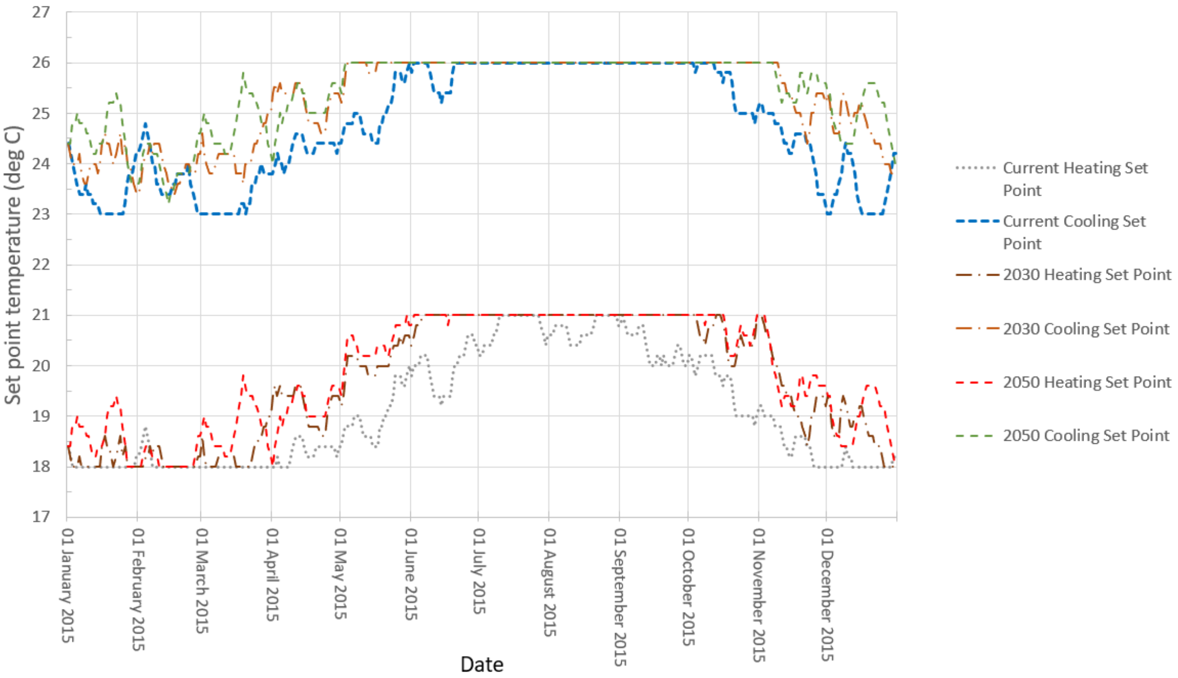
In the thermal adaptation approach (A), the key focus lies in implementation of an adaptive thermal control characteristic on the HVAC system which is less-disruptive in terms of the refurbishment process. The CIBSE TM52 (22) running mean outdoor temperature approach, which is not traditionally used for a mechanically cooled buildings but is applicable for this application, is used to define the comfort temperature and hence the HVAC system control set point temperature. The control set point temperature is then allowed to vary on a daily basis according to the running mean outdoor temperature as shown in table 3 and figure 4 for the current and future weather conditions.

$$T_{comf} = 0.33\, T_{rm} + 18.8 \quad \textbf{Equation 1}$$

Table 3. Simulation scenarios for category A: Thermal adaptation approach

	Description	Set point temperature	Reference
A1	Fixed heating and cooling set points	T_h= 21°C T_c= 23°C	CIBSE Guide A (Fanger theory) (47).
A2	Adaptive cooling set points only	T_h= 21°C $T_c \leq 26$°C; T_c varies as the mean outdoor temperature	CIBSE TM52 (22)
A3	Adaptive heating and cooling set points	$T_h \geq 18$°C; T_h varies as the mean outdoor temperature $T_c \leq 26$°C; T_c varies as the mean outdoor temperature	CIBSE TM52 (22)

Figure 4 Floating HVAC system control set point in the current, 2030s and 2050s weather scenarios.



