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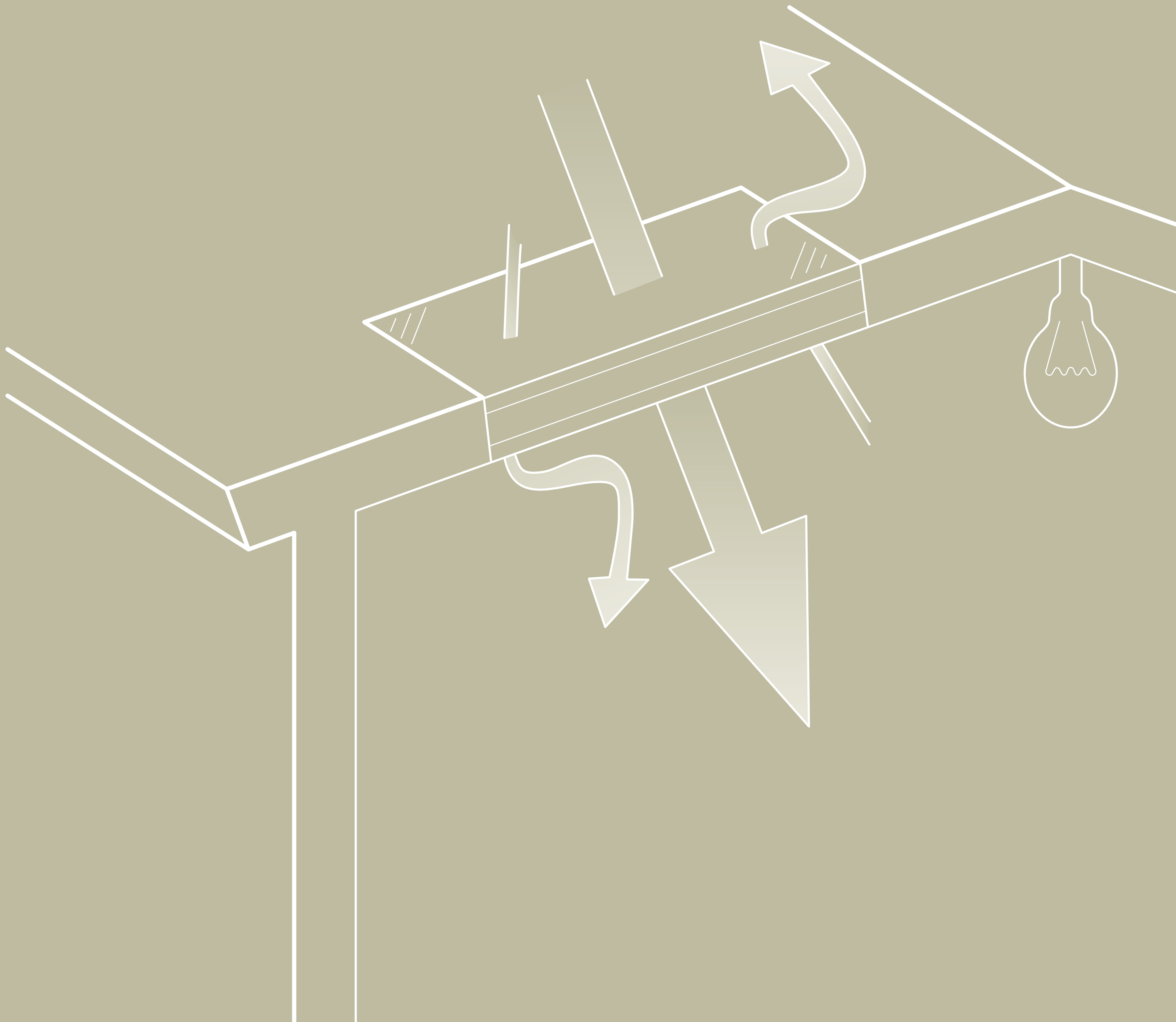
Corus Colors

Colorcoat® Technical Paper

Integrated lighting solutions for low energy buildings



Corus and low energy design

Since the 1970s, Corus have been at the forefront of technology in pre-finished steel building envelopes. In more recent times, the need to conserve energy and reduce the building contribution to climate change has informed the direction for envelope design. 90% of the CO_2 emitted from a building comes from the use phase and Corus are now actively researching methods for the building envelope to contribute to the minimisation of this. The first Colorcoat® Technical Paper “Creating an air-tight building envelope” gave building designers and installers practical guidance on minimising heat-loss through air-leakage. This paper continues this theme of low-energy buildings, examining the balance between natural and artificial lighting.

Working together to drive design

In providing an ongoing commitment to the future of the building envelope market, Corus have established the Colorcoat® Centre for the building envelope at Oxford Brookes University. Located within the Oxford Institute for Sustainable Development and one of the largest schools of architecture in the UK, the Centre is commited to providing cutting-edge research to develop the future of pre-finished steel building envelopes.

The work reported here has utilised the leading expertise of Oxford Brookes University, together with advanced computer modelling from the Corus R&D laboratories to provide a definitive view of lighting strategies for low-energy commercial and industrial buildings.

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Overview

Half of all energy consumed in the UK is used in buildings, mainly in heating and lighting but increasingly also in cooling. Minimising energy use is essential both in reducing the building operating costs and as part of an approach to tackle CO_2 emissions and global climate change. This requirement to provide more efficient buildings is the driver behind the latest revisions of building regulations for the conservation of fuel and power, namely Approval Document L in England and Wales, Part F in Northern Ireland and Section 6 in Scotland.

The latest building regulations provide a new format for the compliance method for new buildings other than dwellings. A minimum overall energy performance in terms of a limit on CO_2 emissions must be met for each new building and is calculated by using the Simplified Building Energy Model (SBEM). This signals a change away from considering individual elements of a building towards an all-encompassing view of the building where various factors each have an effect on overall energy use and can be considered on their merits.

Lighting accounts for 20 to 25% of all electricity consumed in Northern Europe. Typically industrial and commercial establishments consume 20 to 30% of their total energy just for lighting. Rooflights can be readily integrated with profiled pre-finished steel cladding systems as part of a strategy to reduce overall energy consumption by providing natural daylight.

This Colorcoat® Technical Paper uses full-building energy modelling to assess the benefits provided by rooflights in large commercial and industrial buildings. Rooflights can readily be incorporated into a pre-finished steel roofing system and when combined with an effective control system can help to minimise energy usage by providing natural lighting and useful solar gain to offset the increased energy losses through the increased area of low insulation. Large areas of rooflights can lead to excessive solar gain causing the building to overheat, a good approach is to use a low level of natural background light with point lighting where required. Covering 10% of the roof area with rooflights gives a good starting point for designing a partially daylit interior. Natural lighting from rooflights is most effective in wide, open spaces, where a slightly increased rooflight area may be considered. High-bay racking and similar bulky equipment can have a dramatic effect on light availability. A reduced level of rooflight area and suitably positioned aisle lighting will provide an effective strategy. The guidance here explores how to do this to optimum effect without creating excessive solar heat gains or thermal losses.

Lighting levels

Units of light

Light output (luminous flux) is measured in lumens (lm). The lumen is defined as the amount of light emitted per second on unit area placed at unit distance from a one candela light source. Illumination is measured in lux (lx), defined as one lumen per square metre.

Daylight Factor (DF) is defined as the ratio of the actual illuminance at a point in a room to the illuminance from an identical unobstructed sky and is the standard method of expressing the daylighting performance of an internal space. A design value for sky illuminance of 5,000 lux is often used, being the equivalent of a heavily overcast, diffuse sky. In the UK, this value is exceeded for 85% of working hours. In this case, a space with a Daylight Factor of 6% would have a illuminance of 300 lux. Daylight factor within a building will vary and can best be represented by a contour diagram.

At the start of the lighting design process, it is important to define the required level of lighting. The building designer must select the most appropriate lighting level for the proposed activity within the building. Increased levels of concentration and intricate tasks will require higher levels of illuminance. Even in speculative buildings, the general class of final use is often known, but assumptions may have to be made. Consideration should also be given to potential future change of use of the building.

It is generally accepted that a degree of natural lighting will enhance the working environment. The colour and reflectivity of the internal surface of the walls and roof will affect the internal illuminance. Use of a “bright white” pre-finished steel liner sheet will provide an excellent internal surface finish for general lighting requirements.

The following table gives some general CIBSE guidelines[2] for recommended illuminance levels for different activities:

Table 1. Recommended illuminance

Standard maintained illuminance (lux)	Activity / interior
200	Foyers, entrances, automatic processes
300	Libraries, sports halls, food court packing, warehouses
500	General offices, assembly, retail shops
750	Drawing office, supermarkets, showrooms
1,000	DIY superstore

It should be noted that the lighting design level has a major impact on the energy consumption and resultant CO_2 emissions. For low energy design, the lowest sensible lighting level should be specified. A practical approach is to specify a low level of background lighting which can come mainly from windows or rooflights, with localised “point” lighting in areas where higher illuminance is required.

Daylighting

Benefits of daylighting

Daylighting can provide psychological, physiological and energy-saving benefits providing it is sensibly applied. For most people, who spend over 80% of their waking hours inside buildings, daylight is welcomed, providing a link with the external, natural environment and its changing conditions. Although studies have not shown that productivity is demonstrably increased, a positive correlation has been proven between occupant satisfaction with the indoor environment and natural light levels. Overall, it is recognized that a sense of well-being is engendered in daylit interiors, leading to improved morale and loyalty of staff. In practical terms, good quality, diffuse daylighting can reduce strong shadow effects on vertical surfaces such as boxes in racking, enabling easier identification.

Definition of daylit spaces

A daylit space is defined within Approved Document L[1] as a space:

- within 6 metres of a window wall provided that the glazing area is at least 20% of the internal area of the window wall; or
- below rooflights and similar provided that the glazing area is at least 10% of the floor area.

In practical terms for large single storey buildings, 10% rooflight area can be considered as a good starting point when considering a daylit requirement.

All building lighting regimes should combine the available natural daylight with efficient artificial lighting and an effective control system.

