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Analysing Daylighting Sufficiency via Thermal Performance-Centred Glazed Fenestration in UK Residential Home-Office Environments

Ryan Gagg [1], Fraser Torpy [2], Biyanka Ekanayake [3], Sara Wilkinson [3], Shen Wei [4], Deo Prasad [5] and Siliang Yang [6,*]

1 School of Built Environment, Engineering and Computing, Leeds Beckett University, Leeds LS1 3HE, UK
2 School of Life Sciences, Faculty of Science, University of Technology Sydney, Sydney, NSW 2007, Australia
3 School of Built Environment, Faculty of Design, Architecture and Building, University of Technology Sydney, Sydney, NSW 2007, Australia
4 The Bartlett School of Sustainable Construction, University College London, London WC1E 6BT, UK
5 School of Built Environment, University of New South Wales, Sydney, NSW 2052, Australia
6 Dave Dickinson & Associates Ltd., Wakefield WF5 9TT, UK
* Correspondence: syang@ddaltd.co.uk

Abstract

The COVID-19 pandemic has led to a rise in residential office utilisation. As a result, it has become increasingly important to configure workspaces and design dwellings to ensure adequate indoor environmental quality. Currently, UK industry best practice largely focuses on rationalising the window-to-wall ratio (WWR) for dwellings. However, there is an increased regulatory stringency on new build glazing thermal performance, without much regard to achieving adequate daylighting. This paper looks into enhancing daylighting sufficiency within newly constructed UK housing to meet the daylight availability requirements of the British Standard—BS EN 17037:2018+A1:2021—whilst simultaneously ensuring daylighting sufficiency, thermal comfort, and sustainability. A quantitative methodology was adopted using DesignBuilder through a calibrated daylighting simulation in association with thermal modelling for a typical semi-detached house in the UK. The performance of five glazing solutions with varying WWR was assessed against BS EN 17037:2018+A1:2021. The WWR of all glazing types was increased from an initial WWR of 15.26% until daylighting sufficiency was realised. The findings show that the house attained inadequate daylighting with the initial WWR of 15.26%, as 77% of frequently occupied spaces achieved an illuminance of 100 lx for 50% of the daylight hours and 300 lx for 42% of the frequently occupied space for 50% of the daylight hours, which failed to comply with the standard. Thus, a larger WWR of 25% is required for the house to comply with the current daylighting standard with the existing glazing type. However, a change of glazing type would enable compliance at a lower 20% WWR. In this study, a refinement strategy was conceived to review a combination of key parameters for refining the glazing selection. However, it was found that no compliant daylighting refinement strategy could be realised without an increase of 3.66 °C to the peak operative temperature. This paper, however, highlights the significance of fenestration selection beyond thermal performance, demonstrating the importance of other design variables such as daylight transmittance, solar heat gain coefficient, glazing heat losses, and peak operative temperatures.

Keywords: daylighting sufficiency; energy efficiency; residential fenestration; indoor environmental quality; window-to-wall ratio

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1. Introduction

Conceived in the early 2000s, remote working was implemented to attain schedule flexibility, work–life balance enhancement, and commuting mitigation, therefore realising reduced expenses and enhancing organisational sustainability [1]. The COVID-19 pandemic expedited the expansion of remote working under the impacts of government-enforced isolation and social distancing protocols [2]. The investment expended in this process caused the diversification of working normalities wherein many residential dwellings have become partly allocated as office spaces [3]. This diversification of workplace locations places a requirement on both employers and employees to have ergonomic and indoor human comfort awareness. This includes daylighting sufficiency to maintain productivity whilst mitigating negative impacts on human well-being [4,5].

However, the initial dwelling design can cause barriers to optimum home office daylighting, along with services and spatial restrictions. Amorim et al. [6] outlines the impacts of dwelling design negatively impacting residents' mental well-being during the pandemic, recommending that future home design could be enhanced by improving the amount of available daylight within designated office space allocations, to mitigate restrictions and provide a suitable home office setup. Xiao et al. [1] also noted that unsatisfactory indoor environmental quality (IEQ) conditions within workspaces contribute to negative impacts on physical and mental well-being. In this context, the increased reliance on residential environments for prolonged work activities intensifies the importance of daylight availability, which is fundamentally governed by the building envelope and its design parameters.

Glazing in residential dwellings is normally designed to support energy efficiency and occupant well-being. However, there is a potential for 50% of dwelling heat to become dissipated through its glazing, and thus window-to-wall ratio (WWR) recommendations have been formulated in an attempt to minimise thermal loss to prevent detrimental upsizing of the heating load, whilst simultaneously ensuring the availability of appropriate daylighting levels [7]. Accordingly, the need to support adequate daylighting for home-based workspaces directly translates into a requirement to optimise fenestration design, particularly the WWR and glazing properties. Fenestration design thus must consider that a bias to thermal loss mitigation can result in insufficient daylighting; conversely, increasing daylighting availability excessively can cause additional solar gain and present an increased likelihood of dwellings overheating [8–11]. Elias [12] determined that a WWR of 10–30% is optimal for UK residential dwellings; furthermore, peer-reviewed analyses further refine this, demonstrating that a target of 20% to 30% is necessary to optimise building energy efficiency and daylight factors across varying orientations [13–16]. However, there has been little research published with lighting adequacy as the baseline for the determination of the optimal UK residential WWR and glazing selection. Kristiansen et al. [8] concur with Elias [12] in recommending future research in this field, with recommendations made to balance daylighting availability, energy consumption, and thermal comfort to create energy-efficient dwellings which deliver a comfortable indoor environment.

Thus, this paper aims to make objective contributions to provide recommendations for daylighting refinement for consideration within the design of UK residential properties, and provide a refinement strategy (demonstrated by a case study) for glazed fenestration within UK new build housing stock which ensures daylighting sufficiency for home office applications, whilst considering energy efficiency and occupant thermal comfort.

2. Research Background

This section aims to critically analyse the content, methodologies, and outcomes within existing knowledge of home office requirements in terms of both visual and thermal comfort refinement. The literature review was conducted through a systematic search of academic

databases, primarily Web of Science and Google Scholar, supplemented by other relevant online sources. Keywords such as "window-to-wall ratio", "residential fenestration" and "UK dwellings" were used to identify relevant studies. The selected literature was then reviewed and analysed to provide an overview of current research and key findings related to the proposed research.

2.1. Home Office Ergonomic Considerations

The UK Government response to the COVID-19 pandemic, along with the enforcement of regional and national lockdowns, included recommendations for home working whenever possible [14]. Perceptions of residential remote working improved throughout the COVID-19 pandemic, with employees demonstrating an increasing preference for working remotely for a percentage of the working week, and it was predicted that this working methodology will remain long after the pandemic ends [17].

A recent UK-wide survey [18] noted that the COVID-19 pandemic led not only to an increase in remote working, but also that 55.3% of respondents were not reminded of mandatory display screen equipment (DSE) regulations. Thus, people were not encouraged to undertake DSE assessments when working at home. Consequently, 23.4% of respondents suffered visual deterioration and 44.9% claimed to have experienced mental fatigue. These findings clearly emphasise the importance of ergonomics (including lighting) within home working environments. Further support comes from Ahmed et al. [3], who again highlighted the importance of home office environment ergonomics and identified a trend between increased work productivity and an ergonomically designed workstation. Whilst the research focus was predominantly on posture and office furniture requirements, it also established a trend between inadequate lighting causing resultant negative impacts on visual fatigue.

2.2. The Importance of Daylighting and Its Requirements

Mardaljevic [19] identified that regular daylight exposure is essential to human health due to the photosensitive retinal ganglion cells relaying light-induced signals to the anterior hypothalamus of the brain; this is known as the circadian pacemaker. However, the requirement for daylighting extends beyond setting occupants' biological clocks, as Aslanoğlu [20] identified that daylighting with accessibility to view-out can support mental well-being, hence enabling tasks to be undertaken safely and comfortably. Ahmed et al. [3] support this through the identification of a trend between increased lighting and reduced visual fatigue. In addition to health benefits, utilising natural daylighting effectively through building design is critical for energy conservation by reducing reliance on electrical lighting [21–23].

BS EN 17037:2018 (that is, Daylight in buildings, a British-Adopted European Standard) [24] was the first major standard to define absolute levels of daylighting illumination within dwellings [19]. Due to the economic impacts of climate-based daylight modelling (CBDM), the simplified daylight factor calculations as used in the BS EN 17037:2018 are often the preferred methodology for establishing daylighting sufficiency. However, as daylight factor calculations use a typical CIE (that is, International Commission on Illumination) overcast sky with adapted target figures, they are not as accurate as the CBDM calculations because the target figures are not based on a project-specific location, but rather use the country's capital city, thus introducing location-based inaccuracy [19]. The most current version of BS EN 17037:2018 Daylight in buildings (+A1:2021) [24] gives recommendations for minimum daylighting provision through vertical openings (residential glazing or windows). Basically, it requires a target illuminance of 300 lx across 50% of the space for a minimum of 50% of the daylight hours, whilst simultaneously requiring a minimum illuminance of 100 lx across a minimum of 95% of the space for at least 50% of the

daylight hours. This standard aligns with the revision of the guide, Site layout planning for daylight and sunlight (also known as BR209) [25], which alleviates the concern raised by Waskett [21] of local authorities not fully aligning and complying with BS EN 17037:2018, as BR209 was outdated and utilises average daylight factors in place of calculated daylight factors. Although documental alignment has now been attained, there is still little guidance to designers defining where 50% of the property space is required to achieve the minimum illuminance requirement.

Littlefair et al. [25] provided advice as to where the daylighting provision should be prioritised (that is, living rooms, kitchens, and bedrooms), downplaying the significance of daylighting in circulation areas, bathrooms, toilets, and storerooms. From a human comfort and energy conservation perspective, this is a subjective statement which aligns with the criticism administered by Waskett [21], whereby the standard does not reflect contemporary living practices factoring open plan living or home offices, and thereby fails to prevent dwellings having inadequate daylighting.

Awada et al. [26] identified that productivity increases of up to 13% could be realised by increasing daylight illumination of workspaces, establishing a trend between enhanced physical and mental health statuses with increased productivity. This emphasises the importance of daylight sufficiency within utilisable areas for a home office environment. This consideration needs to be promoted amongst architectural designers, as a survey from Bellia et al. [27] has shown that occupant restrictions within dwellings were due to limited glazing, where 25% of respondents complained about insufficient daylighting in their home offices.

When considering the required illuminance levels with the diversification of residencies into working offices, lighting recommendations that support human comfort and productivity typically reserved for dedicated office environments are now applicable to residential dwellings [28]. Thus, the recommendations from BS EN 12464-1:2021 (that is, Lighting of indoor workplaces, a British-Adopted European Standard) [29] for levels of task illumination should now be implemented in residential buildings where home office work is occurring. In this standard, a minimum illuminance of 500 lx is required for typical office and IT applications, which, is substantially above the preferred illuminance range identified by Peters and Halleran [28]: 150–200 lx for residencies, dependent upon the room designation. As such, residential lighting designs should accommodate flexible lighting control systems to diversify the attained illuminance between work and typical dwelling applications. It should be noted that a required illuminance of 500 lx is substantially above the minimum target daylight illuminance from BS EN 17037:2018 Daylight in buildings (+A1:2021) [24].

Therefore, the existing UK standards might have set inappropriate levels for the minimum daylighting illuminance recommendations for sufficient daylighting to accommodate the wide range of home office activities which could occur. Whilst the target enables a level of reduction to offset electrical energy from artificial lighting and for circadian entrainment, improvement could be found by setting the current "medium" target levels as the "minimum" standard provision, to further reduce the requirements for supplementary task lighting for home working applications. Conversely, a separately recommended illuminance could be added for home office spaces within the standard.

2.3. WWR—Trade-Off Between Daylight and Thermal Conditions

One methodology of daylighting refinement is by modulating the WWR (that is, the ratio of glazing to the gross wall area) [30], which, however, interacts with building thermal loss [31]. Sayadi et al. [32] noted that a balance is required so that the WWR is not only reduced to such an extent that there is inadequate daylighting, but also not increased to the

degree that it increases the risk of glare and overheating in summer, whilst simultaneously considering heating load demands through increased winter glazing losses. There are limited previous studies factoring all variables for dwellings within the UK, although a similar study in this field was undertaken by Ahmed et al. [33], where an optimum WWR of 30% was reported.

2.4. Glazed Fenestration Refinement for Human Comfort

Daylight refinement through adjustment of the WWR is heavily dependent upon the climate, orientation, and structure type [33]. Thus, the existing research in this field has produced contrasting findings, with Alwetaishi and Taki [34] and Asfour [35] identifying a preferable WWR of 20–30% for residential buildings, whilst Sayadi et al. [32] identifying a WWR of 30–50% as preferable, dependent upon glazing construction.

Amongst the existing research, the WWR is generally decreased to attain energy consumption reduction. Many studies performed this by replacing fenestration with low energy lighting systems (for example, [7]), but without accounting for occupants' subjection to artificial lighting rather than daylighting. This is particularly prominent when considering view access for occupants, as Ko et al. [36] identify that WWRs greater than 25% are required for sufficiency with view sizing.

Other methodologies of glazing refinement rely on physical glazing properties for deriving daylighting and solar gains/losses. Liu and Wu [37] reported that the selection of glazing is critical for controlling solar heat gain and visible light transmission, which interact with the environmental factors in which the glazing is installed. Specifically, control of the internal environment can be made through the initial glazing selection, where the solar heat gain coefficient (SHGC) is selected with consideration for the external climate to control the glazing solar gains, while the visible light transmittance (VLT) of the glazing is selected to control the amount of visible light the glazing will transmit [37–39]. Therefore, the initial selection or specification of glazing is critical for attaining an energy-efficient building that simultaneously delivers indoor comfort.

