Parametric Daylight Envelope

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ABSTRACT: With the increased sophistication of digital tools for assessing daylight and energy in buildings, a great potential exists for optimizing the performance of contemporary building façades. A holistic approach can promote both visually and thermally comfortable spaces, reduce glare and lead to buildings that consume less energy. This is pivotal in addressing environmental awareness and tackling climate change while achieving high user satisfaction. This paper presents a study of an optimised facade commonly found in service buildings. Four types of building envelopes are simulated in terms of climate-based metrics, glare and energy consumption. The first two types have 40% window-to-wall ratio (WWR), with one of them having a light shelf. The third and fourth are 100% WWR with one of them having a parametrically driven fixed screen. This study aims to find an optimum solution in terms of daylight and energy use for cooling, heating and artificial lighting for the climate conditions of London, UK by using an integrated daylight and thermal simulation approach.

Keywords: Daylight, Glare, Climate-based metrics, Radiance, EnergyPlus, Energy consumption

INTRODUCTION

New architectural building forms and facade cladding have emerged with the technological advances of the past century. Typical service buildings in cities now commonly have large and fully glazed facades. Whereas this is a symbol of prestige or simply an emphasis of the architectural form it has certainly led to an increase in energy use in buildings. Windows provide a view and daylight access and therefore large areas are welcome. Various researchers have shown that well-lit workstations will positively affect productivity, increase sales in retail shops and promote faster and better learning in schools. [1] Conversely, large windows also contribute to high solar gains and heat losses which can strongly affect cooling and heating energy loads. So shading devices or glazing with relatively low G-values are a requirement for compliance with building regulations.

Nowadays architects rely on computational tools in order to investigate new forms and structures. Likewise, computational tools may not just be used for form generation, but also for predicting the performance of spaces. On the one hand environmental awareness and climate change have affected building regulations. They are increasingly becoming more demanding in terms of energy efficiency and promoting the reduction of CO_2 emissions. Recent years have witness a great effort being put into the reduction of energy and the adoption of renewable energy in the building sector. Sometimes this is to the detriment of good daylight conscious design. It is no surprise that regulations that address conservation of energy in buildings have limited the glazing area to 40% of the wall or have imposed reduced solar factors in glazing. On the other hand, most office buildings have a fully glazed envelope and any reduction in glazing area or their G-value and visible transmittances have a great impact on the indoor daylight quality in particular on deep plans. It is well known that daylight plays a major role in human wellbeing. Moreover, a reduction in the glazing area may increase the electricity spent on artificial lighting which already forms a large share of overall energy consumption (30% in office buildings). Facade engineering needs to address both daylight and energetic issues. This research aims at that. Two typical facade window-to-wall ratios (40 and 100%) as well as two enhanced daylight solutions that prevent overheating (e.g. shading devices and redirecting daylight systems) are tested for thermal and visual performance. A thorough analyses in terms of energy consumption and daylight quality should result in the optimum model for the climatic conditions of London (Lat 51.4N Long 0W).

CASE STUDIES

Environmental conditions

A simple model representing an office cell is 4m wide, 7m long and 3m high. It is occupied on weekdays from 9am to 5pm. Internal gains are a result of 80W sensible heat input per occupant (8 people) and a total lighting power of 432W (to achieve a 500lx). Light controls have a dimmable daylight sensor for this lux threshold. Heating and cooling set-points are 21^{o} and 25^{o} respectively for the occupied times. Setback temperatures for unoccupied periods for heating and cooling are 10^{o} and 32^{o}, respectively. The space has only one external façade which is south oriented, while the other surfaces are treated as adiabatic so no heat transfer can occur. The U-values for the external façade were defined according to the current Building Regulations Part L2A conservation of fuel and power in new buildings other than dwellings. Therefore the U-value for the opaque wall is 0.35W/m^{2}K and for the glazed area is 2.2W/m^{2}K. The double glazing low-E unit has a g-value 0.57, a visible transmittance of 0.74 and a 0.90 maintenance factor. The enhanced models have different shading coefficients on an hourly schedule. No obstructions are present in the model. The weather file for London Gatwick was available from the Energy Plus software.