In the traditional fabric modification approach (B), the use of composite panels (to replace many of the existing windows) and the exposure of the thermal mass and the application of night purge ventilation have been chosen for this investigation, due to lower investment costs compared to the reconstruction of the entire building envelope.

Table 4. Simulation scenarios for category B: Fabric modification approach

	Description	**Details**
B1	Composite panels	69% of the glazing replaced with composite panels on all four facades
B2	Suspended ceiling removed and night purge ventilation	Including removing the suspended ceiling, re-positioning the services (if necessary) and adding night purge ventilation
B3	B1 and B2 combined	

5.0 Simulation results

The results shown in figure 5 show the effect of implementing the two adaptive comfort control strategies on the base model using current and future medium risk weather data sets for 2030 and 2050.

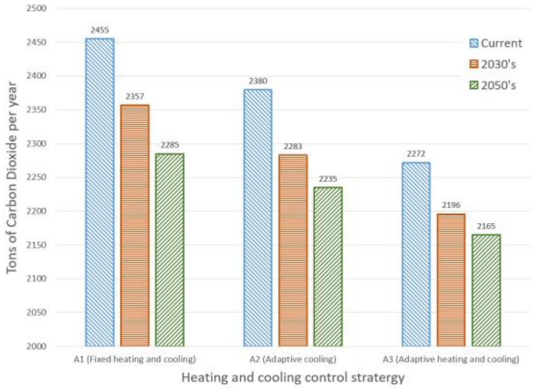


Figure 5 Carbon emissions for heating and cooling set point strategies from current to 2050

The results shown in figures 6, 7 and 8 are for the base building (current design) and modifications to that design intended to improve the building energy performance. B1 is the replacement of much of the buildings single glazing with composite panels. B2 is the exposure and use of thermal mass along with night purge ventilation. B3 is the combination of B1 with B2.

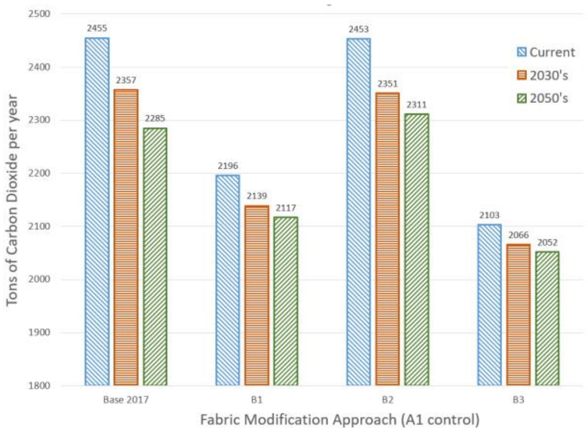


Figure 6 Carbon emissions for fabric modification approaches using fixed heating and cooling set points (A1)

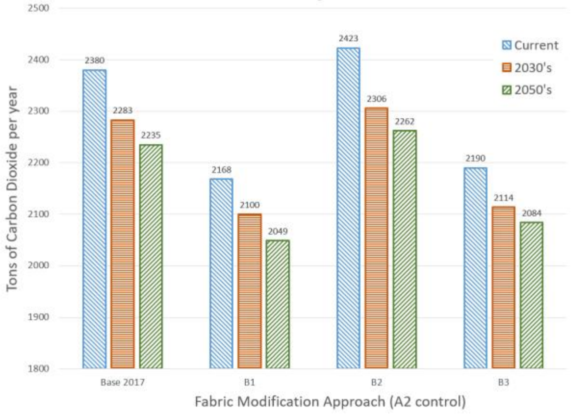


Figure 7 Carbon emissions for fabric modification approaches using fixed heating and adaptive cooling set points (A2)

