Impact of Window Systems on Daylighting Performance, Visual Comfort and Energy Efficiency in Patient Rooms

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Abstract
This paper investigates the influence of glazing characteristics and shading device configuration on energy cost, daylighting and visual comfort. A typical patient room from a hospital design in Belgium is used as a baseline scenario and different window system design alternatives are explored through parametric modelling. Based on the comparative analysis, the paper discusses potential design options that allow for energy efficient and daylit patient rooms with high visual comfort. The methodology combines dynamic energy simulations, daylighting and glare analysis. The results indicate that glazing characteristics and shading device configuration have major impact on energy cost, daylighting and visual comfort and in order to achieve an overall good performance, selecting the right window system configuration is essential. This study also emphasises the need for integrated performance analysis in order to obtain a correct insight into the window system performance.

Introduction
Windows provide access to daylight, view to the outside, contribute significantly to the quality of the indoor environment and impact the heat flow, solar gains and aesthetics of buildings. Inappropriate window design may lead to visual discomfort as well as energy inefficient buildings. However, the influence of alternative window design options on the building performance is usually not explored in the early design stage even though important decisions are made during this stage. As it may not be possible for bedridden patients to move or spend time outdoors, it is even more important for hospital buildings to ensure adequate daylight and visual comfort without unacceptable energy use.

Literature review shows that while various studies focus on window systems performance in regard to daylighting, energy consumption and visual comfort in office buildings (Bellia et al., 2017; Nielsen et al., 2011; Ochoa et al., 2012; Shen and Tzempelikos, 2011), only a limited number of studies address these topics in hospitals (Lo Verso et al., 2015; Shikder et al., 2010). Research on these topics mainly focuses on hot arid climates (Sherif et al., 2016; Wagdy et al., 2017). On the contrary, the positive effects of daylight and window views on hospital users such as reducing stress and length of stay, maintaining or restoring the circadian rhythm and improving sleep patterns are addressed in a large number of studies (Chiu et al., 2018; Choi et al., 2011). Furthermore, there appears to be no comprehensive study that simultaneously takes into account the effect of window systems on the provision of daylight, visual comfort and energy efficiency in patient rooms.

The aim of this study is to evaluate the effect of glazing type and shading device configuration on daylighting, energy performance and visual comfort in patient rooms. A typical patient room from a hospital design in Belgium with a window oriented to the south is used as a baseline scenario. Via parametric analysis the results of alternative window design strategies are analysed and compared in terms of energy cost, daylighting performance and visual comfort considering sDA (spatial Daylight Autonomy), ASE (Annual Sunlight Exposure), UDI (Useful Daylight Illuminance) and DGP (Daylight Glare Probability) based on the patient’s position and view direction.

Methodology
In this study parametric simulations are carried out to examine the annual effect of overhangs and fixed horizontal louvres on performance in comparison with no solar shading. Hence, this study helps to identify window system configurations that can achieve satisfactory year-round performance. Internal shades are not considered in order to analyse the most problematic case for the appearance of glare.

The alternative design options are evaluated in four steps. In a first step, annual simulations are carried out for different glazing types without any shading device. In the second step, various shading device configurations are added to the different glazing types and their influence are assessed on energy cost, daylighting and visual comfort. After analysing and comparing the data for each glazing type, the design options with the lowest energy cost and higher access to daylight and visual comfort are identified. A third step provides a side-by-side comparison of the selected design options with the benchmark design. The final step assesses the visual comfort with a point in time glare analysis at the patient’s position for the design options from the previous step.

The patient room is modelled in Grasshopper, which is a plugin for Rhinoceros (3D modelling tool). Detailed patient room simulation parameters such as construction types, materials, schedules are assigned to the model using Ladybug & Honeybee components for Grasshopper. Parametric simulations are performed using

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the Grasshopper plugin Colibri and for the energy and daylighting analysis Ladybug & Honeybee are used to interface with the simulation engines EnergyPlus, Radiance and Daysim.

**Simulation Model Description**

In order to investigate the role of the various window design alternatives on the energy loads, daylighting and visual comfort a 4.0 m x 6.0 m x 3.0 m (length x width x height) sample patient room with 40% WWR (Window to Wall Ratio) is used as the base case. Only the floor area occupied by the patient is taken into account for the simulation. The service area, including the bathroom, is not considered (see Figure 1).

