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Glare analysis of an integral daylighting and lighting control strategy for offices

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Abstract. Complex Fenestration Systems (CFSs) can significantly impact both the visual and non-visual daylight effects on the occupants as well as the energy performance of buildings. To ensure that those impacts improve the overall situation, proper control algorithms are required if the CFS can be operated. The state of the CFS directly and immediately effects the indoor lighting situation. The thermal condition of the building is usually strongly but not directly influenced by the condition of the façade system due to thermal capacities.

In this study an experimental integral control strategy, called Integrated Lighting Module (ILM) is investigated in terms of it's glare prevention capabilities and compared to a cut-off- and a simple rule based control logic. The ILM is an autonomous software package capable to run on building management hardware to control façade systems and artificial lighting in real buildings in an energetically optimised way. The adaptive sampling algorithm RAYTRAVERSE is employed to calculate Daylight Glare Probability (DGP) values, which are used as a benchmark for the control strategy comparison. The other aspect of this comparison is the opening of the façade, which is evaluated as statistics how often each possible façade state is selected by each control strategy.

1. Introduction

Since finding the optimal state of a Complex Fenestration System (CFS) based on a simulation model is a complex and computationally expensive endeavour, simplifications have to be made. In common control logics, the risk of glare is usually estimated in a very rudimentary way, e.g by setting a limit to the global radiation on the façade. The glare estimation in the Integrated Lighting Module (ILM) is based on luminance evaluations of the façade for each workplace individually. For this study the input data for the ILM originates from an energy plus weather file for the location Innsbruck, Austria for a single office room with south oriented façade and three independently controllable lamella systems, to produce an annual timeline of façade states. Two simpler strategies, operating all three façade parts in the same way are also considered for reference. For all time steps the glare situation is then evaluated by separate ray-tracing calculations. The evaluation of the energetic performance of the control strategies is beyond the scope of this study. With these findings, the glare estimation in the ILM can be validated and potentially in future work be optimized for specific rooms and façade systems. Simulation routines for image-based glare investigations, i.e. Daylight Glare Probability (DGP), are well approved and computationally demanding and therefore often replaced by illuminance-based approximations such as simplified Daylight Glare Probability (DGPs). However, illuminance-based glare metrics are not as well correlated with glare occurence [1] and are particularly poorly correlated with full luminance based DGP values when some solar control is deployed on the façade [2]. In this research, the adaptive sampling algorithm RAYTRAVERSE is employed to calculate DGP values, which drastically reduces the calculation cost while maintaining high accuracy [3, 2]. DGP values are calculated on four working positions within a test office room with three independently controllable lamella systems. Three control strategies, described in section 2.2, are applied and the results are compared and discussed in section 3. The performed simulations are split in two parts as described in section 2.3. First in an annual simulation a time series of façade states, chosen by the respective control strategy, is generated, and afterwards the simulation in RAYTRAVERSE is performed for all occurring façade states. A similar investigation has been pursued in a former work by Wienold [4], which is used as a template for this present study. In [4], cut-off angle and a rule based control strategies are compared to a manual strategy that assumes an occupant controls the blinds in direct agreement with a DGP prediction. Here, we test how well the ILM strategy for simplifying the DGP calculation comes to such an optimized control logic that also considers the thermal and energy impacts of the façade states.

2. Method

RAYTRAVERSE is used to calculate DGP values for the hourly time steps of a weather file for the façade states suggested by the applied control strategies. In this way, glare conditions can be found that may have gone undetected by the ILM's simplified algorithm or occurred during the operation of the comparison strategies.

2.1. Test Office Room

The analysis is performed for an office, situated in Innsbruck, Austria, with three façade parts facing south, whereby each is equipped with an individually controllable lamella system. The facade is 4.5 m wide, 3 m high and the room depth measures 6 m. The upper two thirds of the facade parts are glazed, the lower third is opaque. An energy efficient standard is assumed for the building with U-values of $0.713\,\mathrm{W\,m^{-2}\,K^{-1}}$ and $0.15\,\mathrm{W\,m^{-2}\,K^{-1}}$ for the glazing and the opaque parts respectively. Since the room is assumed to be inside a larger building with similar neighboring rooms, the thermal conductivity through the west, east and north wall as well as through the floor and ceiling is neglected. The thermal evaluation is beyond the scope of this study, but since the ILM algorithm comprises an energetic optimization, the energy standard of the building is relevant. Four working positions are considered in the office, two each at 1.55 m (sensor 1 and 2) and at 3.35 m distance (sensor 3 and 4) to the façade, facing each other (viewing direction parallel to the façade). For all four the DGP is calculated in all time steps. The lamella system consists of circular bend lamellae in light gray colour (RAAL 9007), which can be tilted to angles chosen out of the set $\{0°, 10°, 15°, 25°, 35°, 45°, 60°, 75°\}$. The blinds can either be deployed or fully retracted independently.