Kerr and Reeves [40] defined the comfortable temperature range for occupancy as between 19 °C and 26 °C. With a warming climate, a growing proposition of properties are likely to exceed these temperatures. A multitude of methods can be adopted to reduce overheating, such as the limitation of solar gains through interior/exterior shading, window tinting, passive and mechanical heat rejection, and mechanical cooling [40]. Ozarisoy and Elsharkawy [41] revealed that the UK Government has received notification that further action is required to reduce overheating within buildings, given that heat-related deaths could triple by 2050.

Furthermore, the properties of glazing affect both required cooling load and solar gains. The latest version of CIBSE (Chartered Institution of Building Services Engineers) Guide A [42] establishes that both glazing and fabric solar gains will increase with an increased glazing area, and glazing with a lower correction factor (for example, tinted glazing) will reduce the extent of solar gains. The U-value (thermal transmittance) of a glazing is also correlated to the fabric gains, wherein an increase in glazing U-value will increase the glazing fabric gains [43].

Therefore, to refine glazing for thermal comfort, glazing with a lower SHGC and a lower U-value for reducing thermal transmission would be suitable in warmer climates for reducing internal heat gains. For retrospective treatment, shading devices could be implemented to reduce the direct solar radiation through exposed glazing [37,44]. In summary, the glazing area and WWR, combined with the SHGC and VLT, are key considerations for glazing selections. These factors should be balanced with respect to the

installation climate and the building application to refine thermal load requirements and daylighting sufficiency.

2.5. Daylighting Sufficiency Determination via Simulation

Numerical simulation has been widely verified as an effective method of designing and analysing building performance [45]. To assist in the determination of daylighting sufficiency, accounting for both occupant comfort and energy use, various design tools have been developed to simulate the daylight performance of buildings, such as DesignBuilder and DIALux. Whilst it was shown that DesignBuilder produces results more closely aligned with measured illuminance levels than DIALux in a case study [46], research to date has included insufficient details of modelling parameters and omitted details on orientation, location, and altitude, and been based on small sample sizes [46]. The importance of including these parameters in model estimates is exemplified in Figure 1, where Akimov et al. [47] discussed how such geometrical properties are a dominant factor in determining daylighting availability. Figure 1 also illustrates how an automated daylighting control system would work, with feedback to the main control system on the location and orientation of the façade, as well as fenestration properties and illuminance levels within each zone, which form the daylighting availability input to the control system; when insufficient illuminance is established on the reference plane, the shading device actuator will activate and open the shading devices and will work in inverse operation, in other words, shutting the shading device when excessive illuminance is detected.

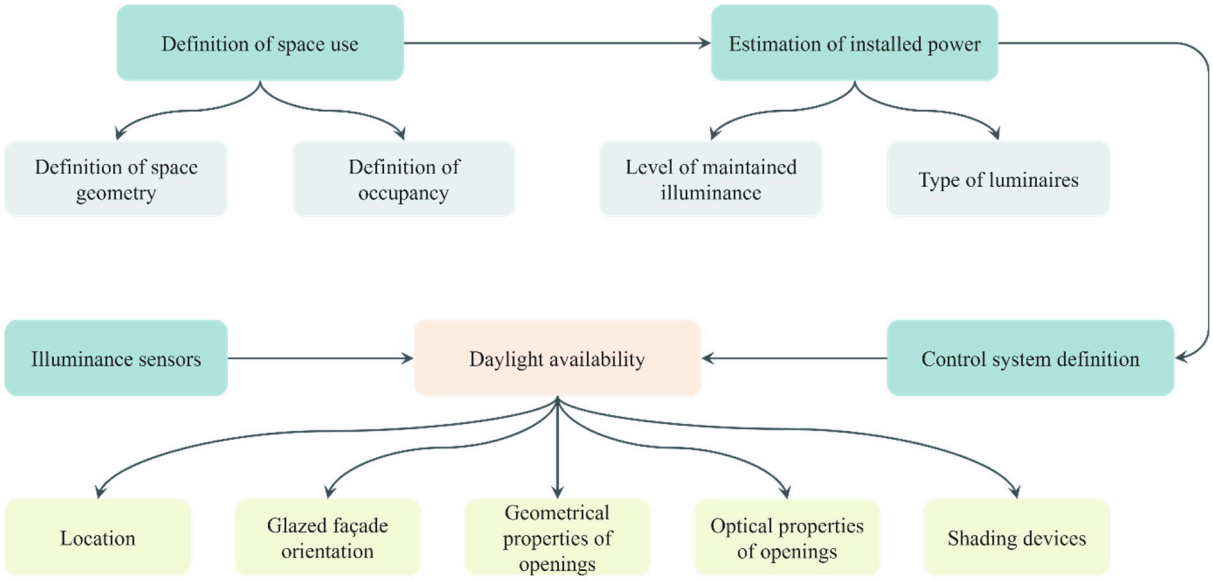


Figure 1. Daylighting control simulation principle [48].

DesignBuilder has the capacity to model such shading simulation, and was also the preferred simulation software utilised by Asfour [35], as it offers favourable glazing property adjustment and can simulate both Spatial Daylight Autonomy (sDA) and Useful Daylight Illuminance (UDI). UDI is the simulation of illuminance distribution across the working plane within a useful illuminance range, which helps determine the actual annual occurrence of illuminance without glare, whilst sDA determines the percentage of an analysis area (working plane) which receives a predefined illuminance threshold. Asfour [35] also highlights that attaining daylight is more important than glare control initially, as mitigation strategies can be implemented retrospectively for the latter; however, this should be balanced against the impact such control strategies would have on attaining daylighting sufficiency, and the users' economical constraints.

2.6. Problem Statement

Due to the COVID-19 pandemic, many employees have had to adjust to working from home. However, this can lead to ergonomic issues that may cause health problems [48]. Employers should provide support in configuring home offices, but both employers and employees need more guidance on working configurations within residential office environments [1]. According to previous research, the design of existing homes can also create barriers to creating an optimal home office due to restrictions in lighting, space, and services, which can negatively impact mental well-being. Whilst it is clear that future home designs should improve the amount of available daylight and allocate designated office space to mitigate these restrictions [6], designs to facilitate these changes are challenging.

Although glazing is important for energy efficiency and occupant well-being in dwellings, it can cause up to 50% of heat dissipation [7]. Therefore, it is necessary to follow the WWR recommendations to minimise thermal loss and ensure appropriate lighting levels. However, fenestration design must balance thermal loss mitigation and daylighting availability to prevent insufficient daylighting or increased solar gains that can cause overheating. Currently, there is little published research related to the WWR and glazing selection that considers lighting adequacy as the baseline [12]. More research is needed to balance daylighting availability, energy consumption, and thermal comfort in energy-efficient dwellings.

Thus, it is important to refine daylighting in the design of UK residential properties to create a comfortable indoor environment while conserving energy [49]. Therefore, this paper aims to provide a case-study-based refinement framework for glazed fenestration within UK new build housing stock which ensures daylighting sufficiency for home office applications, whilst simultaneously factoring energy efficiency and occupant thermal comfort. To achieve this aim, the study addresses the research question, how to achieve indoor daylighting sufficiency via thermal performance-centred glazed fenestration within UK residential office environments? Based on the research question, the objectives of this research are specifically as follows:

(1) To examine daylight sufficiency for home-office applications on a recently constructed 3-bedroom semi-detached property via calibrated representative geometric modelling and simulation;
(2) To investigate potential fenestration alterations to refine daylight sufficiency whilst assessing energy efficiency implications from any resultant thermal loss and resultant upsizing of the heating load (utilising the calibrated geometrical modelling);
(3) To investigate the impacts of the proposed potential fenestration alterations on the peak summer design day operative temperature.

3. Materials and Methods

This study adopted a quantitative method incorporating an assessment of compliance with the numerical guidance on daylighting outlined in BS EN 17037:2018+A1:2021. BS EN 17037:2018+A1:2021 was selected over CIBSE and BREEAM guidance, as it is more significantly recognised in the UK residential context and, as a British Standard, it can be used as a benchmark for demonstrating compliance with broader legal requirements, thereby having a greater legal standing as a British Standard. It was performed in an experimental domain utilising a model simulation of an existing 3-bedroom semi-detached property in England (see Section 3.1 for details), which was then calibrated by recorded illuminance within the physical property. This process ensured accurate model calibration by avoiding the laborious process of analysing subjective qualitative data. Research has found that among different types of residential buildings in the UK, semi-detached houses typically have higher energy consumptions, making them a worthwhile case for investigation [50].

Within quantitative methodologies there are two main methodologies for analysing results: descriptive analysis and inferential analysis [51]. As the proposed study was based on simulation and comparative evaluation of glazing and WWR scenarios, descriptive analysis was adopted for scenario-based assessment.

DesignBuilder (Version 7.3.0.040) was the selected simulation tool, as it is capable of simultaneous daylighting, energy, and thermal comfort analysis and providing accurate calculations through the EnergyPlus and Radiance engines [31]. In this study, annual daylight provision (based on spatial target illuminance) was selected as the parameter for determining daylight sufficiency. Model calibration and result validity were based on actual illuminance levels measured in the physical version of the property. The illuminance targets configured within DesignBuilder, and thus the assessment of sufficient illuminance, was determined by the minimum illuminance targets within the minimum and medium categories of BS EN 17037:2018+A1:2021, which defines the level of recommendation for vertical and inclined daylight openings. This specifies a minimum target illuminance of 100 lx over 95% of the working plane for 50% of daylight hours, and, within the medium category, a requirement for a minimum target illuminance of 300 lx over 50% of the working plane for 50% of daylight hours is defined.

In terms of the fenestration settings, initially, the WWR of the existing glazing to the external walls (wherein party walls are non-inclusive) was retained, but the glazing type was altered to allow performance factors for each glazing solution to be derived. Consequently, the WWR of the baseline case was increased, stepping up to 20% and then increasing in 5% increments until sufficient daylighting was attained for each glazing type.

Assessments on energy efficiency and thermal comfort of the property due to the glazing alterations were also calculated using DesignBuilder with an analysis of heating load and operative temperature. This was undertaken to ensure that the analysis considered multiple coincidental parameters of the WWR alteration to provide sufficient data to make a suitable determination on the enhancement of available daylighting against the converse impacts on both the heating load and peak operative temperature.

3.1. Design Parameters and Settings

The 3-bedroom semi-detached property was constructed in 2020 (Figure 2), and has a latitude of 53°49′7.33″ N, a longitude of 0°21′3.14″ W, and a 10 m elevation. The rear of the property has an 85° east-facing garden, with the front of the property being a 265° west-facing front, which is representative in the UK, where cold climate predominates across the country.

With the property location established, a suitable weather file (GBR_FINNINGLEY_IWEC) was selected within DesignBuilder. As the siting of the property is amongst open farmland, the exposure to wind was altered to "exposed" accordingly in DesignBuilder. The latest England's Building Regulations (Part L Volume 1) [52] was adopted for the modelling.

The ground properties were aligned similarly to those existing around the property (interlocked red herringbone paver) to ensure reflected radiation accuracy. For estimating the effects of energy consumption, models incorporated for the worst-case eventualities (for example, winter and summer extremes), thus ensuring that the recommendations from the study are reflective of current fluctuating climate extremes [53]. With the location settings inputted, the reflective model was then drawn on DesignBuilder, ready for the simulations to take place (Figure 3).

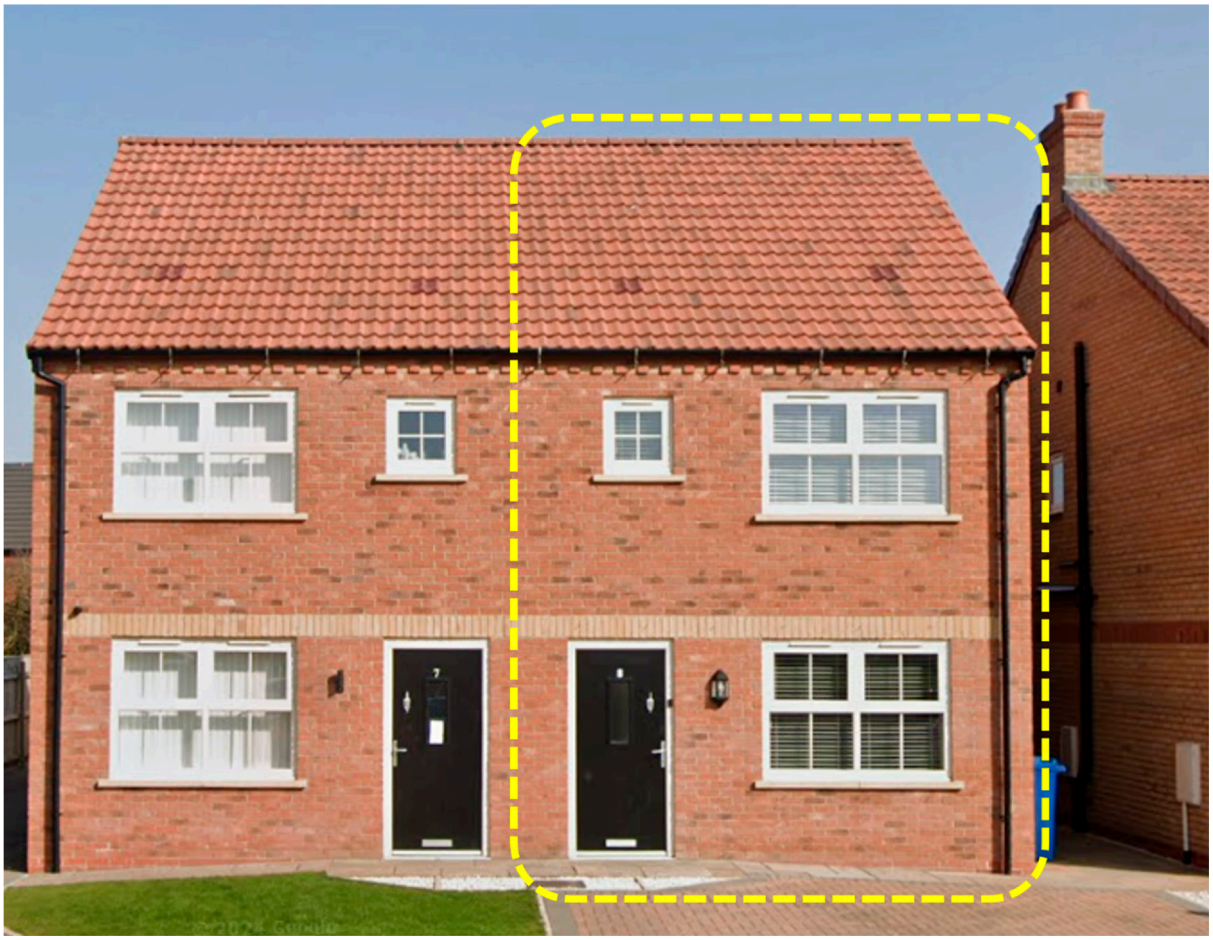


Figure 2. The real semi-detached case study property (circled).