Moreover, in order to study the impact of glazing characteristics on the performance six glazing types with different g-values, U-values and visible transmittance (Tvis) are considered.

Table 1 lists the key properties of the glazing types adopted in this study and Figure 2 shows the position of the coating within the glazing. The double/triple glazing consists of 4 or 6 mm glass panes and 15 or 16 mm cavity filled with gas (90% argon). The Berkeley lab WINDOW 7.6 software is used to determine the thermal and optical characteristics of the glazing. The uncoated glazing acts as benchmark for understanding the influence of the coating. The patient room has one external wall (U-value = 0.22 W/m²K) with a single window facing south; all other surfaces are assumed adiabatic and the properties of the envelope are according to the Belgian standards for new buildings. The patient room is located on the second floor; no external obstruction is taken into account. EnergyPlus weather data for Brussels (latitude 50.90° N and longitude 4.53° E) is used for the simulations.

**Energy Analysis**

The annual energy use and cost for heating, cooling and lighting are calculated using EnergyPlus and taking into account the solar and thermal properties of the glazing with detailed layer by layer glazing system modelling. A daylight-linked lighting control is employed using a lighting schedule generated by the Daysim software through the Honeybee component for annual daylight simulation. The artificial lighting power density is 6.7 W/m². The illumination level setpoint for activating lighting is 300 lux and the lighting sensor is located at the patient’s position. This value is set as the target threshold for daylighting analysis at the reference point as the illuminance necessary for simple examination and reading is 300 lux. If the illumination level drops below this threshold, artificial lighting is switched on to ensure sufficient light at the patient’s position.

Space heating and cooling setpoint temperatures are assumed to be 21°C and 24°C respectively, mechanical ventilation is set to 2.00 (ac/h) and infiltration is considered 0.20 (ac/h). These assumptions are in line with standards provided for patient rooms in Belgium. Mechanical ventilation is modelled with heating and cooling using the EnergyPlus Ideal loads system; the effects of heat recovery and economiser are included. For heating a global system efficiency of 0.85 is considered and for cooling a CoP (Coefficient of Performance) of 1.80. Natural gas (heating) and electricity (cooling and lighting) prices (€/kWh) are based on the Belgian market prices of 2017. It should be noted that the price of electricity for one kWh is approximately four times more than the price per kWh of natural gas.

**Table 1. Glazing characteristics**

<table>
<thead>
<tr>
<th>GLZ</th>
<th>Tvis/g-value</th>
<th>Configuration</th>
<th>Coating features</th>
<th>U-value (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLZ1</td>
<td>0.82/0.80</td>
<td>4-16-4</td>
<td>No coating</td>
<td>2.50</td>
</tr>
<tr>
<td>GLZ2</td>
<td>0.73/0.41</td>
<td>4-16-4</td>
<td>Solar control + Thermal insulation</td>
<td>1.10</td>
</tr>
<tr>
<td>GLZ3</td>
<td>0.61/0.31</td>
<td>6-16-4</td>
<td>Solar control + Thermal insulation</td>
<td>1.10</td>
</tr>
<tr>
<td>GLZ4</td>
<td>0.76/0.74</td>
<td>4-15-4-15-4</td>
<td>No coating</td>
<td>1.70</td>
</tr>
<tr>
<td>GLZ5</td>
<td>0.75/0.53</td>
<td>4-15-4-15-4</td>
<td>Thermal insulation + High (light transmission + g-value)</td>
<td>0.60</td>
</tr>
<tr>
<td>GLZ6</td>
<td>0.68/0.38</td>
<td>4-15-4-15-4</td>
<td>Solar control + Thermal insulation</td>
<td>0.60</td>
</tr>
</tbody>
</table>

