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How to design a building envelope to provide thermal comfort and energy efficiency considering climate change

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Abstract:

Climate change is manifesting itself in various forms and intensity – from hotter temperatures and desertification to record-breaking floods. This paper describes various climate change scenarios and explores ways in which the building envelope design must respond and adapt to the different scenarios in order to provide both thermal comfort and energy efficiency. Increasing thermal comfort and reducing energy use are two key functions of the building envelope and must be considered in conjunction so that ensuring performance in one respect does not compromise performance in the other. Furthermore, design strategies will be tested using morphed weather data for the specific UK site of London by running dynamic thermal models on a typical open plan office.

Keywords:

Thermal comfort, façade & building envelope, morphed weather, climate change, adaptation

1.0 Introduction

Whilst there is considerable uncertainty as to the extent of climate change, there is no doubt that climate change is occurring to a significant degree. The future projections of the impacts of climate change depend not only on the obvious factors such as current and future greenhouse gas (GHG) emission rates, but also ultimately on the decisions that nations will make to combat climate change, whether these decisions be economical, socio-political, or environmental, proactive or reactive, adaptive or mitigatory (or both), regional or global. Many of these decisions will directly affect various industries such as buildings, transportation, and agriculture, as these industries are contributing significantly to the global GHG emissions.

In the UK, the building industry is already taking steps to address the effects of climate change. For example, in 2009, the British Council for Offices increased the summer indoor design temperature of mechanically-ventilated offices from 22°C to 24°C in an effort to reduce carbon emissions and, in the process, to engage occupants in considering adaptive comfort. (Collin *et al.*, 2008) Many more measures can be taken from a mechanical-ventilation point-of-view. However, this paper addresses methods of adapting to or mitigating climate change with the building envelope as a first step, for decisions of glazing type, envelope build-up, solar shading, ventilation type, and improved air tightness come early in the design phase and can play a major role in determining the energy performance and comfort of a building. These improvements to the façade are, therefore, able to reduce the capacity of the mechanical plant equipment such as chillers and boilers in the first place.

2.0 Future climate change scenarios

The Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) has identified a number of emissions scenarios up to the year 2100 (IPCC Working Group III, 2007). Scenario A1F1 is considered ‘high emissions’, A2 is considered ‘medium-high emissions’, B1 is considered ‘medium-low emissions’, and B2 is considered ‘low emissions’. The current GHG emissions follow the trends seen in the medium-high emissions scenario (A2) the most.

Existing trends in radiatively important gas emissions show that CO₂ is the main contributor of these gases, and fossil fuel use is the dominant cause of these CO₂ emissions.

2.1 Main climate impacts

Principal climate impacts and related design factors are summarised by Jake Hacker (Arup, Buildings London Environmental Physics) in the table below. Façade-related design factors are shown in bold.

Table 1: Climate impacts influencing different design factors (Hacker, 2007)

Climate impact	Climate factors	Design factors
Overheating risk and HVAC energy consumption	Average and extreme summer temperatures, high solar irradiance, coincidence of high wet and dry bulb temperatures	Building facade , form, and HVAC services
Flood risk: coastal, fluvial (river), pluvial (drainage), and groundwater	Sea level rise, increased rainfall, and soil moisture	Situation (<i>e.g.</i> , coastal and/or in fluvial flood plain), drainage, existing flood defences, building envelope and materials
Water scarcity	Changes in seasonal precipitation and drought risk	- Water efficiency and availability - Façade cleaning - Rainwater roof collection
Structural failure	Extreme storms	Building form and structure
Subsidence	Soil moisture and rainfall	Ground conditions and building foundations
External thermal discomfort	Increased sunshine hours, heatwaves, wind speed and direction	Building massing, street orientation, facades , shading , trees, greenspace, surface water and water features, location of heat rejection plant

Green landscape & biodiversity	Temperature, changes in seasonal precipitation and drought risk; ‘timing’ of the seasons	- Types of suitable planting - Green facades/roofs
Air quality	Increased sunshine hours, heatwaves, wind speeds and direction	Street canyon ventilation, building massing and street orientations

The effects generally observed as a result of increasing GHG emissions can be found in the IPCC Working Group III, Fourth Assessment Report (2007). The following are a few key observations and their implications for building envelope design:

- **Temperature:** There will be regional differences in the effects on temperature due to increased GHG emissions, but overall, there will be a global rise in temperature. The rise in global temperature means it is imperative to start off with a building envelope design that is already optimised before improvements to the plant and operation of the building should be considered.
- **Humidity:** Higher global temperatures will lead to more intense precipitation and flooding in certain areas (*i.e.*, higher relative humidity levels) but also more droughts in other areas (*i.e.*, lower relative humidity levels). Humidity particularly affects a building design when viewed in conjunction with ventilation. Ventilation profiles will likely change for future needs, and this means bringing different amounts of air with different levels of humidity into a building when compared against current ventilation profiles.
- **Solar radiation¹:** How solar radiation will be affected by climate change is a relatively new area of study. In a paper published by the Journal of Geophysical Research, the average surface solar radiation was noted to have decreased by 2% every decade between 1950 and 1990 but has steadily increased since then. (ETH Zurich, 2009)
Undoubtedly, solar radiation is a key factor in the glazing selection process and in the design of the shading elements to a glazed building. Illuminance is linked to solar irradiance, and the lighting design of a building relies on the available illuminance. If the illuminance level is high, glazed buildings can harvest natural daylight, reducing the need for artificial lighting and reaping significant energy savings.
- **Wind speed:** Wind speeds appear to depend strongly on location as well. Wind speeds affect the design of a building’s ventilation profile, especially those of high-rise buildings and especially if a building is naturally ventilated or employs mixed-mode ventilation. The building simulations carried out for London will use wind speed data given by morphed weather files from the UK Climate Impacts Programme. However, it is important to note that there is significant uncertainty in how the wind speeds in the

¹ When taking snow melt and melting glaciers into consideration, it is important to note the positive feedback loop that occurs with solar radiation. Solar radiation melts snow, glaciers, and ice caps, leading to less solar radiation being reflected and, therefore, more solar radiation being absorbed, fuelling the rate at which ice and snow melts.

UK will be affected by climate change, so the wind data in the morphed weather files should be used with caution.

2.2 UK Climate Impacts Programme

As part of the UK Climate Impacts Programme (UKCIP02), weather data for 14 major UK cities have been morphed by Jake Hacker and Rachel Capon of Arup to represent the various climate change scenarios.

The weather data files are Design Summer Year (DSY) files. For more information on how the morphing of weather data was carried out, please refer to CIBSE TM48: The use of Climate Change Scenarios for Building Simulation: the CIBSE Future Weather Years. Note that the morphed weather data files are currently in the process of being updated for UK Climate Projections (UKCP09), so only the UKCIP02 weather data are available for use as of February 2010.

