Investigating the Productivity of Office Workers to Quantify the Effectiveness of Climate Change Adaptation Measures

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Abstract
The impacts of climate change pose many threats to our current way of life. However, the current mitigation agenda has not yet produced the carbon emission reductions needed implying that some level of adaptation will be required. For buildings this is likely to mean either drastic changes to architecture, occupant behaviour or the increased use of artificial cooling to maintain thermal comfort in the future. The capital cost of sustainable buildings is often perceived to be higher than for conventional buildings and there is little incentive to employ sustainable building adaptations over air-conditioning type solutions, making future reductions in carbon emissions unlikely. In this paper we investigate contributing factors to worker productivity in an attempt to justify the perceived cost of sustainable adaptations. Then as a proof of concept we estimate the potential savings that could be achieved by applying two simple adaptations to an office building to produce a more comfortable environment. It is hoped that this consideration of loss of productivity and its causes will aid not only in the choice of useful adaptation decisions, but also a consideration of payback periods will help persuade building commissioners of their value and overcome the perceptions about sustainable buildings.

Highlights
- Thermal comfort for an office under future climates is estimated.
- Estimated reduction of worker productivity due to climate change.
- GVA data used to equate productivity to savings to incentivise building adaptation measures.

Keywords
Comfort, productivity, climate change, adaptation, building, design

Introduction
The UK Government is committed to an 80% reduction in carbon dioxide (CO_2) emissions from 1990 levels by 2050 and the Kyoto protocol encourages other countries to adopt similar reductions in CO_2 emissions. In order to do this there are many fiscal and societal stimuli to encourage building owners to improve the building fabric, upgrade inefficient heating systems and even generate onsite electricity and heat. Of the UK's workforce over 50% now work in offices compared with 20% at the turn of the 19th century [1]. As a consequence there has been a dramatic increase in office space over the last century, which is still continuing. Furthermore, the life cycle of an office building is around 20 to 50 years, and typically an office building lasts 40 years [1]. Buildings are therefore both a substantial investment and potentially a long-term commitment. As such the impacts of climate change will have to be considered, to ensure that buildings continue to meet emissions targets in the future while maintaining thermal comfort. While in the domestic sector these improvements will perhaps lead to significantly lower energy bills, in the commercial sector (offices etc) energy costs are

typically only a small fraction of staff costs. Why then would a commercial building owner attempt to minimise their energy usage and CO_2 emissions when the benefits are relatively small compared to the benefits of creating a comfortable environment via artificial means to attract and retain high quality employees and maintain high productivity, potentially at the expense of the environment? Morton *et. al* [2] noted in a study about exploring beliefs about climate change, that clients see the sustainable and low energy solutions as a costly approach and often wish to spend the minimum time and money to achieve a building suitable for the intended use and meets current regulations. There was also evidence that the more senior an individual within an organisation the more content they are with current practices, with increased resistance to change. Morton [2] also noted that there was an expectation of increased resistance from clients, who would be unwilling to foot the bill for increased time and money spent on a project to incorporate climate change mitigation and adaptation measures. Therefore there is a need to provide an extra stimulus to incentivise the uptake of sustainable mitigation and adaptation options, and to move away from the current practices of incorporating active cooling to deliver thermal comfort in warm weather. If the thermal environment causes a decrement to individual performance, then productivity will fall. Determining the influence of climate on individual performance is one way of investigating productivity. Other potentially more important effects may be behavioural such as ease of distraction from task, sickness or accidents and absenteeism from the workplace or from work altogether. These will generally result in time off task (productivity = 0) rather than reduced performance. However these are hard to quantify and difficult to mitigate against. In this paper we will look at the impact of internal environmental conditions on worker productivity and how this may be affected by climate change. In conversation with clients and architects as part of this project there is often a desire to avoid the use of air conditioning where possible. This is either because of their desired company environmental image and sustainability targets or because of fears over air-quality and energy use. However, there is also a desire not to spend more money than is necessary on design or building features. It is hoped that a consideration of worker productivity will persuade commercial building owners to adopt sustainable building designs and to use passive or low energy technologies to adapt to the impacts of climate change, despite the likely perception of increased capital cost and possible resistance to change. While many studies and much evidence is available on the subject of worker performance, there is no all encompassing theorem, as many studies focus on particular types of task and evidence is sometimes circumstantial. However, it is hoped that a convincing argument can be derived.

Much is known about how human performance, particularly how physiological mechanisms are affected by hot and cold environments. In extreme conditions of hypothermia or hyperthermia, confusion, illness and collapse will have obvious implications. Between these extremal environmental conditions there are effects that can be attributed to thermoregulatory responses. As the body cools, vasoconstriction reduces blood flow in the skin reducing skin temperature, this can result in for example in stiffness and a loss of sensitivity of the fingers. Furthermore, increased viscosity of synovial fluid stiffens joints, nerve conduction rates reduce and there is a loss in strength and dexterity as muscles cool. In addition, thermal discomfort and shivering can result in distractions and behavioural changes due to over arousal. While in an office environment the heating system should negate the more extreme of these effects, due to the individual nature of thermal comfort it is likely that some individuals will experience discomfort and over arousal due to feeling cold (or too warm). This discomfort may well result in loss of performance due to time off task adjusting heating controls or reduced typing speed and accuracy for instance. The situation is similar for warm environments. When the body is hot, vasodilation enhances the ease of body movement, however sweating may affect grip and there may be distraction effects due to over arousal and physiological strain as core body temperature rises especially in sedentary individuals. Psychological strain may also be a factor if the individual exerts effort to maintain productivity despite environmental conditions, over time this will cause fatigue and result in performance decrement. The extent to which the above reactions will have an effect on activity and performance will depend upon the task being performed and the individual.

