Environmental performance of window systems in patient rooms: a case study in the Belgian context

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Abstract. Hospitals produce high amounts of emissions due to their continuous operation, high flow of people, and intensive HVAC requirements. In order to reduce the environmental footprint of hospitals, it is crucial to improve energy performance while still maintaining a comfortable indoor environment for the occupants. Also to avoid high environmental burdens, it is important to understand the impact of building material selection from the full life cycle perspective. Window systems influence the energy loads and comfort in buildings and provide access to daylight and views. Therefore, windows contribute significantly to the energy consumption and indoor environmental quality of buildings and impact the well-being of occupants. The aim of this study is to determine the influence of various window system design configurations on the environmental performance of patient rooms in Belgium through life cycle assessment (LCA). The method is innovative as it combines dynamic energy simulations and daylight analysis and integrates these in the LCA study of the window systems. The influence of several components is investigated, such as the choice of glazing and shading system. The results are analysed and compared in terms of energy cost for heating, cooling, and lighting, daylighting performance and life cycle environmental impacts. A typical patient room from a hospital design in Belgium is used as a case study. Based on comparative analysis, the paper discusses potential window system design configurations that allow for energy efficient, daylit and environmentally-friendly patient rooms.

1. Introduction

Hospitals are large consumers of natural resources and energy due to their continuous operation, high flow of people, intensive HVAC demand and artificial lighting requirement. In order to reduce the environmental footprint of hospitals, it is crucial to moderate operational energy use through enhanced energy efficiency while still maintaining a comfortable indoor environment that supports the health and well-being of the occupants. So as to avoid high environmental burdens, it is important to understand the impact of building material choices from a full life cycle perspective. Window systems influence energy consumption and thermal/visual comfort in buildings and profoundly affect the indoor environmental quality by providing access to daylight and external view. Therefore, in order to reduce energy demands, emissions from energy use and the environmental burden associated with the choice of building materials, selecting the appropriate window system configuration is a fundamental part of the early design stage decisions and are difficult to change later on.

Literature review shows that only a limited number of studies address the environmental performance of window systems [1,2,3] and there appears to be no study focusing on combining dynamic energy simulations and daylight analysis and integrating these aspects in the LCA study of the window systems. There is hence a need for integrated performance analysis of window systems in patient rooms and this paper provides the first step towards this approach.
This paper presents an integrated approach for the LCA study of the window systems where the link between various window design parameters, and their combined effect on energy consumption, daylighting and environmental impacts are considered. The aim is to determine the influence of various window system configuration on the energy cost, life cycle environmental impact and daylighting in patient rooms. The effect of several components, including glazing type and shading device configuration is investigated. The various window system design alternatives are explored through parametric modelling. The key objective of this study is to identify window system configurations which balance the objectives of a daylit, comfortable and energy efficient patient room with the least environmental impact. The methodology combines dynamic energy simulations, daylight analysis and integrates these in the LCA study of the window systems. The methodology was applied to a typical patient room from a hospital design in Belgium.

2. Methodology
This paper investigates the effect of window system design on the life cycle environmental impact of the patient rooms. The alternative design options are evaluated in three steps. In a first step, the environmental impact study, the energy cost for heating, cooling, and daylight-linked artificial lighting and the daylighting performance of different window systems without any shading device are carried out. In the next step, various shading device configurations are added to the windows and the different design alternatives are evaluated based on environmental cost, energy cost and daylighting. After analysing and comparing the data for each glazing type, the design options with the least environmental and energy cost and higher access to daylight are identified. The final step provides a side-by-side comparison of the benchmark design (without shading) with the best performing selected design options with shading for each glazing type.

The patient room is modelled in Grasshopper [4], which is a plugin for Rhinoceros (3D modelling tool) [5]. Ladybug & Honeybee [6] components for Grasshopper are used to assign detailed patient room simulation parameters including construction types, materials and schedules to the model. Parametric simulations are performed using the Grasshopper plugin Colibri [7] and for the energy and daylighting analysis Ladybug & Honeybee are used to interface with the simulation engines EnergyPlus, Radiance and Daysim. The LCA was performed using the “MMG+_KU Leuven” tool which is an Excel-based tool developed at the research division of Architectural Engineering at KU Leuven in collaboration with VITO (Vlaamse Instelling Voor Technologisch Onderzoek) and BBRI (Belgian Building Research Institute).