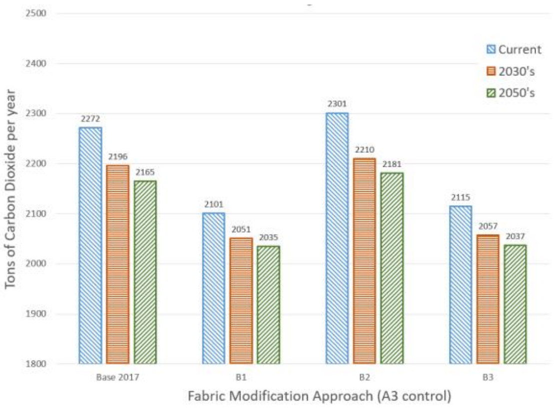


Figure 8 Carbon emissions for fabric modification approaches using adaptive heating and cooling set points (A3)

Analysis of the results showed that the effectiveness of the B2 approach was compromised by the infiltration air change rate which was set at 0.7 air changes per hour in all the modelling results shown above. The installation of composite panels (B1 approach) offers the opportunity to significantly improve the buildings air tightness and so the effects of this have been modelled below in figure 9 using an air change rate of 0.3 air changes per hour.

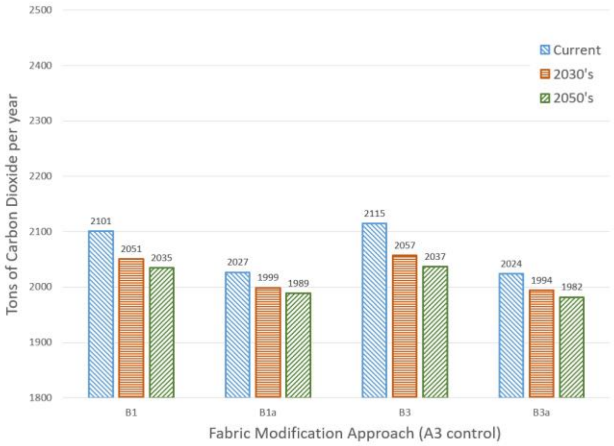


Figure 9 Carbon emissions for fabric modification approaches B1 and B3 using adaptive heating and cooling set points (A3) with reduced infiltration air change rate

The likely costs of making the suggested fabric improvements have been estimated using the Spon’s Architects and Builders’ Price Book 2016 (31) and are shown in Table 5 below. For the increased thermal mass options (B2 and B3) it is the cost over and above a normal major office refurbishment that is presented. An allowance is also made in the B2 cost for developments to the buildings BMS system and a soft-landing approach to its introduction.

Table 5 Estimated costs for fabric modification approaches

	Description	Estimated cost
B1	Composite panels	£943,000
B2	Suspended ceiling removed and night purge ventilation	£599,000
B3	B1 and B2 done together	£1,201,000

Table 6 Estimated percentage saving from the base model A1 under the current weather

	Base case	B1	B1a	B2	B3	B3a
A1 (current)	Base case (reference)	10.6%	14.6%	0.1%	9.7%	14.3%
A2 (current)	3.0%	11.7%	15.8%	1.3%	10.8%	15.6%
A3 (current)	7.5%	14.4%	17.4%	6.3%	13.9%	17.6%
A1 (2030s)	4.0%	12.9%	15.8%	4.2%	12.4%	15.8%
A2 (2030s)	7.0%	14.5%	17.5%	6.1%	13.9%	17.5%
A3 (2030s)	10.6%	16.4%	18.6%	10.0%	16.2%	18.8%
A1 (2050s)	6.9%	13.8%	16.3%	5.9%	13.4%	16.4%
A2 (2050s)	9.0%	91.7%	18.1%	7.9%	15.1%	18.2%
A3 (2050s)	11.8%	17.1%	19.0%	11.2%	17.0%	19.3%

Table 7 Estimated payback for each case

	B1	B1a	B2	B3	B3a
A1	7.8 years	5.5 years	664.1 years	11.1 years	7.2 years
A2	7.6 years	5.4 years	152.3 years	10.8 years	7.1 years
A3	6.1 years	4.9 years	9.7 years	8.1 years	6.2 years

6.0 Discussion

Table 6 reveals that the building is predicted to emit fewer carbon emissions than current in 2030 and 2050. This reduction is not insignificant at 4% in 2030 and 6.9% in 2050 for the (A1) fixed heating and cooling set point strategy. The reduction in carbon emissions is driven by a significant reduction in the heating energy of 21.5% in 2030 and 37.1% in 2050. These reductions are large enough to offset increases in electrical energy consumption, driven by higher cooling loads, of 1.7% in 2030 and 3% in 2050.