The following figure shows how much the temperature is expected to rise in London by the 2050s and 2080s based on the medium-high emissions scenario, which, as a reminder, is the one that is closest to current GHG emissions trends:

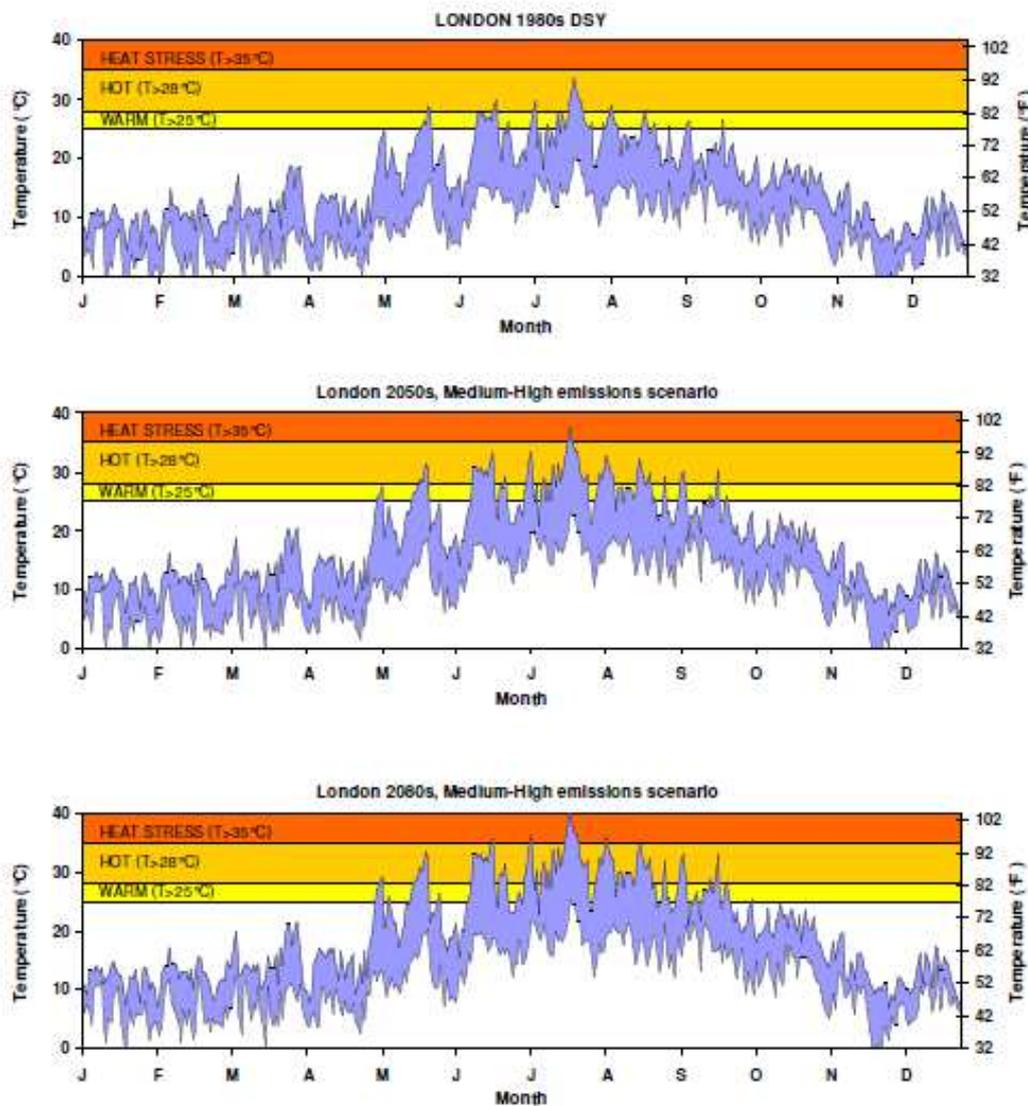


Figure 1: Morphed weather plots for London under a medium-high emissions scenario

It is important to keep in mind that the current weather years provided by CIBSE have solar radiation data simulated from cloud cover data and should not be taken as actual measured data. The solar radiation in the morphed weather data, whilst consistent with UKCIP02 predictions for global solar radiation, has more uncertainty than the temperature predictions.

The next figures show the likely changes in relative humidity, solar irradiance, and wind speed, respectively, for London, Manchester, and Edinburgh for the 2080s under the medium-high emissions scenario.

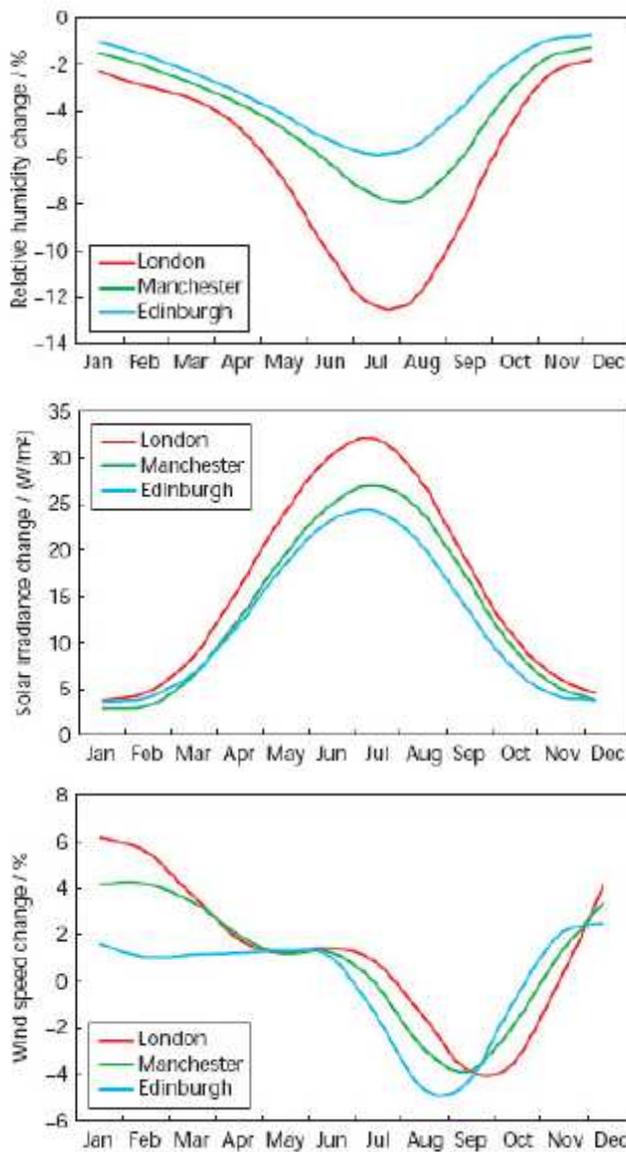


Figure 2: Relative humidity, solar irradiance, and wind speed changes throughout the year due to climate change for London, Manchester, and Edinburgh

One can see from the images above that the changes in variables are dependent on the season and time of year. These changes will affect the way buildings consume energy in the future.

3.0 Identifying carbon, energy, and comfort requirements for the UK building industry

The building industry contributes significantly to GHG emissions, not only in the day-to-day operation of buildings, but also throughout the entire construction process in embodied impacts. It has been estimated that non-domestic buildings account for 18% of the total carbon emissions of the UK. In order for the building industry to play a major role in achieving the UK's carbon reduction targets, it needs to reduce its carbon emissions by a minimum of 80% by 2050. (Carbon Trust, 2009) The next sections show the most current requirements and guidelines related to carbon and comfort for the non-domestic building industry in the UK as of February 2010.

3.1 Target carbon emissions rate

The UK Building Regulation's new Approved Document L: Conservation of fuel and power (to be published in 2010) has proposed target carbon emissions rates for new non-dwellings. The new Part L will also set more stringent air-tightness requirements, which will help reduce infiltration and consequent energy consumption and carbon emissions.

The next figure from the Energy Consumption Guide 19 shows "good practice" vs. "typical" offices' carbon emissions for four types of naturally ventilated and air-conditioned office buildings.