As illustrated within Figure 3, there is no glazing on the north elevation of the property, as this is adjoined to a neighbouring property; therefore, the only areas for glazing are the east, south, and west elevations. Before initial simulations can commence, each material was aligned to the actual dwelling material properties to ensure simulation validity (Figure 4 and Table 1). To ensure that the assumptions made were realistic, all unknown properties were defaulted to the minimum acceptable standard as per the Building Regulations (Part L Volume 1), which are indicated in Table 1.

Table 1. Construction materials and U-values of the building envelope.

Construction	Description	U-Value (W/m^2·K)
External walls	Brick block wall insulated (measured)	0.352
Ground floor	Heated floor (measured)	0.232
Internal floor	Wooden-joist—25 mm chipboard (measured)	3.106
Internal partitions	2 × 25 mm plasterboard with 100 mm air gap (measured)	1.639
Pitched roof	Pitched roof by Building Regulations (Part L Volume 1)	0.150

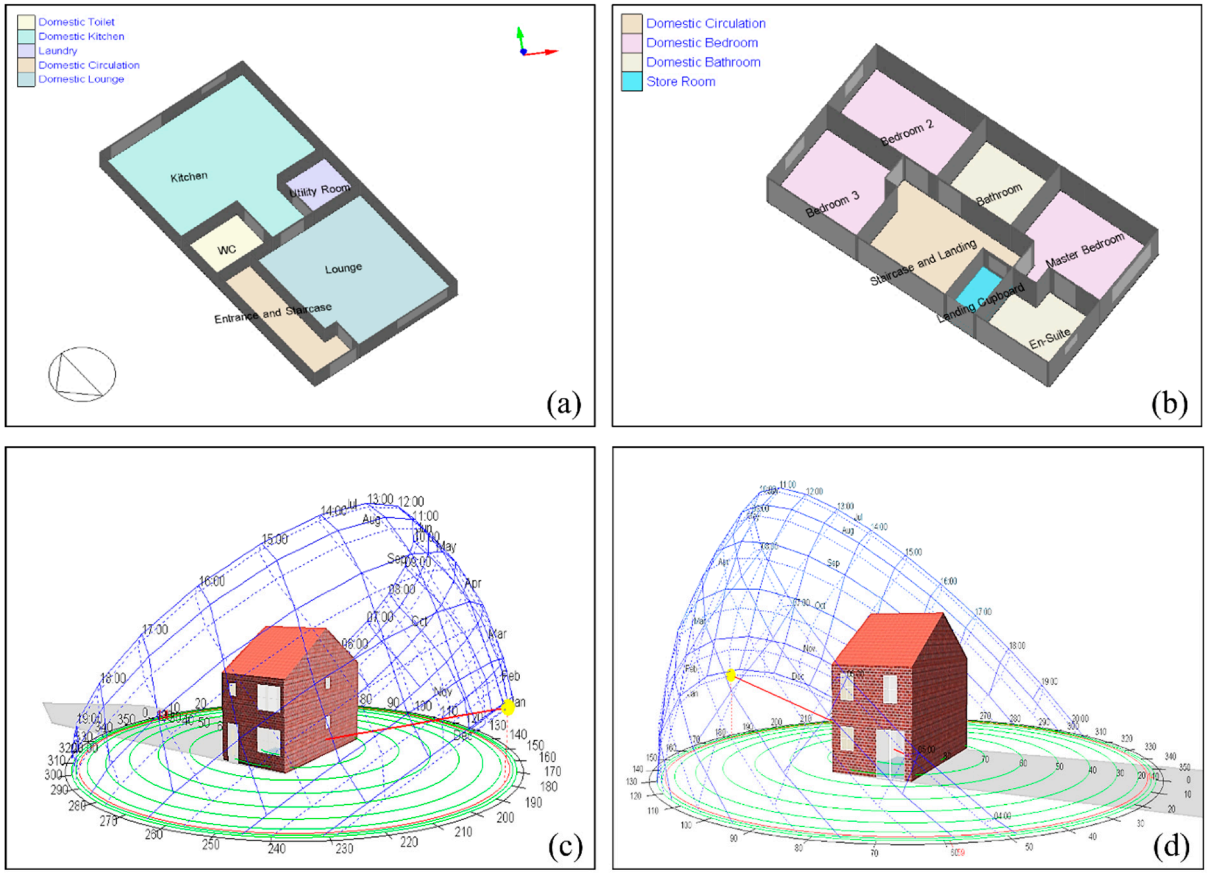


Figure 3. 3D view of the building model: (**a**) ground floor layout, (**b**) first floor layout, (**c**) model rendered and aligned to the sun path—northeast visual, (**d**) model rendered and aligned to the sun path—southwest visual.

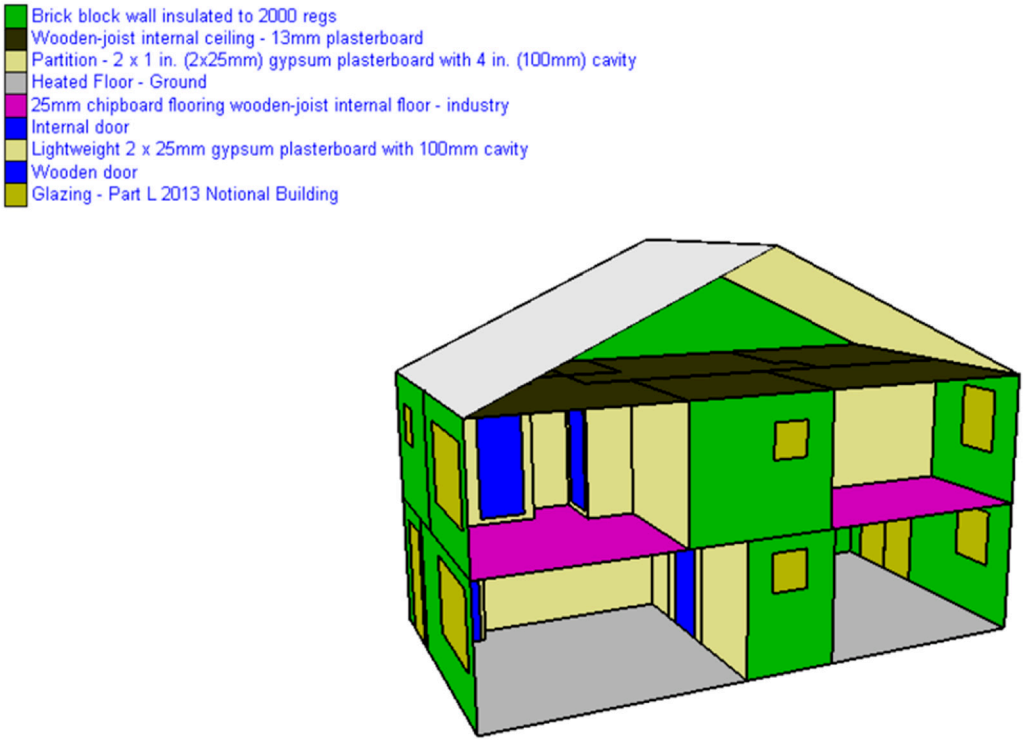


Figure 4. Construction material selections and assumptions.

It should be noted that the presence of underfloor heating on the ground floor, based upon the real situation, was included within the construction properties alongside the solid hardwood internal doors and plywood intermediate flooring. The U-values of the barring glazing were not of critical importance to this study, as the current work was related to the impact of fenestration alterations on daylighting and the consequential energy consumption differential rather than the building materials themselves. Table 2 shows the glazing parameters which were used for the glazing type alteration simulation.

Table 2. Glazing properties of the case studies.

Parameters	Baseline	Case 2	Case 3	Case 4	Case 5
Glazing type	Building Regulation Part L—Notional Building glazing	Double-glazed, Low-emissivity, Clear, 3 mm/13 mm Argon	Double-glazed, Clear, 4 mm/16 mm Argon	Triple-glazed, Low-emissivity, Clear, 3 mm/13 mm Air	Quadruple-glazed, Clear, 3 mm/8 mm Krypton
SHGC	0.360	0.597	0.649	0.474	0.466
VLT	0.639	0.769	0.819	0.661	0.624
U-value ($W/m^2 \cdot K$)	1.600	1.512	1.440	0.982	0.781

As the existing building was subject to superseded U-value requirements due to the latest update to the Building Regulations (Part L Volume 1), the baseline case was selected for the superseded U-value requirement of 1.6 $W/m^2 \cdot K$ (this has now been reduced to 1.2 $W/m^2 \cdot K$). For a reflective assessment, two additional glazing types (Case 2 and Case 3) were investigated, which were compliant with the Building Regulations at the time of the property's construction; a further two cases of glazing (Case 4 and Case 5), which comply with the newly implemented standards, were also assessed. This gives a holistic view of both fenestration selection and arrangement at the time of build and the impact of the new regulations. No parameters other than glazing size or type were adjusted between the simulations.

3.2. Procedure of Study

The following steps were carried out in sequence:

(1) Simulate the baseline case to ascertain preliminary data on daylighting sufficiency.
(2) Verify the simulated results using a calibrated illuminance meter, and, if required, modify model inputs to align to permissible calibration tolerances to ensure simulation validity.
(3) Within the calibrated model, run the simulations for each case (Table 2) on the current glazing area allocated for the building to attain data on daylighting sufficiency and relative energy consumption (heating load diversification due to diverse losses via glazing).
(4) Evaluate both daylighting and energy performances between each glazing type based on the initial WWR at 15.26% (this is the existing WWR of the property).
(5) Round the glazing size (in terms of WWR) for baseline from 15.26% to 20% and then re-simulate, and thus determine the revised results for Cases 2–5. This process was repeated, stepping up in 5% increments until daylighting requirements were met for all glazing types.
(6) Undertake heating load simulations for each glazing type at each WWR variation.

(7) Undertake thermal comfort simulation assessment (looking at operative temperatures) at peak summer design day for each glazing type at each WWR variation.
(8) Undertake carbon impact assessments for each glazing type at each WWR variation.

4. Development of Simulation Models

4.1. Daylighting Model Configuration

For calibration purposes, point-of-time measurements in the baseline model utilised a standard sky and CIE overcast day. For final annual simulations, the software naturally uses diverse sky conditions typical of the associated weather file. BS EN 17037:2018+A1:2021 stipulates that the recommended illuminance levels should be achieved at a working plane height of 0.85 m utilising a 0.5 m room margin; however, a 0.3 m margin was applied to the proposed modelling due to the tight space of the property as per the recommendation of the Building Research Establishment [54]. The simulations were set to exclude unlit hours, wherein the annual daylighting simulations were evaluated over a continuous daily schedule from 06:00 to 18:00. This represents a total time denominator of 4380 active daylight hours annually as per the BS EN 17037:2018+A1:2021 recommendations of daylight availability. To accurately determine spatial daylight sufficiency and Annual Sunlight Exposure (ASE), simulations were performed using DesignBuilder's integrated Radiance engine. Unlike simplified split-flux methods, Radiance utilises a backward ray-tracing algorithm based on the physical behaviour of light. The core of this calculation is the rendering equation, which computes the spectral radiance L_0, leaving a point x in direction ω_0:

$$L_o(x, \omega_o) = L_e(x, \omega_o) + \int_{\Omega} f_r(x, \omega_i, \omega_o) L_i(x, \omega_i)(\omega_i \cdot n) d\omega_i \quad (1)$$

where $L_o(x, \omega_o)$ is the emitted radiance, $f_r(x, \omega_i, \omega_o)$ is the bidirectional reflectance distribution function (BRDF) of the surface, $L_i(x, \omega_i)$ is the incoming radiance from direction ω_i, and $\omega_i \cdot n$ accounts for the cosine of the incident angle.

This methodical ray-tracing approach allows for highly accurate calculation of indoor illuminance across the working plane, accounting for complex reflections and direct solar contributions required for evaluating BS EN 17037:2018+A1:2021 targets and ASE thresholds. The results for each reference point were contrasted against the illuminance compliance thresholds to determine the percentage of compliant daylight hours. For the compliance against BS EN 17037:2018+A1:2021, the thresholds are 100 lx (minimum over 95% of the space) and, simultaneously, 300 lx (target illuminance over 50% of the space).