The greatest reduction in carbon emissions, 7.5%, results from applying the adaptive heating and cooling set points to the model with the current weather data. This reduces to 6.8% in 2030 and 5.3% in 2050 with reference to the 2030s and 2050s base case. The reason for this reduction in benefit is evident in figure 4 which shows the adaptive heating and cooling set points for each weather data set. The potential saving from each data set can be assessed by integrating the values under the fixed heating set point and above the fixed cooling set points. The potential savings are most significant for the current climate scenario and then reduce for 2030 and again for 2050 largely because of the progressive elevation in heating set points. The upper limit to the cooling set point of 26°C also prevents meaningful differentiation between the 2030 and 2050 cooling set points but is necessary due to the limited opportunities for building occupants to adapt their conditions. The relaxation of dress code, the use of desk or pedestal fans and flexibility regarding where to sit in the office (hot desking) are ways in which the occupants could be enabled to make adaptions to suit their preferences for thermal comfort. Using Q2 2017 fuel price data from the UK Department for Business, Energy and Industrial Strategy the annual fuel saving for the current weather data and the base model are £25,529 for A2 (adaptive cooling) and £77,144 for A3 (adaptive heating and cooling). If this form of control is accepted by the building users these savings are very significant compared to the cost of implementation.

Table 6 reveals a significant reduction in carbon emissions of 10.5% for the B1 composite panel option with the current weather data. This figure rises to 12.9% in 2030 and 13.8% in 2050 when the building uses fixed heating and cooling set points. This improvement is due to a reduction in both heating and to a lesser extent cooling energy. In addition to these useful carbon reductions it is likely that the building would experience improved thermal comfort in both winter and summer due to reduced expose to solar gain in summer and a much better insulated façade in winter. Both of these scenarios effect the air and radiant temperatures across the space and thus have the tendency to create variations in the perception of thermal comfort for the occupants. The buildings constant volume air conditioning systems are not well suited to scenarios where the loads vary significantly across the space. The current systems discharge the supply air at the perimeter of the room, thus offsetting, as well as possible, the negative effects of the current façade. With a highly modified façade, particularly if air tightness can also be improved, it may also offer opportunities to distribute the supply air in the space via floor diffusers. Another option to explore is floor mounted local control units which have the ability to mix room air with the supply air (fed from the floor void) to vary the condition within that zone. This would enable a far greater sense of occupant control and improve comfort conditions across the space, but at the cost of additional fan power distributed over the floor plate.

Figure 6 reveals that the increase in thermal mass and the introduction of night purge ventilation (model B2) has minimal benefit. The reasons for this are twofold. Firstly, the night purge ventilation is mechanically driven since the building does not have an openable façade. This means that carbon emissions are generated overnight in order to offset carbon emissions the following day by reducing the cooling energy required. The second, and more significant issue, is that with 0.7 air changes per hour of infiltration the building fabric cools down significantly over night and the increased thermal mass then increases the heating energy the following day compared to the base model. Fitting the composite panels to the building provides an opportunity to improve the building air tightness. The B1 and B3 options were therefore modelled again with a reduced infiltration air change rate of 0.3 in order to assess the potential benefit and labelled as B1a and B3a.

Figure 9 shows the performance for B1 and B3 with the original and improved infiltration air change rates for current and future weather data with the adaptive heating and cooling (A3) approach. The carbon savings for the B1 model are greatest with the current weather data at 3.5% and least in 2050 at 2.3%. The same trend is evident for the B3 approach with savings of 4.3% current and 2.7% in 2050.