**Figure 1. The patient room area taken into account for simulation**

**Figure 2. Coating position within glazing; 1- Outer glass pane**

Dotted line: position of coating(s)
Daylight and Glare Simulation

The key metrics selected to assess the daylighting performance and visual comfort are sDA$_{300,50\%}$, UDI, ASE$_{250}$, and DGP (point-in-time and annual). The metric sDA$_{300,50\%}$ describes the percentage of an analysed area that meets a target illuminance - in this case 300 lux - for at least 50% of the annual occupied hours (Sherif et al., 2016). This threshold is used to evaluate daylight due to the fact that CEN daylighting standard (EN 17037) indicates that the “minimum” daylight provision value requires 300 lux on the task plane during more than 50% of the daylight hours (Paule et al., 2018). ASE$_{250}$ is the percentage of floor area that receives direct sunlight over 1000 lux for at least 250 occupied hours of the year which likely leads to visual discomfort (Sherif et al., 2016). The UDI metric determines when the annual occurrence of illuminances across the task plane is within a range defined as “useful” by occupants. There is much debate and considerable uncertainty regarding the preferred/tolerable upper limit for this range (Mardaljevic et al., 2011; Nabil and Mardaljevic, 2006). As 3000 lux is the upper threshold usually set for schools in UK (UK Education and Skills Funding Agency, 2014) and residential buildings (Mardaljevic et al., 2011) in this study this threshold is set as the upper limit for the simulations. Also the 3000 lux threshold could be more appropriate to act as a proxy for detecting glare.

Achieving a high UDI$_{100-3000lux}$ percentage shows that the space is predominantly daylit and for the majority of the occupied hours does not require artificial lighting (UK Education and Skills Funding Agency, 2014). UDI values greater than 3000 lux indicates that it is too bright and an oversupply of daylight could lead to visual discomfort (Mardaljevic et al., 2011). The aim is to determine whether ASE$_{250}$ and UDI$_{3000lux}$ metric could serve as a proxy for evaluating visual comfort and detect the likely appearance of glare.

In this study DGP is based on a glare view angle for the patient in fowler’s position (patient sitting in a semi-upright position in bed) at 1.15 m above floor level. As DGP values over 0.45 are considered intolerable (Reinhart and Wienold, 2011), this threshold is used for the glare analysis. For step 1 and 2 of this study, after running annual glare analysis, the percentage of the annual occupied hours that DGP exceeds 0.45 threshold is calculated. Considering this study is for patients with limited movement, in step 3 the percentage of the annual occupied time that DGP is lower than 0.40 is calculated which shows the perceptible and imperceptible glare range (Wienold, 2009).

For point in time glare analysis with HDR imaging, using a fish-eye lens the luminance field experienced by the patient is recorded to locate the source of glare at different times of the year. The annual glare map shows that intolerable glare is likely to occur around noon in winter months due to a lower sun angle. Based on the annual temporal glare map, 23rd of October from 10 am to 2 pm is selected for point-in-time glare analysis. Figure 3 shows annual DGP map for GLZ1 and GLZ3, the red parts show when maximum glare tends to appear. It should be noted that the average daily sunlight exposure (SE) on the bed is only provided to understand the impact of shading on the direct sunlight that reaches the patient’s bed, see Figure 4.

The daylighting simulation is performed from 6 AM to 9 PM, as during this period of the day the patients need daylight/lighting. The task level is located 0.9 m above the ground (bed surface) and divided into an analysis grid of 0.3 m spacing, the reference point (sensor) location is selected based on the patients position in the room. The walls, ceiling, floor and shading device reflectance are assumed to be 50%, 80%, 20% and 60% respectively.

![Figure 4. Sample average daily sunlight exposure on the patient’s bed](image)

![Figure 3. Annual hourly DGP map at patient’s position for the highest and lowest light transmission glazing](image)
**Result and Discussion**

**Step 1**
In this step, for each glazing type the annual energy cost, sDA\(_{300/50\%}\), DGP>0.45, UDI\(_{>3000}\)lux and ASE>250 are calculated without a shading device. The data obtained from this step acts as a benchmark for analysing the impact of shading devices. It should be noted that the criteria for evaluating the performance of designs are energy cost, sDA\(_{300/50\%}\)>50% and DGP>0.45. As mentioned before UDI\(_{>3000}\)lux and ASE>250 are calculated to evaluate whether these metrics could predict the occurrence of glare.

As can be seen in Figure 5, uncoated double and triple pane glazing (GLZ1 and GLZ4) show the highest energy cost due to higher heating and cooling loads. Furthermore, triple-pane GLZ6 with the lowest U-value among the glazing types and a g-value of 0.38 shows the least energy cost as a result of lower cooling loads. Figure 5 also shows that lighting energy use is quite similar for all rooms and the difference between the rooms with the highest and lowest light transmission glazing (GLZ1 and GLZ3) is less than 7% which suggests that very high light transmission has a minor impact on reducing the lighting energy use. It is observed from the results that the main contributor to the energy cost is the electricity used for space cooling. As expected the glazing with higher light transmission have higher DGP>0.45, UDI>3000lux and ASE>250 values. However, the values are relatively close for all glazing types and does not show a wide range.