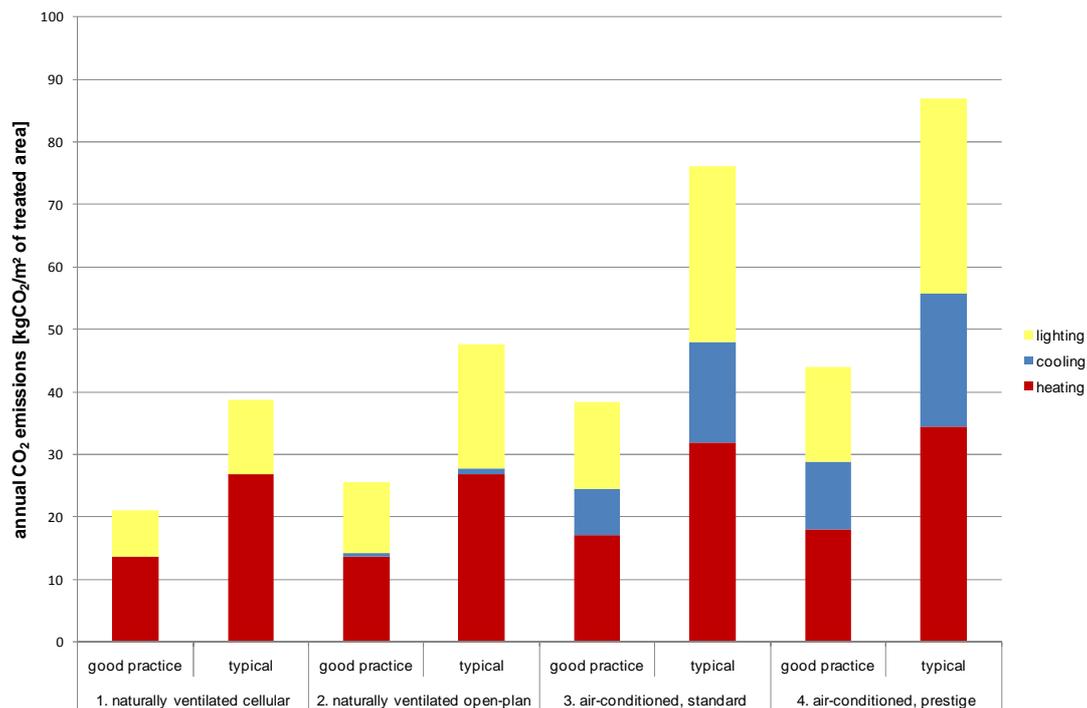


Figure 3: Annual emissions of CO₂ (kgCO₂/m² of treated floor area) using CO₂ emission factors of 0.19 kgCO₂/kWh for gas and 0.52 kgCO₂/kWh for electricity [considering only heating, cooling and lighting] (Carbon Trust 2003)

Although the carbon emission factors used by ECON19 are slightly different from today's figures of 0.206 and 0.591 kgCO₂/kWh for gas and electricity, respectively, these figures still serve as a good indication of what constitutes a "good practice" building.

3.2 Comfort requirements

Thermal comfort can be expressed by using predicted mean votes (PMV) and also by using overheating criteria based on operative temperatures.

Acceptable PMV levels for offices are suggested by CIBSE Guide A: Environmental design as ± 0.5 (*i.e.*, corresponding to 10% people dissatisfied (PPD)).

CIBSE Guide A also gives the summertime overheating criterion for naturally-ventilated buildings, which is $>1\%$ occupied hours over 28°C .

In the future, as the climate becomes warmer in the UK, perceptions of what is thermally comfortable may have to change. Comfort requirements may become more relaxed as building occupants learn to adapt to trends of the external environment.

Although cooling requirements will become more onerous in the summer due to higher temperatures, adaptive comfort is key to keeping energy consumption low in buildings so that there is no positive feedback for global warming in terms of emitting more CO_2 from air conditioning.

4.0 How the façade performance impacts on CO_2 emissions and user comfort under future changes in climate

As mentioned before, a good starting point to implement carbon reduction measures would be at the outset of a building's design conception, in which the building façade plays a key role. We can see from the next figure that heating, cooling, and lighting make up the three most significant non-domestic building end uses that contribute to carbon emissions. Heating, cooling, and lighting requirements rely heavily on the performance of the façade.

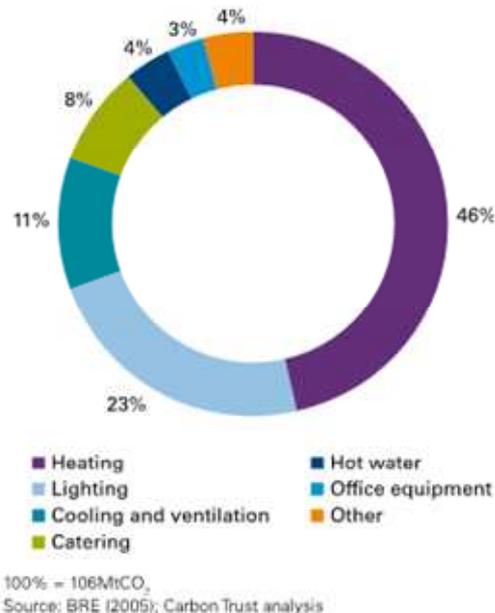


Figure 4: Carbon emissions by end use in the UK's non-domestic buildings

The following is a list of design factors that can be changed on a building envelope to alter the carbon, energy, and comfort performances of buildings:

- **U-values**
- **g-values**
- **Light transmittance**
- Glazing areas
- Glazing location
- Solar shading

- Thermal mass
- **Type of ventilation**
- Air tightness

The factors shown in bold will be tested on a typical open plan office simulated using Arup's in-house software tool, Oasys ROOM, with the assumptions noted below.

4.1 Assumptions

4.1.1 Geometry

A typical model was chosen for the simulations: it represents a building zone and the size has been based on the CIBSE TM35 published in November 2004.

The choice of the geometry of the model has been inspired by a typical zone in an open plan office:

- Width = 9m (typical column distance, six typical 1.5m wide curtain wall units)
- Depth = 6m (according to Part L perimeter depth)
- Floor-to-floor height = 3.85m
- Volume considered for the model = 207.9 m³

The model simulates an office with one wall being external and south-oriented (where the façade is located). The other walls, the floor and ceiling are in contact with rooms with the same conditions thus simulating a typical room surrounded by rooms.

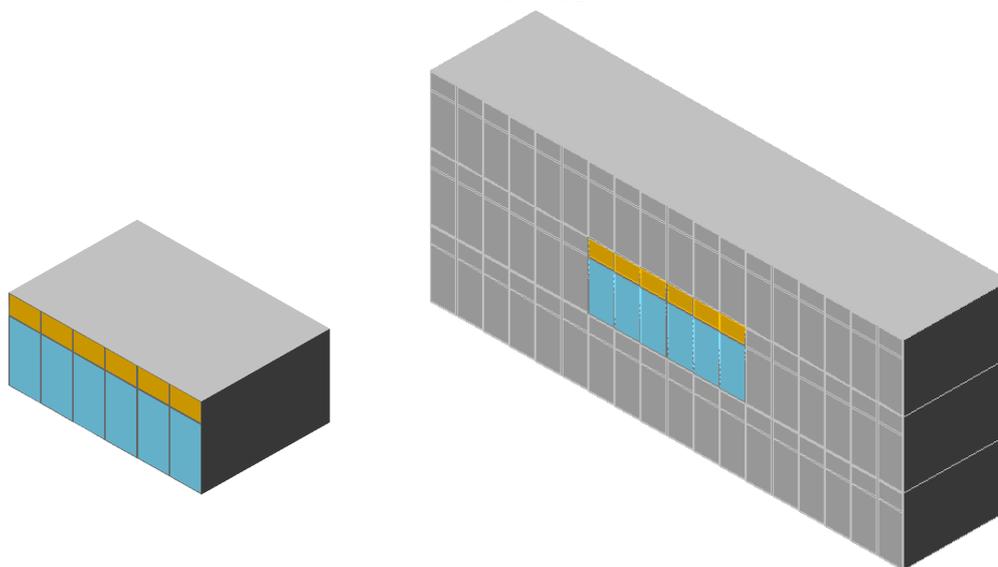


Figure 5: View of the room simulated surrounded by other similar rooms

The curtain wall unit represents 75% of the external wall area being glazed. It includes a vision area (2900mm by 1500mm) and a spandrel area (950mm high).