With the baseline simulation undertaken, illuminance measurement was recorded at the property for the subsequent model calibration. As DesignBuilder runs annual simulations with no shading only, all shading devices were raised, and the results were taken at a reference height of 0.85 m. To ensure measurement height consistency, a pedestal was used so that the illuminance meter positioning did not deviate in height throughout the measurement (Figure 5). The illuminance meter—RS Pro RS-105 Light Meter—has an accuracy of ±4% (Figure 6). The measurement was undertaken on 1 January 2023, at 12:00 pm.

The measurements were taken along an accessible assessment grid (noting that furniture such as wardrobes prevented working plane measurements) for the property in alignment with the illuminance measurement recommendations of The Society of Light and Lighting [55], which was reflected in the DesignBuilder model, as illustrated in

Figure 7. The grid was defined, as close as reasonably practicable considering furniture and obstructions, to the grid calculation method [2] as follows:

$$p = 0.2 \times 5^{log_{10}(d)} \quad (2)$$

where p is the maximum distance between calculation points, and d is the longer dimension of the area being calculated.



Figure 5. Working plane height verification.



Figure 6. The illuminance meter used in the illuminance measurement.

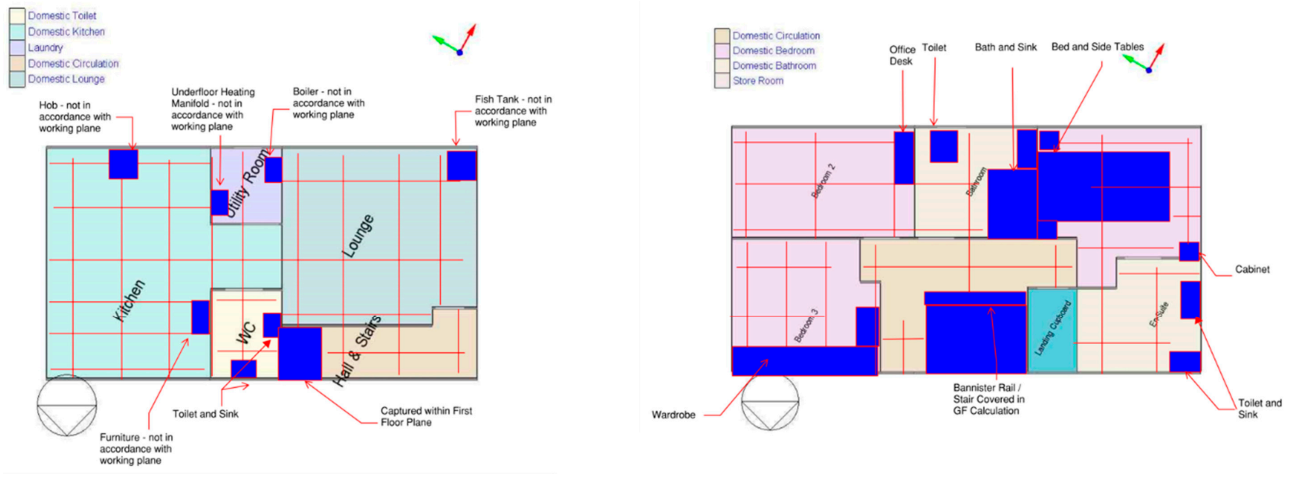


Figure 7. Illuminance measurement grid—ground floor (**left**) and first floor (**right**).

4.2. Model Calibration

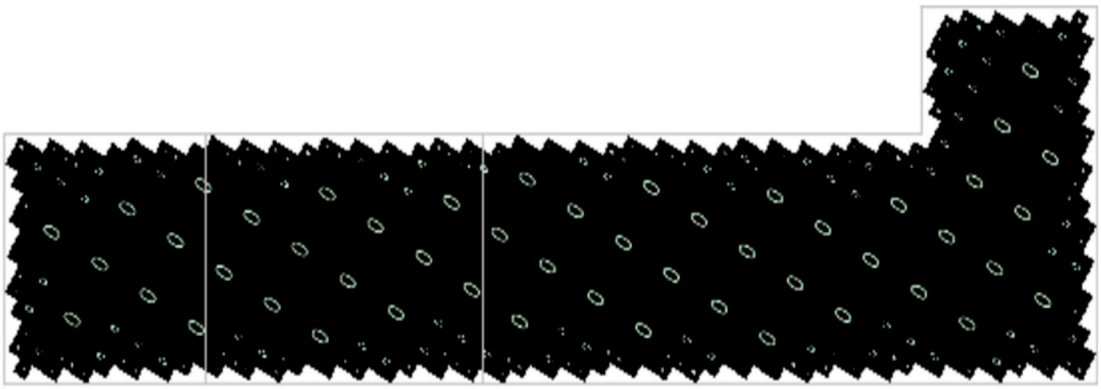
Daylight modelling, as the core research output reflecting daylighting performance of the case study building, was selected for calibration to match real data recorded in the building. The following adjustments for the daylighting model calibration were carried out as per the problems identified from the initial baseline case model:

(1) First of all, no illuminance was attained initially in the hall and stairs (Figure 8), where these spaces were not physically dark. This was due to DesignBuilder limitations—only facilitating opaque doors that have no daylight transmittance. Thus, this was changed in the model to a glazing element on the door in line with the reality; however, the glazing element was suitably adjusted in proportion to the frame to glazing ratio to reflect the as-built door.

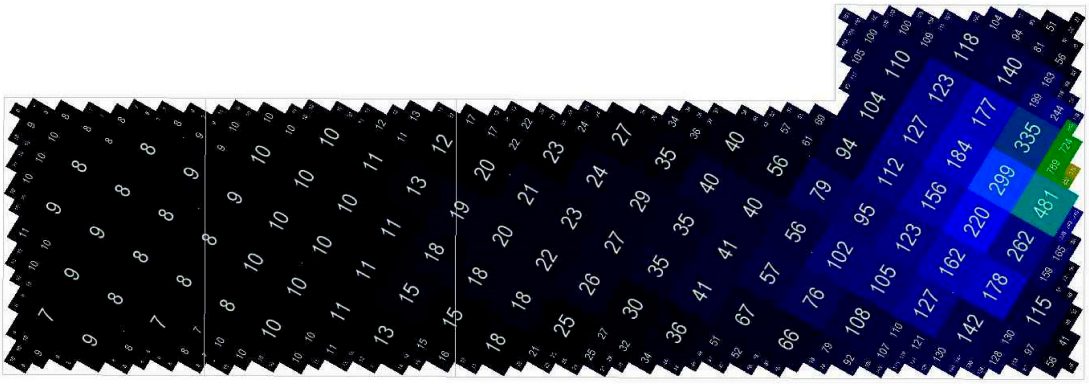
(2) Illuminance measured in the utility room was drastically less than the initial simulation results (Figure 9). This was because the adjacent detached 3-bedroom property located circa 1.5 m south causes extreme shading on the property, and was therefore factored into the model for result accuracy. It should be noted that the neighbouring semi-detached house (left) was a duplication of the case study house (right) in the DesignBuilder model (Figure 9) for simplifying the simulation processes, which does not reflect the real situation shown in Figure 2. However, as the neighbouring property height, set-back distance, and positioning were validated to ensure accuracy, this has no material impact on the study, as the neighboring property serves only as a shade creating entity.

(3) The simulated illuminance around the windows was not reflective of those attained during in situ measurement; hence, window property alteration was undertaken to reflect the installed glazing, with glazing dividers added to the glazing properties.

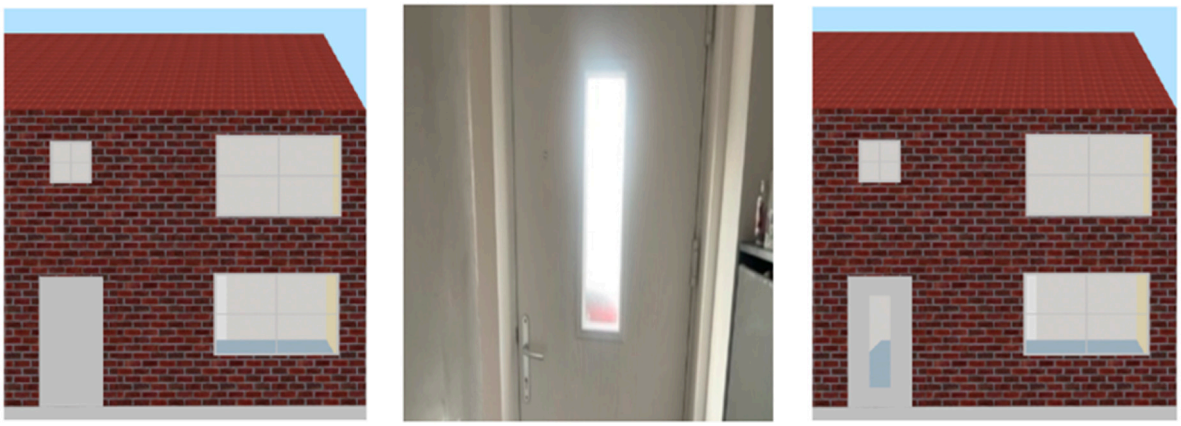
(4) When assessing the illuminance differential, the classification of the sky model had to be aligned to ensure that the correct factors in the daylight calculations were adopted. Reflecting on the weather at the time of the simulation, it was perceived that the sky was not overcast but clear, so the simulation was adjusted to reflect this. Moreover, the time and date of the simulation were also verified to ensure accuracy, as shown in Figure 10.



Pre-calibration (hall and stairs)—Measurements shown in lx



Post-calibration (hall and stairs)—Measurements shown in lx



Pre-calibration (door) Actual door Post-calibration (door)

Figure 8. Model adjustment—front door illuminance correction.

With the abovementioned calibration adjustments made, a secondary simulation was undertaken, which yielded more realistic results. To ensure true calibration, the simulation model was validated against physical in situ illuminance measurements taken at a specific point in time. Because real-world daylight is highly dynamic and exact sky luminance distributions are difficult to perfectly replicate in a simulation, point-in-time daylight models are typically evaluated using relative or percentage error rather than time-series energy frameworks.

To verify model accuracy, the Mean Absolute Percentage Error (MAPE) was calculated to determine the average magnitude of error across the spatial measurement grid. The formula used for the calibration is as follows:

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left[\frac{S_i - M_i}{M_i}\right] \times 100 \quad (3)$$

where M_i and S_i are the respective illuminance values (in lx) determined by physical measurement and simulation at spatial point i, and n is the total number of measurement points within the evaluated space.

In daylight simulation, a point-in-time model is generally considered adequately calibrated when the simulated illuminance values fall within ±20% of the measured values.

As shown in Table 3, the overall MAPE for the spatial grid fell within this acceptable tolerance. Consequently, the daylighting model was deemed calibrated and accurately representative of the physical space, justifying its utilisation for the wider annual simulations. The details of the calibration dataset are available in the Appendix A.

Table 3. Results of daylighting model calibration.

Metric	Calculated Value	Acceptance Target	Result
MAPE	10.33%	≤20%	Pass

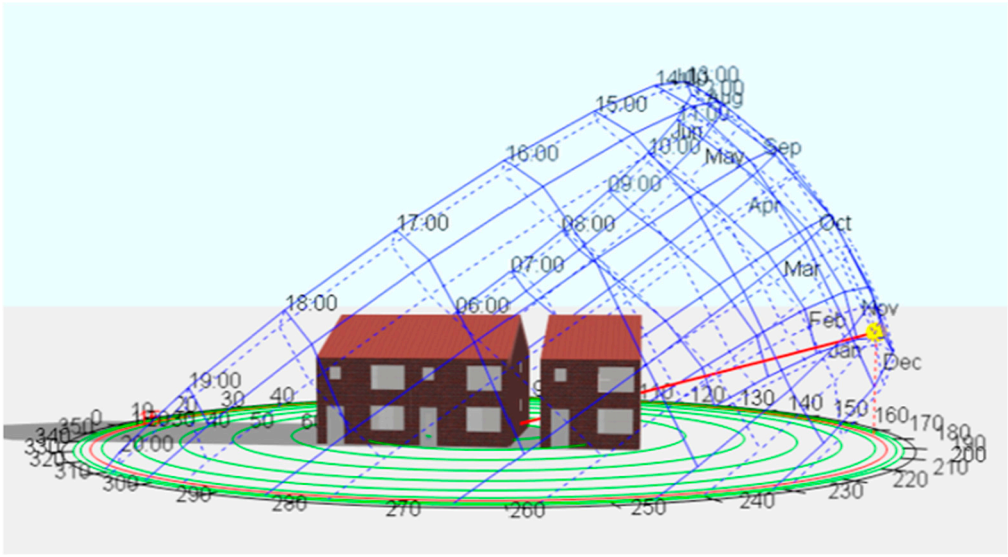


Figure 9. Model adjustment—adjacent building shading correction.

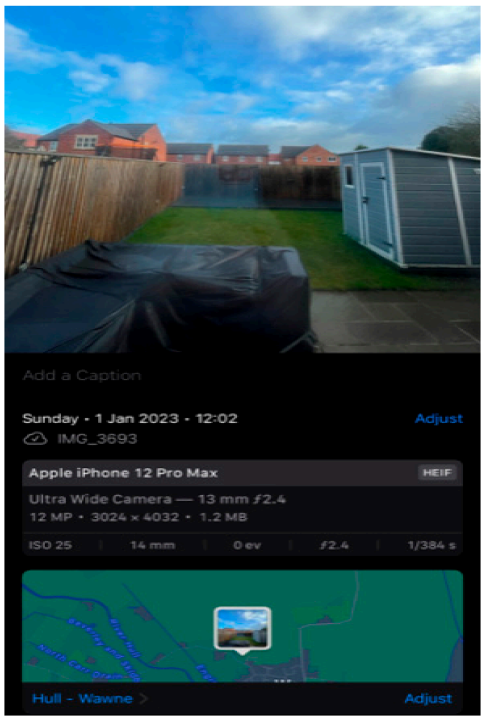


Figure 10. Sky model change justification: more accurately reflect the actual weather conditions at the time of the assessment.