From the discussion above we can surmise that environmental conditions can interfere with human activities, affect task performance and reduce productivity. Therefore it is desirable to establish a rational model of human performance that could be used to investigate the effects of different thermal environments. This would incorporate relevant factors and determine their affect on an individual's performance. This approach is broadly similar to models of human thermoregulation, and it is likely that similar parameters will be involved. There are six basic parameters from which physiological responses are typically estimated [3]. These are air temperature, radiant temperature, relative humidity, air velocity, clothing insulation and the level of activity. These six parameters form the basis of heat balance equations from which it is possible to estimate the level of thermal comfort and human physiological responses such as skin temperature, sweat rate and heart rate.

There have been several studies of how environmental variables such as temperature affect the productivity of office workers [1,4-17]. In the developed world worker wages are typically many times larger than energy bills [18-20]. Ratcliffe [20] estimated that a typical air-conditioned office may have an energy bill of ~£15/m^2 per year whereas its staff costs are ~£3000/m^2 per year, these of course could be calculated for a specific building if required. While recent and projected increases in energy prices mean this is cost is now likely larger than Ratcliffe's estimate, energy prices are still a small percentage of staff costs. As this difference in cost per square metre is so large it may seem financially prudent to include air conditioning as standard and create an isolated fully regulated environment in which to work. This would have the result of creating a comfortable environment in the current climate and if adequately sized under future climates as well.

Paul and Taylor [21] after performing a literature review conclude that there is evidence-linking personal control over temperature and ventilation to comfort and that there is evidence-linking comfort to workplace satisfaction. In addition Heerwagen [22] showed that there was economic benefit for offices to maximise worker satisfaction. The question is now what factors increase worker satisfaction in the office environment, is it the type of building, the internal conditions, size of windows, ventilation or other factors? Paul and Taylor [21] compared two similar university buildings; one was designated a green building and contained many sustainable features while the other was of more conventional design with air conditioning. While their study did not reveal statistically significant trends for lighting and ventilation, perceived temperature was shown to have an effect on user satisfaction. This study was somewhat limited as it only considered two buildings and there was no flow of occupants between buildings. However, despite the limitations there was some evidence that environmental factors can influence how occupants feel about a building. Paul and Taylor [21] further hypothesise that place identity theory predicts that people who feel empathy about the environment would identify with the green building more and would more likely have a positive opinion about the working environment. This also implies that as public concern about the environment and climate change increases, people's opinion of sustainable buildings will improve. This hypothesis is supported by studies of environmental perception and place attachment [23,24]. This may improve staff moral and hence the productivity of workers if staff have a positive opinion about their working environment. It should be possible with careful design to create an office environment that has a sufficiently regulated internal environment to ensure optimal comfort and productivity whilst saving energy. In this report we will explore how different thermal environments affect worker productivity and what impact climate change may have on the output of an office building. This should allow sensible design decisions to be made to create an office environment that is successful both now and in the future and allow the payback of any adaptation measures to be easily estimated.

Thermal Comfort

The human body produces heat as a by-product of performing mechanical work such as walking, lifting weights, typing etc. A certain amount of heat is still produced while idle and the amount increases as the level of activity increases. The amount of heat produced is split between sensible heat radiated and convected from the surface of the skin and latent heat lost via sweating and moisture in the breath. The magnitude of heat loss for a typical adult can vary from around 100W while idle (sleeping or sitting still) to ~600W if performing heavy work such as running or going to the gym. In order to avoid thermal discomfort and serious heat related illness the body needs to be adaptive and lose heat according to the level of work being performed; the ease with which the body can do this will vary depending upon the surrounding environmental conditions. Factors that affect the body’s ability to lose heat include: air temperature and radiant temperature of surroundings, which prevent the body losing sensible heat. Sweat is constantly produced and is not always noticeable; the humidity of the surrounding air affects the ease with which this sweat can evaporate. This is why a dry heat is more comfortable than a humid heat and a humid day in winter can feel relatively warm, it is easier for your body to maintain its temperature. Other factors affecting comfort include air velocity, which assists in the evaporation of sweat from the surface of the skin and increases convective heat loss. Clothing also has an effect on comfort, since clothing covers the body and prevents convective and radiative heat loss directly from the skin. Clothing also acts as insulation and traps heat around the body. In hot environments the body will dilate blood vessels in the skin to increase sensible heat loss, then increase sweat rate to increase latent heat loss, if these are insufficient the core body temperature will rise. Increasing core body temperature raises heart rate and causes fatigue since the body has to work harder to try and maintain its internal temperature. The resulting heat stress and discomfort may lead to behavioural changes and effects on cognitive performance, for example mental performance, information processing, memory and so on. Many worker tasks require both physical and cognitive functions, for example typing requires speed and accuracy while processing information. Thermal discomfort will affect different aspects of tasks in different ways, as such it is necessary to consider a metric of thermal comfort that accounts for all of these factors and the level of activity being undertaken. One such metric is the predicted mean vote (PMV) [3] and will be discussed later.

Moderate heat stress of a few degrees above optimum can have an adverse effect on the performance of tasks due to relaxation and a reduction in arousal. This is believed to be an autonomic response to regulate body temperature corresponding to the limit of vasodilatory control, prior to the onset of sweating. However, it has also been noted that conscious effort can negate this effect [13]. Where subjects are exposed to high temperatures suddenly (i.e. walking into a hot room) this can act as a stimulus to exert conscious effort. However, in practice subjects will be exposed to slowly increasing temperatures over the course of a day circumventing the potential for increasing conscious effort leading to a decrease in arousal and productivity. If temperatures increase further then thermal discomfort may result leading to an increase in arousal and an associated performance increase (for low to moderate levels of thermal discomfort), however discomfort may also lead to distraction resulting in time off task (i.e. complaining, opening / shutting windows, changing posture, lapses in concentration etc).