Façade Variations

A. 40%WWR (parametrically optimized opening)
B. 40%WWR + Light shelf (enhanced A case)
C. 100%WWR
D. 100%WWR + 3d parametrically designed ‘screen’ (enhanced C case)

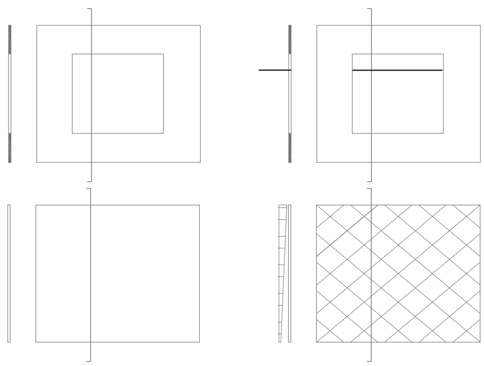

Figure 1: identified cases, section and front view.

Software packages

Various software packages were used for generating the previously defined geometries and its optimisation. The 3d modelling software, Rhinoceros, was used for space modelling and its plug-in Grasshopper for screen generation. Galapagos was used for 40%WWR opening optimization (its XY dimensions), based on average daylight factors. DIVA plug-in was used for Daylight and thermal analyses. This interfaces with RADIANCE (also used independently), Daysim, Evalglare and Energy Plus software. To estimate daylight in the tested office space, Daylight Autonomy (DA) and Useful Daylight Illuminance (UDI) were measured by calculating the ‘climate-based metric’ in DIVA. After running a climate-based analysis in DIVA, hourly lighting schedules are generated. These schedules are used later in E+ simulations for thermal simulations.

Window opening optimization - 40% WWR

Window opening optimization of the 40% WWR base case was achieved by using Galapagos, an evolutionary solver plug-in for Grasshopper. Galapagos was used to optimize the dimensions of the window on a 40% WWR base case in order to get the highest average daylight factor. It is important to highlight that this could potentially be a very time consuming process if Climate-based metrics were used as an optimization criteria. Whereas daylight factor calculations are much faster and assumed acceptable for this purpose. The ‘genomes’, or the variables, for the evolutionary solver were two scale factors, the vertical and the horizontal ones. The multiple fitness function had the task of maximizing the daylight factor, while keeping the window area on the 40% of the area of the wall.

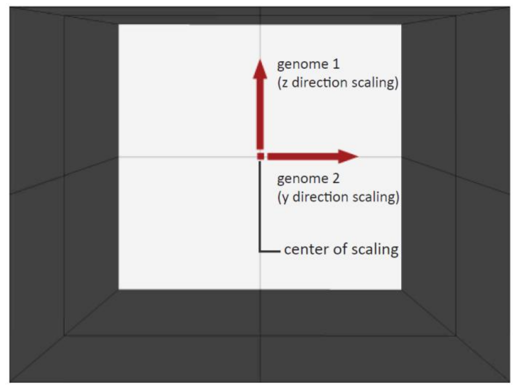

Figure 2: 40% WWR facade opening optimization.

Enhancing the 40% WWR base case

The light shelf was positioned at the height of 2m and its ‘‘depth’’ is 0.8m, which is the scenario that showed the best performance according to Carli M. et al. [4].

Screen Geometry and Parametric Variation of the Depth

The screen was designed to control solar gains. External shading devices are more thermally efficient because they intercept solar radiation before it enters the room. The screen should also improve the daylight levels because “light shelves” are integrated in its design. (Fig. 3) In order to optimize its performance, different types of shading were tested in terms of DF, DA and UDI. The final version has a changeable ‘depth’ that can be seen in the side view of the screen. (Fig. 3) The changeable ‘‘transparency’’ of the screen according to its height is a direct result of the ‘‘zoning’’ concept. The upper part has the highest transparency, as it contributes the most to the indoor daylight levels and allows light penetration deep into the room. The lowest part is characterized by smaller openings in order to reduce high daylight levels in the area in close proximity to the window. Although these lower small openings mainly illuminate areas below the working plane, overheating may still occur. For this reason small shading fins are added to allow only diffuse light during the summer. The mid-section allows the view outside.

