

Investigating the Energy Efficiency, Environmental and Daylighting Performance of Coated Glazing

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Facades are a crucial interface between exterior and interior conditions and greatly influence the architectural quality of buildings. Glass plays an important role in the building envelope by providing daylight, views and ventilation and hence can contribute significantly to indoor environmental quality and impact occupants' comfort and well-being. Glass also plays an important role in the energy balance of the envelope and hence in both energy loads and environmental performance of a building. In order to avoid high energy consumption, reduce environmental impact and increase the quality of the space selecting the appropriate size and type of glazing along with the orientation and shading based on the building's function, the climatic conditions, site and occupants' needs are a fundamental part of early design stage decisions and are difficult to change later on. The challenge is to improve the building quality by providing a balance between energy efficiency, comfort and saving resources. To reduce energy consumption through glazing taking into account the thermal insulating properties is insufficient, it is also necessary to consider the coatings impact on the physical properties of glass regarding radiation. Coatings are often used to improve the thermal insulation, solar control, acoustic insulation of glazing in order to reduce heat loss, maximize solar gains in winter and minimize it in summer and improve indoor environmental conditions. Multiple configurations of coatings are available on the market to date. The goal of our study is to determine the impact of coated glazing on the energy performance, daylighting and the environmental performance of buildings where occupants spend substantial time inside. This paper incorporates an integrated performance analysis method and presents an energy analysis, daylighting and a life cycle assessment (LCA) study of several coated glazing for patient rooms in Belgium.

Keywords: Energy efficiency, Environmental performance, Daylighting, Coated glazing

1. Introduction

In the European Union 40% of total energy consumption is due to the building sector (Stazi et al. 2012) and the healthcare sector accounts for more than 5% of the greenhouse gas emissions in Europe (Stevanovic et al. 2015). Hospitals are considered one of the most energy demanding building types that produce high amounts of emissions and waste due to their constant operation, high flow of people, intensive HVAC (heating, ventilation and air conditioning) requirements and polluting outputs. Strategies are hence needed to reduce the energy consumption and environmental impacts while still providing quality care for patients.

Windows not only provide daylight, views and ventilation but also impact the heat flow, solar gains and aesthetics of buildings and contribute significantly to the quality of the indoor environment, energy consumption and environmental performance of buildings and also influence the health and productivity of the occupants (Choi et al. 2012; Vanhoutteghem et al. 2015). In order to avoid high energy loads, reduce environmental impact and increase the quality of the space selecting the appropriate glazing based on the building's function, the climatic conditions, site and occupants' needs are a fundamental part of early design stage decisions and are difficult to change later on. This can be achieved by incorporating an integrated performance analysis method where the link between various glazing characteristics and their combined effect on energy efficiency, environmental impact and indoor environmental quality are considered. This paper presents an integrated approach to find a balance between increasing energy efficiency while maintaining a comfortable and daylighted indoor environment with the least environmental impact. The methodology combines energy simulations, daylighting analysis and life cycle assessment (LCA). For this study, energy and daylighting simulations are performed with EnergyPlus and Ladybug & Honeybee respectively, while for the LCA study the MMG+_KU Leuven tool is used.

2. State of the Art

Literature review shows that while there are many studies on glazing with regard to energy consumption, comfort and lighting in office buildings (Ochoa et al. 2012; Susorova et al. 2013) these topics have been less explored in hospitals (Alzoubi et al. 2010; Sherif et al. 2014). Most previous research on glazing performance mainly focus on energy, daylighting and comfort (Carlos and Corvacho 2015; Manz and Menti 2012; Ochoa et al. 2012; Sherif et al. 2014; Skarning et al. 2016; Stegou-Sagia et al. 2007; Vanhoutteghem et al. 2015) whereas the environmental aspects are less explored and the existing research mainly focuses on the LCA of building façade (Delem 2016; Kim 2011) or envelope (Azari 2014; Stazi et al. 2012). Furthermore, only a limited number of studies concentrate on the environmental performance of window systems (Citherlet 2000; Papaefthimiou et al. 2008; Salazar and Sowlati 2008)

and there appears to be no comprehensive and recent study that simultaneously takes into account the effect of glazing on the energy use, comfort, daylighting and the environmental performance of buildings. This paper is an initial step towards an integrated performance analysis method.