The maximum savings occur for the traditional fixed heating and cooling set point option (A1) where for B1 the saving is 4.5% and for B3 5.1%. These savings are almost entirely from the heating energy and in the majority of cases increasing the air tightness slightly increases the cooling energy requirement. The decision was taken not to increase the night purge ventilation rate to compensate for the loss of 0.4 AC/hr of infiltration. Had this been done the effect on the building cooling energy could have been reduced but at the expense of increased night purge fan energy. This is an area that could be investigated in further studies.

The figures in table 5 show that the costs associated with upgrading the façade, even in the least cost and least disruptive manner, are significant. The fuel saving cost for the base model compared to the B1a (composite panel with reduced infiltration), using current weather data, with adaptive heating and cooling set points (A3) is £170,780 per year. This is calculated to return a simple payback of 4.9 years as shown in Table 7.

Relaxing the heating and cooling set points based upon the weather conditions over the previous week is predicted to save significant levels of carbon emissions. This paper presents whole building emissions rather than those specifically from heating and cooling only. Had the latter been done a more significant effect would have been seen. However, ultimately it is how the building as a whole performs that is important to the client and building owners.

Setting up IES VE to utilise adaptive heating and cooling set points was time consuming and this is likely to reduce the uptake of modelling this type of control. It seems possible for software vendors to be able to adapt their applications to be able to generate these adaptive control options directly within the software. Users could simply be presented with a choice of offset from the comfort temperature calculated from the running mean temperature. This would then automatically vary the set points each day based upon the adaptive comfort approach with minimal user set up time required. This is a move that would be welcomed by those interested in exploring this option more widely.

There is scope for research to be carried out into the application of adaptive set points for existing buildings. Some work has been carried out on the cooling scenario but little appears to have been done for heating as of yet. Given that this could be retrofitted into BMS systems it is a potential option to reduce building carbon emissions with minimal cost for buildings with centralised systems. However, the widespread use of radiators fitted with TRV’s, and terminal units (e.g. FCU) with standalone controllers does limit the applicability of this type of control.

7.0 Conclusion

Current guidance on application of the adaptive thermal comfort theory is intended for use in naturally ventilated buildings, i.e. where the occupants have adequate control over their internal climate by adjusting the window / façade openings. This introduces uncertainty regarding thermal comfort and occupant satisfaction when implementing an adaptive thermal control strategy in a mechanically cooled building. The adaptive adjustment of heating set points has also not been studied and so requires research to verify its applicability and limitations. This study predicts significant energy, carbon and financial savings are possible if an adaptive thermal comfort strategy is used to adapt the heating and cooling set points within reasonable limits. Software vendors could incorporate this form of adaptive set point control within their software to enable analysis of these options to be analysed in a far more time efficient manner. Perhaps most importantly, further research is necessary to test the applicability of this form of control to buildings with centrally controlled HVAC systems to ensure that it can be applied without causing occupant dissatisfaction.

Improving the building façade would bring many benefits, including reduced carbon emissions and fuel cost. The replacement of much of the glazing with composite panels will affect the daylighting performance and may increase the reliance upon artificial lighting, however, fully glazed facades commonly employ internal blinds to reduce glare and so the overall effect may not be so significant. Daylight sensing controls were not included in this study and so it is possible that the savings resulting from façade improvements have been slightly exaggerated. However, in a refurbishment scenario the installation of an energy efficient lighting system and intelligent controls could help to reduce this impact. Government support in the form of grants, or low interest rate loans, would help to make these options more financially attractive. With so many similar buildings in the UK, perhaps, it is time to consider investing to improve their quality in order to help meet our Carbon Emission targets.

Increasing the thermal mass and using mechanically driven night purge ventilation is confirmed to be a poor choice for adaptation for this building. If air tightness could be improved this solution is more effective but still impossible to justify from a fuel cost saving perspective. Improving the air tightness when installing the composite panels may be possible and this study shows significant fuel cost savings, in the region of £50,000 per year. This highlights the importance of maintaining or improving air tightness when retrofitting existing buildings.

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