4.1.2 External environment

The 2006 CIBSE DSY weather data for London were used as the “current” scenario. The 2020s, 2050s, and 2080s DSY weather data for London for a medium-high emissions scenario were used for predicting future trends.

4.1.3 Internal environment

Assumptions regarding internal gains and operation of building are taken from SBEM. They are as follows:

- Occupancy: 6 people in 54 m² = 1 person every 9 m² floor

- Lighting: 8 W/m² (Note: The SBEM figure of 18.75 W/m² seems too high and has, therefore, been reduced to 8 W/m², which assumes a low-energy lighting system.)
- Equipment: 15 W/m²
- The set point temperatures used are the following:
 - Heating set point temperature: 22°C
 - Cooling set point temperature: 24°C
- The following infiltration and ventilation rates were used:
 - Infiltration: 0.15 ac/h
 - Ventilation maximum (if mechanical): 1.0 ac/h
- If the office is naturally ventilated, it has modulating opening sizes to maintain the room temperature between heating and cooling set points. The openings are completely closed when the external air temperature is higher than the internal air temperature in the summer.
- In terms of exposed mass, the ceiling is exposed concrete, but the floor is carpeted.
- The daylight transmitted through the glazed façade can be used to reduce the usage of artificial light, and the following assumptions were made:
 - An automatic control based on on/off switches has been considered to operate two lines of lighting fixtures, parallel to the façade. The room has therefore been subdivided in two zones independently operated.
 - The average daylight factor (at desk level) for these two zones has been used to derive the expected internal illuminance and the amount of hours when artificial light needs to be used.
 - The minimum required internal illuminance has been assumed to be 500 lux, which is a typical value for offices (according to BS EN 12464-1). The lighting system assumed, as mentioned earlier, uses 8W/m².

The different glass options considered (see Section 4.1.4) will influence the amount of natural light transmitted inside the building and the consequent electricity demand for the artificial light.

4.1.4 Variable factors

The following is a list of variables considered in the models:

- U-values: 1.2, 1.5, and 1.8 W/m²K. These U-values represent a realistic range for curtain walls.
- g-value & light transmittance (LT) combinations as shown in the following table:

Table 2: Combination of g-values and light transmittances

g-value	0.10	0.18	0.26	0.33	0.38	0.42	0.60
LT [%]	10	30	50	60	65	70	75

The 0.10 g-value represents a combination of glass and external shading device, the g-values from 0.18 to 0.42 apply to double glazed units with selective coatings and no shading, and the 0.60 g-value applies to a double glazed unit with low emissivity coating and no shading.

- Ventilation: mechanical ventilation, natural ventilation (1m² upper opening & 1m² lower opening, 2.8m separation distance), and mixed-mode ventilation (same opening sizes, cooling plant operates on dry bulb air temperature); night cooling was not modelled.

Each combination of the variables above was simulated using four different weather data files, so there are a total of 252 models.

4.1.5 Plant efficiencies and carbon intensity factors

The following table shows the assumptions for plant efficiencies and carbon emission factors for the UK:

Table 3: Assumed efficiencies and carbon emission factors

Heating	Heating efficiency	0.89
	Gas carbon emission factor	0.206 kgCO ₂ eq/kWh
Cooling	Cooling efficiency	3.4
	Electricity carbon emission factor*	0.591 kgCO ₂ eq/kWh

Source of carbon emission factors: (Pout & BRE, 2009)

* Includes electricity tariffs

It was assumed that an unlimited capacity heating and cooling plant was available for modelling purposes. Also, no fan or pump energy was modelled.

4.2 Results and findings: CO₂ emissions

4.2.1 Mechanically-ventilated offices

Below is a graph comparing the annual combined cooling, heating, and lighting CO₂ emissions of a mechanically-ventilated office model with a U-value of 1.5W/m²K for the four different climate scenarios considered.

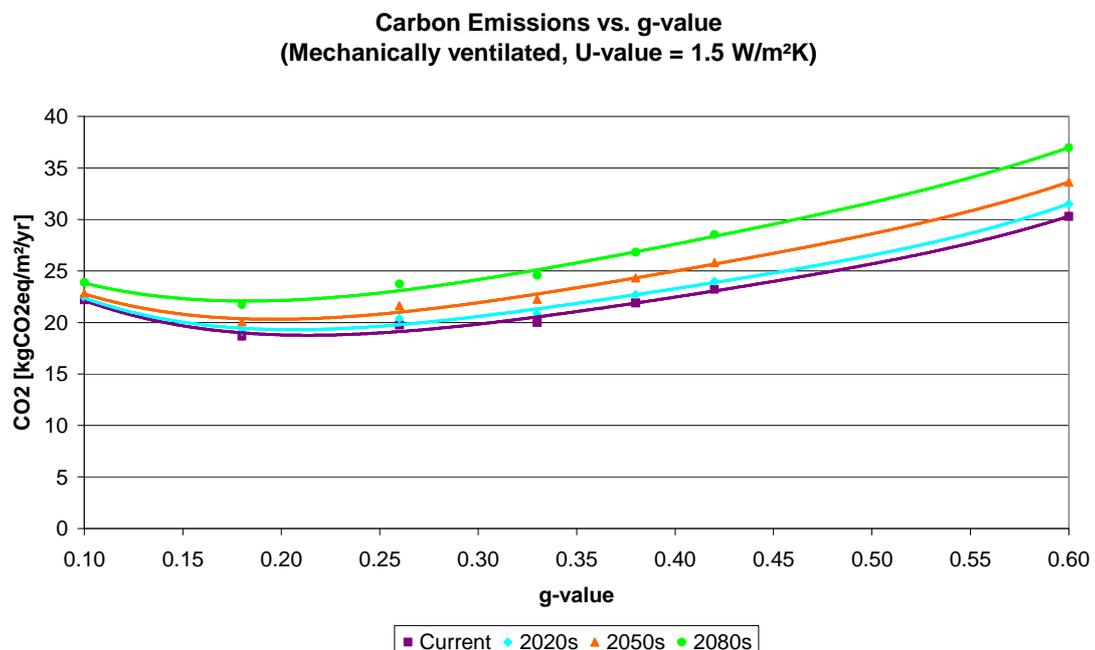


Figure 6: Carbon emissions for mechanically-ventilated office model with U-value = 1.5 W/m²K

It can be seen in the graph above that minimum carbon emissions for the mechanically-ventilated office model occur around a g-value of 0.20. Therefore, the

graph gives an indication of an optimal g-value that balances the cooling requirements with those of artificial lighting due to the solar gains.

The glass percentage (75%) and solar performance representing the CO₂ emissions in the graphs can be interpreted as a combination and applied to different façade layouts; e.g., a glass having 0.26 g-value and covering 75% of the façade is equivalent to a glass having a g-value of 0.42 and present on 46% of the façade.

When the current data are compared to future scenarios, it can be seen that the CO₂ emissions gradually increase when the morphed data are used; the best carbon performance to be achieved in 2080 (g-value 0.18) is significantly higher than the minimum achieved currently. This means that, in order to maintain its efficiency in the future, the design of the building envelope should address the need to create carbon savings (e.g., by using flexible facades, changing their solar properties in relation to the external conditions, see section 5.1).

The next graph shows the trend of the carbon emissions relative to U-value for the current weather data.