Provision of daylight in large single storey buildings

There are two options for providing daylight to the interior of large single storey buildings:

High-level vertical glazing elements

Known as clerestory glazing within the exterior walls. The glazing ratio is limited by the proportionally low area of wall, in relation to roof area. Their main disadvantage is the rapid decay in natural lighting (daylight factor) with distance from the window, an important consideration given the deep plan nature of many buildings. For this reason, they are not suitable for multi-bay buildings. Positioning of high bay racking or bulky equipment will also obstruct natural light penetration from the sides. Daylight quality and quantity is highly dependent upon orientation of the building. Large areas of vertical glazing can also result in localised solar gains and can make some kinds of work difficult.

Rooflights

Consisting of translucent elements within the roof cladding construction, through which natural daylight can be well distributed, with little dependence upon orientation at low roof pitches.

There is a wide range of rooflight types and constructions, which are dependant on the choice of cladding system, but these fall into two categories:

- **In-plane,** where the rooflight is profiled to match the roof cladding. This is the predominant design used with pre-finished steel cladding on portal framed buildings. These are generally manufactured from Glass Reinforced Polyester (GRP), Poly Vinyl Chloride (PVC) or Polycarbonates. The thickness varies from 1 mm to 3 mm dependant on the material used and the structural requirements.
- **Out-of-plane,** which include barrel vault and domed designs. These are designed to sit above the roof level. They are fixed to a kerb or upstand, which is attached to the cladding. The upstand must be insulated but will introduce some additional heat losses. This type of rooflight is generally only used on membrane or standing seam type roofs where in plane rooflights are not possible. Out-of-plane lights are generally more expensive, provide less light and generate more potentially problematic interfaces.

Rooflights are generally constructed as double or triple skin arrangements and can either be fabricated on site or preassembled in a factory. In practice most rooflights will need to be triple skin to achieve the limiting U value standard of 2.2 W/m^2K as specified in the latest building regulations. Lower U values are available with some systems. Surface coatings can be applied to the rooflights to improve durability and reduce build up of dirt, which would reduce the level of light transmittance.

Artificial lighting

Artificial lighting types

Artificial lighting in large volume portal frame buildings has traditionally been provided by high or low bay reflector luminaries with high outputs of up to 1000 W. These luminaries typically use Metal Halide lamps which produce an intense bluish bright light that is easy on the eyes. Although Metal Halide lamps have high energy efficiencies they have disadvantages when designing to reduce CO_2 emission levels. Some lamps have a ‘warm up’ period that can take up to 7 minutes for the lamps to reach the maximum output making them unsuitable for on / off controls and more expensive specialist lamps are required if dimming is required. To take full advantage of the benefits of daylighting, an efficient lighting control system is required to maintain constant light levels which is difficult to implement with high output Metal Halide lamps.

A modern and energy efficient approach is to use T5 Fluorescent High Bay fixtures. Although the initial cost is higher, T5 fluorescent fixtures require less energy than metal halide, and offer improved control capability and lower maintenance costs. A typical 54 Watt T5 lamp produces up to 5,000 lumens and will lose only 5-6% of lumen output over it’s life whilst metal halide lamps can deteriorate by 35% over the same period. Office lighting fixtures can also utilise the benefits of T5 lamp technology. In this case, T5 lamps provide an even ambient light on the ceiling surface, eliminating high contrast light and reducing the risk of eyestrain. T5 fluorescent lamps are ideal for use with occupancy sensors and photo cells, and are cost effective and versatile when dimmed.

It is important to note that any strategy for a low energy building should start with intrinsically efficient components; the use of energy efficient lighting with a good control system should be considered as part of a strategy in conjunction with appropriate areas of rooflight.

Lighting controls

An effective operational control system is essential to minimise the use of artificial lighting and gain the maximum benefit of natural daylight from installed rooflights. Without an efficient control system, natural daylight from windows or rooflights will have limited beneficial effects on energy usage or carbon footprint.

Control systems can work on the basis of:

- **Hi-Lo dimming** – switching between two power output settings. This can be used with most lamps, but when operating at the low level setting, lamps operate at a much lower efficiency. This is a relatively basic control system which is inexpensive, but does not deliver the energy-saving reductions of more sophisticated systems.
- **Automatic switching** – switching individual lamps on and off. This is only really applicable with fluorescent fixtures where there are several lower-output lamps. Again, this is a relatively simple option, but does not achieve the best benefits.
- **Continuous dimming.** This is only applicable to fluorescent lamps such as T5 and is the most complex system, but does deliver the best energy-saving results as the lighting is most closely matched to the availability of natural light.

All control systems usually incorporate a time delay or difference between the light intensities at which lamps are switched on and off to prevent over frequent switching, for example when clouds pass over the sun.

Good commissioning of control systems is essential to ensure that performance is “as designed” and meets operational requirements. A poorly designed system may result in manual over-ride and failure to deliver the designed energy savings.

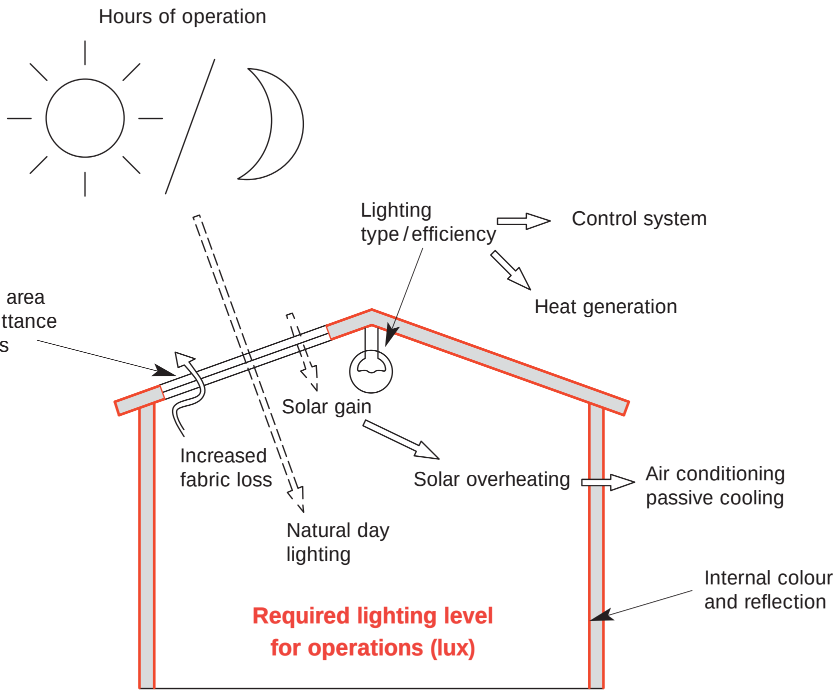
The computer modelling used to generate the recommendations given in this Colorcoat® technical paper assumes the use of an efficient continuous dimming control system. It is important to note that the energy savings reported here will not be achieved unless this approach is adopted in practice.

Use of rooflights

Factors, which must be considered when selecting rooflight area

When considering the percentage rooflight area for a building, the designer will need to look at the interaction of a number of conflicting requirements and aim to achieve a balance, which satisfies the building operations and regulatory requirements as well as minimising overall energy usage.

Fig. 1. Effects of rooflights on building operations and environment



Summary of effects of increased level of rooflights

Positive effects

- Provision of natural daylight.
- Reduced CO_2 from lighting.
- Solar heat gains in winter.

Negative effects

- Increased fabric heat losses.
- Excessive solar gains and overheating during summer.
- Cost of installation.
- Increased maintenance requirement.

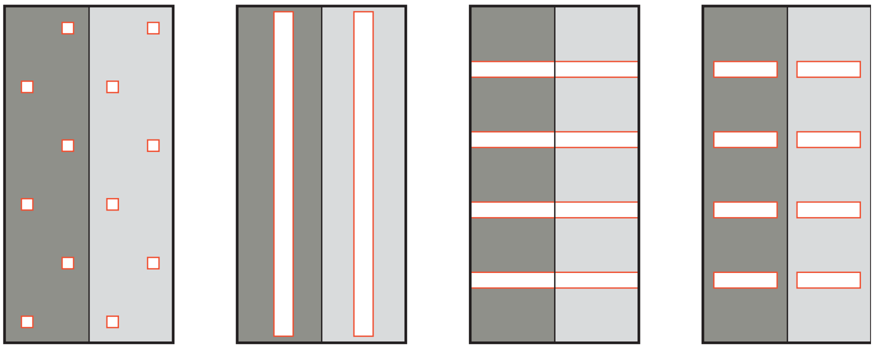
Considerations when specifying rooflight layout

The arrangement of rooflights should aim to give an even distribution of light. In some circumstances additional or reduced areas of rooflight could be considered for areas of different activity within the building. However, this approach could cause issues if there is a future change of use of the building, so in general, rooflights are distributed with relative uniformity over the roof area.

There are four general approaches for installation of rooflights:

1 Chequerboard
2 Continuous
3 Ridge to eaves
4 Mid-slope

Fig. 2. Options for rooflight layout



Chequerboard **Continuous** **Ridge to eaves** **Mid slope**

Rooflights are significantly more fragile than pre-finished steel cladding. Even when specified as “non fragile” it is wise to design such that they will never be walked over. This consideration must be taken into account when specifying the layout and would generally discount the 'continuous' and 'ridge to eaves' arrangements. In all cases the designer should ensure that the position of rooflights is obvious throughout the life of the building, taking account of any colour fade / discolouration, which may occur. It is common practice to use fasteners with a Poppy Red coloured head around rooflights to ensure their visibility. For further information regarding safety practices for work on roofs and rooflights, refer to ACR(CP)001:2003[3], “recommended practices for work on profiled sheeted roofs”.

The supplied and installed cost of rooflights vary greatly dependant on type and ease of installation. As a general guideline, in-plane rooflights will cost in excess of double the price of a similar area of insulated pre-finished steel cladding. For this reason, it is economically sensible to specify the minimum area of rooflights, which will give the majority of the daylighting benefits.

Out-of-plane rooflights are significantly more expensive and are far more complex to install. This must be taken into account when comparing the overall costs of a profiled metal roof with in-plane rooflights against other constructions, such as flat roofs, which require out-of-plane rooflights.