3. Methodology

The effect of glazing type on energy consumption, environmental performance and daylighting in a patient's room in a hospital is investigated through building simulations. A base case is taken as reference and analysed by varying one parameter at a time in the model. This approach is chosen to compare the effects of one parameter in detail while all the other parameters are fixed. The sample patient room is used as the base case with a fixed user scenario and glazing type as the variable element. For each variation, the energy consumption, the life cycle environmental impact and the daylight availability are analysed. This section presents the assumptions and the parameters analysed.

3.1. Simulation Model Description

The glazing types are selected based on Belgian standards for new buildings, hospital patient room standards, climatic conditions and the availability on the Belgian market. Table 1 lists the key properties of the glazing types adopted in this study and Figure 1 shows where the coating is positioned in the glazing systems. Glazing with different g-values and visible transmittance (Tvis) are considered to investigate the role of permanent solar shadings (glazing with solar control coating) on the energy loads and to evaluate the impact of various light transmission on daylighting and lighting energy use. The glazing consists of two glass panes (4 or 6 mm) and a 16 mm cavity filled with gas (90% argon). The Berkeley lab WINDOW 7.5 software is used to determine the thermal and optical characteristics of the glazing systems.

The uncoated glazing is selected as a reference for comparison as the glass panes used in most of the coated glazing listed in Table 1 use this type of glass. The uncoated glazing moreover acts as a benchmark for understanding the impacts of coatings. This glazing does not comply with new building construction standards for windows in Belgium as the U-value of the whole window should not exceed 1.50 (W/m²K). For all the glazing types, a highly insulated aluminium frame with a U-value of 1.40 (W/m²K) is assumed.

In order to investigate the energy efficiency, daylighting and environmental performance of the various glazing types, 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 (based on a recently built hospital in Belgium). The window dimensions are 1.5 m x 3.2 m (height, width) with a 0.8 m sill height. For this patient room, the glazing unit is considered as the variable element; the rooms are named based on their glazing. 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. No external obstruction is taken into account. EnergyPlus weather data (TRY, Test Reference Year) for Brussels (latitude 50.90 N and longitude 4.53) is used for the simulations.

Table 1. Glazing characteristics

GLZ [Tvis/g-value]	Coating	Tvis	g-value	U-value (W/m ² K)
GLZ [0.82/0.78]	No coating	0.82	0.78	2.50
GLZ [0.82/0.63]	Thermal insulation	0.82	0.63	1.10
GLZ [0.76/0.52]	Solar control + Thermal insulation	0.76	0.52	1.10
GLZ [0.73/0.42]	Solar control + Thermal insulation	0.73	0.42	1.10
GLZ [0.59/0.43]	Solar control + Thermal insulation	0.59	0.43	1.10

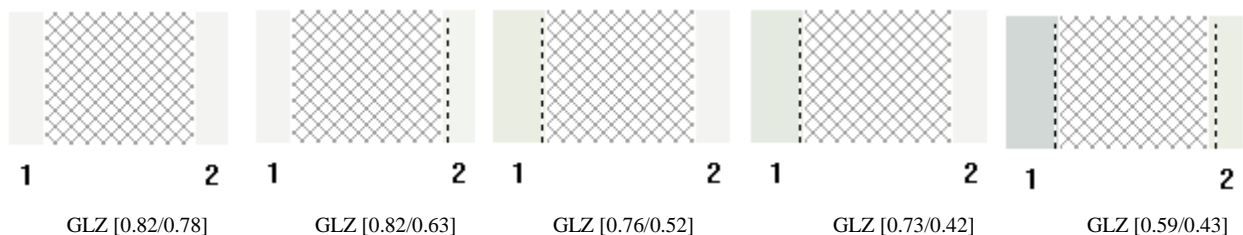


Fig. 1 Glazing coated surfaces; 1- Outer glass pane 2- Inner glass pane

Dotted line: position of coating

3.2. Step 1: Energy Analysis

The patient room is modelled in DesignBuilder based on the patient room specification, occupants' behaviour and 24 hours x 7 days occupancy. The annual energy demand of the rooms are calculated using EnergyPlus as simulation engine and taking into account the specific solar and thermal properties of the glazing with detailed layer by layer glazing system modelling and the adopted lighting control strategy. Room heating and cooling set-point temperatures were assumed to be 22°C and 24°C respectively, relative humidity between 30% to 60% and mechanical ventilation was set to 2 (ac/h). Internal gains from people and lighting are 120 W and 140 W respectively. These assumptions are in line with standards provided for patient rooms. Mechanical ventilation is modelled with heating and cooling using the EnergyPlus Ideal loads system; the effects of heat recovery and economiser are included. A lighting control strategy responsive to daylight is employed so that the influence of the glazing on the lighting energy use can be compared. After obtaining the simulation results for each room, the overall energy performance of the various glazing types is investigated.