Wyon *et. al* [13] carried out tests of mental performance on 36 male and 36 female 17-year old subjects in climate chambers. Results indicated that the effects of elevated temperatures and moderate heat stress on mental performance are not straightforward, even when experienced comfort and skin temperature showed a highly linear correlation with temperature. There was also indication of a reduction in mental performance at levels of moderate heat stress (26-27°C) due to decreased arousal. It was concluded that moderate heat stress of a few degrees centigrade above optimum has a marked effect on the mental performance of the test subjects when temperatures rise slowly. Tasks requiring concentration and thought are adversely affected, but memory tasks are improved up to 26°C, declining rapidly after. These findings are supported by several later studies [8,9,11,12,14-17].

Arousal

Performance at a task will depend upon the subject's arousal level compared to that required for optimum performance. A task that is boring will be de-arousing and a subject will perform better if their arousal level can raised by some means. Stimulation caused by a heat, cold or draughts may increase arousal but may also lead to distraction and time off task if the arousal is increased too much. A warm environment however, can be soporific reducing arousal level and hence performance will decrease. If a task is demanding and arousing then thermal stress may lead to over-arousal of the subject and performance will fall compared with that in a moderate thermal environment. It can therefore be beneficial to design to create an environment that produces the optimal amount of arousal for the tasks being performed, i.e. repetitive tasks will require greater arousal and hence a temperature further away from comfort may be beneficial.

Many office workers use computers for a significant part of the day. Computing is a special task requiring close attention to details and visual cues. The requirements of computers for the user to follow specific logic based procedures results in a high optimal arousal level. Computer use also imposes a particular posture on the subject, limiting metabolic heat loss by reducing the available surface area. Attempting to maintain high arousal levels in unfavourable thermal environments can lead to user fatigue and diminishing performance.

Productivity and Relative Performance

CIBSE TM24 'Environmental factors affecting office worker performance: A review of evidence' [1] concludes that published studies provide convincing evidence to show that environmental factors affect worker performance. The studies considered showed that although short-term exposure to discomfort can improve the performance of simple tasks, the general consensus is that optimum conditions for comfort are also most appropriate for performance. Pertinent factors identified included: motivation, perceived temperature, noise, lighting, air quality and space layout. Psychological factors such as motivation and the impact of space layout are hard to quantify but the other factors can all be measured and their impact assessed.

There have been several studies linking environmental variables to productivity. The work of Seppänen *et. al* [8] gives us an insight into how air temperature might affect productivity. Based upon measurements of task performance at different activities from 24 different studies. Statistical investigation of the results of these studies yielded the following relationship between relative productivity and air temperature.

$$RP = 0.1647524(T_c) - 0.0058274(T_c)^2 + 0.0000623(T_c)^3 - 0.4685328 \quad (1)$$

where RP is the relative productivity and T_c is the room air temperature (°C).

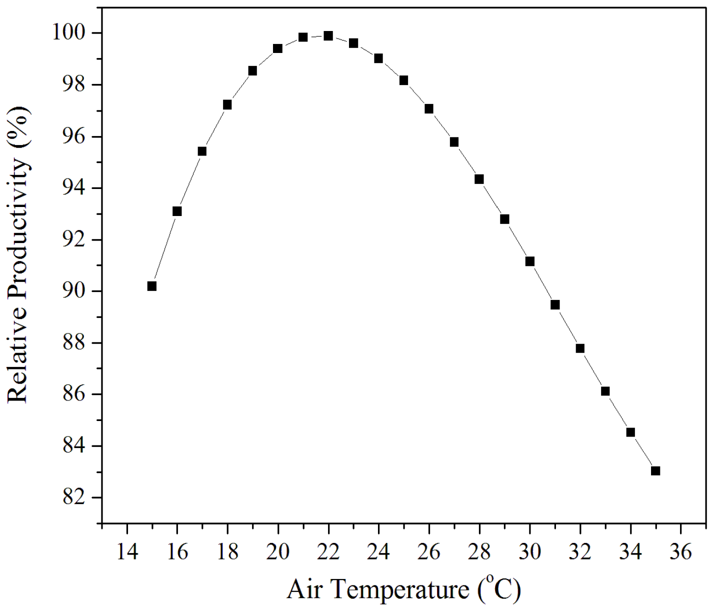


Figure 1 Plot of the Seppänen et. al [8] relationship between productivity and temperature.