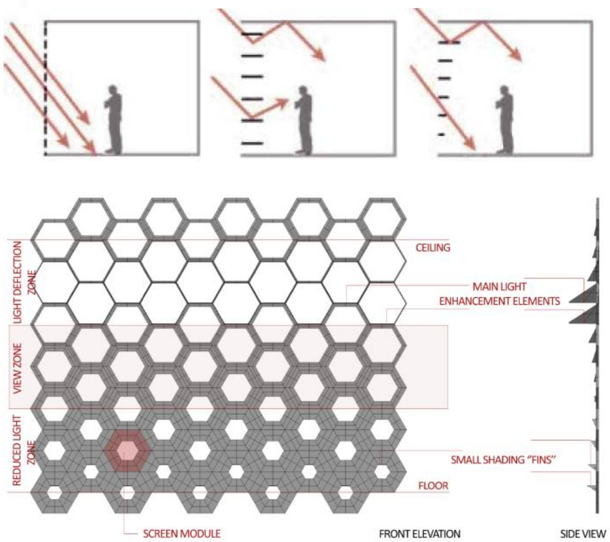

Figure 3: Shading Screen Concept and Screen geometry, front elevation and side views

VISUAL AND THERMAL PERFORMANCE INDICATORS

Daylight simulations

Climate-based daylight modelling is any evaluation that is founded on the totality (e.g. sun and sky components) of contiguous daylight data for some location for a period of a full year [2]. The main difference when compared with Daylight Factor calculations is that Daylight Factor discards the sun contribution (overcast sky) and is a simple ratio of the indoors to the unobstructed outdoors horizontal illuminance. This calculation is effective for simple analysis and initial phases of design but is insensitive to building orientation, its location or sky and sun variability for different times of the day and days of the year. Therefore, climate-based metrics can provide a much more detailed analysis of the daylight performance in a space. Daylight Autonomy is defined as the "percentage of the occupied hours of the year where a minimum illuminance threshold is met by daylight alone'' [3]. In this work, the target illuminance was set at 500lux which means the daylight autonomy reveals the percentage of the time occupied when the illuminance is over 500lux. However, DA does not tell the actual illuminance level nor gives estimation if these are well exceeded and may lead visual discomfort. Useful Daylight Illuminance provides information on the quality of daylight since it defines the illuminance that fall within the range 100–2000lx as 'useful'. Illuminances below 100lx are assumed falling short and above 2000lx in excess.

Further analyses of RADIANCE illuminance images for a particular hour and day of the year allow a qualitative comparison of the performance of the different enhanced systems.

Glare analysis

An integrated daylight and thermal simulation process should also address glare as there is a strong correlation between occupants' visual comfort and daylight quality. Therefore, annual glare analyses were done in order to classify the tested cases. This analysis was limited to one camera position, assumed to be a real situation in which a person would be sitting at the table. Therefore, both camera and target height were set up at 1.3m. This was limited due to time constraints to run annual glare simulations.

Daylight Glare Probability (DGP) annual maps were generated for a determined typical view position to assess the likelihood of occurrence of visual problems.

Thermal simulations

The energy consumption for all 4 cases was calculated with Energy Plus. Results are presented for heating, cooling and lighting on a yearly basis. A limitation of the E+ is to only model planar surfaces, which has affected the simulation of the 4th case (100%WWR + screen). Also the software can only consider one shading coefficient to each glazing unit. This makes the complex modelling of the screen very difficult. To overcome this limitation a simplified shading object was defined in E+ with a shading coefficient schedule calculated as the hourly illuminance ratio on the vertical surface with and without the complex shading. It is important to emphasize that this is an approximation to the amount of light that enters the room and a simplification of its uneven distribution.