3.3. Step 2: LCA Study

To investigate the life cycle environmental impact of the various coated glazing systems, an 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). This tool is an expert calculation tool which is based on the MMG method; the national method in Belgium to quantify the environmental performance of building elements. The LCIA method in the MMG methodology combines environmental impact categories from the CEN standard (EN15804), referred to as CEN indicators, and additional ones in line with the ILCD handbook (General Guide For Life Cycle Assessment - Detailed Guidance 2010), referred to as CEN+ indicators.

The CEN indicators include global warming, ozone depletion, acidification, eutrophication, photochemical ozone creation, abiotic depletion resources-elements, abiotic depletion-fossil fuels and the CEN+ indicators cover human toxicity, particulate matter formation, ionising radiation: human health, ionising radiation: ecosystems, ecotoxicity, water scarcity, land occupation, land transformation. For each impact category the results are expressed as characterised results (equivalents) and as external environmental costs (monetary values, EURO). For the latter, the characterization values for each environmental indicator are multiplied by a monetisation factor (e.g. $X \text{ kg CO}_2 \times Y \text{ €/kg CO}_2$). This factor reflects the extent of the potential damage to humans and/or the environment, expressing it in a financial amount for the purpose of avoiding potential damage or compensating elsewhere (if less expensive) or settling any damage incurred. These euro based figures express the environmental damage that is not incorporated in market prices but are passed on to society through e.g. sickness and damage to biodiversity (Environmental profile of building elements 2013); further details on the method can be found in Denocker and De Backer (2014).

The environmental impacts associated with production, maintenance and disposal of the glazing are assembled based on the EPD (Environmental Product Declaration) and data obtained from the AGC (Asahi Glass Co., Ltd) Glass Europe. This was then integrated into the MMG+_KU Leuven tool to model and calculate the impacts of the window systems (glazing + frame) at product level. For the patient rooms LCA, the rooms are modelled in the MMG+_KU Leuven tool also integrating the results obtained from EnergyPlus and finally the environmental impacts are calculated and studied. Further details about the procedure is provided in figures 2 and 3.