As rooflight area increases, there are diminishing returns on natural lighting, combined with increasing risk of solar overheating. The optimum area will depend on a number of factors. The results of full building energy modelling reported in this Colorcoat® Technical Paper give guidelines as to this optimum level for a variety of building operations.

In general a mid-slope approach offers the most practical solution with a good balance between an even distribution of natural light, without the increased number of potentially problematic interfaces created by a chequerboard layout and maintains easy access over the entire roof structure for maintenance, unlike ridge to eaves and continuous arrangements.

Building modelling

Modelling tools

The Corus Colorcoat® centre for the Building Envelope based at Oxford Brookes University and Corus Research and Development have examined how varying rooflight percentage area affects:

1. The available natural lighting at a given illuminance.
2. The risk of solar overheating.
3. The risk of overheating from the combined effect of solar gain and internal processes heat generation.
4. The differences between air conditioned and naturally ventilated buildings.
5. The light distribution in a building with internal fitments.
6. The effect of different geographical location.
7. The effect of reduced light transmittance typical through deterioration in service.

The results have been derived from a combination of dynamic thermal simulation and daylighting analysis. Two different analysis packages have been used to ensure consistency of results. In each analysis the effect on overall building energy use and CO_2 emissions was determined. Thermal simulation was undertaken with both Tas and IES, using hourly recorded weather data for the UK. These tools require the geometry of the building and all constructions and thermo physical details of the materials used. In addition, information on internal heat gains (people lighting and equipment) has been used to calculate heat loads and thermal comfort indicators throughout the year.

In all cases, lighting gains were controlled in accordance with modelled available daylight in the space to give the required illuminance. Daylighting analysis was carried out using both Lumen Designer and Radiance. In the former case, an average daylight factor (percentage of outside illuminance) for the entire space was calculated. In the latter, daylight factor was calculated per square metre throughout the space, enabling more precise control of lighting. In practice, lighting would be controlled by zoning, each zone being provided with a light sensor to either switch off or dim the lamps within that zone in response to local daylight availability. In practice, modelling will always overestimate the energy efficiency of the building as control systems are not 100% efficient and lamp efficiency will degrade over time.

Principle calculations have not used the Simplified Building Energy Method (SBEM) as used for regulatory compliance since this is not advanced enough for these kind of calculations. The recommendations arrived at from the modelling will provide a good starting points for compliance through SBEM or other available software.

The modelled building

A typical 66 x 48 m (3,168 m^2) out of town retail building was taken as the base building. It was assumed to have insulated pre-finished steel cladding with U-values sufficient to comply with 2006 regulations.

Rooflights were assumed to be evenly distributed across the roof and varied in length to give different percentages of total roof area. They were of triple skin polycarbonate construction, with U-value of 2.0 W/m^2K and light transmission of 0.64, which is typical for commercially available triple skin rooflights.

A number of base parameter for the building were set, some of which were then varied to simulate different situations:

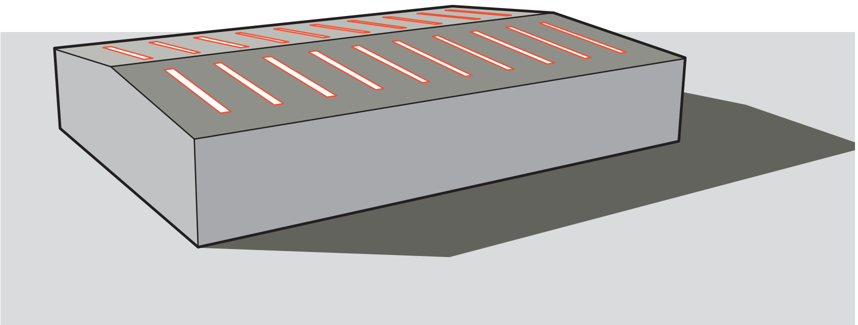
- **Lighting:** 5.6 W/m^2
- **Equipment:** 2 W/m^2
- **Ventilation:** 0.12 ac/h
- **Infiltration:** 0.5 ac/h
- **Cooling:** 25°C (when used)
- **Heating:** 19°C
- **Occupation:** 6 days 0800 h -1800 h
  or 7 days
  24 hour operation
- **Location:** S.E. England

Carbon dioxide emissions resulting from gas heating and electricity use were taken to be as quoted in the 2006 revision of Approved Document L[1]:

Natural gas: 0.194 $kgCO_2/kWh$
Grid electricity: 0.422 $kgCO_2/kWh$

The results obtained are specific to the modelled building, however the principles can be applied to most buildings of this form. It should be noted that changes to building geometry, inclusion of large areas of glazed façade and building orientation will all have an effect on the actual results.

Fig. 3. Tas representation of modelled building



Daylight availability and lighting control

From the daylighting model, using different settings for required lighting level, it was possible to determine the percentage of occupied hours that artificial lighting could be switched off. The model has assumed that the lighting control system is 100% efficient and that the artificial lighting requirement is continuously varied to maintain the required light intensity. In practice the control system would be set such that it did not respond until the light level fell outside of preset upper and lower levels. The result of this is that the calculations over-estimate the energy saving from lights being switched off or dimmed due to available natural lighting. For day-time operations a more practical assumption would be an additional 10% CO_2 emissions from artificial lighting, to prevent excessive switching, dependant on the control system and its settings. 24-hour operations will be more efficient as there will be long periods at night when the control is effectively constant.

The effect of rooflight area on availability of natural light

The graphs below illustrate the modelled light intensity at different percentage rooflight areas for:

1 8am to 5pm, day time operation.
2 24 hour operations.

It should be considered that operating patterns for the building may change during the design life.

The building has been modelled without any internal fittings (for example racking or process equipment) and the results are most applicable to wide, open spaces such as sports halls. The effects of internal racking are considered later.

8am to 5pm operation

For operations requiring 300 lux, the additional natural daylight availability through increased percentage rooflight area is very significant up to 10%. (which provides 75% of the maximum available natural lighting). Increasing rooflight area beyond 10% does not yield a substantial increase in daylight availability.

For operations requiring 1,000 lux, the additional natural daylight availability through increased percentage rooflight area is very significant up to 14%. (which provides ~60% of the available natural lighting). Increasing rooflight area beyond 14% does not yield a substantial increase in daylight availability for the additional investment. It should be noted that the maximum available natural lighting will be less than 100% occupied hours.

24 hour operation

The total maximum light availability for 24-hour operation is approximately half that for a day-time operation. During night-time operations rooflights do not provide any natural lighting or solar gains and should be regarded as a source only of additional fabric heat loss. Although the shape of the curves suggest that a higher level of rooflights may be beneficial, this must be balanced against the additional fabric heat losses. In practice, a strategy which adopts a slightly lower level of rooflights for buildings where 24 hour operation is likely will give the lowest overall energy usage.

Fig. 4. Annual daylight availability (London, 8h-17h weekdays)

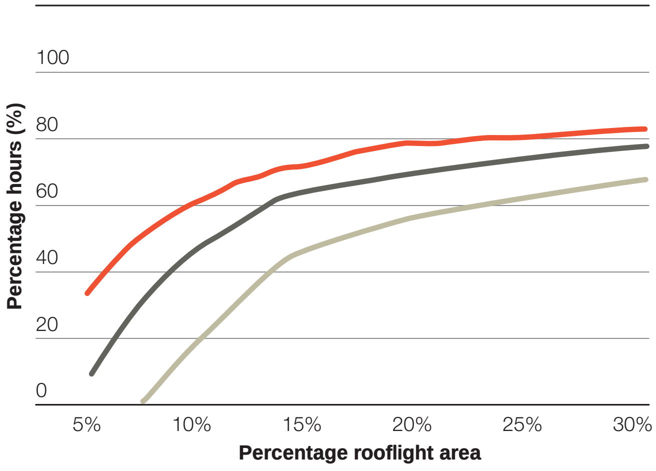
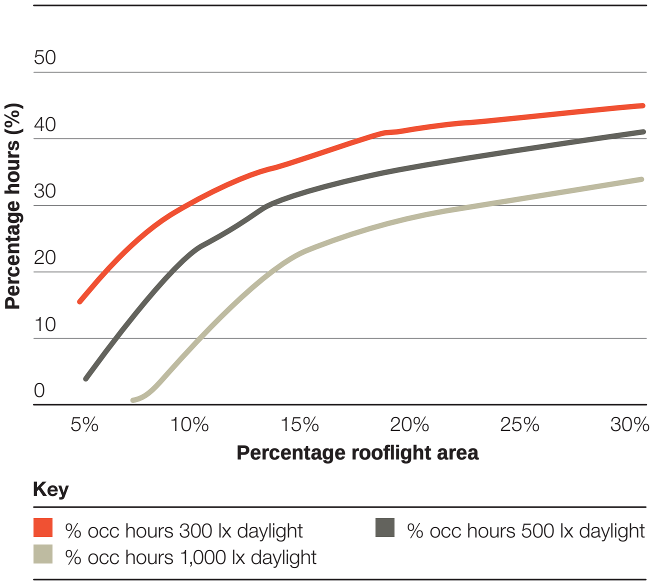


Fig. 5. Annual daylight availability (London, 24/7)



The available natural light intensity for a range of percentage rooflight areas, has been modelled throughout the year at different times of the day. The charts below illustrate the light intensities for 10% rooflight area. For considerable periods of time during the day, the light intensity (lux) inside the building is considerably higher than the designed requirement, particularly during the summer months. This can be as high as 1,200 lux. The main requirement for additional artificial lighting will be during the winter months when there is limited daylight. Increasing percentage rooflight area, does not alter the light availability pattern but does increase the illuminance, particularly at higher levels.