CO_2 emissions

The CO_2 emissions from lighting, heating and cooling were compared for the different case studies. This was calculated by adopting different carbon emission factors for electricity (0.517kg CO_2 per KWh) used in lighting and cooling and for gas (0.198 kg CO_2 per KWh) used in heating. These different carbon factors highlight the importance of reducing cooling and lighting loads since they are more carbon intensive. This analysis only addresses regulated carbon emissions (from heating, cooling and lighting). Since the equipment and auxiliary energy used was assumed the same in all 4 cases unregulated CO_2 emissions are not considered important for this comparison.

DISCUSSION OF RESULTS

Results have shown that when the enhanced systems (light shelf and screen) are applied, each of the cases (40% and 100%WWR base case) experience significant changes in energy consumption. (Fig. 4) For instance, 40% WWR with light shelf consumes 19% more energy for heating and 66% less energy for cooling. In the case of 100% WWR, the enhanced solution consumes 62% more energy for heating and 54% less energy for cooling. On the other hand, the introduction of additional elements has affected the daylight levels in the back of the room, so supplementary artificial light is necessary to achieve the desired lux levels. Enhanced 40% and 100%WWR consume 21% and 61% more energy for lighting than the base cases, respectively [5].

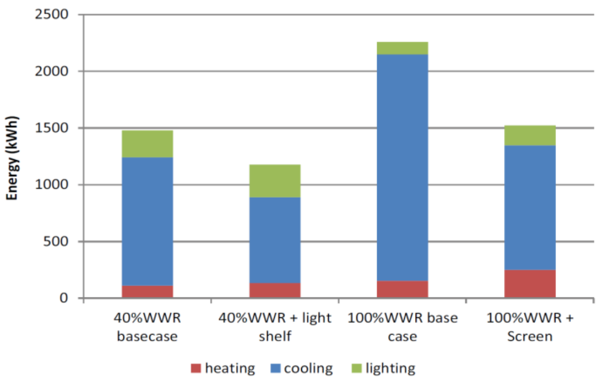

Figure 4: Comparison of the energy consumption (heating, cooling and lighting) for the four cases

However, when considering the overall energy consumption (Fig. 4) after applying the shelf, the energy use of the 40%WWR case was reduced by almost 20%, which is in line with the EU 20 20 20 targets (20% reduction in energy consumption, 20% adoption of renewable energy and 20% reduction in CO_2 emissions). The introduction of the screen on the 100%WWR case shows a greater reduction of almost 25%. This comes as a confirmation that additional facade elements can help reducing energy consumption in buildings in London, which has predominantly overcast skies.

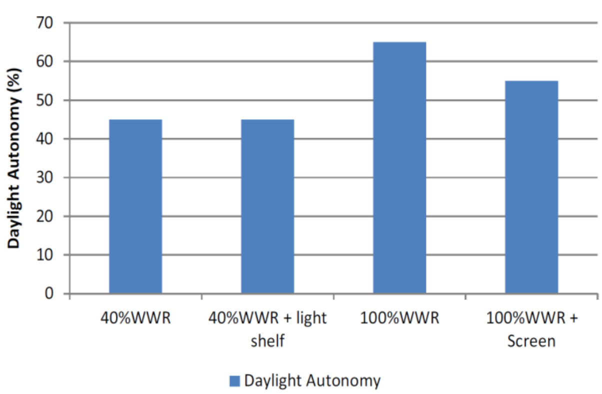

Figure 5: DA comparison for the four scenarios

Regarding the daylight quality, climate-based metrics have shown significantly higher DA for the 100%WWR in comparison to the 40%WWR which can result in healthier environments for the occupants (Fig. 5). When the enhanced solutions are compared, 100%WWR with the screen performs better than the 40%WWR + light shelf in terms of DA (55% and 45%, respectively). Both 100%WWR with and without screen achieve the benchmark of the DA threshold for 50% of the time on the annual basis. Although the other two models are relatively close (45%).