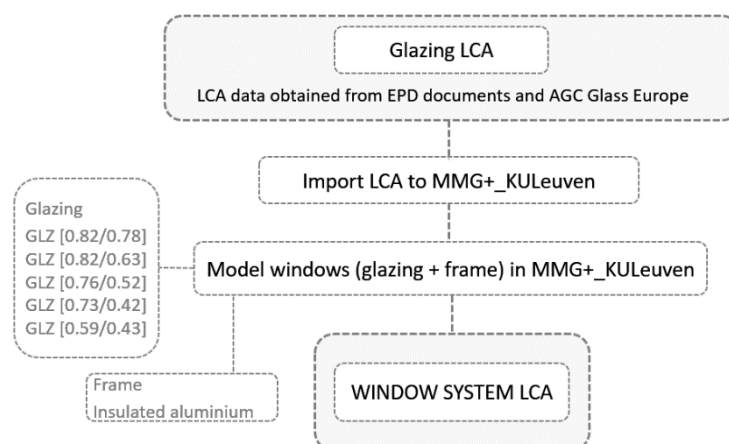


Fig. 2 Window system LCA method

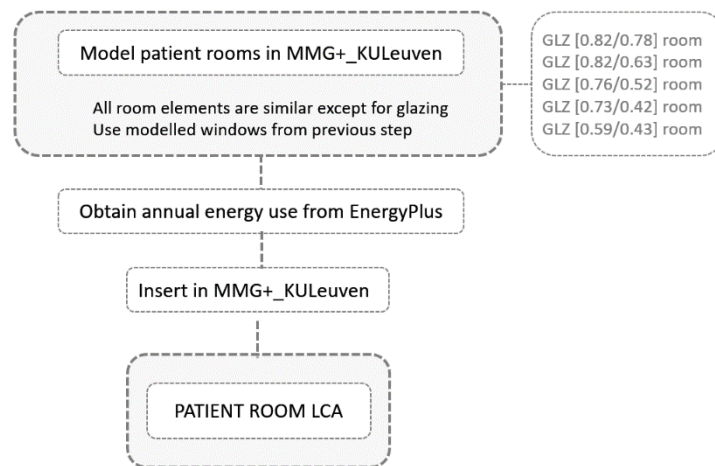


Fig. 3 Patient room LCA method

3.4. Step 3: Daylighting Analysis

In this study dynamic or climate-based daylight modelling is used, which provides daylight predictions under realistic sun and sky conditions based on available weather data. This approach was preferred to the daylight factor method due to the fact that it gives a better representation of actual daylight qualities. Daylight factor is calculated under standard CIE¹ sky conditions, the sun's position is not relevant and variations in daylight for different climates, locations and building orientations are not taken into account.

For the daylighting analysis, the patient room is modelled in Grasshopper, which is a plug-in for Rhinoceros (3D modelling tool). After the model was created, materials and other simulation parameters are assigned using the plugins Ladybug & Honeybee, which use Daysim for annual daylight availability.

Daysim is a Radiance-based simulation tool that calculates the annual indoor illuminance/luminance level based on weather data. Radiance is a validated, physic-based backward ray tracer that can simulate indoor illuminance distributions due to daylight (Reinhart 2010). The output from Daysim is a data file containing the annual illuminance values for the analysis points in the room.

The occupied time for daylighting simulation is set to 7 AM to 8 PM due to the body's need for daylight in these hours to reinforce circadian rhythm. The daylight illuminance analysis points are located in a grid with a spacing of 0.3 m and a height above ground of 0.9 m and the reference point (sensor) location is selected based on the patient's position in the room.

For daylight availability this study uses DA (Daylight Autonomy) value with a minimum illuminance of 125 lux. DA is defined as 'the percentage of the occupied hours of the year when a minimum illuminance threshold is met by daylight alone' (Reinhart 2010). As the illuminance necessary for simple examination and reading is 300 lux this value is analysed for the reference point to ensure sufficient daylight at the patient's position. Both the threshold illuminance of 125–300 lux and the 100–2000 lux interval are studied. Literature review shows that daylight illuminance levels are beneficial when in the range of 100–2000 lux (Grynning et al. 2014). After determining the daylight illuminance values at the reference point, the insufficient illuminance is supplied by lighting to meet the minimum illuminance value (125 lux); the lighting control strategy used is 'Linear/off'. For daylight calculations the walls, ceiling and floor reflectance are 50%, 80% and 20% respectively.

4. Result and Discussion

4.1. Step 1: Energy Analysis

The annual energy consumption in all rooms is dominated by heating as shown in Figure 4. The results show that GLZ [0.76/0.52], GLZ [0.73/0.42] and GLZ [0.59/0.43] rooms with lower g-values and solar control coating display similar energy performance. The heating energy for the room with uncoated glazing (GLZ [0.82/0.78]) is approximately 30% higher compared to the room with solely a thermal insulation coating (GLZ [0.82/0.63]) and the cooling energy is approximately 45% higher compared to rooms with solar control coated glazing (lower g-values). Results indicate that the room with a 0.43 g-value has the best energy performance amongst all rooms. Figure 4 shows that lighting energy is quite similar for all rooms which suggests that very high light transmission ($T_{vis} > 75\%$) has a minor impact

¹ Commission Internationale de l'Eclairage (International Commission on Illumination)

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on reducing the lighting energy use. As can be seen in figures 4 and 5 daylight-linked control lighting reduces lighting energy by approximately 50%.