However, as discussed above air temperature is only one factor that affects worker productivity. Fisk and Seppänen [4] devised a relationship between worker productivity and ventilation rates, this relationship is based upon the ventilation producing arousal and increasing productivity to a point where distraction results. However, Fisk and Seppänen [4] have surprisingly not tried to combine the temperature and ventilation relationships to produce a more holistic approach to modelling productivity. Daylighting is also believed to increase productivity [18], however a quantitative effect is not yet known. Daylight leads to higher indoor illuminances than is typically achieved with artificial lighting for much of the time. Although higher illuminances may improve productivity there appears to be added benefit of daylight over artificial light. There is believed to be photobiological effect on our circadian cycle and improved psychological well-being as a result of daylighting over artificial lighting, this is backed up by reductions in health complaints by occupants with window seats [18]. Lan [12] stated that productivity bears a close relationship to the indoor environmental quality (heat, cold, noise, light, etc.), but evaluating office worker productivity remains a challenge. Lan's study [12] indicated that participants could maintain their performance by exerting more effort when workload demand increased during thermal discomfort. However, this requires a conscious effort and can result in a lower motivation to work. Motivation is a recognised factor in improving productivity and is almost certainly influenced by the occupant's perception of how highly valued they are within the company. Occupants who are dissatisfied with the working environment might therefore exhibit reduced productivity for psychological reasons rather than physiological ones. While these factors will influence the performance of individuals, many are not easily quantifiable. This makes analysis of improved building design on occupant performance difficult. This paper focuses on the assessment of productivity in an effort to justify the use of sustainable design features and climate change adaptations. In this case it is factors affecting thermal comfort that are under consideration as other factors such as air quality, motivation etc. are a function of the building architecture, location and the tasks being performed and are not likely to change as a result of climate change. If measures are taken to provide a healthy environment, with good air quality and provision for daylighting included in the basic building design, then one might expect the main detractors from occupant performance to be climate related.

If we are to focus on the impact of the six basic environmental parameters on performance then a suitable metric is required to assess impact. Roelofsen [9] compiled a direct relation between loss of performance and thermal comfort based upon several studies of worker performance and models of how humans respond to thermal load. Roelofsen stated that the thermal environment is important both to the building design and to the building management and that creating a comfortable working environment can give the organisation a consistent financial advantage [9]. The relationship proposed by Roelofsen [9] is a direct relation between the loss of performance and the predicted mean vote (PMV) [3]. This can be done by incorporating the calculations of equivalent thermal situations with a human model [25] and with a comfort model [3] by means of a regression analysis.

The relation is as follows:

$$P = b_0 + b_1 PMV + b_2 PMV^2 + b_3 PMV^3 + b_4 PMV^4 + b_5 PMV^5 + b_6 PMV^6 \quad (2)$$

Where P is the loss of performance as a percentage and the values $b_{0\text{-}6}$ are regression coefficients, given in Table 1.

Table 1 Regression coefficients in the loss of performance equation [9].

Coefficient	On the cool side of neutral	On the warm side of neutral
b_0	1.280207	-0.15397397
b_1	15.995451	3.8820297
b_2	31.507402	25.176447
b_3	11.754937	-26.641366
b_4	1.4737526	13.11012
b_5	0	-3.1296854
b_6	0	0.2926092

This approach is perhaps more useful than those mentioned above since the PMV relationship includes more variables than just air temperature unlike the relationships proposed by Seppänen and Fisk [8]. PMV is a method for measuring and analysing the thermal environment based upon a heat load model for a hypothetical person. PMV varies according to the level of activity, the amount of clothing, air velocity, humidity and both air and radiant temperatures. The PMV scale ranges from -3 to +3 with 0 being neutral, negative values being too cool and positive values being too warm. Roelofsen's [9] relationship between productivity and PMV can be seen in figure 2. The red data point indicated thermal neutrality (PMV = 0), we can see that there are maxima in relative productivity either side of neutrality with the greatest being on the cool side. This is to be expected as discussed previously an increase in arousal due to slight discomfort will improve productivity.

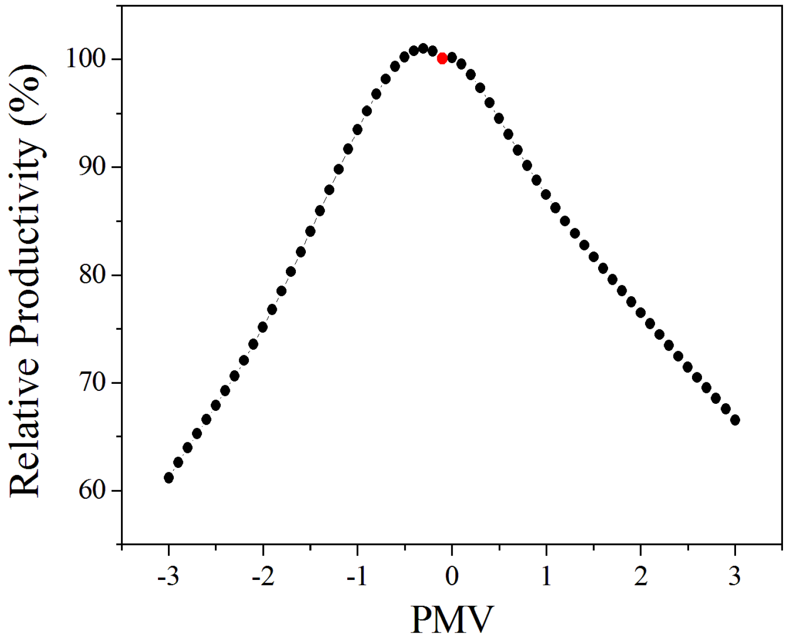


Figure 2 Plot of Roelofsen's [9] relationship for productivity for positive values of PMV.

A similar PMV based approach was derived by Lan et al. [14], based upon assessment of productivity at different temperatures, which was then converted to PMV, all other environmental variables remained constant. Both Lan's and Roelofsen's relationships show a peak in productivity on the cool side of neutral. However, Lan's relationship [14] is less sensitive to changes in environmental variables than both Roelofsen's [9] and Seppänen's [8]. This is most likely due to the smaller sample size and the narrow range of environmental variables studied.