4.3. WWR Alterations

Fundamentally, DesignBuilder facilitates a generic façade WWR change, which imposes a WWR increase with the glazing in alternative positions within the wall, and thus might not be reflective of the property type to create functional glazing in relation to a particular study. As such, the glazing was manually changed in size to alter the WWR, with the glazing location remaining constant. Figure 11 shows an example of the glazing change for the case study property at a WWR of 25%, in comparison with the adjacent property remaining at the initial WWR of 15.26% in the DesignBuilder model.

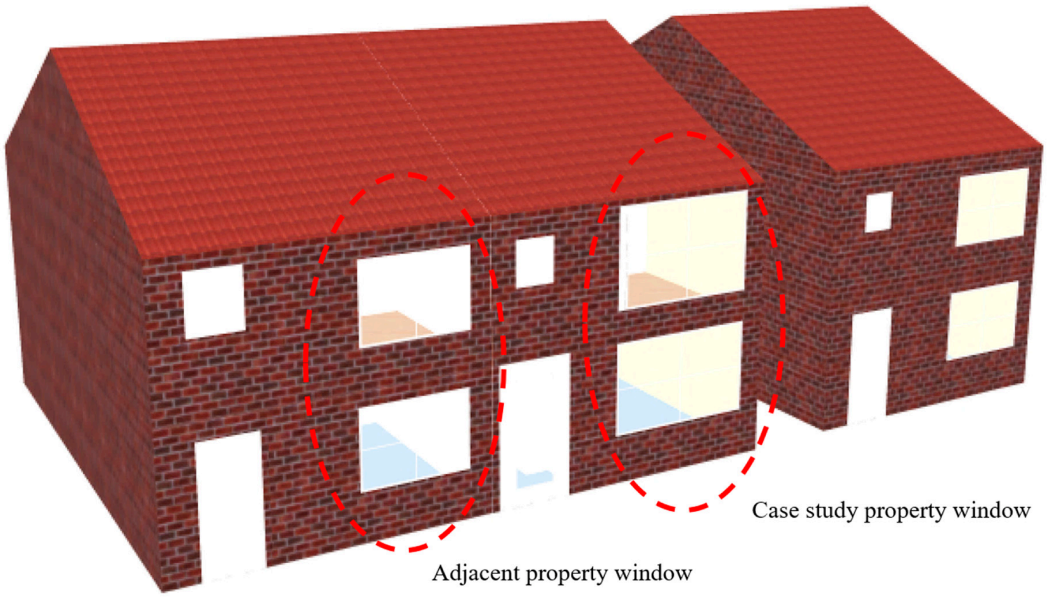


Figure 11. Window size alteration in DesignBuilder.

Table 4 shows the breakdown of the details of WWR alterations in relation to each window on the property to the gross wall area.

Table 4. WWR alterations of the case study property.

Zone	Level	Glazing Area (m^2)		
		WWR = 15.26%	**WWR = 20%**	**WWR = 25%**
Kitchen (window 1)	Ground floor (East)	0.843	2.006	2.006
Kitchen (window 2)	Ground floor (East)	1.737	1.993	1.993
Kitchen (window 3)	Ground floor (East)	1.737	1.600	1.600
Utility room	Ground floor (South)	0.406	1.001	1.651
Hall and stairs	Ground floor (West)	1.781	1.781	1.781
Lounge	Ground floor (West)	2.228	2.994	3.746
Master bedroom	First floor (West)	2.228	3.003	3.761
Bathroom	First floor (South)	0.341	1.002	1.651
Bedroom 2	First floor (East)	0.932	1.000	1.607
Bedroom 3	First floor (East)	0.931	1.005	1.605
Ensuite	First floor (West)	0.384	0.384	0.821
Total glazing area (m^2)		13.548	17.769	22.222
Gross west wall area—front of property (m^2)			22.840	
Gross south wall area—right of property (m^2)			43.085	
Gross east wall area—rear of property (m^2)			22.844	
Gross wall area (m^2)			88.769	

With the daylighting calibration sufficiently undertaken, the settings for the annual simulation where then configured as shown in Figure 12, wherein the software automatically shifts between all possible sky types based on the local weather file. As BS EN 17037:2018+A1:2021 thresholds are based on percentage of daylight hours, unlit hours were naturally excluded from the analysis.

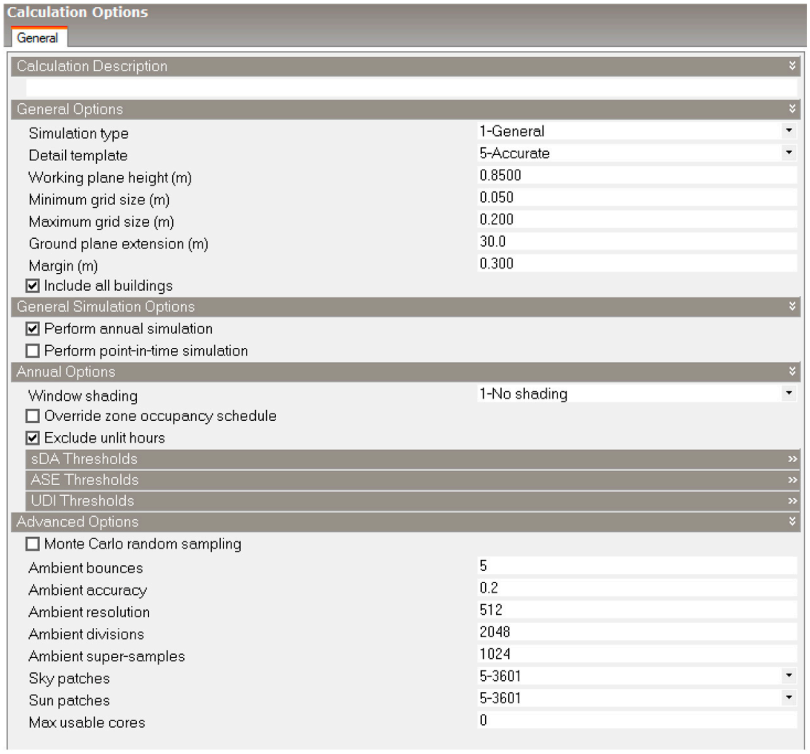


Figure 12. Calculation parameters in DesignBuilder.

4.4. Energy and Thermal Comfort Simulation Configuration

In terms of energy efficiency assessment, a simulation was undertaken on heating load only (as homes in the UK context are not designed to be cooled), based on a gas boiler heating system reflective of that currently installed within the property. This system remained constant throughout the possible thermal load differential due to the glazing alterations. To ensure that no influence from heat transfer from adjacent properties occurred and that the heating system was sized effectively to heat the property, the energy simulation was run without any adjacent properties, and with a design margin ratio of 1.25 in DesignBuilder. The nominal sizing of the gas boiler capacity ($\dot{Q}_{boiler,nom}$) within the EnergyPlus simulation engine (integrated with DesignBuilder) was calculated using Equation (4) [56].

$$\dot{Q}_{boiler,nom} = C_{p,w} \cdot p_w \cdot \Delta T_{loop,des} \cdot \dot{V}_{loop,des} \cdot f_{size} \quad (4)$$

where $C_{p,w}$ is the specific heat of water at the boiler design outlet temperature, p_w is the density of water at standard conditions (that is, 5.05 °C), $\Delta T_{loop,des}$ is the hot water loop design temperature decrease, $\dot{V}_{loop,des}$ is the loop design volumetric flow rate, and f_{size} is the boiler's sizing factor.

To assess the impacts of the glazing changes on the internal thermal comfort, an assessment of the peak summer design day temperature was undertaken, which allows the assessment of temperature differential as a direct result of the fenestration alteration. The summer design day operative temperature is used strictly as a comparative metric to isolate the impact of fabric solar gain. In this simulation, the windows were assumed closed (no purge ventilation) to create a worst-case baseline for comparison, and that this does not replace a formal overheating risk assessment (for example, CIBSE TM59). The airflow calculation method, which takes into account both sensible and latent gains and is based on operative temperature rather than just zone air temperature, was used to ascertain and assess the worst-case eventuality and temperature extremes [57]; while the operative temperature (T_{OP}) is given by Equation (5) [56] as:

$$T_{OP} = \gamma T_{MRT} + (1 - \gamma) \cdot T_{drybulb} \quad (5)$$

where γ is the radiative fraction, T_{MRT} is the mean radiant temperature for the thermal zone, and $T_{drybulb}$ is the mean zone air temperature.

4.5. Daylighting Sufficiency—Annual Sunlight Exposure Analysis

To validate the effectiveness of the refinement solutions, a simulation of Annual Sunlight Exposure (ASE) was undertaken, which acts as a proxy for glare risks. The ASE measures the percentage of a working plane area that receives direct sunlight exceeding a specific illuminance threshold (1000 lx) for more than a defined number of occupied hours per year (250 h), thereby creating a percentage of a working plane area that receives direct sunlight exceeding a specific illuminance threshold for the defined period [58]. DesignBuilder uses its Radiance-based daylighting engine to simulate hourly illuminance values on a defined working plane grid throughout the year and contrast this for each point across the working plane to determine a percentage of the working plane where this condition is met [31]. The assumptions made for the energy and thermal analysis simulations are defined within Table 5.

Table 5. Thermal model inputs and supplementary analytical data.

Parameter	Assigned Value/Strategy
Carbon emission factor	0.183 $kgCO_2/kWh$
Equipment gains	5 W/m^2 (kitchen zone: 300 W/m^2)
Heating setpoints (living spaces)	21 °C (active setpoint)/18 °C (setback)
Heating setpoints (bedroom)	19 °C (active setpoint)/17 °C (setback)
Infiltration (airtightness)	0.7 ACH
Lighting gains	5.0 W/m^2
Natural ventilation	2.36 L/s (background/trickle only; windows assumed closed)
Occupancy and metabolic rate	1 person (117 W/person, representing "typing/office work")
Occupancy schedule (kitchen)	07:00–10:00 fully occupied 19:00–23:00—20% occupied
Occupancy schedule (all other areas)	06:00–18:00 (Monday–Friday)

5. Results and Discussion

5.1. Daylighting Sufficiency

Figure 13 shows the initial baseline case simulation results from the calibrated model, demonstrating a direct trend between increasing daylighting sufficiency, at each illuminance target and increasing WWR. Note that the landing and landing cupboard showed 0% of annual daylight hours within the compliant thresholds due to glazing restrictions present as part of a semi-detached property type.

Figure 14 shows that the baseline as-built 15.26% WWR allowed approximately 77% of the considered floor area to be illuminated by daylight to a target of 100 lx for 50% of the annual daylight hours, while 42% of the floor area was illuminated to 300 lx for 50% of the annual daylight hours. Thus, the annual daylight hours for the considered floor area had a variance of −18% at 100 lx and a variance of −8% at 300 lx, with reference to 95% and 50% of the assessment area, respectively.

As such, it can be determined that the current fenestration arrangement as now mandated by the BS EN 17037:2018+A1:2021 does not retrospectively accommodate sufficient daylighting [24]. Furthermore, none of the glazing solutions simulated met these requirements with the WWR remaining constant. Given that the property was constructed in 2020 and thus not subject to the compliance, this reflects that houses as recent as 4 years old might also have insufficient daylighting with respect to the most recent illuminance guidelines. Furthermore, these findings indicate that the property will be more dependent upon supplementary task lighting to attain the task illuminance recommended, in concurrence with previous work [29].

In general, the results presented in Figure 14 demonstrate a trend between annual daylighting and the WWR, wherein the baseline case glazing required a WWR of 25% to become sufficient under BS EN 17037:2018+A1:2021 [24], whilst all other simulated glazing types were also compliant with this WWR. Therefore, it can be concluded that an increased WWR should have been implemented during construction to rectify inadequate daylighting at the dwelling, noting that no glazing type simulated could achieve daylighting sufficiency with the current WWR of 15.26%.