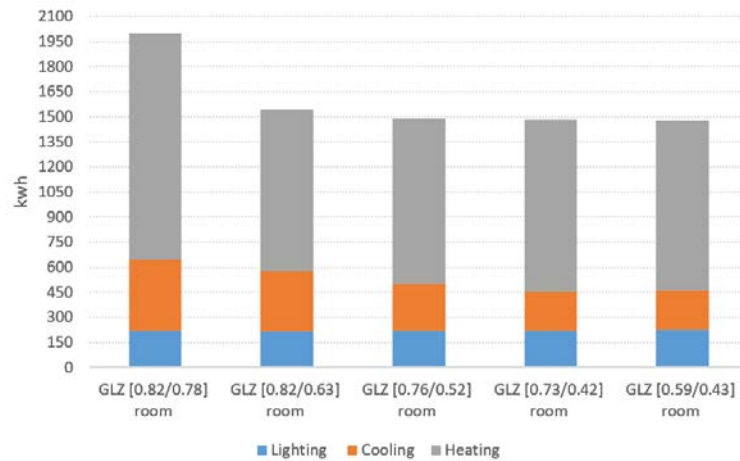


Fig. 4 Annual energy loads of the patient rooms

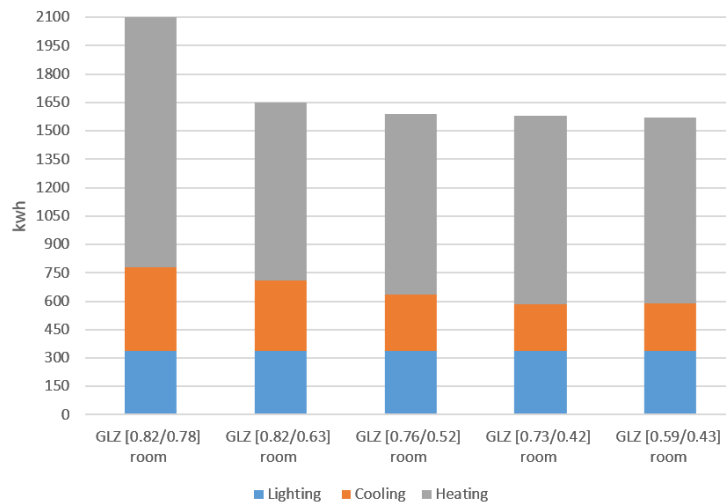


Fig. 5 Annual energy loads of the patient rooms without daylight-linked lighting control

4.2. Step 2: LCA Study

As can be seen in Figure 6, all glazing units with 6 mm + 4 mm glass panes have higher impacts compared to the glazing with two 4 mm glass panes, revealing that the impacts are dominated by the amount of glass. When comparing the windows with uncoated (GLZ [0.82/0.78]) and coated (GLZ [0.82/0.63]) glazing with the same amount of glass the difference between impacts are rather small; showing that the coating has a minor effect on the environmental impacts. Furthermore, the environmental impacts of solar control + thermal insulation coated glazing are similar once again proving that the contribution of the coatings on the environmental impact is low. The results show that the most significant environmental impacts in all windows are related to global warming and particulate matter formation.

Figure 7 shows that the room with the uncoated glazing has the highest environmental impact due to higher operational energy use; the operational energy refers to the energy consumed for space heating, cooling and lighting. The four remaining rooms show a similar performance (Figure 7) while the rooms with solar control coating and lower g-values perform slightly better; the difference between the three rooms with solar control coating are minor. The results indicate that global warming has the highest impact contribution in all rooms; this is due to the operational energy and the production stage. It should be noted that in the MMG+_KU Leuven tool the energy use for space cooling is represented in the appliances and lighting category.