2.1. Simulation model description
The patient room dimensions are 4.0 m x 6.0 m x 3.0 m (length x width x height) with 40% WWR (Window-to-Wall Ratio). The simulations only take into account the floor area occupied by the patient, the service area is excluded from the model (see Figure 1). In order to investigate the impact of glazing characteristics on the performance, six glazing types are considered. The double/triple glazing consists of 4 and/or 6 mm glass panes with 15 or 16 mm cavity (90% argon). The Berkeley lab WINDOW 7.6 software is used to determine the thermal and optical characteristics of the glazing. Table 1 lists the key properties of the glazing and Figure 2 shows the position of the coating within the glazing. The uncoated glazing acts as a benchmark for understanding the impact of the coating. Coated aluminium is the choice of material for shading devices. 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. The patient room is located on the second floor and no external obstruction is taken into account. The simulation is performed with the EnergyPlus weather data for Brussels (latitude 50.90° N and longitude 4.53° E).

2.2. Energy analysis
EnergyPlus is used to calculate the annual energy use for heating, cooling and artificial lighting; taking into account the solar and thermal properties of the glazing with detailed layer by layer modelling of the glazing system. Daylight-linked lighting control is employed which incorporates a lighting schedule generated by Daysim software using Honeybee component for annual daylight simulation. The illumination threshold for activating lighting is 300 lux, as this value represents the illuminance
necessary for simple examination and reading. The lighting sensor is placed at the patient’s position to ensure sufficient light at this location.

![Image of patient room area](image)

**Figure 1.** The patient room area taken into account for parametric model dimension

**Table 1.** Glazing characteristics

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

| GLZ: Glazing   | Tvis: Visible transmittance | Configuration: 4, 6 Glazing thickness (mm) - 15, 16 Cavity thickness (mm) |

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

Dotted line: position of coating(s)

Space heating and cooling setpoint temperatures are assumed to be 21°C and 24°C respectively. Mechanical ventilation and infiltration are set to 2.00 (ac/h) and 0.20 (ac/h) respectively. 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. In order to calculate the energy cost for heating a global system efficiency of 0.85 and for cooling a CoP (Coefficient of Performance) of 1.80 are considered. Natural gas (heating) and electricity (cooling and artificial lighting) prices (€/kWh) are based on the Belgian market prices of 2017; the price of electricity for one kWh is approximately four times the price per kWh of natural gas.

2.3. Daylight analysis

This study used climate-based daylight modelling which provides hourly daylight predictions for an average year derived from weather data. Honeybee is used to interface with the Radiance based daylighting analysis tool Daysim. The output from Daysim is a data file containing the annual illuminance/luminance values for the analysis points in the room.

UDI (Useful Daylight Illuminance) and sDA (spatial Daylight Autonomy) are used to assess the daylighting performance. The metric sDA_{300:50%} describes the percentage of an analysed area that meets the target illuminance of 300 lux for at least 50% of the annual occupied hours. This threshold also represents the “minimum” daylight provision value required by CEN daylighting standard (EN 17037: 2018) on the task plane during more than 50% of the daylight hours [8]. UDI_{100-2000lux} determines when daylighting levels are within the range defined as useful for the occupants and UDI_{>2000lux} presents the times when excessive levels of daylight could lead to visual discomfort [9]; This metric could also act
as a proxy for detecting the likely appearance of glare. UDI metric describes the hourly varying daylight illuminances for the entire year at each of the calculation points [9].

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 plane level is located 0.9 m above the ground (bed surface) with a grid of sensor points with a 0.3 m spacing, the reference point (sensor) location is selected based on the patients position in the room (see Figure 1). The walls, ceiling, floor and shading device reflectance are assumed to be 50%, 80%, 20% and 60% respectively.

2.4. LCA study

The “MMG+-KU Leuven” tool is based on the MMG method: the national method in Belgium to quantify the environmental performance of building elements. The LCIA (Life Cycle Impact Assessment) method applied in the MMG method combines the environmental impact indicators CEN and CEN+ [10]. The CEN indicators consist of seven environmental impact categories in line with the European standard and the CEN+ indicators include ten additional impact categories considered in Belgian legislation. For each impact category, the results are expressed as characterised results (equivalents) and as external environmental costs (monetary values, €). The environmental life cycle costs are calculated by multiplying the characterization values by a monetisation factor. This value represents the costs required to avoid, repair or compensate the damage caused by the environmental impacts [11]. Further details regarding this method can be found in De Nocker and De Backer [12].

The environmental impacts associated with each glazing type are assembled based on the data obtained from the AGC (Asahi Glass Co., Ltd) Glass Europe. The aluminium shading material is modelled via SimaPro and the environmental impacts are calculated. These inventory data are then further processed in MMG+-KU Leuven tool. In order to calculate and study the life cycle environmental impact of the patient rooms, the selected design options are modelled in the MMG+-KU Leuven tool (with and without shading device). In this study energy consumption data estimated via EnergyPlus is the basic input for the MMG+-KU Leuven tool.