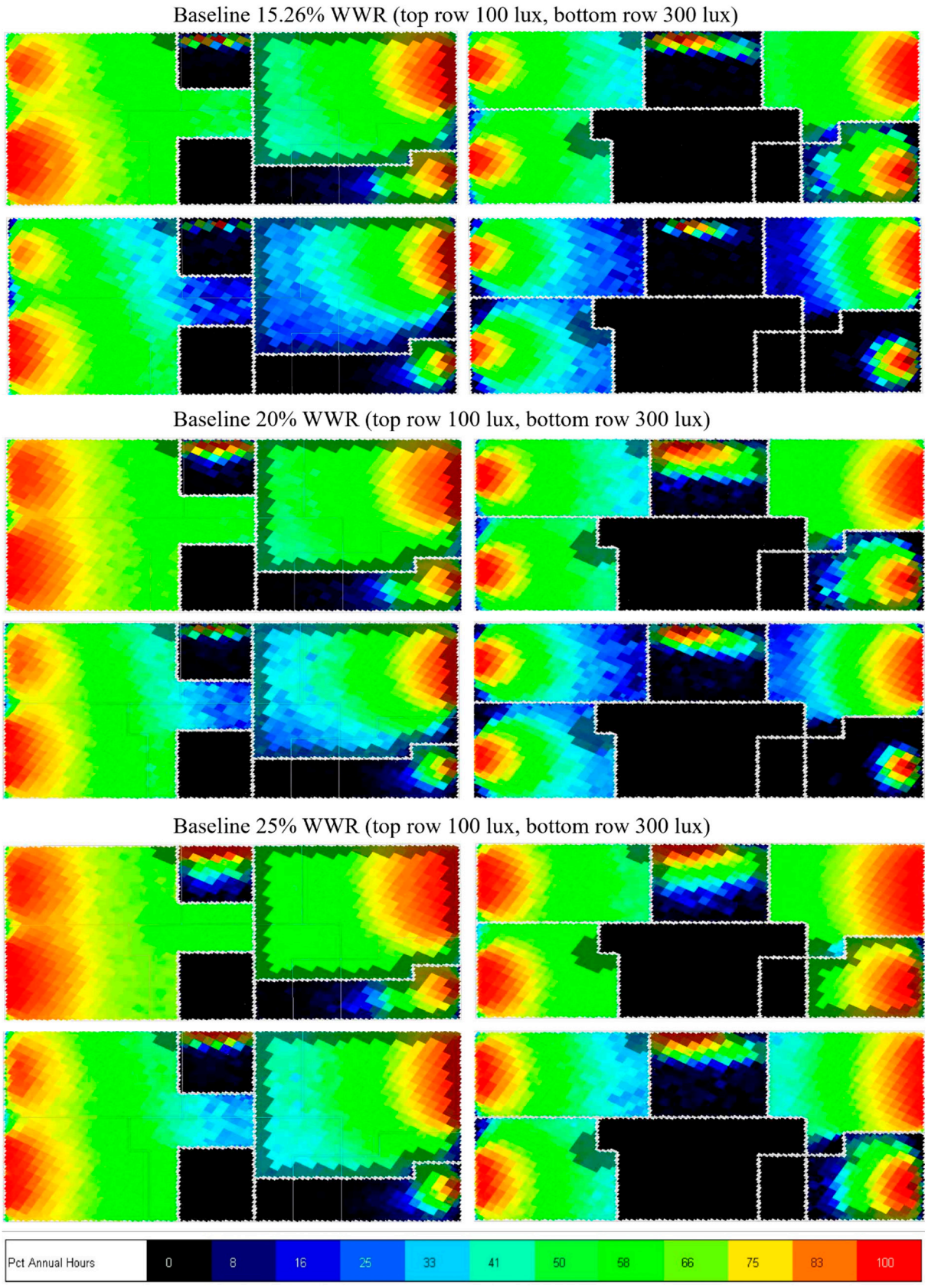


Figure 13. Baseline case predicted annual daylight hours—ground floor (left column), first floor (right column).

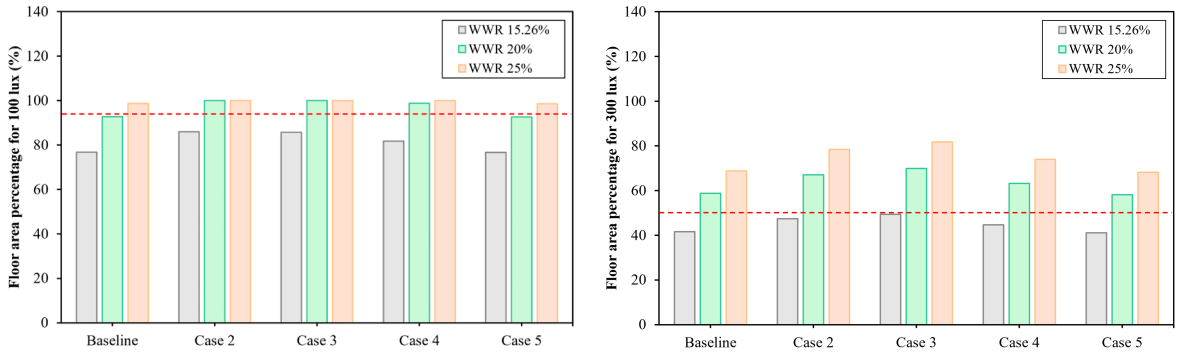


Figure 14. Glazing selection impact on daylighting availability against target illuminance—100 lx (**left**) and 300 lx (**right**). The dotted line indicates the percentage of the assessment area.

5.2. Thermal Load Implications

Figure 15 shows a trend between the WWR and heating load (because of the increased glazing heat losses) for the different cases of glazing. The results indicate that an increased WWR for daylighting refinement would have a negative impact on heating load. For instance, adopting the 1000 h utilisation of the heating system per annum (as per the actual operation for the property), the baseline case (that is, the notional building glazing) incurred a 0.23 kW differential between a 15.26% WWR and a 25% WWR, hence an annual heating load variance of 230 kWh.

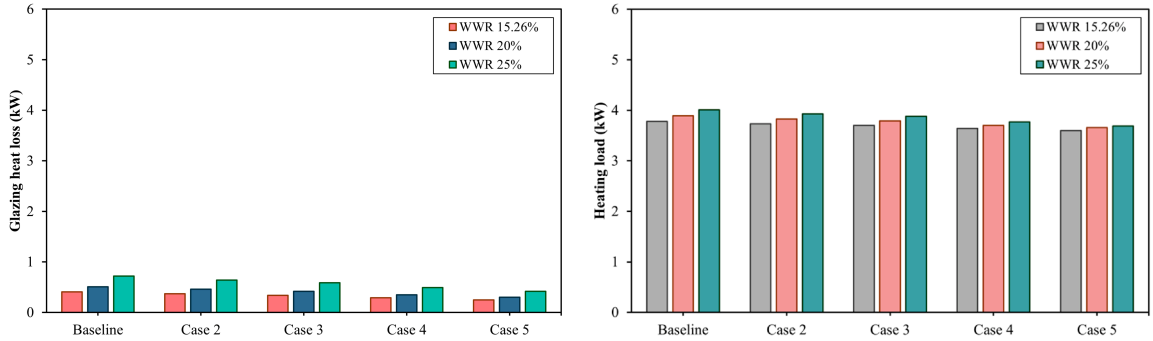


Figure 15. Glazing selection impact on heat loss (**left**) and heating load (**right**).

Case 5 (quadruple-glazed, clear, 3 mm/8 mm krypton) was the best-performing solution for retaining the lowest heating load among the selected cases for the property due to its relatively lower glazing heat losses. This not only demonstrates the importance of assessing the WWR for light provision, but also highlights the value in assessing alternative glazing characteristics which can yield lower heating demand, with an inverse ratio identified between the U-value of a window glazing and the heating load for dwellings. In summary, increasing the WWR alone is not always the optimal solution, and the glazing type selection is of equal importance when reviewing the daylight transmission as well as the glazing U-value, therefore creating a balance between increased heating load and increased daylighting.

5.3. Operative Temperature

The impact of fenestration alterations on the peak operative temperature was one of the foci of this study. Figure 16 shows a summary of the peak results, with a direct ratio identified between the WWR and peak operative temperature under a summer design day. It can be seen in each WWR group that the lowest operative temperature was detected in the baseline case (that is, the notional building glazing), and the highest operative temperature was for Case 3—double-glazed, clear, 4 mm/16 mm, argon. Thus,

the current findings demonstrate the significance of the impact of fenestration alteration on the peak operative temperature. As a matter of fact, in every WWR assessment, the peak operative temperature exceeded the CIBSE guiding operative temperature in summer, both for dwellings with maximum 23–25 °C and for offices with maximum 22–25 °C [42]. However, the comparison was the extent of deviation against the baseline case, which already surpassed peak operative temperature comfort. As such, this study serves as further evidence of the need for mitigation measures in new build residential properties to alleviate the risk of overheating, as this proxy comparison indicates.

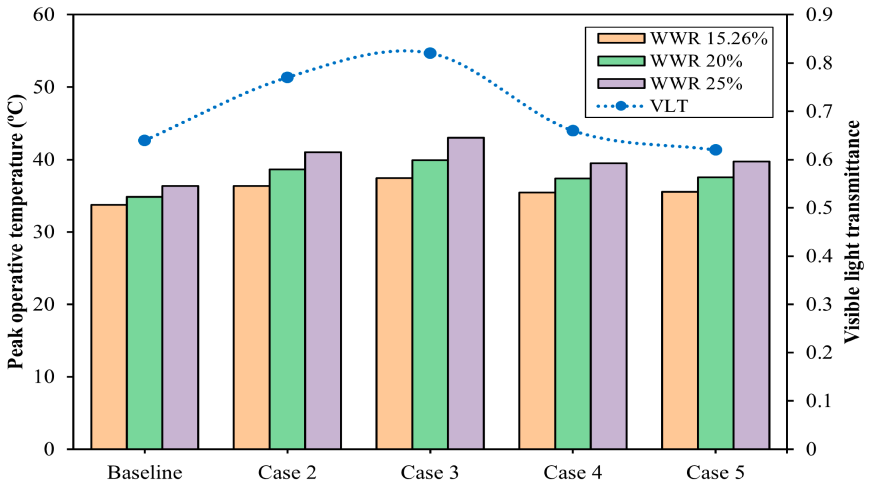


Figure 16. Impact upon the peak operative temperature under a summer design day.

The glazing VLT showed a general pattern of increasing daylight transmission causing an increased operative temperature (Figure 16).

However, this pattern was not absolute: for example, Case 5 (quadruple-glazed, clear, 3 mm/8 mm krypton) provided the lowest VLT, but did not have the lowest peak operative temperature. This outcome again shows the importance of detailed calculation and simulation for each glazing type.

5.4. ASE-Based Glare Risk Proxy Assessment

The impacts of glare probability have been investigated in terms of ASE, as increasing daylighting availability which is so extreme that the proposed office space is unusable due to compromise of human comfort would be counterproductive. ASE is frequently used to analyse glare because direct sunlight exposure is the primary cause of glare. Therefore, ASE was adopted as a glare proxy. Figure 17 demonstrates the result of the ASE analysis, as a proxy for glare, identifying areas which are exposed to more than 1000 lx for more than 250 h per annum.

The impact from the ASE assessment followed a typical trend, in which an increased WWR created an increased risk to glare exposure; however, the results show that the risk was extremely marginal, with the most extreme detriment of approximately 2.18% witnessed within Case 5 between 15.26% WWR and 25% WWR. This marginal detriment could be due to the nature of the property, as the semi-detached property has no glazing on the northern elevation, thereby reducing the impacts of glare through the WWR increase. The results show that Case 4 performed most optimally, with only a detriment of 0.81% witnessed between the 15.26% WWR and the 20% WWR. In this example, the outlier was within Case 4; as expected, it performed most optimally at a 15.25% WWR; however, it unexpectedly performed more effectively at a 25% WWR than at a 20% WWR. This could be due to the fact that the larger WWR increased the dispersion of daylighting to such an extent that it reduced the severity of marginally incompliant "hotspots" created by the

lighting dispersion at a smaller WWR. As such, this re-emphasises the need for accurate modelling and simulation relative to the deployment of the WWR and glazing type being installed. Moreover, it shows that increasing the WWR did not necessitate a substantial change in glare risk, albeit the glare risk did typically marginally increase with a larger WWR. In summary, the results from across the dwelling indicate that the change in glazing type and WWR created marginal ASE detriment, and therefore the risk to increased glare exposure was minimal. However, the potential issue should still be controlled at a local level with occupant-installed blinds and shading devices as appropriate.

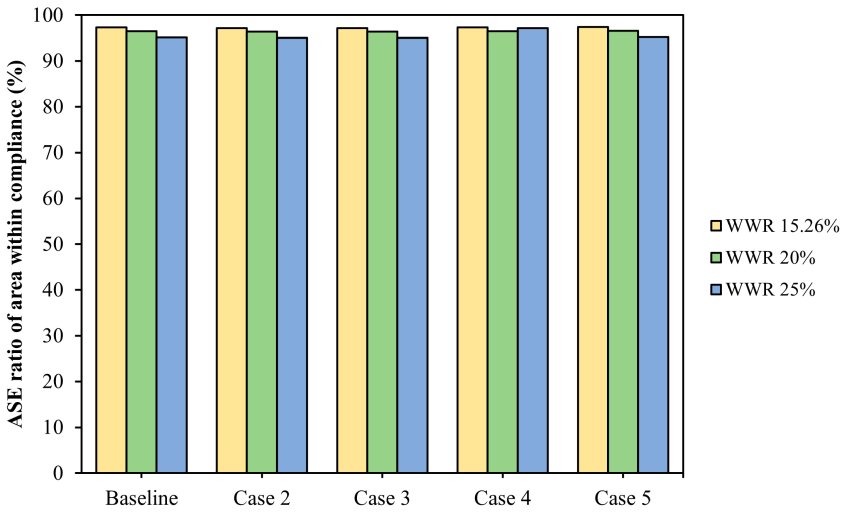


Figure 17. ASE ratio of area within compliance: percentage of space exposed to >1000 lx for >250 h per annum.

From the results of Sections 5.1–5.4, each glazing characteristic has a consequential impact on the glazing performance in modulating the daylighting, energy, and thermal conditions for the dwelling; when reviewing each individual characteristic, it is clear that each characteristic needs to be reviewed simultaneously to provide an acceptable solution. Therefore, we review refinement strategies in Section 5.5.

5.5. Refinement

This section identifies a refinement strategy to factor all glazing characteristics (variables) simultaneously to derive the most suitable solution for the property, hence outlining recommendations from the fenestration alteration assessment whilst mitigating detrimental effects on energy efficiency and the operative temperature to maintain indoor thermal comfort. Figures 18 and 19 present the refinement selection matrix for the property at the time of build and at the time of the study, respectively, to reflect the compliance gaps between previous and current Building Regulations. To ensure best practice, the process started by identifying the glazing type's compliance against the Building Regulations (Part L Volume 1) [52]. Glazing types compliant with the Building Regulations at the time of build (Figure 18) and at the time of the study (Figure 19) are identified in column 7 in each table. Further best practice was undertaken through the analysis of compliance with the minimum thresholds (both 100 lx and 300 lx) recommended by BS EN 17037:2018+A1:2021 (indicated in column 6), illustrating the effect of the glazing compliance by being above the specified illuminance target for the required percentage of daylight hours. The green highlighting denotes that an individual glazing type complies with both the Building Regulations and BS EN 17037:2018+A1:2021.