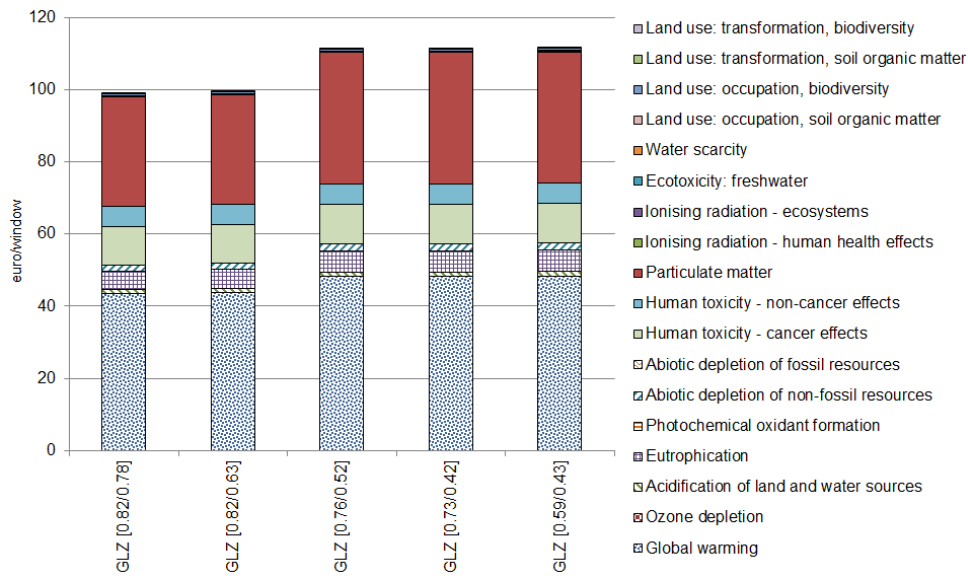


Fig. 6 Environmental impact of the window systems (4.80 m² window)

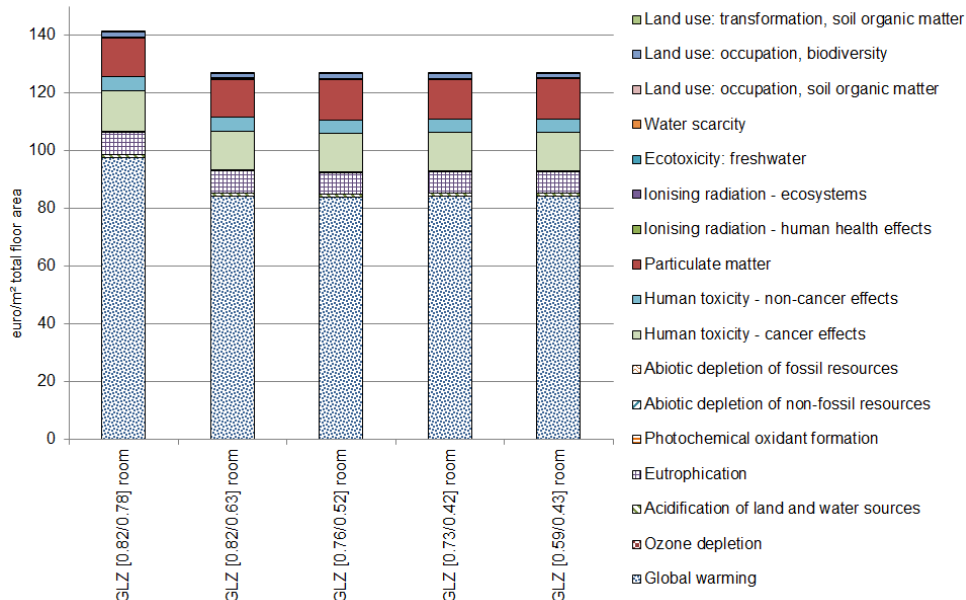


Fig. 7 Environmental impact of the patient rooms (24m² floor)

4.3. Step 3: Daylighting Analysis

Figure 8 shows the DA percentages at the analysis points in the rooms for 125 lux and 300 lux respectively. As can be seen in Figure 8 (a) for 125 lux target illuminance, all glazing types show a quite uniform performance with approximately 70-76% DA at the selected reference point. Figure 8 (b) shows that with higher target illuminance of 300 lux the DA value at the reference point in the room with GLZ [0.59/0.43] is ca 10% lower compared to other rooms with higher light transmission but still receives sufficient daylight of ca 58% DA; which shows that 58% of the year the target illuminance of 300 lux is met at the reference point with daylight alone. Sufficient daylight for regularly occupied floor area based on LEED² metrics is considered to be 55-75% sDA (spatial Daylight Autonomy). As expected higher daylight autonomy is observed near the window, while lower values is found at the back of the room. It should be noted that one third of the room at the back is service area and does not require daylighting. Table 2 shows the average annual illuminance at the reference point for the glazing.