Method

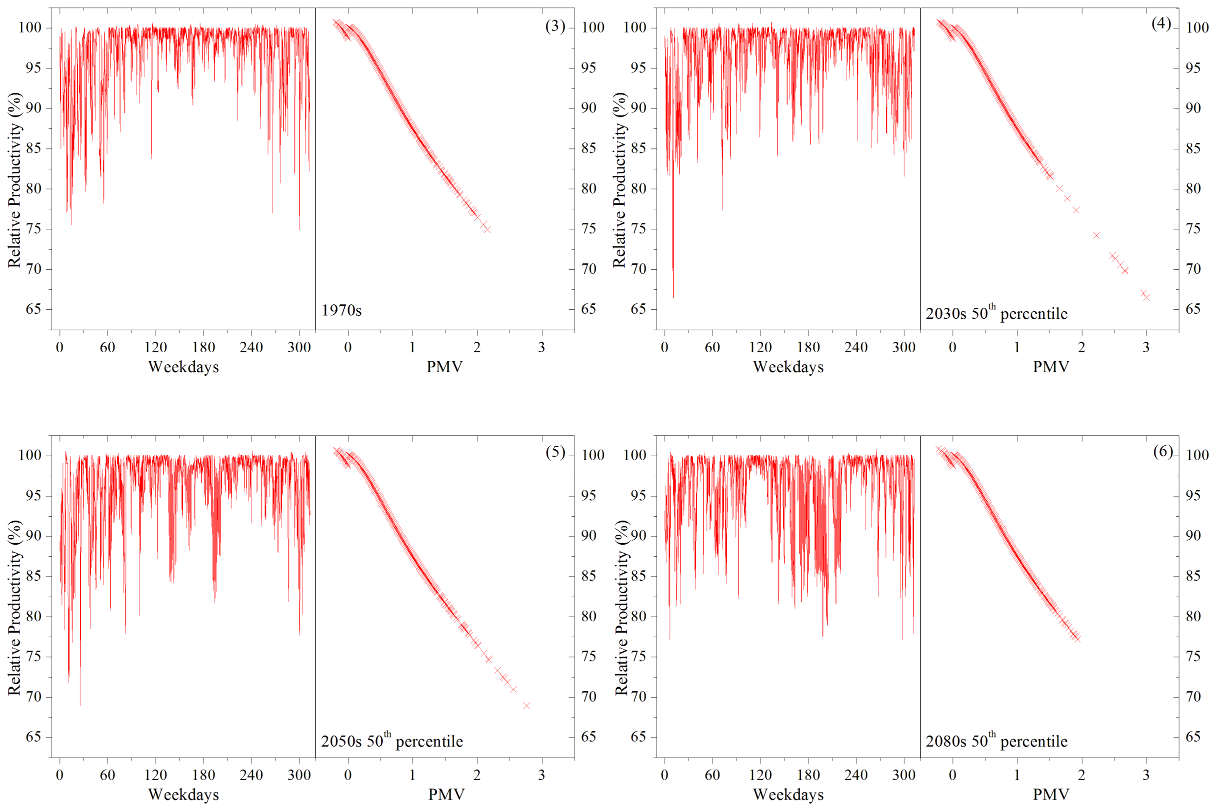
The above discussions have identified that human performance may be affected by distraction in hot, cold and moderate environments. A simple practical approach is to consider is that if a person is distracted, then productivity will fall proportional to the 'time off task'. As this is quantifiable, it is worth exploring further, to a practical approximation, if a worker is paid £80 for 8h work, and he or she spends 30mins distracted, attending to the thermal environment (thinking, complaining, changing posture, opening / closing windows, adjusting clothing, altering controls etc.), then the cost of the lost productivity may be around £5. If this is multiplied up for the number of workers and days worked, it can be seen that estimates of 'time off task' have practical value. This is a simplified approach and does not consider the value of the work being performed only the wages of the individual but as a first approximation it gives an illustration of the worth of taking measures to improve worker comfort and performance.

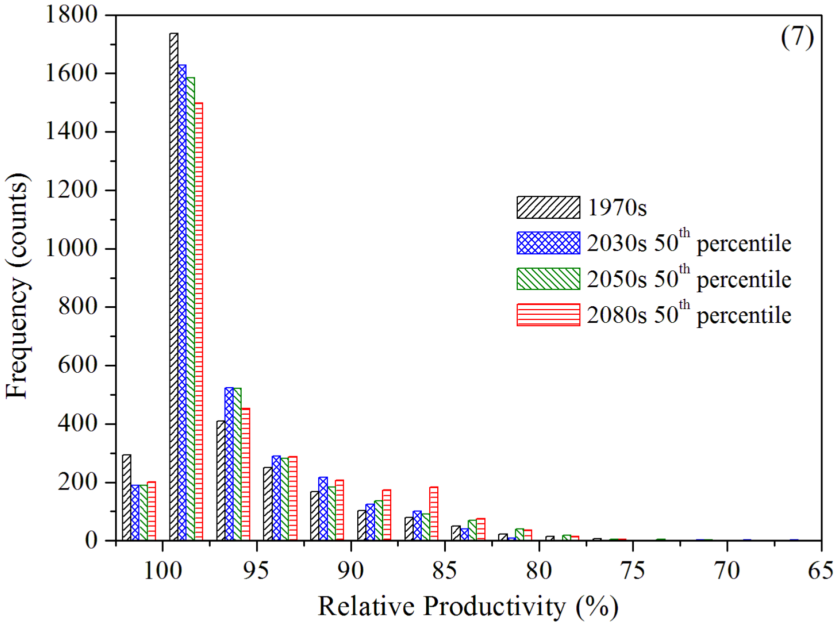
Using a thermal model of a council office building thermal simulations were performed using the Integrated Environmental Solutions virtual environment software [26], building details can be found in the appendix. Weather files [27] indicative of the current climate and future climates under a high emissions scenario (A1FI) were used for future time periods corresponding to the 2030's, 2050's and 2080's. The weather files used are based upon the latest climate projections for the UK (UKCP09) [28]. UKCP09 climate change data presents a distribution of possible climatic futures for the UK. The weather files [27] reduce this distribution to a handful of probabilistic weather files that can be used for building thermal simulation. While the weather files are probabilistic and several probability levels are available to map out the entire range of likely climatic change [29] only the central estimate (median, 50th percentile) was used in this study for brevity. While more probability levels would add more detail about the effectiveness of different adaptation measures, this extra detail is not needed for this study.