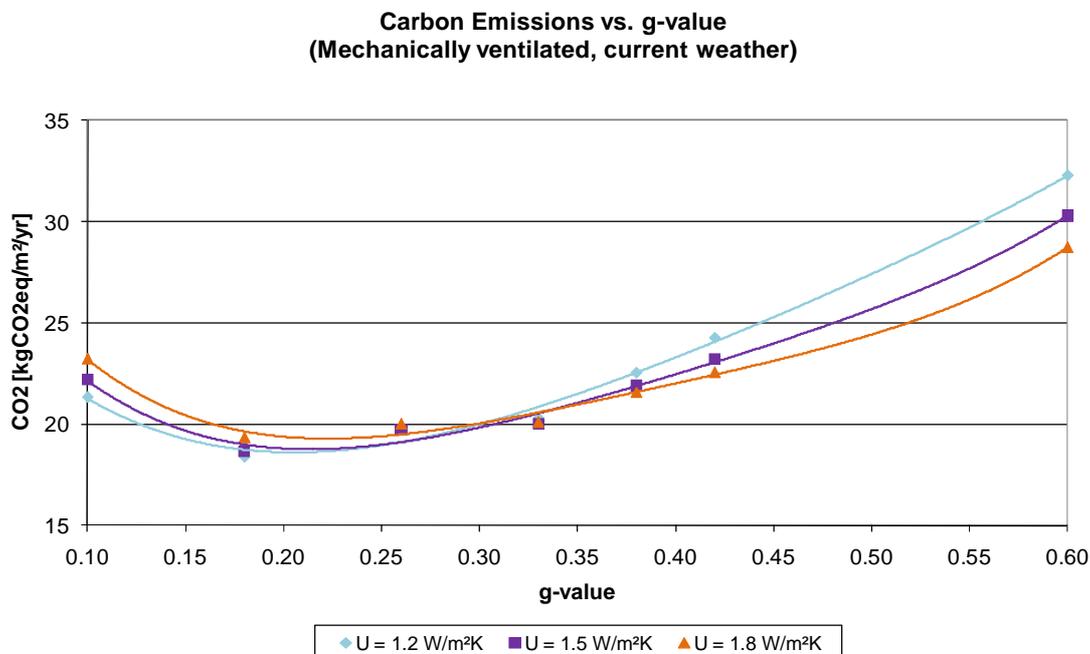


Figure 7: Carbon emissions for mechanically-ventilated office model using current weather data

A relatively “poor” U-value of 1.8 W/m²K performs worse than U-values of 1.2 and 1.5 W/m²K in terms of carbon emissions when the g-value is lower than approximately 0.30. However, when the g-value is higher than 0.30 and, therefore, solar gains are high, “better” thermal insulation (e.g., U-values of 1.2 and 1.5 W/m²K) actually results in higher cooling and overall energy consumption because more solar gains are trapped inside the space that need to be removed in summer (Kragh & Simonella, 2007). On the other hand, when aiming for the best carbon performance, the U-value does not seem to be relevant for the range considered.

4.2.2 Naturally-ventilated offices

The following is a graph comparing the annual combined cooling, heating, and lighting CO₂ emissions of a naturally-ventilated office model with a U-value of 1.5W/m²K for the four different climate scenarios considered:

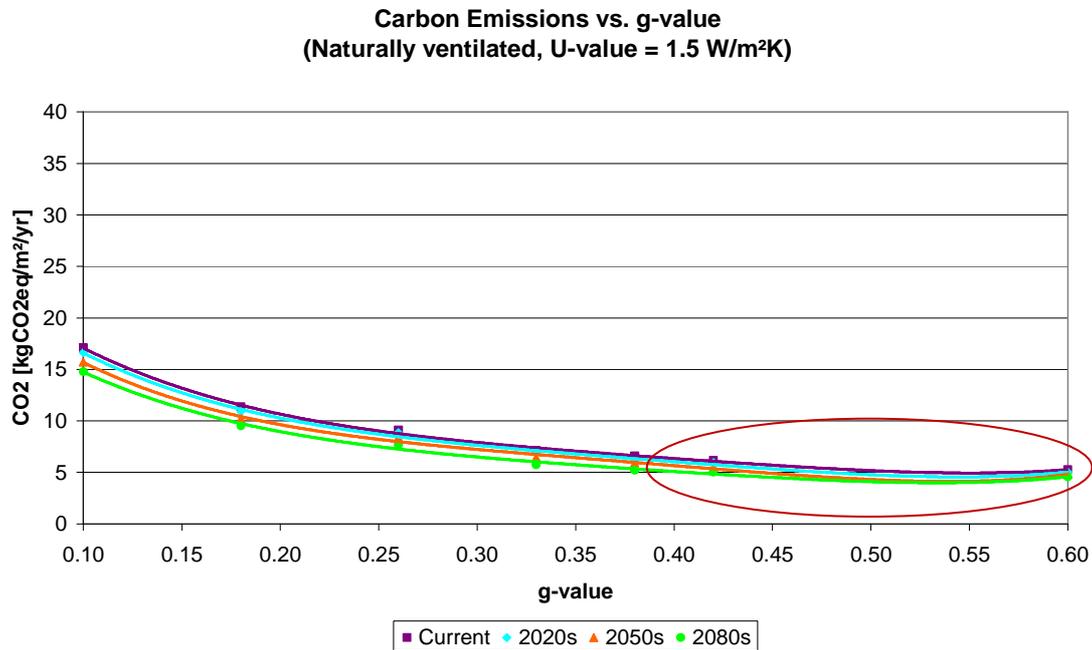


Figure 8: Carbon emissions for naturally-ventilated office model with U-value = 1.5 W/m²K

The naturally-ventilated office models do not have a cooling plant. Therefore, the graph only shows heating and lighting energy consumption. The trend shown is the higher the g-value, the more the solar gains and visible light transmittance, and, therefore, the less the heating and artificial lighting energy required. However, it should be noted that the risk of overheating increases with the increase of the g-value, as shown in section 4.3. As the weather gets hotter from global warming, the carbon emissions for the naturally-ventilated offices reduce over time from the current weather scenario to the 2080s weather scenario because the heating energy required decreases.

For the naturally-ventilated office model, the difference in carbon emissions between the current and future weather scenarios is not as significant as it was for the mechanically-ventilated office model. This is because there is only a heating plant, indicating winter temperature increases due to climate change is not as drastic as those in the summer. The naturally-ventilated scenario should be read in conjunction with the effect of the g-value on thermal comfort; a high g-value on a 75% glazed façade would not be considered in the design without the addition of external shading or the reduction of the glazed area. When the external shading is deployed, the benefit of higher daylighting access is obviously reduced. With fixed external shading, the beneficial solar gains (decreasing the heating demand) will be lower.