2.2. Control Strategies

Three control strategies are applied and the obtained results in terms of DGP and degree of façade opening are compared to each other. The ILM strategy performs a simplified energetic optimization and avoids glare risk, operating each façade part independently. The other two control strategies serve as reference and follow simple rule based decisions, which are applied on all three façade parts in parallel, whereby excessive entry of solar radiation is avoided, but no special attention is given to glare concerns.

2.2.1. Integrated Lighting Module The ILM strategy comprises a daylight calculation after the three-phase-method via RADIANCE [5] and a simplified thermal module based on the (outdated) standard ISO 13790:2008 [6], whereby the thermal entry is calculated using two dimentional solar heat gain coefficient values for all eligible façade states. The calculation effort is split into a pre-calculation for the specific site, room geometry and façade system and an optimization procedure during the simulation time step or, in case of an application in a real building, in real time. Most of the daylight calculation, namely the calculation of the view factor matrices for each window, the bidirectional scattering distribution matrices for each façade position and the daylight matrix is done during the pre-calculation. During the time step the daylight vector is calculated from the direct normal and diffuse horizontal solar radiation, the global horizontal illuminance and the sun position, which is then multiplied to the matrices so that the internal lighting and glare situation can be retrieved for all possible façade states. For the thermal calculation the exterior temperature is taken into account as well. The glare estimation within the ILM is simplified and bases on the calculation of luminance values in a rough resolution of ten points per glazed facade part viewed from each working possiton. To detect glare situations, hard limits are defined for the luminance which could be observed by the workers. If any worker observes a maximal luminance of $3000\,\mathrm{cd\,m^{-2}}$ or more, or if the mean luminance observed is higher then $1000\,\mathrm{cd\,m^{-2}}$, glare is detected and the corresponding façade state is excluded from the optimization in this time step. More details on the algorithm of the ILM and it's application in a real office are published in [7]. For all other façade states the artificial lighting energy demand is simplified estimated via the missing illuminance to $500\,\mathrm{lx}$ per working place with a fixed factor of $80\,\mathrm{lx\,W^{-1}}$ from the available horizontal daylight illuminance on each working desk. The total energy demand for all remaining façade states to choose from is calculated comprising the artificial lighting energy demand and the heating or cooling energy demand (whereby the artificial energy demand is also considered as an additional internal gain), whereby primary energy factors are assumed for heating, cooling and artificial lighting. Since the energy calculation holds some simplifications, the final façade state choice is not just the one with the lowest total energy demand, but from all façade states causing an estimated energy demand of $110\,\%$ or less than the absolute minimum, the one allowing the maximum sum of the vertical illuminance values in the workers viewing position is chosen.

2.2.2. Reference Control Strategies For reference, a rule based strategy, and a cut-off strategy are also employed. The rule based strategy closes the blinds with a constant slat angle of 45° if the global radiation on the façade is higher then $200\,\mathrm{W\,m^{-2}}$ and opens the façade otherwise. The cut-off control strategy closes the blinds just so far, that direct solar radiation is prevented from entering the room, if the global solar radiation hitting the façade is above $150\,\mathrm{W\,m^{-2}}$ and opens the façade otherwise.

2.3. Simulation and Evaluation

The simulation procedure is split in two parts. The goal of the first part is to determine the façade states for every hour in the provided weather file. The second part is the analysis of the glare situation.

2.3.1. Façade States The global vertical irradiation on the façade is calculated from the direct normal and diffuse horizontal irradiation. The sun position is derived for each time stamp for the chosen location. In case of the rule based strategy a simple comparison of the global vertical irradiation values with the threshold of 200 W m^{-2} leads to the times when the façade is open and when it is closed. For the cut-off strategy the sun position vector is projected to the vertical surface perpendicular to the façade to obtain the sun's profile angle, which is then compared to all available lamella profile angles to obtain the most open façade state without allowing direct sunlight to enter the room for all timestamps, where the global vertical irradiation on the façade is 150 W m^{-2} or above. The ILM is a software package provided in matlab.

2.3.2. Glare Calculation For the evaluation of the glare situation with RAYTRAVERSE, the room has been modelled as a RADIANCE scene. Contrary to the setup in the ILM where the blind system has been modelled as bidirectional scattering distribution functions (BSDFs), for the RAYTRAVERSE analysis the blind system was geometrically modelled via the genblinds command for all selectable lamella angles and exchanged in the RADIANCE scene according to the choice of the control strategy at work. The RAYTRAVERSE API has been implemented in a python script to systematically perform the annual dalyight simulation retrieving the DGP results for the three different control strategies.