While the whole building was simulated, data is presented only for a single open plan office space. This room is located on the first floor and faces SSW / NNE and displayed the greatest levels of overheating. The office development is a naturally ventilated building with a conventional construction and typical internal gains, details can be found in the appendix. Using the output of the thermal simulations productivity was calculated for workers located in the open plan office using the relationship proposed by Roelofsen [9]. The authors feel that this is likely to be the most relevant of the relationships discussed above as it takes into account environmental variables such as humidity, which is an important factor for comfort in the UK, but also the level of activity and clothing allowing the relationship to be applied to other building types than offices. The relationship described by Roelofsen [9] was chosen for this study over that proposed by Lan [14] as it is derived from comfort theory and based on larger test groups. Additionally the productivity decrement predicted by Roelofsen [9] corresponds well with the self-estimated performance presented by Lan [14]. This is important, as the perception of productivity should capture information about motivation of individuals to work, which could be missed in simple task performance tests. For this exercise PMV values output the thermal modelling software [26] were used, these correspond to a metabolic rate of 70Wm^{-2} typical for light work such as typing and clothing insulation of 0.9 clo, this can be considered as 0.8 clo typical of office attire (long sleeve cotton shirt (no tie), trousers, etc.) and 0.1 clo for the insulation provided by the chair and seated posture. Other values can be used to calculate PMV using the full relationship [3,30] if desired.

Results and Discussion

Using the relationship proposed by Roelofsen [9] we can plot the relative productivity for different levels of climate change. Figures 3-6 show how productivity levels vary during working hours over the year. Also shown is how productivity varies with PMV over the same period. Productivity levels are presented for the base climate of the 1970s (the period 1961-1990 is typically used as the base climate) and three future time periods (2030s, 2050s and 2080s). Figure 7 shows a histogram of the distribution of relative productivity for the four climates considered. We can see that even in the current climate there is loss of productivity as a result of high temperatures (and hence high PMV) and the situation worsens as the level of climate change increases. Figure 7 shows that as the climate changes the distribution of relative productivity widens and the median of the distribution moves to lower values of relative productivity. As the results show each of the climate files displays different weather patterns and there is variation in when productivity is lost. As we move further into the future there is an increase in summer time overheating and hence a decrease in productivity but also a decrease in cold related winter discomfort and an associated increase in productivity. It is clear that while the building heating system can militate against most negative PMV thermal discomfort there are still instances where the building is slow to respond to changes in external temperatures. The sharp dips in spring and autumn are due to high solar gains when the sun is lower in the sky, this results in high radiant and air temperatures as more of the rooms internal surfaces are exposed to direct sunlight. In the 2080s there are fewer high PMV events early in the year (perhaps due to more cloud) but more later in the summer. This illustrates the importance of considering more than one combination of weather and climate when designing buildings. The results indicate that the office would benefit from adaptation measures to improve thermal comfort both now and in the future, such as brise-soleil, increased thermal mass or insulation. Another, less sustainable option would be the incorporation of air conditioning into the office space. Sustainable options are often perceived to be more expensive [2]. This is important, as this preconception will affect the design regardless of whether or not it is true. As a follow-up to the work of Morton et al. [2] a survey of clients and building industry professionals on the barriers to low carbon school design [currently under review] one individual commented about the perceived cost of sustainability features *"It is on the design team to change this wrong perception and to produce specific comparison studies showing alternative options together with cost implications and* CO_2 *reductions."* It seems clear that this is still an issue that affects the design process, as such we need a metric that can persuade clients of the benefits of different sustainability and adaptation options. It is hoped that the cost of lost productivity approach presented here could help solve this issue. The cost of the lost productivity can be estimated in terms of staff wages and hence potential payback periods for different adaptation measures could be estimated according to how much thermal comfort is improved.





Figures 3-7 Plots of relative productivity versus time for occupied hours over the year (left pane) and relative productivity versus predicted mean vote (right pane). Data shown for the base climate and the 2030s and 2050s at the 50^th^ percentile probability level under the A1FI emissions scenario. Figure 7 Histogram showing distribution of relative productivity for the 1970s and the 2030s, 2050s and 2080s at the 50^th^ percentile.