4.2.3 Mixed-mode ventilation offices

The following is a graph comparing the annual combined cooling, heating, and lighting CO₂ emissions of a mixed-mode office model with a U-value of 1.5W/m²K for the four different climate scenarios considered:

**Carbon Emissions vs. g-value
(Mixed mode, U-value = 1.5 W/m²K)**

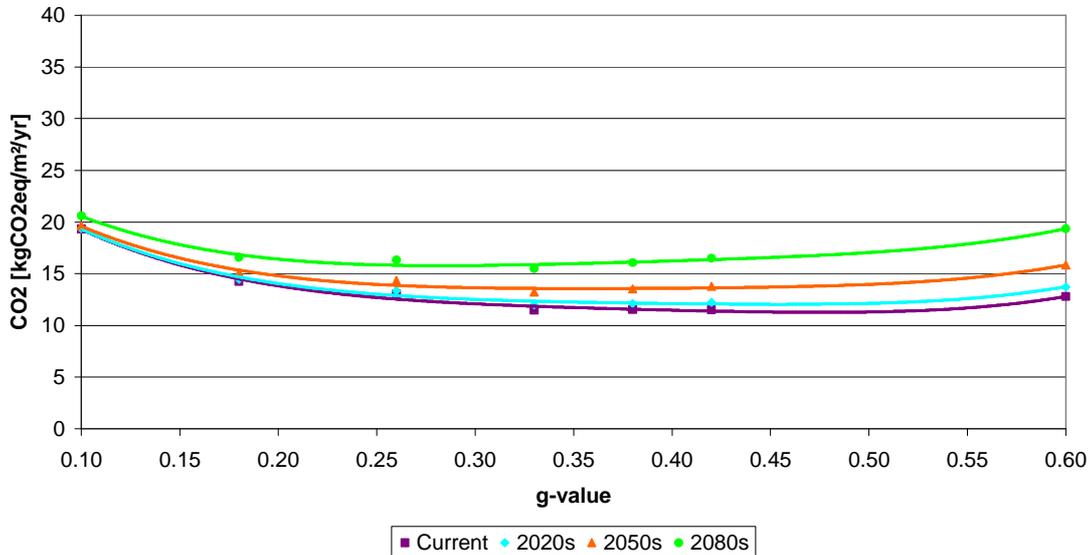


Figure 9: Carbon emissions for mixed-mode office model with U-value = 1.5 W/m²K

For the mixed-mode office model, the difference in carbon emissions between the current and future weather scenarios is noticeable but not as significant as it was for the mechanically-ventilated office model. It can be seen that there is an optimal g-value range for the four different weather scenarios considered based on the above graph, and the ranges are as follows:

- Current weather: optimal g-value \approx 0.40-0.55
- 2020s weather: optimal g-value \approx 0.35-0.50
- 2050s weather: optimal g-value \approx 0.30-0.45
- 2080s weather: optimal g-value \approx 0.25-0.35

The optimal g-values for the mixed-mode cases lie between the upper and lower limits analysed, as was the case in the mechanically-ventilated office models because the space needs to contend with both heating and cooling requirements.

4.2.4 Summary

When the g-value is low, the differences in total carbon emissions amongst the mechanically-ventilated, naturally-ventilated, and mixed-mode cases are not very large. When the g-value is high, however, the differences in total carbon emissions for the three different modes of ventilation are noticeably great. This shows that solar radiation plays an important role in determining total carbon emissions in highly-glazed offices as well as determining the ventilation strategy. Limiting the solar gains is, therefore, one of the first key steps to designing an office building that can cope with future climate change.

Differences in U-value do not affect significantly the CO₂ emissions for the building type and the orientation considered.

4.3 Results and findings: Comfort comparisons

For comparison purposes, the overheating criterion normally used for naturally-ventilated offices has been applied to the mechanically-ventilated and mixed-mode cases as well. This means the dry resultant temperature (DRT or operative

temperature) has been used as a measure of comfort. Also, only the 1.5 W/m²K U-value cases were considered, and the results are presented in the next few graphs.