Glazing type	Glazing U-value (W/m^2K)	Target illuminance (lx)	Floor area to be considered within range (%)	ASE floor area within range (%)	BS EN 17037:2018+A 1:2021 Daylighting sufficiency	Glazing U-value compliant with Building Regulations	Annual heating demand (kWh)	Total carbon ($kgCO_2$)	Peak operative temperature on summer design day (°C)	Selection preference
Part L Notional Building glazing (WWR 15.26%, target 100 lx)	1.60	100.00	76.76	97.34	No	Yes	3780	691.74	33.73	
Part L Notional Building glazing (WWR 15.26%, target 300 lx)	1.60	300.00	41.59	97.34	No	Yes	3780	691.74	33.73	
Double glazed, low emissivity, clear, 3mm/13mm argon (WWR 15.26%, target 100 lx)	1.51	100.00	85.92	97.21	No	Yes	3730	682.59	36.33	
Double glazed, low emissivity, clear, 3mm/13mm argon (WWR 15.26%, target 300 lx)	1.51	300.00	47.40	97.21	No	Yes	3730	682.59	36.33	
Double glazed, clear, 4mm/16mm argon (WWR 15.26%, target 100 lx)	1.44	100.00	85.71	97.21	No	Yes	3700	677.1	37.44	
Double glazed, clear, 4mm/16mm argon (WWR 15.26%, target 300 lx)	1.44	300.00	49.37	97.21	No	Yes	3700	677.1	37.44	
Triple glazed, low emissivity, clear, 3mm/13mm air (WWR 15.26%, target 100 lx)	0.98	100.00	81.78	97.34	No	Yes	3640	666.12	35.42	
Triple glazed, low emissivity, clear, 3mm/13mm air (WWR 15.26%, target 300 lx)	0.98	300.00	44.72	97.34	No	Yes	3640	666.12	35.42	
Quadruple glazed, clear, 3mm/8mm krypton (WWR 15.26%, target 100 lx)	0.78	100.00	76.65	97.43	No	Yes	3600	658.8	35.52	
Quadruple glazed, clear, 3mm/8mm krypton (WWR 15.26%, target 300 lx)	0.78	300.00	41.14	97.43	No	Yes	3600	658.8	35.52	
Part L Notional Building glazing (WWR 20%, target 100 lx)	1.60	100.00	92.74	96.53	No	Yes	3890	711.87	34.85	
Part L Notional Building glazing (WWR 20%, target 300 lx)	1.60	300.00	58.83	96.53	Yes	Yes	3890	711.87	34.85	
Double glazed, low emissivity, clear, 3mm/13mm argon (WWR 20%, target 100 lx)	1.51	100.00	100.00	96.40	Yes	Yes	3830	700.89	38.63	
Double glazed, low emissivity, clear, 3mm/13mm argon (WWR 20%, target 300 lx)	1.51	300.00	67.05	96.40	Yes	Yes	3830	700.89	38.63	
Double glazed, clear, 4mm/16mm argon (WWR 20%, target 100 lx)	1.44	100.00	100.00	96.40	Yes	Yes	3790	693.57	39.94	
Double glazed, clear, 4mm/16mm argon (WWR 20%, target 300 lx)	1.44	300.00	69.83	96,40	Yes	Yes	3790	693.57	39.94	
Triple glazed, low emissivity, clear, 3mm/13mm air (WWR 20%, target 100 lx)	0.98	100.00	98.80	96.53	Yes	Yes	3700	677.1	37.39	✓
Triple glazed, low emissivity, clear, 3mm/13mm air (WWR 20%, target 300 lx)	0.98	300.00	63.25	96.53	Yes	Yes	3700	677.1	37.39	✓
Quadruple glazed, clear, 3mm/8mm krypton (WWR 20%, target 100 lx)	0.78	100.00	92.59	96.62	No	Yes	3660	669.78	37.54	
Quadruple glazed, clear, 3mm/8mm krypton (WWR 20%, target 300 lx)	0.78	300.00	58.20	96.62	Yes	Yes	3660	669.78	37.54	
Part L Notional Building glazing (WWR 25%, target 100 lx)	1.60	100.00	98.65	95.17	Yes	Yes	4010	733.83	36.32	✓
Part L Notional Building glazing (WWR 25%, target 300 lx)	1.60	300.00	68.82	95.17	Yes	Yes	4010	733.83	36.32	✓
Double glazed, low emissivity, clear, 3mm/13mm argon (WWR 25%, target 100 lx)	1.51	100.00	100.00	95.04	Yes	Yes	3930	719.19	41.04	
Double glazed, low emissivity, clear, 3mm/13mm argon (WWR 25%, target 300 lx)	1.51	300.00	78.45	95.04	Yes	Yes	3930	719.19	41.04	
Double glazed, clear, 4mm/16mm argon (WWR 25%, target 100 lx)	1.44	100.00	100.00	95.04	Yes	Yes	3880	710.04	43.05	
Double glazed, clear, 4mm/16mm argon (WWR 25%, target 300 lx)	1.44	300.00	81.70	95.04	Yes	Yes	3880	710.04	43.05	
Triple glazed, low emissivity, clear, 3mm/13mm air (WWR 25%, target 100 lx)	0.98	100.00	100.00	97.21	Yes	Yes	3770	689.91	39.48	
Triple glazed, low emissivity, clear, 3mm/13mm air (WWR 25%, target 300 lx)	0.98	300.00	74.00	97.21	Yes	Yes	3770	689.91	39.48	
Quadruple glazed, clear, 3mm/8mm krypton (WWR 25%, target 100 lx)	0.78	100.00	98.50	95.26	Yes	Yes	3690	675.27	39.72	
Quadruple glazed, clear, 3mm/8mm krypton (WWR 25%, target 300 lx)	0.78	300.00	68.09	95.26	Yes	Yes	3690	675.27	39.72	

Figure 18. Glazing selection refinement at the time of property construction.

At the time of build (Figure 18), all five window-glazing cases, including the baseline case, were compliant with the previous Building Regulations, but failed to comply with BS EN 17037:2018+A1:2021 for all the cases with the WWR of 15.26%. Apparently, the house was designed and built to provide a thermal performance-centred glazed fenestration only.

The remaining variables were analysed, showing that Case 4 (triple-glazed, low emissivity, clear, 3 mm/13 m air) provided the lowest peak operative temperature and total carbon emissions for the different WWRs, but Case 2 (double-glazed, low emissivity, clear, 3 mm/13 mm argon) and Case 3 (double-glazed, clear, 4 mm/16 mm argon) offered slightly more daylighting (column 4). On the other hand, Case 4 was compliant with BS EN 17037:2018+A1:2021 for both WWR scenarios of 20% and 25%, which is considered the finest solution for the 20% WWR scenario accommodating all variables and not compromising

thermal comfort more than necessary. It was, however, the second-most critical factor due to the excessive operative temperature once the lighting compliance thresholds were reached.

Glazing type	Glazing U-value (W/m^2K)	Target illuminance (lx)	Floor area to be considered within range (%)	ASE floor area within range (%)	BS EN 17037:2018+A 1:2021 Daylighting sufficiency	Glazing U-value compliant with Building Regulations	Annual heating demand (kWh)	Total carbon ($kgCO_2$)	Peak operative temperature on summer design day (°C)	Selection preference
Part L Notional Building glazing (WWR 15.26%, target 100 lx)	1.60	100.00	76.76	97.34	No	No	3780	691.74	33.73	
Part L Notional Building glazing (WWR 15.26%, target 300 lx)	1.60	300.00	41.59	97.34	No	No	3780	691.74	33.73	
Double glazed, low emissivity, clear, 3mm/13mm argon (WWR 15.26%, target 100 lx)	1.51	100.00	85.92	97.21	No	No	3730	682.59	36.33	
Double glazed, low emissivity, clear, 3mm/13mm argon (WWR 15.26%, target 300 lx)	1.51	300.00	47.40	97.21	No	No	3730	682.59	36.33	
Double glazed, clear, 4mm/16mm argon (WWR 15.26%, target 100 lx)	1.44	100.00	85.71	97.21	No	No	3700	677.1	37.44	
Double glazed, clear, 4mm/16mm argon (WWR 15.26%, target 300 lx)	1.44	300.00	49.37	97.21	No	No	3700	677.1	37.44	
Triple glazed, low emissivity, clear, 3mm/13mm air (WWR 15.26%, target 100 lx)	0.98	100.00	81.78	97.34	No	Yes	3640	666.12	35.42	
Triple glazed, low emissivity, clear, 3mm/13mm air (WWR 15.26%, target 300 lx)	0.98	300.00	44.72	97.34	No	Yes	3640	666.12	35.42	
Quadruple glazed, clear, 3mm/8mm krypton (WWR 15.26%, target 100 lx)	0.78	100.00	76.65	97.43	No	Yes	3600	658.8	35.52	
Quadruple glazed, clear, 3mm/8mm krypton (WWR 15.26%, target 300 lx)	0.78	300.00	41.14	97.43	No	Yes	3600	658.8	35.52	
Part L Notional Building glazing (WWR 20%, target 100 lx)	1.60	100.00	92.74	96.53	No	No	3890	711.87	34.85	
Part L Notional Building glazing (WWR 20%, target 300 lx)	1.60	300.00	58.83	96.53	Yes	No	3890	711.87	34.85	
Double glazed, low emissivity, clear, 3mm/13mm argon (WWR 20%, target 100 lx)	1.51	100.00	100.00	96.40	Yes	No	3830	700.89	38.63	
Double glazed, low emissivity, clear, 3mm/13mm argon (WWR 20%, target 300 lx)	1.51	300.00	67.05	96.40	Yes	No	3830	700.89	38.63	
Double glazed, clear, 4mm/16mm argon (WWR 20%, target 100 lx)	1.44	100.00	100.00	96.40	Yes	No	3790	693.57	39.94	
Double glazed, clear, 4mm/16mm argon (WWR 20%, target 300 lx)	1.44	300.00	69.83	96,40	Yes	No	3790	693.57	39.94	
Triple glazed, low emissivity, clear, 3mm/13mm air (WWR 20%, target 100 lx)	0.98	100.00	98.80	96.53	Yes	Yes	3700	677.1	37.39	✓
Triple glazed, low emissivity, clear, 3mm/13mm air (WWR 20%, target 300 lx)	0.98	300.00	63.25	96.53	Yes	Yes	3700	677.1	37.39	✓
Quadruple glazed, clear, 3mm/8mm krypton (WWR 20%, target 100 lx)	0.78	100.00	92.59	96.62	No	Yes	3660	669.78	37.54	
Quadruple glazed, clear, 3mm/8mm krypton (WWR 20%, target 300 lx)	0.78	300.00	58.20	96.62	Yes	Yes	3660	669.78	37.54	
Part L Notional Building glazing (WWR 25%, target 100 lx)	1.60	100.00	98.65	95.17	Yes	No	4010	733.83	36.32	
Part L Notional Building glazing (WWR 25%, target 300 lx)	1.60	300.00	68.82	95.17	Yes	No	4010	733.83	36.32	
Double glazed, low emissivity, clear, 3mm/13mm argon (WWR 25%, target 100 lx)	1.51	100.00	100.00	95.04	Yes	No	3930	719.19	41.04	
Double glazed, low emissivity, clear, 3mm/13mm argon (WWR 25%, target 300 lx)	1.51	300.00	78.45	95.04	Yes	No	3930	719.19	41.04	
Double glazed, clear, 4mm/16mm argon (WWR 25%, target 100 lx)	1.44	100.00	100.00	95.04	Yes	No	3880	710.04	43.05	
Double glazed, clear, 4mm/16mm argon (WWR 25%, target 300 lx)	1.44	300.00	81.70	95.04	Yes	No	3880	710.04	43.05	
Triple glazed, low emissivity, clear, 3mm/13mm air (WWR 25%, target 100 lx)	0.98	100.00	100.00	97.21	Yes	Yes	3770	689.91	39.48	✓
Triple glazed, low emissivity, clear, 3mm/13mm air (WWR 25%, target 300 lx)	0.98	300.00	74.00	97.21	Yes	Yes	3770	689.91	39.48	✓
Quadruple glazed, clear, 3mm/8mm krypton (WWR 25%, target 100 lx)	0.78	100.00	98.50	95.26	Yes	Yes	3690	675.27	39.72	
Quadruple glazed, clear, 3mm/8mm krypton (WWR 25%, target 300 lx)	0.78	300.00	68.09	95.26	Yes	Yes	3690	675.27	39.72	

Figure 19. Glazing selection refinement at the time of the study.

However, at a 25% WWR (Figure 18), the baseline case would be the glazing recommendation, as the operative temperature was the lowest (36.32 °C), and thus this case provides the optimum thermal and daylighting sufficiency combination. In this instance, it was also found that Case 5 (quadruple-glazed, clear, 3 mm/8 mm krypton) significantly reduced the total carbon emission against the baseline by approximately 8%, but was not the ideal solution, as the peak operative temperature would increase by 3.4 °C, which was not deemed appropriate due to increasing the risk of compromising occupant comfort. It should be noted that between the baseline scenarios, the 25% WWR invoked a 2.59 °C increase to the peak operative temperature on the summer design day over that of the

same glazing type at the as-installed WWR of 15.26%, although the latter could not attain daylighting sufficiency.