If we use the estimates of Ratcliffe [18] we can estimate the cost of lost productivity per m^2 as a result of thermal discomfort over the year for each of the time periods using:

$$Cost = \left[\frac{1}{100} \times \frac{\sum P}{hours_{occupied}} \right] \times £3000 m^{-2} \tag{3}$$

where *P* is the loss of productivity for each hour of occupancy given by the relationship of Roelofsen [9]. However, since we have a specific building in mind and we know its location and its use we can adjust equation 3 to take into account the Gross Value Added (GVA) instead of Ratcliffe's [18] estimate. GVA is the value of goods and services produced by an area, sector or producer minus the cost of the raw materials and other inputs used to produce them. GVA is mainly composed of the income of employees (earnings) and the business (profits) as a result of production. The productivity per worker within a given sector can be calculated by dividing the GVA for that sector by the number of people employed in that sector measured as Full Time Equivalents (FTE). The change in relative productivity as a function of user comfort can be applied to the economic output of a worker. The building used in this study is to be located in the region "Cornwall and the Isles of Scilly". For this region, the most recent data (2009) [31] shows that GVA in the "Public Administration and Defence" sector was £402 million, and that the sector employed 10,516 FTE. This results in a value of productivity of £38,227/FTE. The study building has an occupant density of 9 m^2/person therefore the value per unit area of building is £4,247/m^2. Hence equation 3 becomes:

$$Cost = \left[\frac{1}{100} \times \frac{\sum P}{hours_{occupied}} \right] \times £4247 m^{-2} \tag{4}$$

This approach enables an analysis to be better matched to the value of activity being undertaken in a building. For example, if the same building were used for the purposes of supplying "Financial Services" then the productivity per unit area would be £7,889/m^2 [31]. Or if the same building and function were located in London, then the value per unit area would be £5,890/m^2 [31]. Clearly, these changes in the value of productivity would change the point at which various interventions become financially viable for a given location and service/industry. In addition, whilst detailed area and sector based economic data can be used to make generic assessments, individual businesses can make more specific assessments based on their known financial performance. Hence the cost of lost productivity per m^2 based on thermal conditions over the year for each time period is:

Table 2 Estimated average lost productivity and its associated cost per m^2 (to the nearest £) for different time periods.

Time Period	**Lost Productivity**	**Approximate Cost / m^2**
Base Climate (1970s)	3.2%	£134
2030s 50th percentile	3.5%	£148
2050s 50th percentile	3.9%	£164
2080s 50th percentile	4.3%	£181

We can see that as the climate warms then the cost of lost productivity increases. The productivity decrement as a result of climate change is relatively small for this office due to the high internal and solar gains resulting in overheating even in the current climate. However, adaptations to combat climate change will likely reduce current overheating also. Increases in summertime overheating are only part of the picture, there is also a reduction in cold related thermal discomfort (negative PMV), which increases productivity over the winter months as the climate changes. The use of GVA data gives an impression of not only the loss in terms of earnings but also of the value of the work being performed. Thus we could consider offsetting the cost of any climate change adaptations or building improvements, designed to make the internal environment more comfortable against the negated cost of lost productivity.

Despite being able to justify the cost of sustainable technologies in the building there still may be resistance to change. This is partly due to the fact that an obvious and relatively easy (and potentially cheaper) solution would be to add a large air conditioning plant to a building to control the internal environment close to PMV = 0. However, the use of active cooling technologies such as air conditioning comes with energy and CO_2 implications. With increasing energy prices and increasing concern about man-made climate change, it is possible that public opinion about air-conditioning type technologies will deteriorate. Air conditioning is often implicated as a possible cause of poor air quality in buildings, sick building syndrome (SBS) and the associated health problems, resulting in time off work [32-

36]. However, since energy costs are small compared to staff costs and GVA, the use of air conditioning potentially means that the internal environment can be held at a particular value of PMV (and productivity). However, typically the greater the control over the internal environment the greater the associated energy cost. As environmental control is relaxed the productivity decrement will increase. In light of 'locked-in' climate change due to historic carbon emissions, the cooling loads required are predicted to increase over time and if the general solution remains to fit a larger cooling plant then the problem will only escalate. This may well lead to exponentially increasing costs if current trends in energy prices continue, costs that may not be apparent or estimable during the design phases. As such it may be desirable to passively control the internal environment and forgo the use of air conditioning. Such passive measures also have the benefit that they do not have a high running cost and low or zero emissions thus helping the mitigation agenda. Furthermore the study by Paul and Taylor [21] suggests that 'green people' will associate more readily with a green building and will have a more positive outlook on the internal environment (even if internal conditions are no different from a conventional building). This empathy towards green and sustainable buildings may inflate the association between building type and comfort leading to reduced distraction. However, such buildings typically take longer to design and model and may be more expensive to build. By considering the potential avoided loss of earnings due to increased performance and productivity it is possible to justify the increased expense (or change the perception thereof) associated with designing and commissioning a 'sustainable' building capable of maintaining comfort conditions in a changing climate.

As a proof of concept we can consider incorporating two simple adaptation measures into the thermal model. The basic design of the building already incorporates a large roof overhang to provide shading on the upper floor and there are many trees on the proposed site to provide shade (both of which are included in the thermal model), so the adaptations considered here will focus on reducing internal heat gains. This should have the effect of reducing current and future overheating and increasing thermal comfort. The adaptations considered are the replacement of the standard fluorescent lighting with high efficiency LED lighting and the reduction of equipment loads equivalent to replacing desktop computers with efficient laptop computers. The building as designed has a lighting load of 12W/m^2, fluorescent luminaires of the sort typically used in offices have an efficacy of ~50lm/W. The current state of the art LED technology has an efficacy of ~130lm/W, if we assume that these will soon be commercially available as luminaires we can arrive at a reduced lighting load of 5W/m^2 (if we allow a few extra fittings to account for the directional nature of LEDs). Similarly the building as designed has an equipment load of 15W/m^2, this will likely include desktop computers, photocopiers and printers. There is assumed to be one computer per person, if these were replaced with high efficiency laptops or terminals it is estimated the equipment load could be reduced to 7W/m^2. Both of these options will also reduce electricity usage and lower carbon emissions and hence could also be considered mitigation options. However, both options will also likely have an increased capital cost associated with them. Simulations incorporating these adaptation measures were performed and a new predicted mean vote and relative productivity for occupied hours calculated. The resulting cost of lost productivity is shown in tables 3 and 4, when compared to the values presented in table 2 the avoided cost of lost productivity as a result of the adaptation measure can be calculated (shown in table 5).