Fig. 6. Contour map of daylighting levels within the modelled building using 10% rooflights throughout the day and year

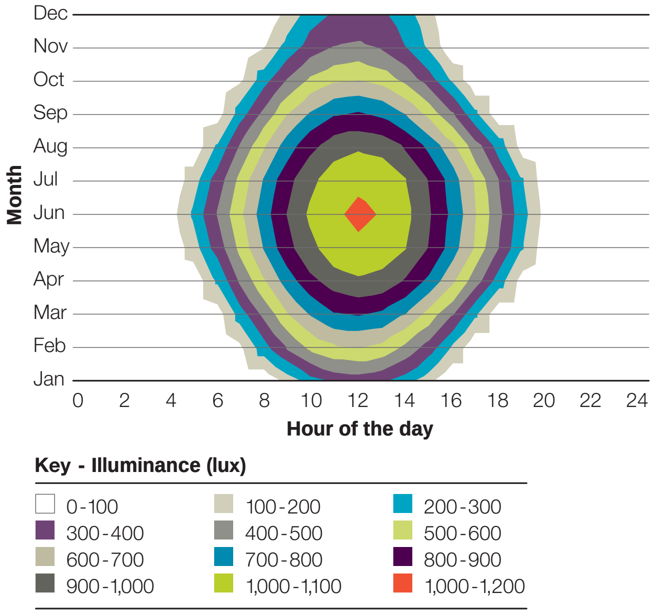
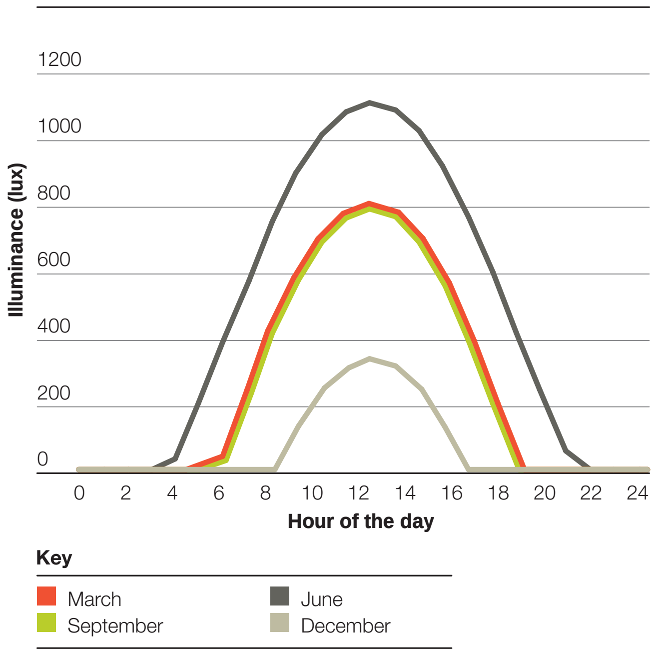
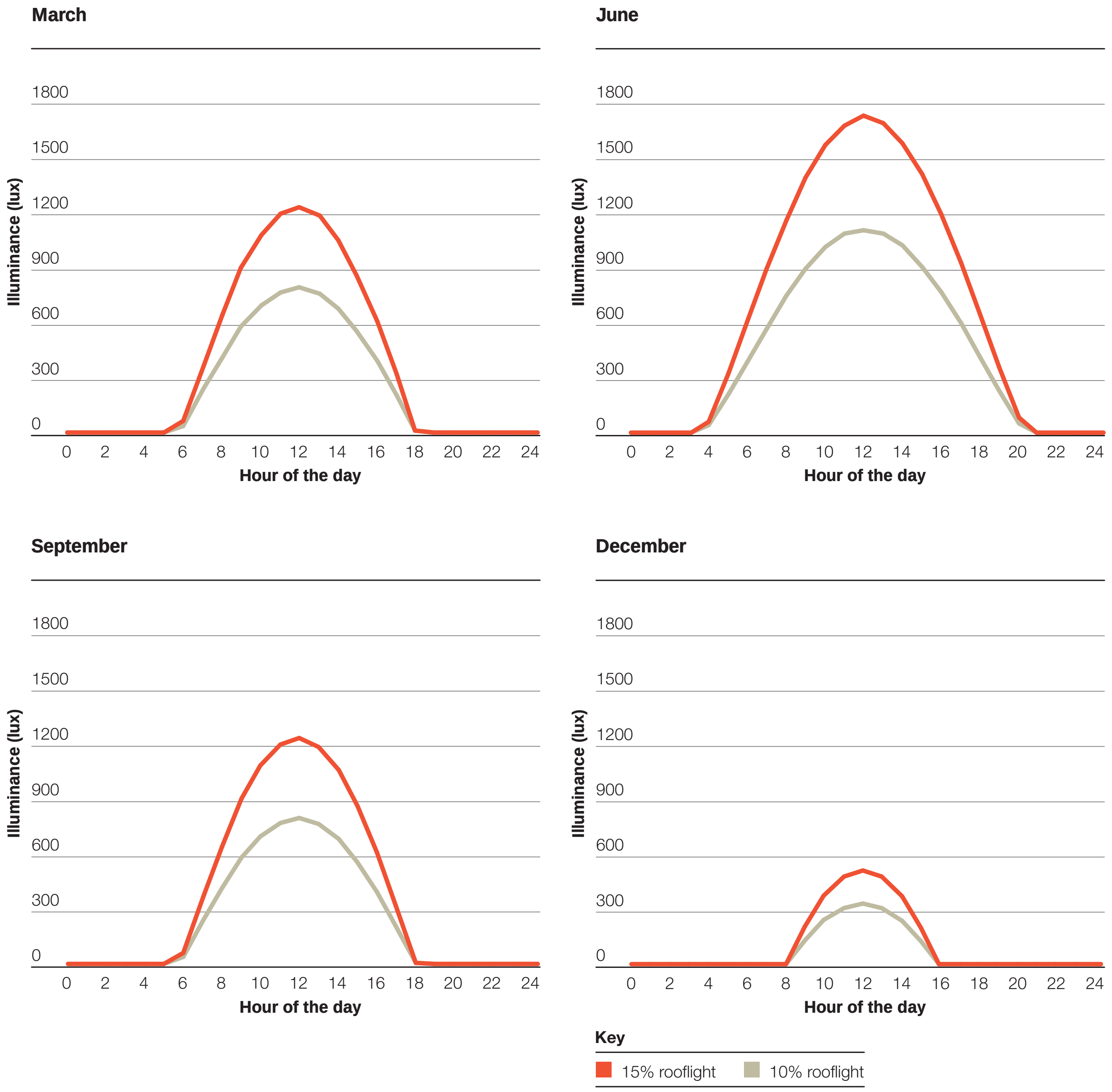


Fig. 7. Slice through the contour map showing lighting levels through the day on four specific dates



The graphs below show the natural daylight available at different dates in the year for 10% and 15% rooflight areas. The graphs demonstrate that increasing the percentage area of rooflights has a small effect on the time below a design illuminance value (eg. 300 lux) when artificial lighting will be required, but has a very dramatic effect on the maximum light available, particularly during the summer. This in turn can lead to increased solar over-heating.

Fig. 8. Internal illuminance at different periods in the year



Solar gain and overheating

Criteria for solar overheating

In addition to letting beneficial daylight into the building, rooflights also transmit infrared radiation, which generates heat within the building. This process is referred to as “solar gain”. In winter, solar gains can provide additional heat which can reduce the peak heating load, however solar gains need to be managed to prevent overheating during summer periods. Overheating can result in increased ventilation requirements or high air conditioning loads which will significantly increase energy demand and resultant CO_2 emissions to maintain a comfortable working environment.

Studies of global warming carried out by UK climate impacts program (UKCIP) predict that in all scenarios an increase in summer temperatures will occur. This will increase the risk of solar overheating and highlights the importance of taking this into account during the building design. The key concern is that there is a potential for significant increases in building energy consumption and consequently CO_2 emissions due to the increased use of mechanical comfort cooling systems.

Approved Document L[1] requires that buildings should be constructed so that:

1 Naturally ventilated spaces do not overheat when subject to a moderate level of heat gain.
2 Mechanically ventilated or cooled spaces do not require excessive cooling plant.

For Approved Document L[1] compliance, a calculation is required to check the effects of solar gain in summer to limit high internal temperatures using procedures detailed in CIBSE TM37: Design for improved solar shading control, CIBSE 2006[4]. The regulations require that to achieve compliance, a number of passive measures are used to limit the negative impact of solar gain.

Approved Document L states that reasonable provision would be to show for every occupied space which is not air-conditioned that either:

a When the building is subject to the solar irradiances for July as given in the table of design irradiances in CIBSE Design Guide A[5], the combined solar and internal casual gains (people, lighting and equipment) per unit floor area averaged over the period 06:30 to 16:30 solar time (GMT) is not greater than 35 W/m². or
b The operating temperature within the building does not exceed 28°C for 1% of the occupied hours. This is the benchmark for thermal comfort as used in CIBSE guide A[5], dependant on the building use.

These criteria give a good basis for investigating the effects of solar gain through rooflights.

Peak solar loads

The solar gain through transparent or translucent elements of a building are dependant on the orientation of that element. The solar loads per square metre averaged over day time hours for a July day are summarised in table 2.

The actual solar heating load inside the building is dependant on the percentage area and the solar energy transmission of the rooflights.