3. Results and Discussion

Figure 1 to Figure 3 illustrate the annual occurrences of glare achieved by the three control strategies. The detailed results for each sensor position are reported by Figure 5 to Figure 4, whereby office hours between 07:00 and 17:00 have been assumed. The degree of façade opening for all three windows is illustrated by the frequency of chosen lamella angles in Figure 7. The comparison of the results of the DGP calculations show, that the simplified glare calculation in the ILM works well in terms of preventing glare situations, as can be observed in Figure 1.

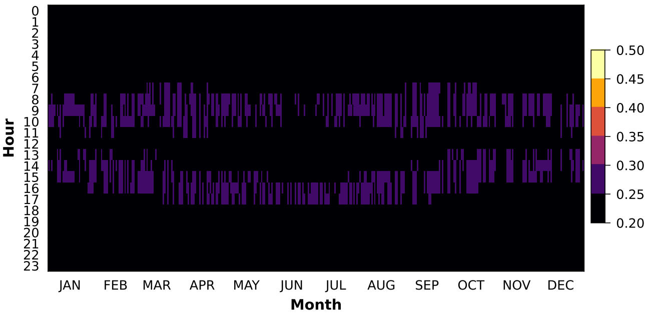

Figure 1. Hourly maximum DGP at four locations achieved by control strategy *ILM*.

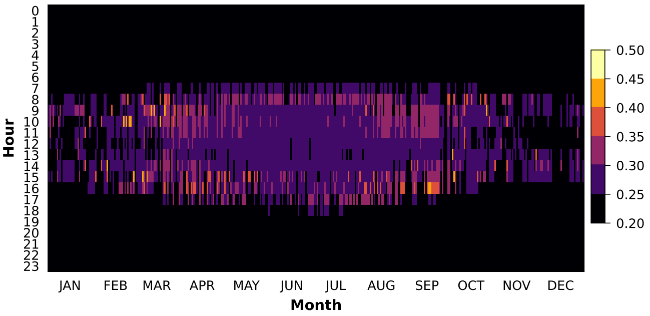

Figure 2. Hourly maximum DGP at four locations achieved by control strategy *cut-off*.

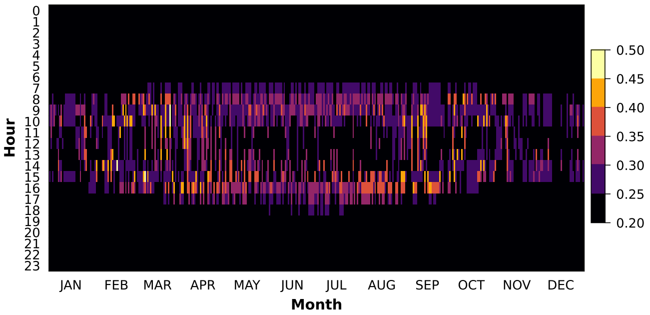

Figure 3. Hourly maximum DGP at four locations achieved by control strategy *rule based*.

Also Figure 5 to Figure 4 show, that the 95 percentile values of hourly DGP for the ILM of the working positions close to the façade (sensor 1 and 2) are comparable to the values achieved by the two reference control strategies at the working places further away from the façade (sensor 3 and 4). However, the glare results of the cut-off strategy are already in a well acceptable range, so the ILM can be considered over critical in this regard.

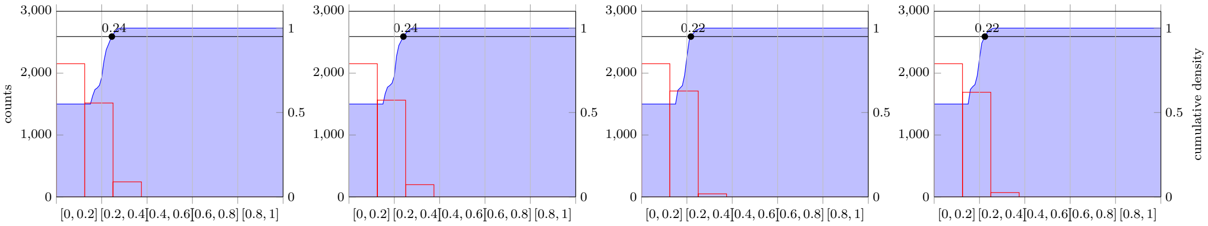

Figure 4. Cumulative frequency and 95 percentiles of hourly DGP at four sensor locations achieved by control strategy *ILM*.