Table 3 Estimated cost of lost productivity per m^2 for different time periods with reduced lighting gains.

Time Period	**Lost**	**Approximate**

	Productivity	Cost / m^2
Base Climate (1970s)	3.0%	£127
2030s 50th percentile	3.2%	£138
2050s 50th percentile	3.6%	£152
2080s 50th percentile	3.9%	£166

Table 4 Estimated cost of lost productivity per m^2 for different time periods with reduced equipment gains.

Time Period	**Lost Productivity**	**Approximate Cost / m^2**
Base Climate (1970s)	3.1%	£132
2030s 50th percentile	3.4%	£143
2050s 50th percentile	3.7%	£157
2080s 50th percentile	4.0%	£170

Table 5 Estimated avoided cost of lost productivity per m^2 for different time periods for the two adaptations considered.

Time Period	**Avoided Cost / m^2 LED**	**Avoided Cost / m^2 Laptops**
Base Climate (1970s)	£7	£2
2030s 50th percentile	£10	£5
2050s 50th percentile	£12	£7
2080s 50th percentile	£15	£11

We can see for the two example improvements that the avoided cost as a result of increased productivity increases over time. What is interesting is that reducing lighting gains is a more effective adaptation strategy than reducing equipment gains despite the W/m^2 reduction being smaller. This is due to the higher radiant fraction of lighting compared to equipment gains. It is assumed that equipment gains are mainly convective and a radiant fraction of 10% was used by default in the model whereas lighting has a radiant fraction of 45%. Radiant heat is harder to remove from a space than convective heat as it is absorbed by surfaces. The higher radiant temperature of the space reduces thermal comfort and lowers productivity. This highlights another important aspect of considering adaptation strategies; different strategies will vary in effectiveness depending upon the design and construction of the building in question. The office in question is of a medium weight construction and has thermal mass located in the external walls and floor slabs, reducing lighting gains may have been even more effective if the design of was heavy weight construction or less so if of lightweight construction. As such it is important to consider each building design separately and consider several options to choose the best adaptation strategy. The analysis presented here which considers thermal comfort can be considered more robust than simply looking at air temperatures and hours of overheating in office spaces, and converting PMV to relative productivity and its associated cost should allow a financial incentive to be presented in favour of adaptation.

The open plan office studied has a usable floor area of 342m^2, increased productivity savings of £7/m^2 (LED adaptation) equates to ~£2394 (per annum) in the current climate, increasing to ~£5130 by the 2080s using the GVA for this sector [31]. From this we can see that the increased cost of any extra design work and the procurement and installation of higher efficiency fittings could be paid off relatively quickly. This is just a simple illustration and we have not considered net present value calculations or savings from reduced electricity usage, future carbon taxes or potential changes in user behaviour, however the principle is the same. Many climate change adaptation measures that affect the internal environment could also be considered mitigation measures in the short term as they save energy as well as combating the effects of climate change. It is conceivable that this process could be implemented at the design stage for the majority of climate change adaptation/mitigation measures. This would allow the potential payback periods of different measures to be considered and compared in a meaningful way. Since we used a method of estimating productivity [9], which uses the PMV [3] measure of thermal comfort instead of just air temperature we can also compare the potential savings from physical adaptations to the building to behavioural adaptations such as allowing a relaxed dress code during hot periods (reducing clothing insulation), or other types of adaptation such as the implementation of desk or ceiling fans (increased air movement). Being able to see a return on investment associated with improved productivity will hopefully act as a stimulus for the incorporation of sustainable climate change adaptation measures into building designs. Consideration of value more holistically should hopefully overcome the perception that sustainable low energy buildings are expensive. The method proposed here also allows a comparison between different adaptation and mitigation measures improving value for money spent on interventions. We can further surmise that as people's empathy towards green technologies and sustainable buildings increases as a result of the climate change mitigation agenda, this may become a greater factor in how people perceive an internal environment, further increasing the productivity gap between sustainably adapted buildings and conventional buildings.

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Appendix

Building details.

- 3 storeys, floor area = 3037 m^2, ext wall area = 2387 m^2, glazed area = 804 m^2.
- Ground floor:- soil/clay (0.75m), Brickwork (outerleaf) (0.25m), cast concrete (0.1m), EPS slab (0.0635m), chipboard (0.025m), carpet (0.01m). U-Value = 0.2499 W/m^2K.
- Ceiling/floor:- carpet (0.01m), cast concrete (0.1m). U-Value = 2.2826 W/m^2K.
- Internal walls:- plasterboard (0.013m), brickwork (0.105m), plasterboard (0.013m). U-Value = 1.6896 W/m^2K.
- External walls:- Brickwork (0.1m), EPS slab (0.0585m), concrete block (medium) (0.1m), plaster (0.015m). U-Value = 0.3495 W/m^2K.
- Flat Roof:- U-Value = 0.2497 W/m^2K.
- Windows:- low-e double glazing, U-Value (including frame) = 1.9773 W/m^2K.
- Naturally ventilated, side-hung, 50% of glazed area openable to 20°.
- Weather files for the Bodmin area were used.

For open plan office areas and meeting rooms.

- Occupancy:- 9 m^2/person
- Lighting:- 12 W/m^2
- Equipment:- 15W/m^2

For circulation areas.

- Occupancy:- 9m^2/person
- Lighting:- 5W/m^2
- Equipment:- 2W/m^2