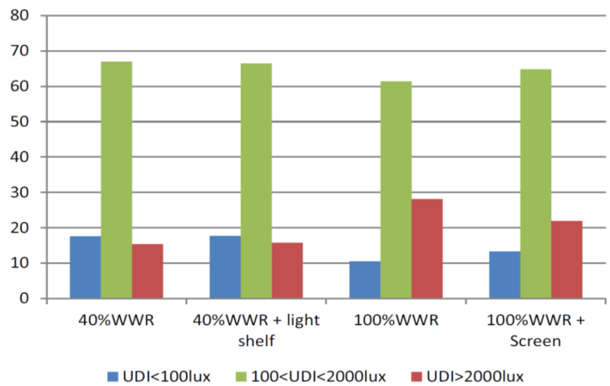

Figure 6: UDI comparison graph

All the four models have the highest percentage of UDI in the useful range (100<UDI<2000lx), with 68% for the 40%WWR and 61% for the 100% WWR (Fig. 6). Both 40%WWR cases have a higher percentage of UDI in the fell short range (<100lx, around 18%) than the exceed range (>2000lx) at around 15.5%. This situation is reversed for scenarios with larger windows and 100%WWR without/without screen have an UDI <100lx of 10 and 12% respectively. Simulations have shown that the screen reduces the ‘exceeded’ (>2000lux) illuminance in the area close to the window from 28% down to 21%. The UDI in that range for the 40% WWR base model is 15.5% while after applying the light shelf it remains the same (15.5%). Overall, this improves the daylight uniformity in the ‘screen’ case since the ratio of the maximum illuminance to the minimum values is lower [5].

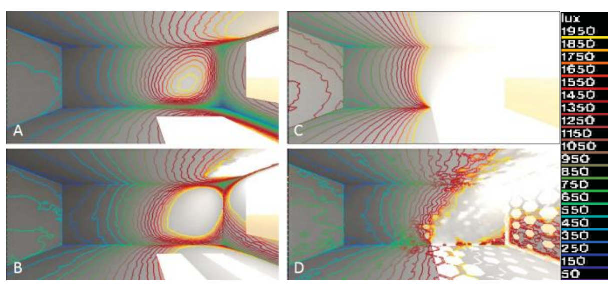

Figure 7: Equinox days Illuminance comparison (sunny sky)

Further analyses in RADIANCE have shown a slight increase of illuminance on a sunny equinox day in the back of the room after the light shelf is applied, while the screen resulted in an illuminance decrease. (Fig. 7)

The 3d illuminance picture (Fig. 8) for winter solstice day shows different light distribution in all four cases. In winter time, on a sunny day, most of the workplane has an illuminance above 500lx. Conversely, on an overcast day (10,000lx) less than a third of the workplane area is above that threshold. On the other hand, the 100%WWR model has the greatest workplane area with illuminance above 2,000lx for the summer solstice which may be a sign that certain part of the room is receiving too much daylight.

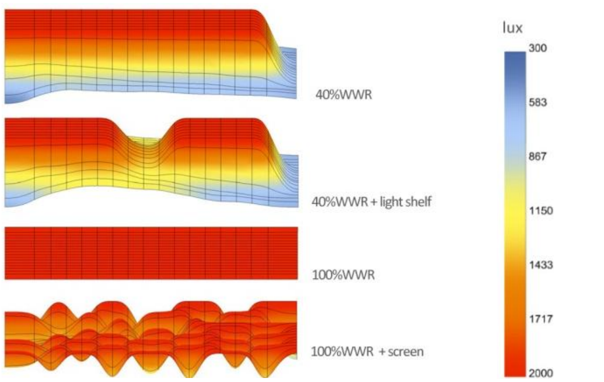

Figure 8: Illuminance distribution perpendicular to the window (on the right), at the winter solstice (sunny sky). A low solar altitude allows deep penetration of high illuminance. The effects of the light shelf and of the screen are noticeable in the second and fourth cases.

An oversupplied area is defined as an area with illuminance 10 or more times above the threshold (500lx) during more than 5% of the time occupied [3]. These can cause glare and overheating problems and intensive use of air-conditioning. (Fig. 9) Both 40WWR models have lower oversupplied areas than the 100%WWR but the impact of the light shelf is minimal. The adoption of a higher threshold may highlight the real impact of the light shelf. On the other hand, applying a screen to a fully glazed facade reduces the oversupplied area significantly.