3. Result and discussion

3.1. Step 1

In this step, for each glazing type the environmental impact, annual energy cost, UDI100-2000lux, UDI-2000lux and sDA300/50% are calculated without a shading device. The data obtained from this step acts as a benchmark for analysing the impact of shading devices on environmental performance. It should be noted that the criteria taken into account for evaluating the performance of the design options are environmental cost, energy cost, sDA300/50%>50% and UDI.

As can be seen in Figure 3, uncoated double and triple pane glazing (GLZ1 and GLZ4) show the highest energy and environmental cost due to higher heating and cooling loads. Moreover, triple pane GLZ6 which has a g-value of 0.38 and the lowest U-value among the glazing types shows the least energy and environmental cost; this is due to the lower heating and cooling loads. As for daylighting performance GLZ6 still maintains a sufficient level (58% sDA). The results show that there is ca. 18% difference between the sDA value for the highest (GLZ1) and lowest (GLZ3) light transmission glazing. However, GLZ3 has the highest UDI100-2000lux and lowest UDI-2000lux compared to the other glazing types which indicates higher access to useful daylighting levels and visual comfort.

3.2. Step 2

The second step consists of analysing different overhang and fixed horizontal louvres configurations for each glazing type. The parameters of the parametric analysis are shown in table 2. The shading device depth range is in accordance with the suns position for this latitude (peak sun angle is ca. 63°) and the height of the window. The shading devices are modelled without mounts and/or anchors. The performance criteria taken into account for evaluating the performance of the design alternatives are similar to the previous step. After adding the shading devices to the benchmark design and 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 the design option without shading device still acts as a benchmark for that type of glazing.

**Figure 3.** Benchmark designs performance without shading device (40% WWR – South orientation)

**Table 2.** Value of parametric variables

| Variables            | Minimum | Maximum | Step |
|----------------------|---------|---------|------|
| Overhang depth       | 0.5 m   | 1.0 m   | 0.10 m |
| Slat depth           | 0.1 m   | 0.3 m   | 0.05 m |
| Number of slats      | 5       | 10      | 1    |

**3.2.1. Overhang.** In this stage for each glazing type, the design option with the least energy cost and sufficient daylight (sDA$_{300/50\%}>50\%$) are selected; shown as highlighted grey cells in Figure 4. The results show that overhangs decrease sDA levels but still increase the useful daylighting levels and visual comfort (lower UDI$_{>2000\text{lux}}$) for all glazing types compared to the benchmark design even for coated glazing with higher WWR (50%). Moreover, the increase in window size for coated glazing results in slightly higher energy costs. In the next phase, the environmental cost of the selected design option for each glazing is calculated. As can be seen in Figure 5, the options with uncoated glazing (GLZ1 and GLZ4) and GLZ6 have the highest and lowest environmental costs respectively, similar to the previous step. The results show that the selected designs with coated glazing have higher environmental costs compared to the benchmark design, this is due to the increase in window size (50% WWR) which leads to higher quantities of overhang material and energy loads.

**3.2.2. Fixed horizontal louvres.** In the first phase after running energy and daylighting simulations for all glazing types the design options that meet sDA$_{300/50\%}>50\%$ criterion are identified and highlighted in a light grey tone as shown in Figure 6. The darker grey cells represent the slat depth which shows better energy and daylighting performance for the specified number of slats for each glazing type. The results show that the selected design options (darker grey cells) for each glazing type have fairly similar energy costs and the main difference between the options are the daylighting levels. In the second phase, the environmental performance of the selected design options for each glazing type are calculated and analysed, see Figure 7. The findings show the environmental impact of each design option is directly linked to the quantity of material used for the shading system. However, for designs with coated glazing the difference between the best and worst case scenario is ca. 2.5%. As for uncoated glazing design options the difference is less than 2%; this is due to lower operational energy use for cooling. The results
indicate that the optimal shading device configuration differs based on the project goal i.e. in this study the goal is to have the least environmental and energy cost with sufficient daylighting levels and visual comfort. The black cells in Figure 6 show the best performing design option for each glazing type that fulfils this goal.