² Leadership in Energy and Environmental Design (green building rating system)

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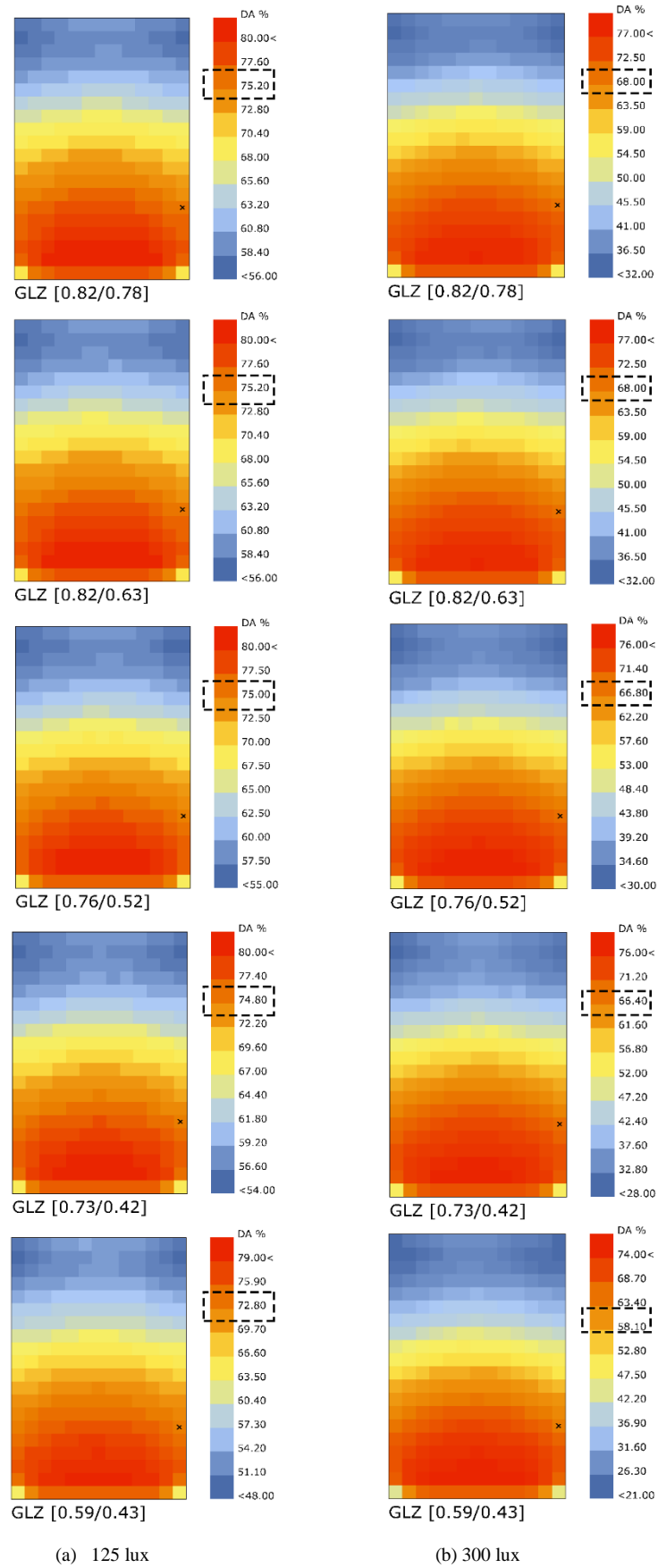


Fig. 8 DA (Daylight Autonomy) values
The value at the patients position (marked by x) is outlined with box

Table 2. Average annual illuminance at the reference point

GLZ [Tvis/g-value]	Coating	Lux
GLZ [0.82/0.78]	No coating	1017
GLZ [0.82/0.63]	Thermal insulation	1017
GLZ [0.76/0.52]	Solar control + Thermal insulation	938
GLZ [0.73/0.42]	Solar control + Thermal insulation	894
GLZ [0.59/0.43]	Solar control + Thermal insulation	695

Figures 9 and 10 show the annual hourly illuminance values under TRY conditions at the reference point when the illuminance is between 100-2000 lux. Two extreme cases are presented, the rooms with the highest and lowest light transmission glazing. The main difference between the figures is from April to September, as shown the hourly illuminance values of minimum 2000 lux are more frequent for the room with high light transmission glazing which can lead to visual discomfort. Also there is a difference between the figures at the two ends (winter period) but the difference is not significant.