Table 2. Peak solar loads for July

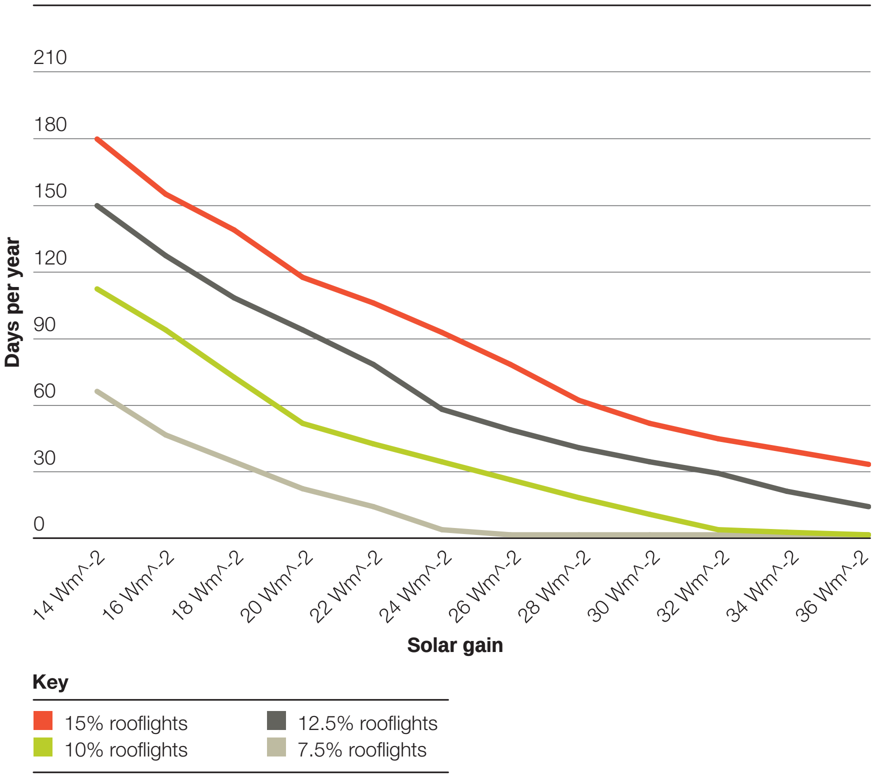
Orientation	**Solar load on external surface W/m²**		
	London	Manchester	Edinburgh
North	124	127	125
NE / NW	203	206	198
East / West	319	332	326
SE / SW	367	395	404
South	355	391	413
Flat / low pitch roof	655	672	647

Effect of rooflight area on solar gain

The solar gains for increasing percentage rooflight areas have been calculated for the model building and are illustrated in fig 9, which shows the number of days in a year when the solar heat gains will reach a given value. The data presented is for 7.5%, 10%, 12.5% and 15% rooflight area.

For a building with over 10% rooflight area, there is an increasing risk of solar overheating. A building with 15% rooflight area will always have days with more than 35 W/m² solar gains. The additional effects of internal process heat generation must also be taken into account and must be added to the solar heat loads. This is covered in the following section.

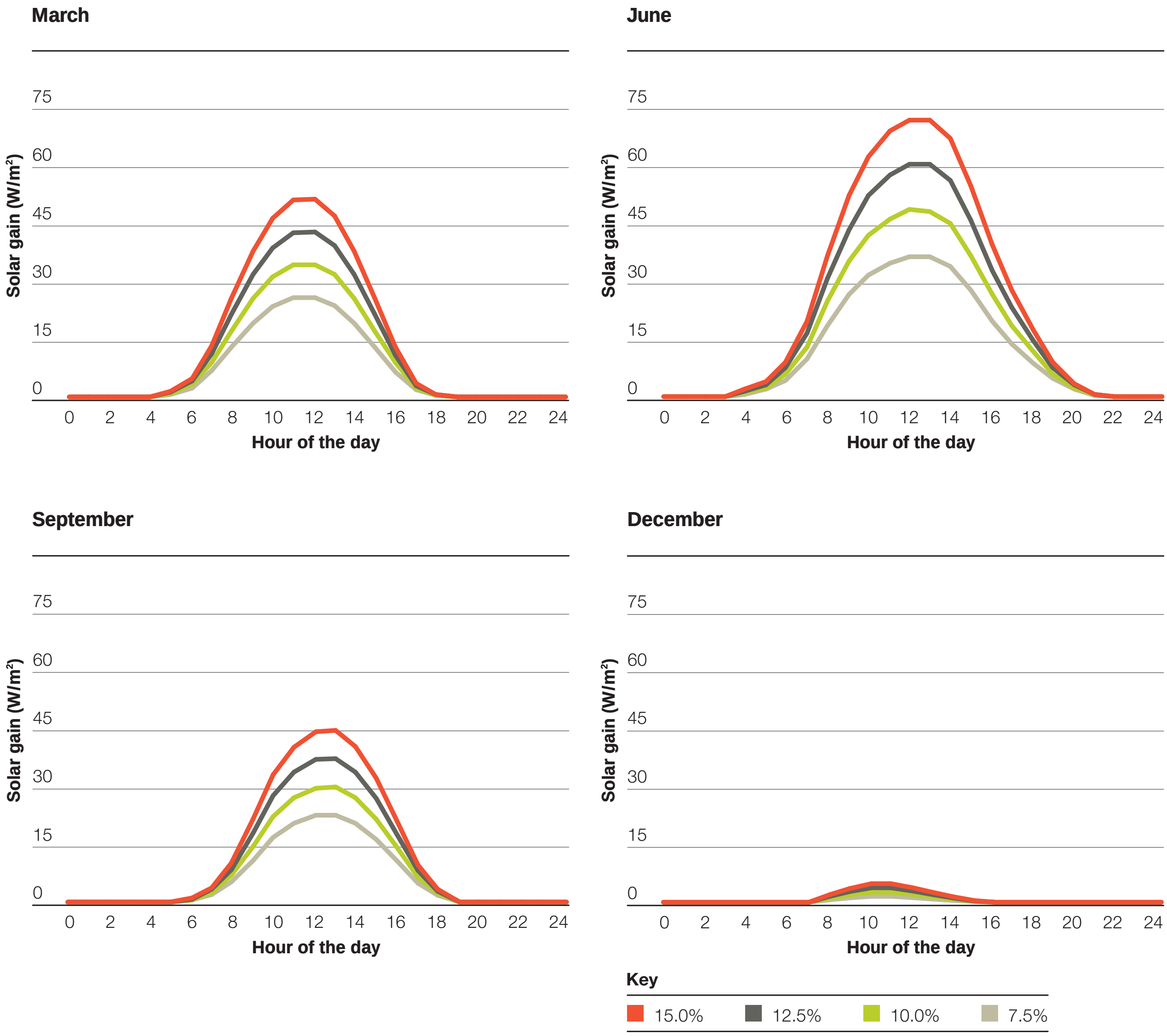
Fig. 9. Days per year (y axis) for which solar gains through the rooflights will exceed a given value (x axis)



Note. Approved Document L[1] stipulates that 35 W/m² should not be exceeded to limit the risk of overheating.

This is further illustrated by the graphs below which are based on actual weather data. These show the internal solar gains on specific days during the year and demonstrate that with rooflight area greater than 10% there is a much greater risk of the building overheating based on 35 W/m^2 average heating load. The overall solar gain is directly proportional to the rooflight area.

Fig. 10. Solar gains at different periods during the year for varying percentage rooflight area



March

June

September

December

Effect of internal process

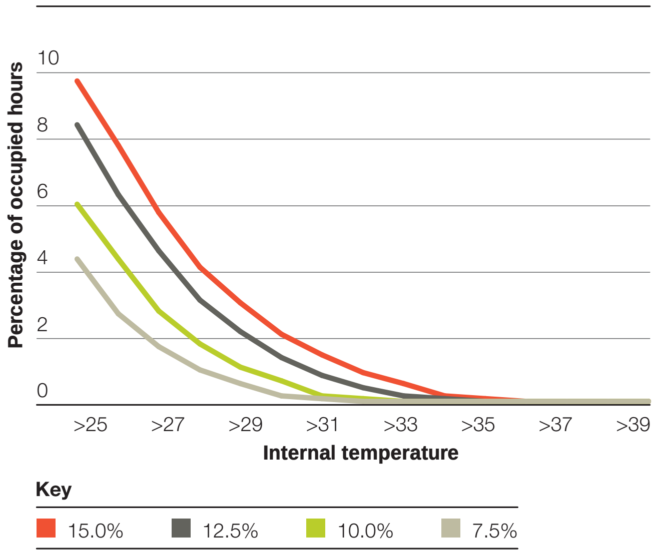
In most buildings, there is an additional effect of internal gains from the process, artificial lighting and people in the building. To assess whether overheating is likely, these internal gains need to be added to solar gains to determine the total heat gain.

To demonstrate the effect of total heat gain in practical conditions, three internal processes have been modelled and the results presented here.

2 W/m^2	Typical warehouse 24 hour operations.
25 W/m^2	Retail outlet / DIY store. Daytime operations.
50 W/m^2	Food processing plant 24 hour operations.

Warehouse operations (2 W/m^2 process heat gain)

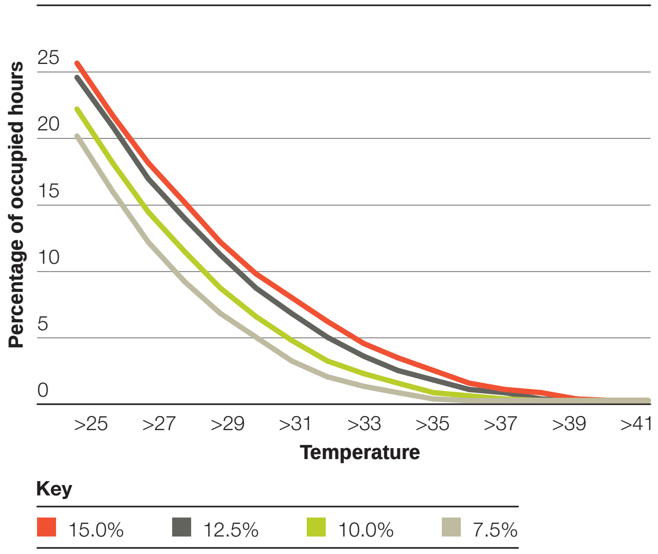
Fig. 11. Time when temperature will exceed a given value (day time operation)



The low internal heat generation and low lighting levels (300 lux), have a very limited effect on the overall internal heat gain, which is dominated by the solar effects.