**Step 2**
For the second step, for each glazing type different shading device configurations are analysed. The parameters of the parametric analysis and their minimum and maximum values are shown in Table 2. This range is in accordance with the sun position for this latitude (Peak sun angle is ca. 63\(^\circ\)) and the height of the window. The shading systems are modelled without mounts or anchors. The performance criteria taken into account for analysing different design alternatives are similar as in the previous step. The aim is to identify and compare the best performing option with the least energy cost, glare and sufficient daylight (sDA\(_{300/50\%}\)>50%) for each glazing type to the benchmark design option.

![Figure 5. Benchmark designs performance without shading device (40% WWR – South orientation)](image)

**Table 2. Value of parametric variables**

<table>
<thead>
<tr>
<th>Variables</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Step</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overhang depth</td>
<td>0.5 m</td>
<td>1.0 m</td>
<td>0.10 m</td>
</tr>
<tr>
<td>Slat depth</td>
<td>0.1 m</td>
<td>0.3 m</td>
<td>0.05 m</td>
</tr>
<tr>
<td>Number of slats</td>
<td>5</td>
<td>10</td>
<td>1</td>
</tr>
</tbody>
</table>

After running the simulations it is evident that for some coated glazing a higher WWR (50%) is required due to the fact that the sDA\(_{300/50\%}\)>50% criterion is not met. However, for each glazing type the design option with no shading (previous step) still acts as a benchmark for that glazing and the results of the higher WWR design option with shading are compared to them.

**Overhang**

The best performing design options for each glazing type that fit the criteria are highlighted in grey. As seen in Figure 6, using an overhang increases visual comfort (lower DGP>0.45 and UDI>3000lux) and decreases daylight for all glazing types compared to the benchmark design even for coated glazing with higher WWR (50%). For coated glazing the increase in window size causes the energy cost to be slightly higher. The main aspect influencing the optimal depth of the overhang is the glazing characteristics and the required daylighting levels. It should be noted that the term “optimal” used in this study refers to the best performing design options based on the analysed criteria.

**Fixed horizontal louvres**

After running 180 simulations for all glazing types the design options that meet sDA\(_{300/50\%}\)>50% criterion are identified and highlighted in a light grey tone (Figure 7). The darker grey cells represent the slat depth which show better performance for that number of slats for each glazing type. Looking at the dark grey cells for each glazing type it is evident that the energy cost is similar and
**Figure 6. Performance of the design options with overhang**

Units: Energy cost (€/year) DGP (>)0.45 (%) sDA 300/50 (%) UDI >3000 lux (%)

<table>
<thead>
<tr>
<th>Slot Depth</th>
<th>Energy cost</th>
<th>DGP (&gt;)0.45 (%) sDA 300/50 (%) UDI &gt;3000 lux (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No shading</td>
<td>N.01</td>
<td>N.02</td>
</tr>
<tr>
<td>Overhang Depth</td>
<td>0.5</td>
<td>0.6</td>
</tr>
</tbody>
</table>

**Figure 7. Performance of the design options with horizontal louvres**

Units: Energy cost (€/year) DGP (>)0.45 (%) sDA 300/50 (%) UDI >3000 lux (%)