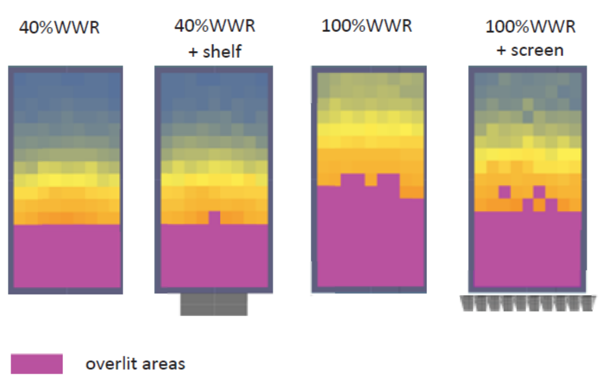

Figure 9: Overlit areas comparison for the four scenarios

Since London has predominantly overcast skies, the Daylight Factor method was also addressed. When both enhanced solutions are compared, the 100%WWR + screen shows higher ADF than the 40%WWR + light shelf (3.4% and 2.6%, respectively). However, both are within the recommended range of 2 to 5% to be considered a well daylit space occasionally needing a complement of artificial lighting. It is important to mention that both are not at the risk of overheating since the ADFs are lower than 5%. However, the 100%WWR without the screen has an ADF of 5.5% which suggests a potential overheating problem. This can be related to the previously defined 'oversupplied' areas in the room under clear skies. Finally, the DF in a room for a 10,000lx overcast sky distribution highlights that both of the enhanced models do not increase the daylight levels.

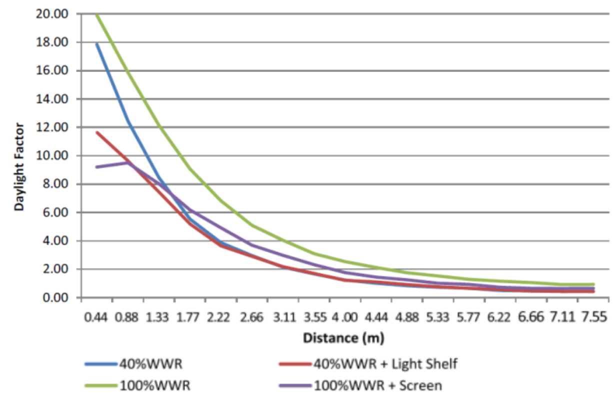

Figure 10: Daylight Factor comparison graph

According to temporal maps obtained from simulations run in DIVA, the 40% WWR base case has the lowest Daylight Glare Probability (DGP), while the 100% WWR without screen has the highest. A common situation for all tested cases is the high DGP especially in the winter period when the sun has a low angle of 15°**.** Glare analyses have shown a reduction in glare after the screen and the light shelf are applied to the envelope. (Fig 10)

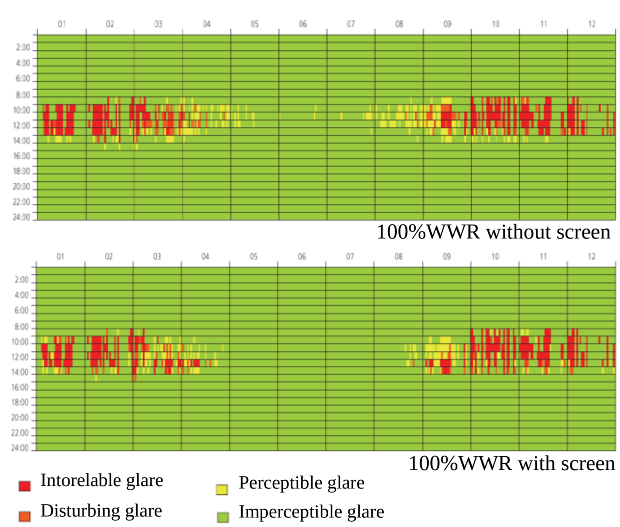

Figure 10: Temporal maps of annual glare throughout the day

The results have shown that most of the disturbing and intolerable glare happens in the winter period. To be more precise, months with high DGP are from October to March. Therefore, in order to see the difference in percentage between each of the cases tested, an hourly average DGP was calculated for the Jan-Mar period. (Fig. 11) However, it is important to say that in these average values are included all the hours of the day (which resulted in lower DGP values that it is in reality). Nevertheless, the ratio would be the same even if, for instance, the night hours have been neglected, so the DGP comparison is considered to be valid.