| GLZ1 [0.82/0.80] 40% WWR | Energy cost | sDA<sub>300/50%</sub> (%) | UDI<sub>100-2000 lux</sub> (%) | UDI>2000 lux (%) |
|-----------------|-------------|-----------------|-----------------|-----------------|
| GLZ2 [0.73/0.41] 50% WWR | 91 | 71 | 89 | 60 | 89 | 56 | 89 | 55 | 89 | 53 | 88 | 51 |
| GLZ3 [0.61/0.31] 50% WWR | 88 | 62 | 88 | 52 | 87 | 47 | 88 | 46 | 88 | 42 | 88 | 42 |
| GLZ4 [0.76/0.74] 40% WWR | 103 | 63 | 100 | 51 | 99 | 47 | 99 | 46 | 99 | 46 | 99 | 46 |
| GLZ5 [0.75/0.53] 50% WWR | 84 | 72 | 82 | 61 | 82 | 58 | 82 | 56 | 82 | 55 | 81 | 53 |
| GLZ6 [0.68/0.38] 50% WWR | 78 | 65 | 77 | 66 | 77 | 54 | 77 | 53 | 77 | 50 | 78 | 49 |

**Figure 4.** Energy and daylighting performance of the design options with overhang. Units: Energy cost (€/year) sDA<sub>300/50%</sub> (%) UDI<sub>100-2000 lux</sub> (%) UDI>2000 lux (%) 

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

Figure 8 and 9 show the side-by-side comparison of the benchmark design (without shading) and the optimal design options for each glazing type with shading devices. Figure 8 shows that the design options with fixed horizontal louvres have better performance in most analysed criteria compared to the other designs, except for higher environmental costs in some design options. This is due to the quantity of the material used for the shading system, which in some cases is slightly higher. Moreover, some design options with horizontal shades show lower sDA values (ca. 10% less in the most extreme case) compared to the benchmark design but still maintain a sufficient level (sDA<sub>300/50%</sub>≥50%). The comparison also shows that fixed horizontal louvres reduce UDI>2000 lux values which could reduce the likely appearance of glare and increase visual comfort. The results, as can be seen in Figure 9, reveal that GLZ5 and GLZ6 design options show the least environmental impacts compared to the other glazing. This is mainly due to lower operational energy use for heating and cooling. As for GLZ5 design option with louvres this is also the result of smaller window size and less quantity of shading material.
Figure 6. Performance of the design options with horizontal louvres

N: Number of slats  Units: Energy cost (€/year) sDA (300/50%) UDI (00-2000lx) (%) UDI (2000lx) (%)

| Slats | 0.10 | 0.15 | 0.20 | 0.25 | 0.30 |
|-------|------|------|------|------|------|
| 5     | 108.7 92 | 106.8 61 | 104.9 40 | 102.9 50 | 100.9 50 |
| 6     | 108.8 92 | 106.9 61 | 104.9 40 | 102.9 50 | 100.9 50 |
| 7     | 108.8 92 | 106.9 61 | 104.9 40 | 102.9 50 | 100.9 50 |
| 8     | 108.8 92 | 106.9 61 | 104.9 40 | 102.9 50 | 100.9 50 |
| 9     | 108.8 92 | 106.9 61 | 104.9 40 | 102.9 50 | 100.9 50 |
| 10    | 108.8 92 | 106.9 61 | 104.9 40 | 102.9 50 | 100.9 50 |

Figure 7. The environmental performance of the design options with horizontal louvres

GLZ1 [0.82/0.80] 40% WWR (DG)
GLZ2 [0.73/0.41] 50% WWR (DG)
GLZ3 [0.61/0.31] 50% WWR (DG)
GLZ4 [0.76/0.74] 40% WWR (TG)
GLZ5 [0.68/0.38] 50% WWR (TG)
GLZ6 [0.75/0.53] 50% WWR (TG)
4. Conclusion

The findings show that the glazing characteristics and the shading device configuration impact the design performance significantly and hence the selection and configuration of the window system design should be considered carefully during the early design process. The results highlight the fact that the window size and shading device configuration have a major impact on daylighting levels and visual comfort. This is especially important for patient rooms where adequate daylighting level is necessary and the patients have limited movement and generally are unable to adapt by moving around in the space. It is observed from the results that in the design options with shading, the main contributors to the environmental impacts are the window size and the quantity of material used for the shading system. The results show that design options with coated glazing have lower life cycle environmental impacts compared to options using non-coated glazing with similar conditions due to the reduction in energy use. The results also indicate that the most significant environmental impact indicators in all the design
options are associated with global warming, particulate matter formation and human toxicity (cancer effects). This study shows that a comprehensive and integrated performance analysis approach is required to have a correct insight into the window system design performance. It can be concluded that a parametric study which considers the impact of window system design options (WWR, glazing characteristic, shading device, etc.) on various performance criteria (energy cost, environmental cost, sDA, UDI, etc.) can assist architects in understanding the cross effects. Thus, this approach can support the selection process of the most preferred window system design configuration based on the project objectives.

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