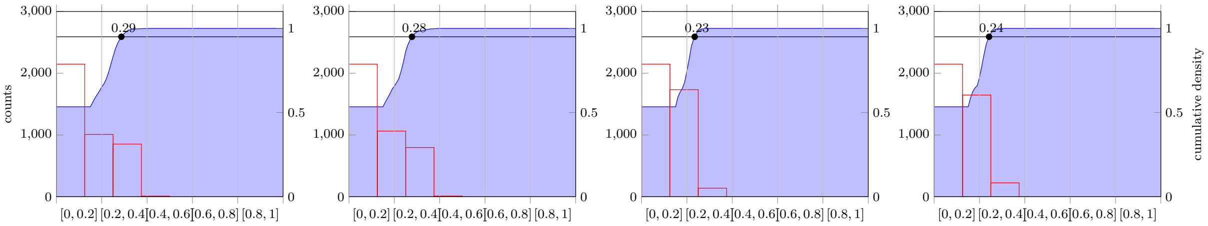

Figure 5. Cumulative frequency and 95 percentiles of hourly DGP at four sensor locations achieved by control strategy *cut-off*.

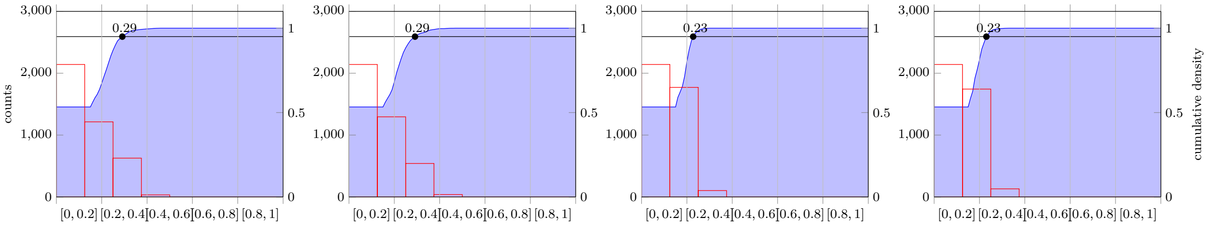

Figure 6. Cumulative frequency and 95 percentiles of hourly DGP at four sensor locations achieved by control strategy *rule based*.

Comparing the frequencies of chosen lamella angles in Figure 7 shows the downside of this restrictive glare avoiding behaviour, which results in much longer time periods with further closed blinds compared to the reference strategies.

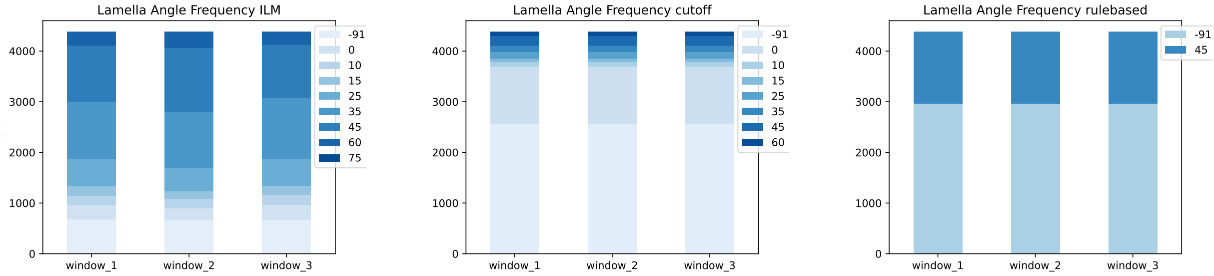

Figure 7. Frequency of chosen lamella angles in hours for all three windows. The angle of −91° indicates, that the blinds are retracted. Left: ILM. Center: rule based strategy. Right: cut-off strategy. While the ILM can choose the lamella angles and deployment of the façade for all three windows independently, the other two strategies always retract or deploy the lamellae for all three windows at the same angle.

Further investigations in fine tuning the ILM have to be made, e.g. by adjusting the luminance threshold for the simplified glare estimation. The established setup proved well applicability as a test bench for control strategies and/or façade systems in terms of glare avoiding potential and opening of the façade. Future work should also include a thermal investigation in a dynamic building simulation environment to comprise the evaluation of the control strategies and/or façade systems potential to facilitate solar gains in the heating period and the ability to prevent the room from overheating in the cooling period. Further optimization of the setup process (e.g. by integration into a BIM workflow) and of the code concerning the calculation per time step will help to facilitate the application of the ILM in real buildings in the foreseeable future.

Acknowledgments

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