Retail outlet / DIY store (25 W/m^2 process heat gain)

Fig. 12. Time when temperature will exceed a given value (day time operation)

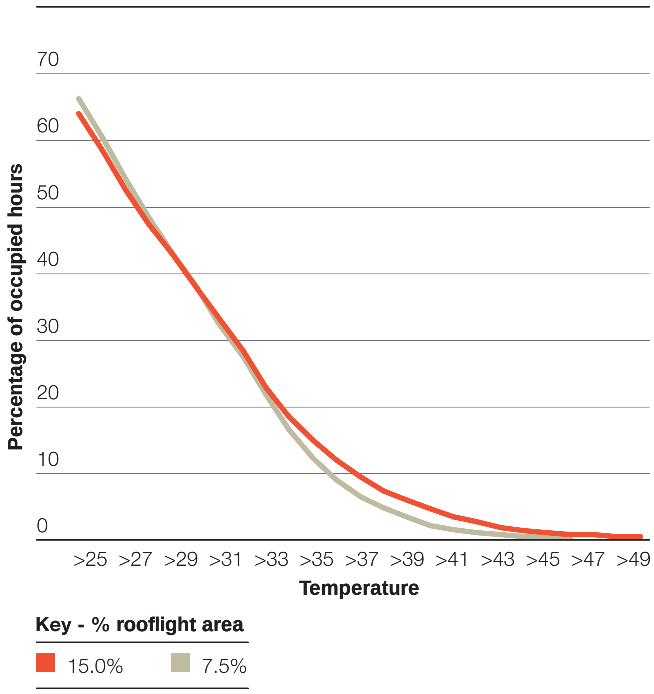


The internal heat gains from higher general lighting levels (500 lux) and localised point / display lighting are substantial. When combined with the additional solar heat gains, there is a significant period when 28ºC is exceeded.

When specifying rooflights, some form of ventilation or air conditioning should be considered which will have associated additional CO_2 emissions.

Food processing plant (50 W/m² process heat gain)

Fig. 13. Time when temperature will exceed a given value (24 hour operation)



The effects of the process heat generation are dominant and the building will overheat and will require mechanical ventilation or air conditioning. In this situation the percentage area of rooflights makes very little overall difference. The lower fabric U value of the rooflights allows additional heat to escape, except on very sunny days, when additional solar gain, through rooflights will occur. This can be seen where the modelled cases (7.5% and 15%) actually cross over on the graph. For this type of application, careful consideration must be given to cooling or ventilation requirements.

Effect of process heat generation and rooflight area on risk of overheating

The matrix to the right summarises the risk of a building overheating for increasing process heat generation and increasing rooflight area. Rooflight areas greater than 15% will almost certainly lead to a certain amount of overheating. For buildings, which have high internal process heat gains, the designer will need to establish how he can minimise additional gains, combined with an effective ventilation or air-conditioning system.

Fig. 14. Risk of overheating for varying processes

Process heat gain	Percentage area rooflights						
	5.0%	7.5%	10.0%	12.5%	15.0%	17.5%	20.0%
2 W/m²	🟩	🟩	🟩	🟧	🟧	🟥	🟥
25 W/m²	🟩	🟧	🟧	🟧	🟥	🟥	🟥
50 W/m²	🟧	🟧	🟧	🟥	🟥	🟥	🟥

Key

🟩 Total heat gains are manageable
🟧 Careful consideration required to manage total heat gains
🟥 Total heat gains likely to cause over heating

The air-conditioned building

Many buildings such as retail outlets and supermarkets have air-conditioning installed to maintain the internal operating temperature within a set range. This may be a requirement of the processes within the building, storage requirement for perishable goods, or to maintain occupier comfort.

Air-conditioning control systems will usually be operated to maintain the temperature between set upper and lower limits. Decreasing the acceptable temperature range will have a very significant impact on the amount of time the heating / cooling system is operating and will increase the total CO_2 emissions. This is demonstrated by the graphs below for two different controls.

The effect of percentage area of rooflights on overall CO_2 generation is very marginal, as can be seen from these two graphs, is more dependant on other factors in the building design. It should be noted in both cases that as the area of rooflights is increased, the heating and cooling requirements also increase. The effect of heating and cooling on total CO_2 emissions is balanced by the beneficial effect of natural lighting, although this will only be achieved if an effective lighting control system is installed.

It must also be considered that many retail premises have high levels of display window glazing, which dependant on the geographic orientation will also contribute to the effective solar load and subsequent air-conditioning requirement within the building, as well as providing additional fabric heat losses and additional heating requirement. However, display glazing often has little effect on lighting levels and any saving through reduced artificial lighting, so the effect of display glazing is generally to increase the overall energy requirement.

Fig. 15. Retail building (heated to 19ºC, cooled to 24ºC, 24/7): CO_2 emissions vs % rooflight

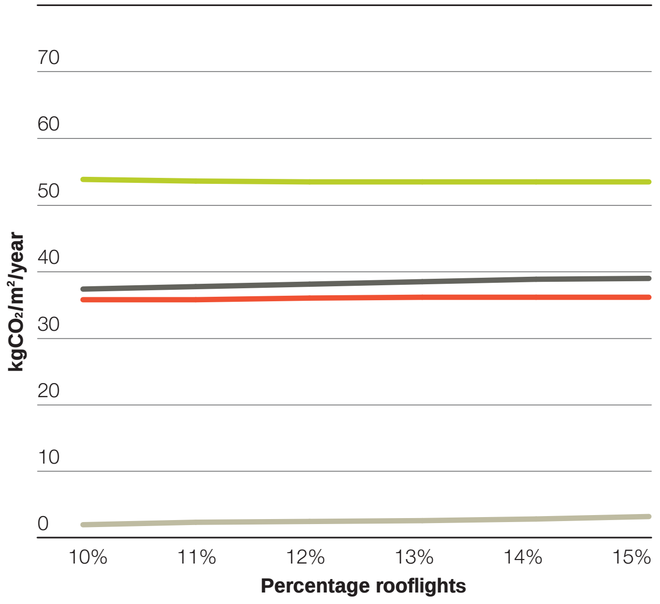
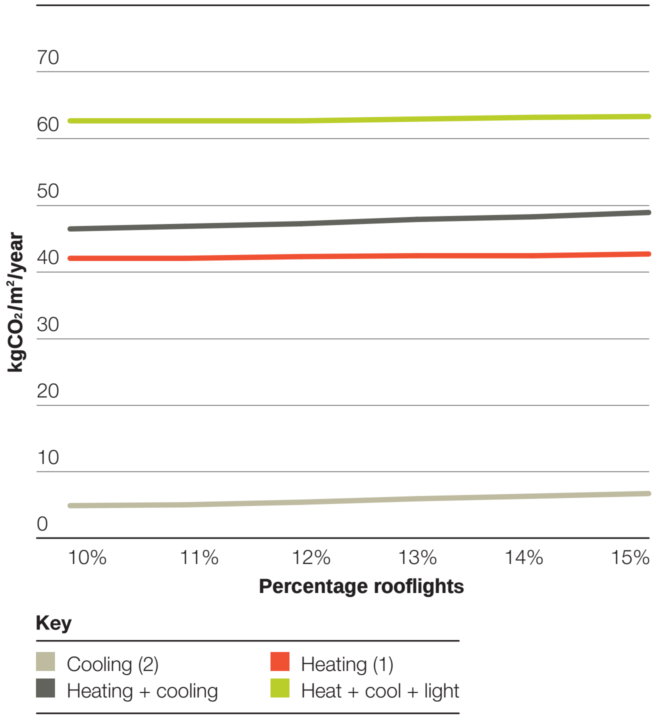


Fig. 16. Retail building (heated to 20ºC, cooled to 22ºC, 24/7): CO_2 emissions vs % rooflight



The naturally or mechanically ventilated building

The majority of industrial buildings are not air-conditioned and rely on either natural or mechanically generated ventilation. The use of mechanical or natural ventilation generates far lower CO_2 emissions than air-conditioning equipment. In many cases, ventilation is created by simply opening access doors. This can create a security problem and allow dust and debris to be blown into the building.

The effect of solar gain and internal temperature variations should always be considered to ensure that a satisfactory working environment is maintained. Increasing rooflight area has been shown to have a significant effect on increasing the solar gain and temperatures within the building. The graph below demonstrates the large increase in internal temperature variation, with increased percentage rooflight area, for the modelled building. The temperature ranges have been calculated, based on real weather data for the summer period. It can clearly be seen from this graph that on the sunniest days, percentage rooflight areas in excess of 10% can cause particularly large and uncomfortable variations in internal working temperatures.

The temperature variations within the building will be most extreme during the summer months when there are high levels of solar irradiance, leading to very high day-time operating temperatures, combined with ambient night time temperatures. This effect can also be significant through out the year. Large temperature variations on individual days will only result in small average variations when calculated throughout the year. The graph below demonstrates the average daily temperature variation for increasing rooflight area. Individual daily variations on the sunniest of days will be in the region of four times the average level. As can be seen, increasing rooflight area increases both the average and actual operating temperature range within the building. This increases the risk of solar overheating and unacceptable temperature variation within the building.

Fig. 17. Daily temperature variation throughout the summer period modelled with 5%, 10%, 15% and 20% rooflight area

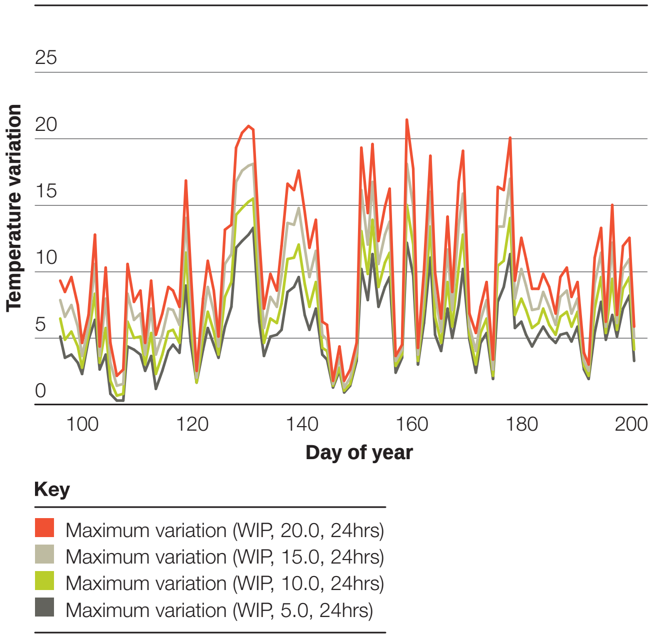
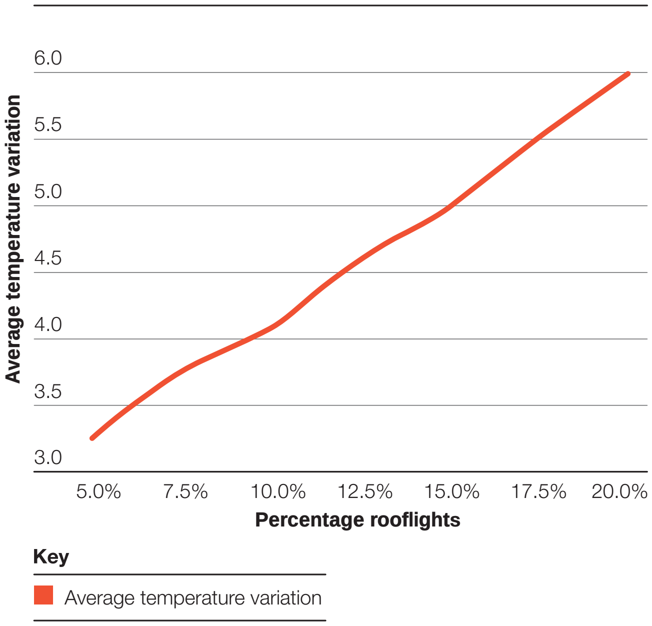