**Comfort vs. g-value
(Current weather, U = 1.5 W/m²K)**

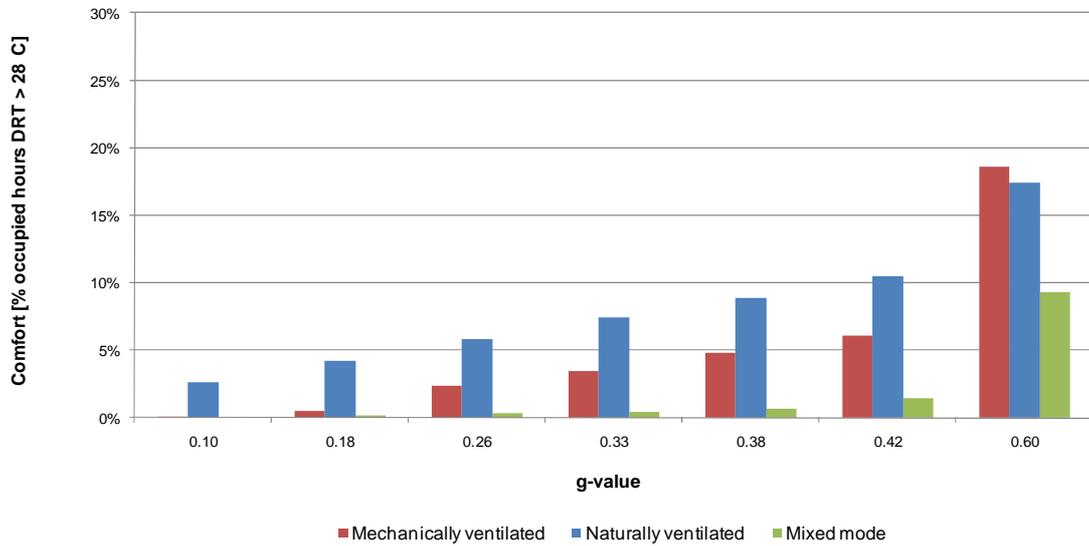


Figure 10: Comfort results for current weather

**Comfort vs. g-value
(2020s weather, U = 1.5 W/m²K)**

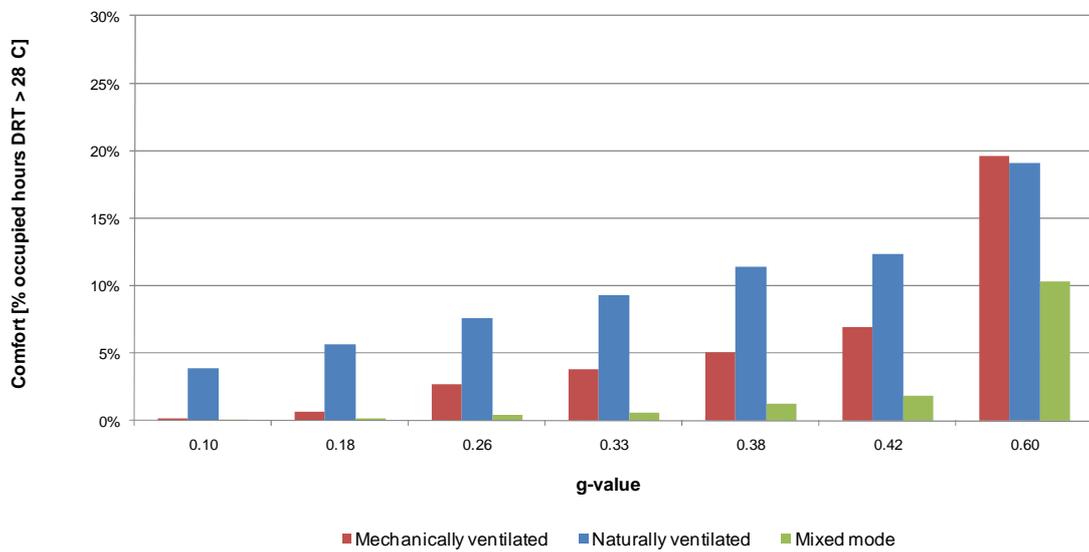


Figure 11: Comfort results for 2020s weather

**Comfort vs. g-value
(2050s weather, U = 1.5 W/m²K)**

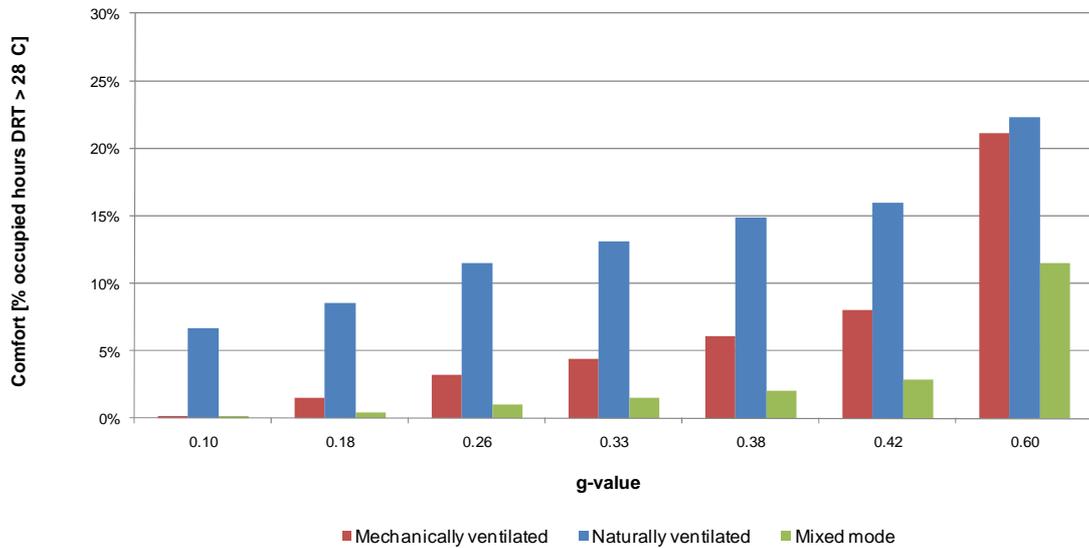


Figure 12: Comfort results for 2050s weather

**Comfort vs. g-value
(2080s weather, U = 1.5 W/m²K)**

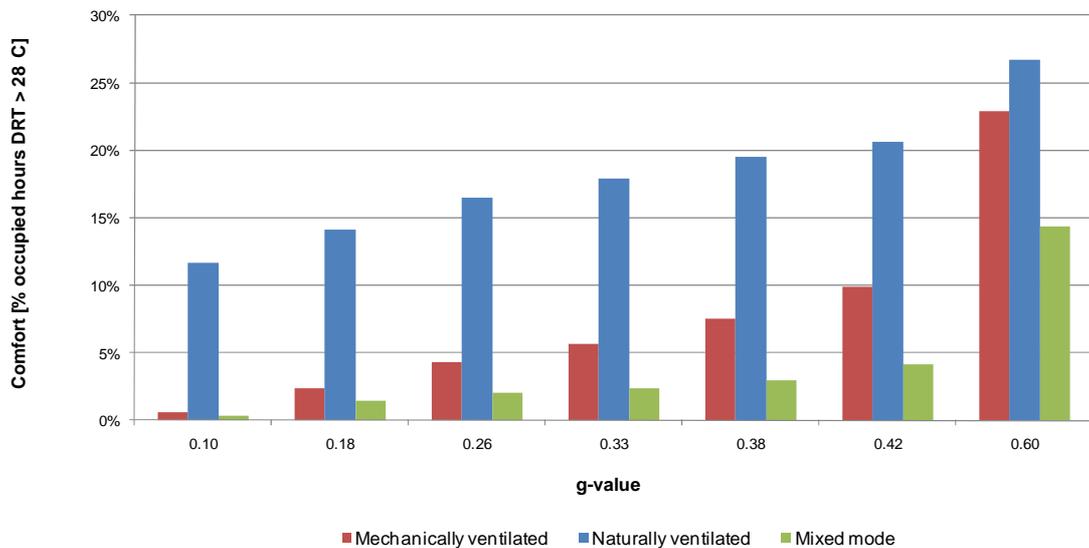


Figure 13: Comfort results for 2080s weather

When comparing the comfort results shown in the graphs above, the differences between the mechanically-ventilated, naturally-ventilated, and mixed-mode office models show that natural-ventilation, on its own, may not be a suitable solution to addressing the carbon and comfort balance in question, as it fails to eliminate overheating risk in all cases (when the configuration assumed is considered), even when the analysis is carried out using current weather data.

The mechanically-ventilated office models only work in very limited cases, generally where the g-value is 0.10 and for a few cases when the g-value is 0.18.

The figure below shows the effect U-value has on comfort for the mechanically-ventilated office model with a g-value of 0.18.

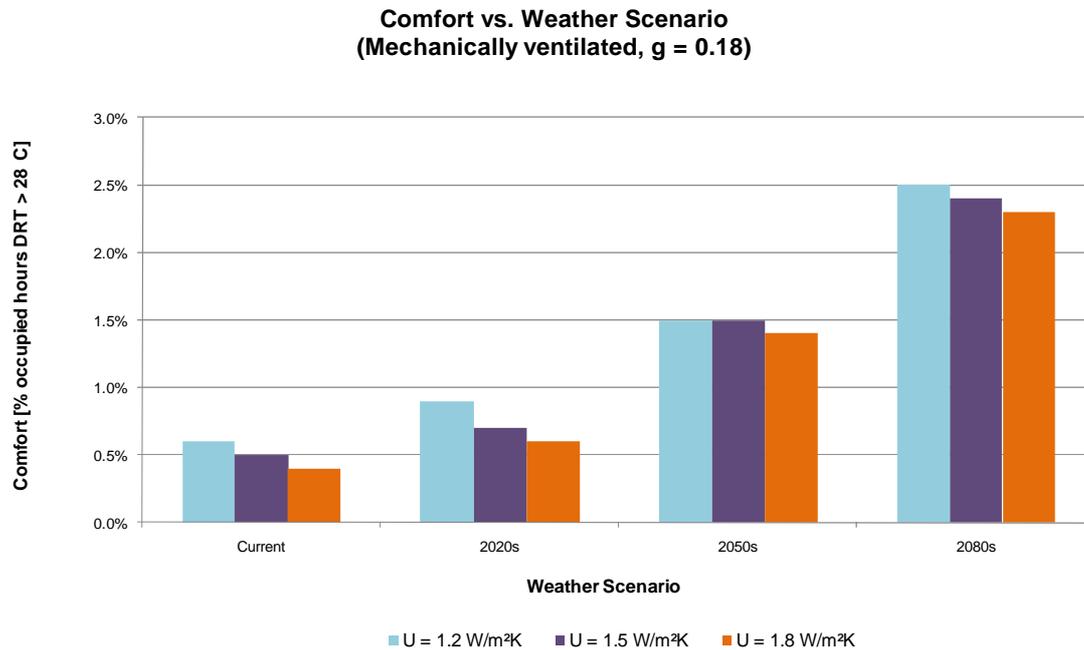


Figure 14: Comparing comfort results based on U-value for the mechanically-ventilated office model with a g-value of 0.18

The graph shows that U-value has a slight effect on comfort. Also, for this particular g-value, a U-value of 1.8 W/m²K results in a more comfortable environment than a U-value of 1.2 W/m²K, when the percentage of occupied hours where the operative temperature is greater than 28°C is used as a metric.

The mixed-mode ventilation option performed the best out of the three types of ventilation considered. For the various weather scenarios, the highest g-values of the mixed-mode office model that failed the overheating criterion are as follows:

- Current weather: g-value ≈ 0.38
- 2020s weather: g-value ≈ 0.33
- 2050s weather: g-value ≈ 0.26
- 2080s weather: g-value ≈ 0.10

Taking carbon emissions and thermal comfort into consideration, it appears that mixed-mode ventilation combined with sensible g-values is a promising way forward.

5.0 Proposed building envelope responses

When identifying the strategies to adapt the building envelope to future climate change, the durability and adaptability of the facades are important aspects to consider. Facades are generally designed to last 25 years. In order to reduce the waste impact, materials and products can be chosen considering their longevity and facade elements can be designed to be replaced or disassembled by adopting generic connections to enable easy upgrade of the façade at a later date.