<table>
<thead>
<tr>
<th>Slot Depth</th>
<th>N.01</th>
<th>N.02</th>
<th>N.03</th>
<th>N.04</th>
<th>N.05</th>
<th>N.06</th>
<th>N.07</th>
<th>N.08</th>
<th>N.09</th>
<th>N.10</th>
<th>N.11</th>
<th>N.12</th>
<th>N.13</th>
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<th>N.18</th>
<th>N.19</th>
<th>N.20</th>
</tr>
</thead>
<tbody>
<tr>
<td>N.01</td>
<td>N.02</td>
<td>N.03</td>
<td>N.04</td>
<td>N.05</td>
<td>N.06</td>
<td>N.07</td>
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<td>N.17</td>
<td>N.18</td>
<td>N.19</td>
<td>N.20</td>
<td></td>
</tr>
</tbody>
</table>
the main difference between the options are daylighting levels and the occurrence of intolerable glare. The results indicate that the optimal shading device design option differs based on the glazing characteristics and project goal i.e. in this study the goal is to have at least $\text{sDA}_{3000/50\%}>50\%$ with the least annual energy cost and percentage of the annual occupied hours that DGP exceeds the 0.45 threshold. The black cells show the best performing shading device option for each glazing type that fulfills this goal. It should be noted for each glazing type if few design options show similar performance the selected optimal design is based on showing better performance in two out of three mentioned criteria. It is observed that the optimal design options (black cells) have more slats (9-10) but the depth of the slat changes based on WWR and glazing light transmission.

**Step 3: Side-by-side comparison**

Figure 8 shows the side-by-side comparison of the benchmark design (no shading) with the optimal design options for each glazing type from the second step for the two shading devices. As mentioned before, in this step for the selected design options $\text{UDI}_{100-3000\text{lux}}$ and $\text{DGP<0.4}$ is also investigated. Figure 8 shows that the designs with fixed horizontal louvres show better performance in all analysed criteria compared to the designs with overhang. Moreover, fixed horizontal shades show better performance in all criteria except daylighting levels compared to the benchmark design. Moreover, the design options with fixed horizontal louvres have the highest useful daylight illuminance levels ($\text{UDI}_{100-3000\text{lux}}$) compared to the other two options. As can be seen in Figure 8, the percentage of the annual occupied hours that DGP values are within the perceptible and imperceptible range are higher for design options with fixed horizontal louvres. Moreover, the DGP values are in accordance to the CEN daylighting standard (EN 17037) for medium glare protection level which implies that the maximum amount of time throughout the year when DGP exceeds the 0.4 threshold is 5% of the usage time. The results indicate that fixed horizontal louvres have significant impact on reducing glare and increasing visual comfort especially in high light transmission glazing. Also with the right configuration high levels of daylight with lower energy cost can be achieved.

**Step 4: Point-in-time glare analysis**

In this step, a point-in-time glare analysis is conducted for the best performing design options from the previous step with the highest and lowest light transmission glazing (GLZ1 and GLZ3). Figure 9 provides an overview of the patients view angle and the false colour and HDR image of the scene for a sample design option. Figures 10, 11 and 12 show a fish-eye visualization of the patient’s view.
point from 10 am to 2 pm on 23rd of October. As expected, the figures show that horizontal louvres have a higher impact on controlling the source of glare (direct sunlight) compared to an overhang. The results show that both shading devices fail to prevent glare before noon caused by low sun angles.

**Conclusion**

The outcomes of this study revealed that the glazing characteristics (U-value, g-value and TVis) and the shading device configuration have a major impact on the design performance of a south-oriented patient room and
hence should be carefully selected during the early design process. The results highlight the fact in order to meet the daylighting analysis threshold the window size and shading device configuration should be considered carefully especially for the designs with lower light transmission glazing. This is important especially for patient rooms (e.g., for bedridden patients) where adequate daylight levels is necessary. It is observed from the results that the main contributor to the energy cost is the electricity used for space cooling, this fact shows when selecting glazing the effect of g-value on the cooling loads should be considered even in Belgium where heating is the dominant factor. This study also shows that UDI-3000lux and ASE-250 can act as a proxy and a fast first approximation to estimate the likely appearance of glare (Torres and Verso, 2015). However, the results indicate that there are exceptions to this hypothesis and higher UDI-3000lux values are not always in line with higher DGP values. This indicates that in order to fully understand the impact of window system design on visual comfort a glare analysis should be performed. Further research should include the impact of different orientation and other shading device on the performance. As both shading devices fail to prevent the glare caused by low sun angles before noon, it would be favourable to study the influence of internal blinds with bed-located controls for patients with limited movement.

It can be concluded that focusing on individual aspects during the design process is not sufficient to get a correct insight into the window systems performance and an integrated approach is required. A parametric study considering the effect of different metrics (energy use, sDA, UDI, ASE, DGP) on window system design options (WWR, glazing characteristic, shading device) can support architects in understanding the cross effects. Hence, this approach can support the choice of the most preferred window system design solution based on the project goals.

References


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