Fig. 18. Average daily temperature variation for increasing rooflight area



The effect of internal racking

The distribution of both natural daylight and artificial light within a building will be highly dependant on the presence and nature of internal equipment or racking. A building such as a sports hall with a wide open space and evenly spaced mid-slope rooflights, will have a fairly constant light intensity. However, the installation of internal equipment, and in particular high bay racking in a warehouse or distribution centre, will create areas of full and partial shadow, with much lower light intensities. In this case, the available natural daylight will not be fully realised and high levels of additional artificial lighting will be necessary.

A typical DIY retail building has been modelled in three cases:

1 With no racking in the building.
2 With high bay racking installed with:
  a The rooflights positioned directly over each aisle.
  b The rooflights positioned directly over the racking.

In practice there will be a range of positions between these 2 extremes.

The following parameters for the building and racking have been used:

Height to the rooflight of	8 m
Racking height of	3 and 6 m
Racking width	3 m
Aisle width	3 m
Rooflight area	up to 16.6%
Standard CIE overcast sky	

The building was modelled with 16.6% rooflight area, as this would correspond to 1m wide rooflights at a pitch of 6 m, which corresponds to the pitch of the racking. In practice the pitch of the rooflights may not correspond to the pitch of the racking. Lighting levels were calculated at three different heights on the front of the racking. The results are shown in table 3.

Fig. 19. Modelled cases 19(a) and 19(b) showing examples of aligning rooflights either directly above aisles or directly above racking

Fig. 19(a). Rooflight over aisle

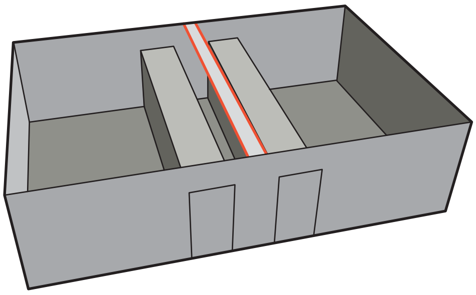


Fig. 19(b). Rooflight over racking

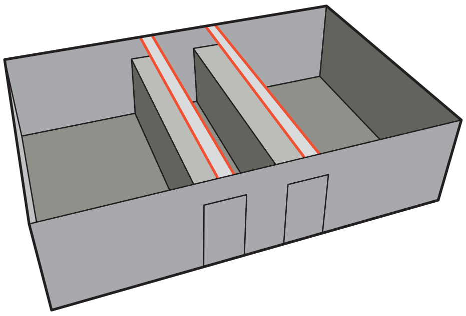


Table 3. Light intensities for the modelled cases

Case	Illuminance (lux)		
	Top of rack	@ 1m height	Floor level
No racking, mid-slope rooflights		1,700	
Rooflight over aisles. 3m racks	750	560	520
Rooflight over aisles. 6m racks	1,200	350	350
Rooflight over racks. 3m racks	580	520	400
Rooflight over racks. 6m racks	300	50	20

Effect of increasing rooflight area

As the rooflight area increases, the overall light intensity within the building will increase, however this will also increase the shadow effects in areas which are not directly lit. There may also be some areas, which are in direct sunlight and may be subject to glare. Even with 16.6% rooflight area, there is inadequate lighting at the base of the taller racking. In general it is not always practical to design the rooflight positions around the racking layout. It must also be considered that the internal material use or layout of the building may change during the service life of the building.

It is generally a better option to use the rooflights to provide a good background light level with artificial lighting aligned with the aisles.

Effect of altering racking / aisle separation and rooflight / racking height

Increasing the aisle width in relation to the racking will increase the light availability in the lower positions on the racking and will decrease the contrast between the top and bottom of the racking. However, to maximise warehouse capacities there is a tendency to minimise aisle width and maximise rack width and height. In both cases this will reduce the available daylight reaching the lower portions of the racking. To maximise the warehouse capacity racking is usually constructed as high as is practical within the bay. Decreasing the separation between the rooflights and the top of the racking, will again reduce the available daylight within the aisles.

In summary, where high bay racking (or large equipment) is to be installed within the building, the lighting from rooflights is limited. A good approach would be to use a modest level of rooflights (approximately 7.5%) to give a good background light level with point lighting where required.

Practical experience of SBEM (used for proving compliance with Approved Document L[1]) indicates that buildings with less than 10% rooflight area have more difficulty in achieving the target CO_2 emission rate. However SBEM does not take into account the reduced lighting effect created by high bay racking. The building designer will need to balance the SBEM requirements against effective lighting gains.

The effect of geographical location

As the latitude increases from Southern England (London 51.5ºN) to Scotland (Edinburgh 55.9ºN), the solar altitude decreases and weather patterns are different. Sky luminance is decreased, reducing the mean interior illuminance for the same daylight factor by 10-11%, as shown in Figure 20.

The total CO_2 generated from heating and lighting were calculated for Southern England (Slough 51.5ºN) and Scotland (Edinburgh 55.9ºN) and are shown in Figure 21. For the cases studied, carbon dioxide emissions from heating were 17% greater in Edinburgh, whilst emissions for lighting increased by 9%. It should be noted that the additional lighting will also have contributed to building heating.

In general with increasing latitude:

- The external ambient temperature will decrease.
- The average sky illuminance will decrease.
- Increased rooflight areas will be required to achieve the same internal level of natural daylight.
- Increased use of electrical lighting will generate internal heat gains which will partly offset the additional heating requirements generated by the lower external ambient temperatures. This creates a large increase in CO_2 generation.
- The gains from increasing rooflight area to maintain internal illuminance will need to be carefully balanced against the increased fabric heat losses through the rooflights incurred due to the lower external ambient temperatures.
- The risk of solar overheating will be reduced, however this can be highly dependant on the local weather patterns.

In summary, comparing buildings further north to those in the south, overall building energy consumption and CO_2 generated will increase on moving north, although there are so many factors in play that this effect is difficult to predict. On moving north, the positive benefits of rooflights are less pronounced due to the lower light intensities from the sky. However, using the approach of a modest level of rooflights coupled to specific lighting where necessary is still the most practical solution.

Fig. 20. Effect of latitude on average light levels at midday for different percentage rooflights (London 51.5 ºN, Edinburgh 55.9 ºN)

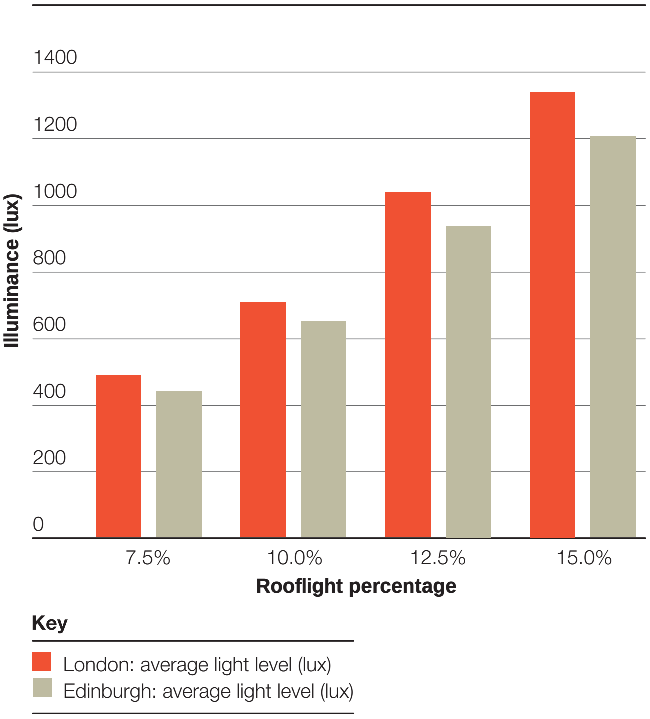
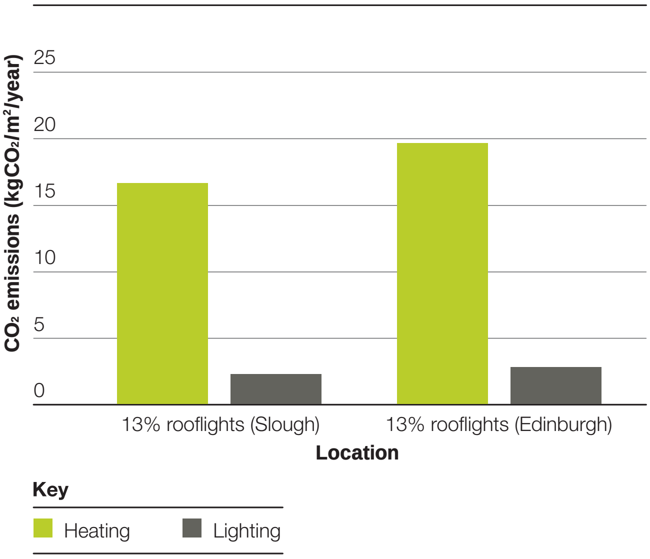
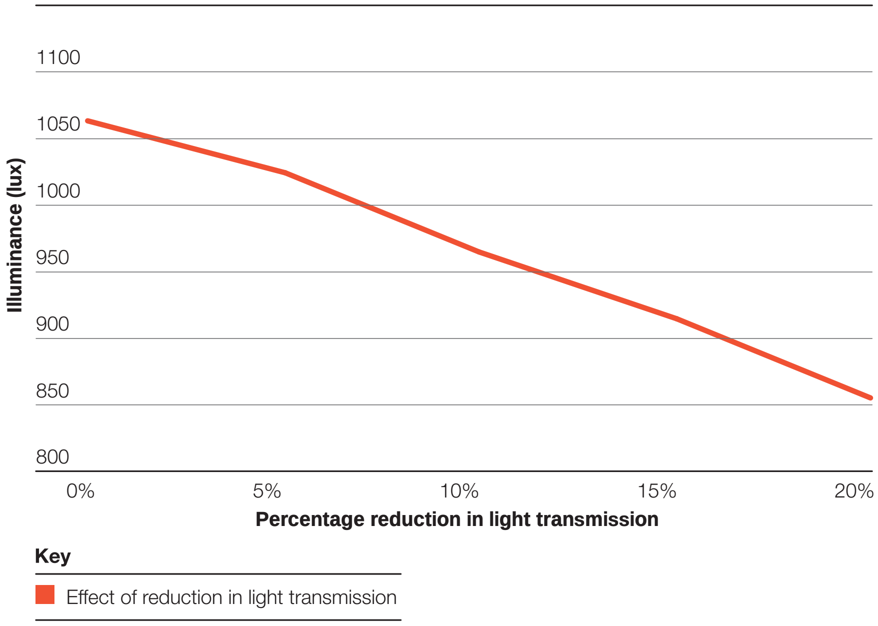