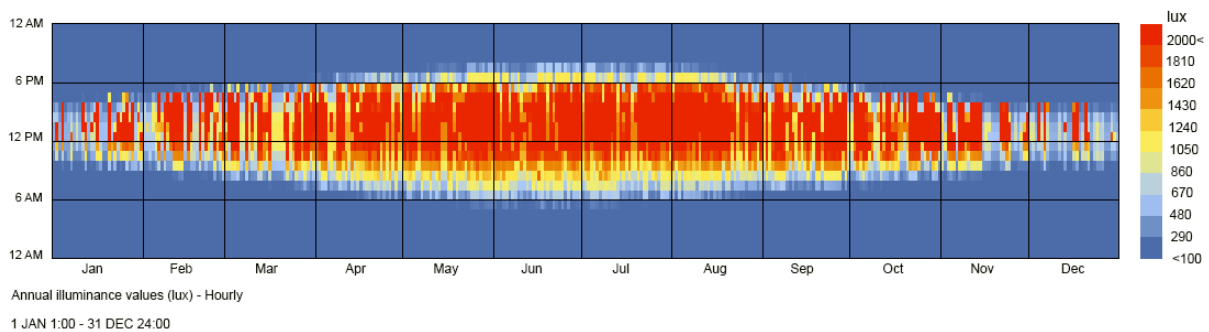


Fig. 9 GLZ (0.82/0.63): Annual hourly illuminance map of the reference point

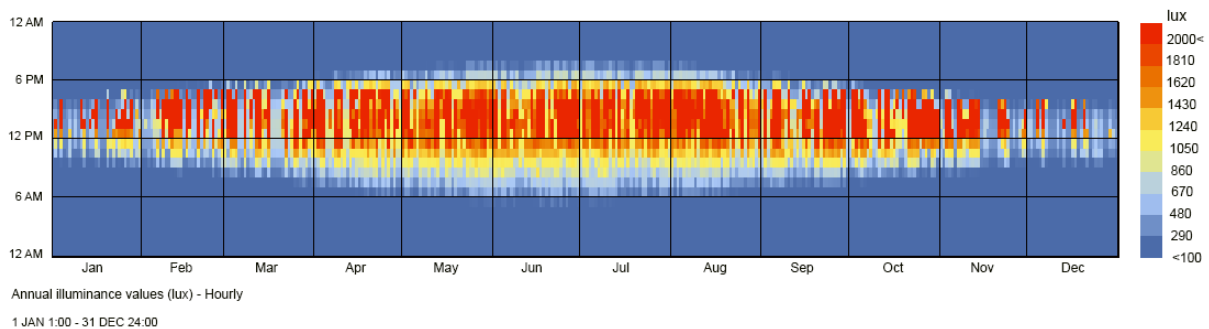


Fig. 10 GLZ (0.59/0.43): Annual hourly illuminance map of the reference point

5. Conclusion

The characteristics of the glazing with coating have major impacts on the energy loads. When selecting glazing the effect of the g-value on the cooling loads should be considered even in Belgium where heating is the dominant factor. From the glazing considered, the rooms with solar control coating show the best overall performance while the room with 0.42 g-value performs slightly better. The simulations moreover highlight the fact that glazing with light transmission of approximately 60% and solar control coating (lower g-values) allows for efficient daylighting and lower cooling loads. The study also shows that automatic daylight-linked lighting control has a significant effect on the lighting energy use.

The results show that glazing with coating and thicker glass panes have slightly higher environmental impacts at product level - regardless its application - but due to their contribution in lowering the operational energy (building level), the impacts of the patient rooms are slightly lower compared to the rooms with uncoated and/or thinner glazing.

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The results moreover indicate that the coatings analysed lead to lower life cycle environmental impacts of the patient room compared to the situation using non-coated glazing due to the reduction of the energy loads which are higher than the increase of impacts caused by the coating material. The environmental impact of the glazing is mainly influenced by the amount of glass used rather than by the coating.

This paper is an initial step towards an integrated performance analysis method which takes into account the effect of glazing characteristics on the energy consumption, environmental performance and daylighting. Further research should include the impact of different orientation and WWR as well as externally placed shading systems on coated glazing performance. Glare analysis and visual comfort should also be studied.

The results indicate that focusing on individual aspects is not sufficient to get a correct insight in the glazing performance and an integrated approach which simultaneously considers all aspects is required. It can be concluded that selecting the suitable glazing characteristic based on the climatic conditions and building function is a very important issue to be addressed in the early design stage.

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