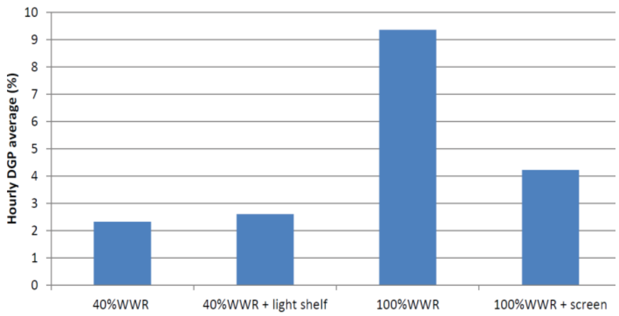

Figure 11: Percentage of Daylight Glare Probability (DGP) for each scenario.

Annual glare analyses have shown the real need for additional shading in both the 40%WWR and 100%WWR models with an average DGP for the period Jan-Mar of 2.32% and 9.36%, respectively. After applying a light shelf to the 40%WWR and a screen to the 100%WWR, the DGP has changed to 2.6% and 4.22%, respectively.

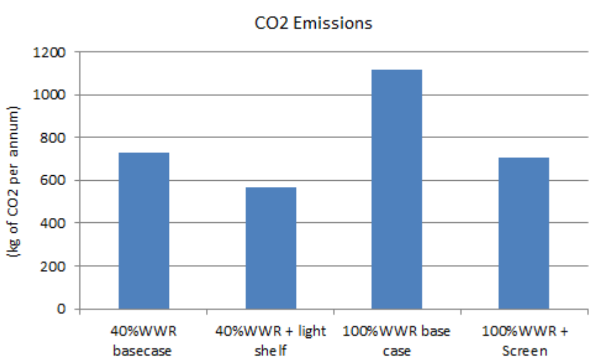

Figure 12: Regulated CO_2 emissions comparison for the four cases studied

Carbon analyses showed the lowest regulated CO_2 emissions for the 40%WWR with the light shelf, a total amount of 565kg of CO_2 per annum. In comparison to the worst performing 100%WWR case (1120kg of CO_2 per annum), the light shelf scenario had almost 50% lower CO_2 emissions (Fig. 12). The introduction of the screen on the 100%WWR had a positive effect on the final regulated CO_2 which was reduced by 37% over the 100%WWR baseline scenario. Furthermore, 100%WWR with Screen performed better than the 40%WWR basecase, even though the energy consumption chart showed higher energy consumption for the 100%WWR with screen.

CONCLUSIONS

This paper presents a method to optimise a window position as well as the generation of an enhanced daylight systems and shading devices to promote good visual performance. Four solutions are then tested with dynamic thermal and cumulative daylight analyses.

Daylight enhancement systems such as light shelves do not improve significantly the daylight levels in London due to a high percentage of overcast skies in the city. However, a major advantage of the light shelf is to provide shading to the lower part of the windows and therefore reducing the cooling loads in summer without compromising the advantage of solar gains during winter. It has been seen that some of the tested cases perform better in terms of daylight than in energy performance or vice versa. Likewise, some were better at minimising glare or at improving the uniformity of daylight or minimising overheating**.** Analyses had also shown the importance of the cooling load reduction through the use of shading. Likewise, improving indoor daylight quality and reducing lighting consumption represent an efficient way of reducing carbon emissions.

Consequently, a compromise has to be made, or a particular issue has to be assumed as a priority. For the purpose of this paper if an equal significance was given to both daylight quality and energy consumption, the light shelf would be assumed as the better solution from the 4 cases analysed. On individual assessments the Screen is the better solution in terms of daylight and the light shelf in its energy performance and carbon emissions.

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