Fig. 21. Effect of latitude on CO_2 emission



The effect of rooflight transmittance

Fig. 22. Effect of reduction in light transmission upon average light level at noon (12.5% rooflight area)



Depending upon the materials used (polycarbonate or GRP) and the number of layers (double or triple-skin), in-plane rooflights can have a light transmission factor of 0.6-0.8 when newly installed, meaning that between 60% and 80% of available light is transmitted. However, over the 20-25 year service life, a number of factors combine to reduce light transmission:

- Discolouration (yellowing) due to ageing of the material by exposure to solar ultraviolet light. Modern rooflights suffer less from this than has historically been the case.
- Moss, lichen and mould growth.
- Atmospheric particulate deposition (soot, dust, etc).
- Bird fouling.

The extent of the light transmission decrease depends upon the material used and the cleaning schedule. The effects can be minimized by using low discolouration polycarbonate, as specified by some manufacturers and by regular inspection and cleaning of the rooflights. Some deterioration in daylight performance is unavoidable and should be allowed for in the initial calculations.

Reduction of light transmission reduces daylight factor and solar gain and hence affects energy requirements for both artificial lighting and heating. An extreme case for a 40% reduction in rooflight transmission shows that lighting requirements rise as expected, whilst the decrease in solar gain, is largely balanced by the extra heat produced by lighting, leaving the heating requirements little changed. See the table below.

In summary, as rooflight transmission decreases with age, total energy use will rise through a combination of factors, in this case by 6%.

Table 4. Effect of rooflight deterioration on CO_2 generation for a building with 10% rooflight area

	New rooflight as installed. Transmission 0.64	**Old rooflight with 40% reduction in light transmission to 0.384**
Heating CO_2 kg/m^2/yr	16.00	15.55
Lighting CO_2 kg/m^2/yr	3.45	5.01
Total heat and light CO_2 kg/m^2/yr	19.45	20.56

The effects of global warming

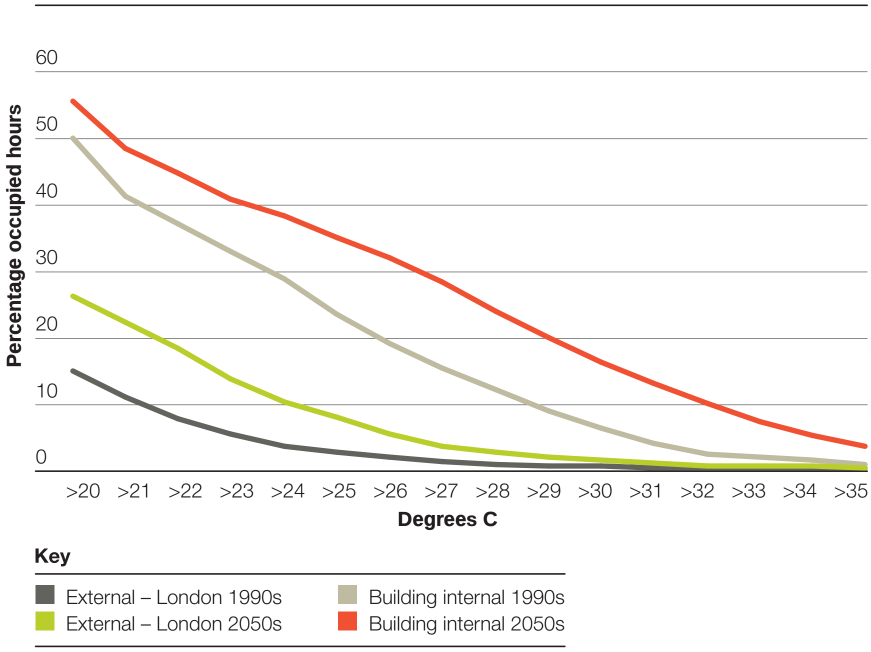
It is generally accepted that UK peak and average temperatures will increase substantially over the course of this century, triggered mainly by rising man-made carbon dioxide emissions. Summers will become hotter and drier, and winters milder and wetter. In the shorter term, UK summers are already getting warmer, with 2003 and 2006 ranking fourth and first hottest respectively since records began in 1659 (source: Meteorological Office).

Using reference climate data from the 1990's, a future weather scenario has been created in line with UKCIP (UK Climate Impact Programme) predictions for medium to high CO_2 emissions in the 2050's. The retail building model with 12.5% rooflight area has been modelled to compare overheating for current and future climates in the southeast of England. This used typical available climate data for the 1990's and the predicted data for the 2050's.

It can be seen from the graph that hours overheating are increased substantially for the future scenario, implying that cooling would be needed if thermal comfort for the occupants is to be assured. It can be concluded that limiting the extent of solar gain by using a moderate percentage of rooflights is one method of 'future proofing' a building if the trend towards a warmer climate is assumed.

Solar radiation will increase by a similar factor to average temperature, making over-provision of rooflights a potential source of unmanageable solar gain. It can be concluded that the problems associated with solar gain and overheating will become more pronounced with global climate change.

Fig. 23. Retail building (9-5 Mon-Fri): 12.5% roof light area. No cooling. Percentage occupied hours over set temperature



Conclusions

The modelling work reported here has confirmed that rooflights provide an efficient means of incorporating natural daylight into large single-storey commercial and industrial buildings. However, this also highlights that to optimise the design of the building, an integrated approach to building design must be adopted. Rooflights cannot be seen to be a function of the envelope alone, but must be considered as part of a lighting strategy which also includes efficient lamps and control systems. Likewise, rooflights and electric lighting also have an effect on heating and cooling requirements, so reinforcing the need for a holistic approach to building design.

In-plane rooflights can be readily and economically incorporated into profiled pre-finished steel roofs, indeed this is one of the benefits of the ubiquitous low-pitch pre-finished steel roof. Care must be taken in designing-in rooflights to ensure that a good distribution of light is achieved without impairing access to the roof, so the mid-slope approach is generally adopted.

When designing for a partially daylit interior, it is sensible to consider using rooflights for 10% of the total roof area as a starting point. This provides an economical solution, which gives the vast majority of the benefits of higher levels of rooflighting without raising the likelihood of over-heating to a great degree. Where internal heat gains are likely to be limited, high intensities of light are required and the building is intended to be used for day-time only operation, it may be sensible to raise this value towards 14%. For 24-hour operation in lower light levels, with considerable internal heat gains, it could be beneficial to reduce rooflight area below 10%.

There are many factors to be balanced in designing the lighting, heating and cooling strategy for a building and where the final use is not known at the time of erection, as is the case for many speculative constructions, it is difficult to adopt an all-encompassing approach to design. In this case, it would usually be wise to use 10% rooflights to provide background lighting, with localised point lighting being installed in areas, which require higher levels. Most of the calculations reported here considered an open building, but it has also been shown that the presence of bulky equipment or high-bay racking can have a dramatic effect on the effectiveness of rooflighting, reinforcing the optimum strategy of providing a low level of background light through rooflighting, backed up by point lighting where required. In these cases a figure of 7.5% rooflights would provide a good starting point.

In summary

- Rooflights can help to minimise energy usage by providing natural light and can be readily incorporated into a pre-finished steel roofing system.
- The incorporation of rooflights increases natural light availability but at the same time introduces areas of low insulation into the roof. Thermal losses here are virtually matched by solar gains through the rooflights, although in the summer this can become problematical.
- The energy savings gained from rooflights will only be realised if they are combined with an effective lighting operations control system.
- Covering 10% of the roof area with rooflights gives a good starting point for designing a partially daylit interior. In some cases, up to 14% could be beneficial, but at high levels, consideration needs to be given to the total heat gains in the building.
- High-bay racking and similar bulky equipment can have a dramatic effect on light availability. A good approach is to use a lower area of rooflights to provide a level of natural background light with point lighting where required.

Further information

1 Approved document L: Conservation of fuel and power (2006 edition).

2 Lighting levels: CIBSE Concise Handbook, Chartered Institute of Building Services Engineers, 2001.

3 ACR(CP) 001: 2003 Recommended Practice for Work on Profiled Sheeted Roofs (orange book).

4 TM37: CIBSE Technical Manual TM37 ‘Design for Improved Solar Shading Control’, CIBSE 2006.

5 CIBSE Guide A, Environmental Design CIBSE, 2006.

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