At the time of the study (Figure 19), the notional U-value targeted reduction was in place, and therefore only Cases 4 and 5 were compliant with the current statutory Building Regulation targets across all five window-glazing cases, while none of the cases complied with BS EN 17037:2018+A1:2021. Looking at the 20% WWR, only Case 4 was compliant with both the Building Regulations and BS EN 17037:2018+A1:2021, and thus was preferable in terms of thermal comfort and daylighting sufficiency, though there was an increase in the operative temperature (about 3.66 °C) compared to the baseline Notional Building glazing case. For the 25% WWR, both Case 4 and Case 5 glazing types were compliant, but the peak operative temperature of Case 4 was slightly cooler (about 0.24 °C cooler) than that of Case 5, which at both 100 lx and 300 lx offered overall superior annual illuminance. Furthermore, Case 4 had a higher ASE area in range, at 97.21%, than Case 5 at 95.26%; therefore, Case 4 signifies a lower glare risk proxy. In addition, Case 4 only brought a slightly higher total carbon emission than that of Case 5 (only about 2.1%). Overall, the recommendation remains a 20% WWR with Case 4 (triple-glazed, low emissivity, clear, 3 mm/13 m air) due to better environmental performance (that is, lower resultant heating demand, carbon emission, and operative temperature) and lower indicative glare risk.

In this eventuality, both thermal comfort and the daylighting sufficiency matrix are preferred based upon the selected window-glazing types, with WWR variations reflecting the best practice. The results show that there is room for flexibility when choosing window glazing, and that, considering daylighting alongside glazing heat losses, the resultant operative temperatures, and associated carbon emissions, a suitable equilibrium of the indoor environmental conditions can be achieved.

6. Conclusions

With the increased demand for work-from-home from UK employees, sufficient daylighting for home offices, without substantially compromising operational sustainability and thermal comfort, is indispensable. This study aimed to provide a refinement strategy for the fenestration of a UK dwelling with an as-built window-to-wall ratio (WWR) of 15.26%, ensuring daylight sufficiency for home office environments whilst considering impacts on energy efficiency (through heating load assessments) and an indicative assessment of the likely risk of deteriorating occupant thermal comfort (indicated by peak summer design day operative temperature). This study is devoted to tackling the insufficient daylighting availability within the dwelling compared with the corresponding UK standard. Basically, the study found that a change of glazing type and a larger WWR of 20% (as the minimum tested configuration) is required to implement a daylight sufficiency in the modelled dwelling, although this can result in an increase in operative temperature of 3.66 °C, which can be minimised with a selected glazing type of "triple glazed, low emissivity, clear, 3 mm/13 mm air", thus reducing both heating demand and carbon emissions. Most importantly, this study reveals that the current thermal performance-centred glazed fenestration cannot achieve indoor daylighting sufficiency within UK residential office environments, and modifications are necessary for the existing systems to become fit-for-purpose. The findings of this study are particularly relevant to architects, residential building designers, retrofit practitioners, building performance consultants, housing developers, and policymakers involved in the design and improvement of UK dwellings. Furthermore, the outcomes of this study can be considered in the development of housing stock, whilst considerably this needs to be managed on a case-by-case basis, considering diverse layouts and orientations from this study.

7. Limitations and Future Research

In this paper, only the minimum and medium recommended target illuminances of daylighting provision were considered for a single dwelling under a test weather condition. It would thus be of value for research to be expanded to include the "high" target illuminance of 750 lx as defined in BS EN 17037:2018+A1:2021. Furthermore, as this study focuses on recommendations for UK developers who do not install or specify blinds as a standard, additional studies should be undertaken to assess glare control to provide recommendations for occupants with home offices. Thus, it is suggested that a future study look at numerous property types, in diverse orientations, utilising diverse shading mechanisms and lighting harvesting systems to provide generalised recommendations whilst also acknowledging implications to the occupants' view-out.

Moreover, no shading devices have been factored into this study, as in the UK's new build dwellings, they are not supplied with blinds as default; as such, the onus falls on the occupants to install them for security and glare control purposes. This study focuses primarily on ensuring daylighting sufficient from a glazing specification and WWR perspective, to enable home office daylighting. Whilst ASE simulations have been utilised to analyse the daylighting availability, there is a requirement for holistic visual comfort assessments to be undertaken on a case-by-case basis within dwellings. This is because no simulation can provide predictions accurate enough to be used as precedents by developers. In addition, occupants will naturally have different heights and tolerances for glare, and have their office spaces configured differently (seat heights and positions), therefore uniquely impacting the visual discomfort risk profile.

The selection of blinds and control of these blinds are differently selected by individual occupants, as are the colours of the rooms that the occupant decorates, thereby creating different levels of reflection and likelihood of glare. For complete accuracy, an individual assessment would be needed on the office configuration prior to selecting wall colours, blinds, and seating positions to fully ensure visual comfort—future studies could investigate a framework for providing guidance to occupants on ascertaining visual comfort for dwelling-based offices. Thus, the study could be further expanded with an assessment of supplementary adaptable shading devices and further enhanced with a superior calibration methodology.

While this study utilises Annual Sunlight Exposure (ASE) to identify floor areas receiving excessive direct sunlight, a key limitation of this approach is that ASE serves only as a coarse proxy for glare risk rather than a definitive glare metric. ASE measures spatial illuminance on a horizontal plane, indicating where direct solar radiation enters a space, but it does not quantify actual human visual discomfort. True visual comfort and glare are view-dependent phenomena driven by luminance contrast within an occupant's specific field of vision. Therefore, to holistically establish visual comfort, future research must transition from horizontal illuminance proxies to view-based luminance metrics, specifically Daylight Glare Probability (DGP). This was not adopted for this study, as general recommendations cannot be achieved with user-specific preferential analysis. Subsequent studies should model realistic home-office workstation layouts and evaluate DGP from the exact eye-level perspective and view vectors of a seated occupant facing a computer monitor. Furthermore, future assessments should integrate specific "view-out" analyses as required by the BS EN 17037 standard, ensuring that occupant-controlled shading mechanisms deployed to mitigate DGP do not inadvertently compromise the psychological benefits of an outdoor view. Such analyses can be coupled with a more accurate determination of occupant thermal comfort, wherein further validation could be undertaken as to the indicative glazing thermal penalties using dynamic hours-of-exceedance modelling via CIBSE TM59 and Part O frameworks.

In terms of the modelling, as the DesignBuilder simulation process only factors typical overcast or clear sky conditions, point-of-time measurements averaging measured values over several days would cause difficulty in aligning measured results across the diverse actual external weather conditions with simulated scenarios. Therefore, the most appropriate way to enhance calibration accuracy would be to undertake internal measurements over a year, and average these against an annual daylighting simulation—this is a limitation of this research, but an opportunity for future work.

Additionally, the same study could be replicated to overcome the single-case scope limitation, with additional dwellings of known construction materials and glazing properties (including optical) to enhance simulation accuracy, and utilising diverse layouts and orientations wherein the baseline case could be less favourable; thus, refinement strategies could be found that do not impact the carbon emission reduction or peak operative temperature. With respect to thermal comfort, the use of hours-of-exceedance analysis could be implemented to overcome the peak operative temperature limitations. Furthermore, diversification of material properties in diverse locations would be particularly useful in dwellings built per the latest standards and guidelines, to review if daylighting requirements are now being met in broad areas where they apply. Also, the adoption of qualitative data sets could be incorporated, such as using the Predicted Mean Vote (PMV) for glazing alteration and peak operative temperature assessment. Finally, further studies could be undertaken on the physical alteration of glazing strategies to ascertain real-life data.

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Nomenclature

Symbols

$C_{p,w}$	specific heat of water at boiler design outlet temperature [J/kg·K]
d	longer dimension of area being calculated [m]
$f_r(x, \omega_\mathrm{i}, \omega_\mathrm{o})$	bidirectional reflectance distribution function [-]
f_{size}	boiler's sizing factor [-]
i	spatial point [-]
$L_i(x, \omega_\mathrm{i})$	incoming radiance from direction ω_i, $\omega_\mathrm{i} \cdot n$ [W/sr·m^2]
$L_o(x, \omega_o)$	emitted radiance [W/sr·m^2]
M_i	measured data at instance i [-]
n	total number of measurement points within evaluated space [-]
p	maximum distance between calculation points [m]
$\dot{Q}_{boiler,nom}$	gas boiler capacity [kW]

S_i	simulated data at instance i [-]
$T_{drybulb}$	mean zone air temperature [°C]
T_{MRT}	mean radiant temperature for thermal zone [°C]
T_{OP}	operative temperature [°C]
U-value	thermal transmittance [W/m^2·K]
$\dot{V}_{loop,des}$	loop design volumetric flow rate [m^3/s]
Greek Symbols	
γ	radiative fraction [-]
$\Delta T_{loop,des}$	hot water loop design temperature decrease [°C]
ρ_w	density of water at standard conditions [kg/m^3]
Abbreviations	
ASE	annual sunlight exposure
CBDM	climate-based daylight modelling
CIE	International Commission on Illumination
DSE	display screen equipment
IEQ	indoor environmental quality
MAPE	mean absolute percentage error
PMV	predicted mean vote
SHGC	solar heat gain coefficient
sDA	spatial daylight autonomy
UDI	useful daylight illuminance
VLT	visible light transmittance
WWR	window-to-wall ratio

Appendix A. Model Calibration Data for Illuminance

Test Point	Level	S_i	M_i	$S_i - M_i$	Abs. % Error
1	Ground Floor	137.00	143.00	−6.00	4.20%
2	Ground Floor	59.00	56.00	3.00	5.36%
3	Ground Floor	251.75	280.00	−28.25	10.09%
4	Ground Floor	109.00	98.00	11.00	11.22%
5	Ground Floor	61.25	60.00	1.25	2.08%
6	Ground Floor	226.75	200.00	26.75	13.38%
7	Ground Floor	201.00	202.00	−1.00	0.50%
8	Ground Floor	122.50	119.00	3.50	2.94%
9	Ground Floor	73.75	72.00	1.75	2.43%
10	Ground Floor	43.50	45.00	−1.50	3.33%
11	Ground Floor	35.75	30.00	5.75	19.17%
12	Ground Floor	224.75	200.00	24.75	12.38%
13	Ground Floor	127.00	135.00	−8.00	5.93%
14	Ground Floor	90.25	88.00	2.25	2.56%
15	Ground Floor	482.50	471.00	11.50	2.44%
16	Ground Floor	188.75	190.00	−1.25	0.66%
17	Ground Floor	103.75	104.00	−0.25	0.24%
18	Ground Floor	7.00	10.00	−3.00	30.00%
19	Ground Floor	2.00	3.00	−1.00	33.33%
20	Ground Floor	0.00	0.00	0.00	0.00%
21	Ground Floor	0.00	0.00	0.00	0.00%
22	Ground Floor	50.00	51.00	−1.00	1.96%

Test Point	Level	S_i	M_i	$S_i - M_i$	Abs. % Error
23	Ground Floor	64.25	96.00	−31.75	33.07%
24	Ground Floor	148.75	152.00	−3.25	2.14%
25	Ground Floor	282.75	315.00	−32.25	10.24%
26	Ground Floor	1155.00	1279.00	−124.00	9.70%
27	Ground Floor	50.00	50.00	0.00	0.00%
28	Ground Floor	65.25	60.00	5.25	8.75%
29	Ground Floor	138.25	141.00	−2.75	1.95%
30	Ground Floor	351.00	482.00	−131.00	27.18%
31	Ground Floor	48.50	48.00	0.50	1.04%
32	Ground Floor	65.25	60.00	5.25	8.75%
33	Ground Floor	113.00	110.00	3.00	2.73%
34	Ground Floor	7.75	7.00	0.75	10.71%
35	Ground Floor	22.50	21.00	1.50	7.14%
36	Ground Floor	173.75	223.00	−49.25	22.09%
37	First Floor	116.00	131.00	−15.00	11.45%
38	First Floor	82.00	108.00	−26.00	24.07%
39	First Floor	33.00	43.00	−10.00	23.26%
40	First Floor	37.00	38.00	−1.00	2.63%
41	First Floor	770.00	781.00	−11.00	1.41%
42	First Floor	94.00	91.00	3.00	3.30%
43	First Floor	52.00	50.00	2.00	4.00%
44	First Floor	90.00	63.00	27.00	42.86%
45	First Floor	102.00	100.00	2.00	2.00%
46	First Floor	37.00	37.00	0.00	0.00%
47	First Floor	63.00	78.00	−15.00	19.23%
48	First Floor	76.00	81.00	−5.00	6.17%
49	First Floor	56.00	70.00	−14.00	20.00%
50	First Floor	839.00	1007.00	−168.00	16.68%
51	First Floor	178.00	204.00	−26.00	12.75%
52	First Floor	74.00	80.00	−6.00	7.50%
53	First Floor	8.00	5.00	3.00	60.00%
54	First Floor	3.00	2.00	1.00	50.00%
55	First Floor	0.00	0.00	0.00	0.00%
56	First Floor	0.00	0.00	0.00	0.00%
57	First Floor	0.00	0.00	0.00	0.00%
58	First Floor	0.00	0.00	0.00	0.00%
59	First Floor	0.00	0.00	0.00	0.00%
60	First Floor	0.00	0.00	0.00	0.00%
61	First Floor	125.00	120.00	5.00	4.17%
62	First Floor	240.00	177.00	63.00	35.59%
63	First Floor	838.00	990.00	−152.00	15.35%
64	First Floor	130.00	125.00	5.00	4.00%
65	First Floor	967.00	1031.00	−64.00	6.21%
66	First Floor	143.00	144.00	−1.00	0.69%
67	First Floor	305.00	309.00	−4.00	1.29%
68	First Floor	37.00	38.00	−1.00	2.63%

Test Point	Level	S_i	M_i	$S_i - M_i$	Abs. % Error
69	First Floor	161.00	175.00	−14.00	8.00%
70	First Floor	32.00	25.00	7.00	28.00%

Metric	Calculated Value	Acceptance Target	Result
MAPE	10.33%	≤20%	Pass

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