The following sections present some building envelope design approaches which can be used to adapt an existing building to climate change or which should be incorporated in new buildings designed to meet current requirements to make them adaptable to future climate. The strategies presented focus mainly on the CO₂

performance and comfort and not on other aspects such as resilience against flood or increased wind pressure.

5.1 Improved façade solar performance

The results of the analyses carried out as part of this paper show that, to maintain comfortable conditions and limit the CO₂ emissions for heating, cooling and lighting for office buildings in the future, the most effective approach is to reduce solar gains. This is a measure that works well with current internal gains and when buildings are cooled during summer; when offices are naturally ventilated or using mixed mode, or have a low internal gains scenario, the strategy may differ.

- Adaptability of external fixed shading devices: The possibility to add (or modify) external shading devices helps in effectively upgrading the façade when higher reduction of solar gains is requested. This is done by preparing connections to accommodate the supporting elements of shading devices to be installed in the future or by allowing the extension or tilting of the slats already installed.
- Incorporating operable shading systems in the façade design: Operable shading systems allow the user to effectively adjust the g-value throughout the year depending on the climate. By having the flexibility to vary the degree of solar gains, the combined objective of optimising energy efficiency and comfort as climatic conditions change will be easier to achieve. As the operation of the shading depends on external conditions, this system requires minimum or no changes to face changes in the future climate. The modification of the control system is a very simple operation and allows upgrading the building to new external or internal conditions.
- In alternative to shading systems, incorporating electrochromic glass which changes its solar properties when activated by electricity.
- Modify solar performance of windows by applying solar control films: Applying solar control films to existing windows is an economic and low impact measure to reduce the solar radiation transmitted through the façade. This may be a temporary solution to extend the life of outdated glazed units.
- Replace transparent units with opaque insulated panels to modify the glazed percentage: The curtain wall units can be modified to suit changes in the internal layout but also to cope with a hotter (or colder) climate.

5.2 Enhance daylight

- Modify façade layout: Qualitatively speaking, strategic locations of clerestory windows and light shelves can bring diffuse natural daylight and spread it more uniformly across the office space. This improves occupant visual comfort whilst reducing the need for artificial lighting.
- Use glare blinds with different slats tilt: Typically, internal venetian blinds have uniform parallel slats but they are lowered mainly to control glare in the immediate vicinity of the façade. While the lower portion of the glazed façade/window needs to be well shaded (closed slats), the upper portion may allow a higher light transmittance (*e.g.*, featuring open slats which reflect the light to the ceiling or with a high perforation). This may reduce the use of artificial lighting and generally improve the occupants' comfort.
- Use shading control systems together with lighting controls in order to make the most of a transparent façade, raising the internal blinds when glare is not an issue and modulating the internal lighting to suit the daylight levels.

5.3 Improve thermal performance

Although the U-value does not seem to have a major impact on CO₂ or comfort from the results presented in this paper, it may be very important for other orientations, building types (residential in particular) and for the office scenario with lower internal gains, possibly in the future.

- Add secondary glazing to decrease the U-value: Adding just an uncoated pane of glass halves the heat loss and improves significantly the airtightness and comfort (increased internal surface temperature).
- Add thin insulation to opaque areas: Vacuum insulated panels (VIPs) consist of a micro-porous core structure enclosed in a thin gas-tight envelope, to which a vacuum is applied. This product provides a U-value of five to ten times that of equivalent thickness of other insulation materials and it is therefore particularly suitable for application to existing buildings.

5.4 Allow natural ventilation

- Replace fixed units with openings to modify the free area for natural ventilation: The existing fixed frames can be modified to accommodate openings. This measure can bring a current fully-closed envelope to a façade allowing natural ventilation or mixed mode operation. Alternatively, a current naturally ventilated building may need more airflow to maintain comfortable conditions in the future.
- Adopt double-skin systems to allow natural ventilation in high-rise buildings and to pre-heat the fresh air in order to extend the use of natural ventilation to mild winter periods.

5.5 Add thermal mass

Thermal mass has a very important impact on the thermal performance of buildings as it helps reducing overheating and achieving an acceptable level of internal comfort.

Architecture nowadays tends to embrace lightweight buildings with a reduced thermal mass. One way to introduce thermal mass in modern buildings is to use phase change material (PCM) which provides a similar effect but is lightweight and thin. Instead of using the mass to accumulate and release heat, PCMs melt and solidify: as the temperature of the environment reaches the melting temperature, the PCM melts and absorbs heat until it is completely liquid; when the temperature diminishes the PCM starts the solidification process giving back, gradually, the heat previously stored. PCMs can be applied cost-effectively also as a refurbishment intervention.

5.6 Use green and living facades

Green and living façades can help absorb CO₂, reducing the overall embodied carbon of a building. Vegetated roofs and walls improve the insulation and can also help reduce heat absorption and, therefore, the building's cooling loads.

5.7 Adaptive comfort

In order to address the comfort issues presented in the cases modelled where the overheating criterion is met or exceeded, it may be necessary to consider adaptive comfort. The following criteria must be met in order for adaptive comfort to work:

- Flexible dress code
- Occupant access to operable windows that they can control
- Shading of occupants from direct solar radiation

- Occupant ability to increase local air movement (*e.g.*, through the use of desk fans, ceiling fans, or ventilation)
- Occupant ability to change their work station (ideally)

Clearly, shading – which has been simplified and implicitly modelled in the range of g-values considered – and access to operable windows are two items that will need to be developed further as design items for the façade if the occupants are to feel thermally comfortable, even in the face of future climate change.

6.0 Conclusions

We have seen that the building industry's response to climate change can take on many different forms ranging from a regulatory approach to a design-based approach. Focussing on the building envelope design, there are a number of parameters that can be adjusted to respond to climate change such as glazing percentage, construction and glazing type, shading type and operation, and ventilation method.

For each weather scenario – current and future – considered, there appears to be an optimal g-value based on the modelled carbon emissions for a specified façade layout and building geometry. The optimal g-value indicates a balance of beneficial solar heat gains in the winter and keeping out unwanted solar heat gains in the summer. U-values, on the other hand, have relatively little impact for this façade and building configuration because of the relatively high internal gains in an office environment. When configurations with lower internal gains (*e.g.*, residential buildings), different orientations or different climate conditions are considered, the impact of U-values becomes more important.

There is also an expressed need for considering adaptive comfort to extend current defined limits of comfort in order to keep energy use low. A clear challenge lies ahead for building engineers and architects to meet the expectations of building occupants and evolving building performance requirements associated with climate change, yet an equally important challenge lies in shifting people's perception of what is acceptable comfort.

7.0 Further work

Other considerations for future work related to building envelope design and climate change are listed below:

Extension of modelling work:

- Consideration of the four main orientations to assess the average performance
- Reduction in glazing area percentage to look at options with less than 75% glazing (although the results in the paper can be applied to different façade layouts by combining glass percentage and solar performance)
- Additional thermal mass for dampening the effects of increased temperatures and solar gain, in combination with a night cooling strategy to the natural ventilation and mixed-mode ventilation models
- Extension of the assessment to other building types (residential, schools, healthcare, hotels, etc.)

Extension of climate change analysis:

- A more detailed analysis of how the nature of the climate change (*e.g.*, changes in solar irradiance vs. changes in dry-bulb temperature) affects the optimal g-value
- Increased weather-tightness against more extreme weather events
- Increased structural integrity

- Good indoor air quality: keeping pollutants out and using green facades as a potential solution
- Visual comfort: further daylighting and glare studies due to different solar radiation figures
- Acoustic comfort: noise profiles will change with different predicted wind speeds and also with quieter, less-polluting cars
- Water resources will become more scarce, leading to the requirement of new cleaning strategies for the façade
- Taking embodied carbon & other embodied impacts (like resources use, water, etc.) into account
- Using a cradle-to-cradle approach to design the façade

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