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Integrated Daylight and Energy Evaluation of Passive Solar Shadings in a Nordic Climate

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Abstract

Modern well-insulated and highly glazed buildings experience increased overheating, even in cold climates. The study focused on external and internal passive solar shadings on a south-oriented façade, having predetermined that external and internal shadings' main function is solar heat gain and glare protection, respectively. A daytime-occupied office space with several external shading geometry variations was simulated using an integrated daylight and energy approach aided by Radiance, Daysim, and EnergyPlus within Grasshopper. The method involved preparation of daylight-driven lighting schedules, and glare-driven internal blinds operation schedules for each design scenario, which were further applied to annual energy simulations. The interdependence of light in visible and thermal form, its impact on the building performance, and the resulting occupant response to the changing indoor conditions are core to this study. The comparative nature of the study allowed to evaluate thermal and visual performance of fixed external shadings in Nordic climates. The chief study findings highlight the gross impact of internal shading operation on overall building performance and indoor comfort, and the holistic benefit of external solar protection that includes reduction of total energy use and improvement of occupants' thermal and visual comfort.

Keywords: passive solar shading, daylight, energy use, glare, thermal comfort, overheating, cold climate

1. Introduction

The world's population, production, and energy consumption are growing, and according to the International Energy Agency (IEA, 2019), the world's total energy use has doubled in the span of the last three decade. The building sector is estimated to use about 40 % of the global energy, yet environmental and sustainable building regulations are fairly new – the energy-efficient practices to reduce the building consumption emerged in Europe in the 1990s. Even though only around 25 % of all European buildings are non-residential, it is estimated that their average specific energy consumption per floor area is 40 % more than of the residential sector (BPIE, 2011)

There is a scientific consensus regarding climate change, which affirms that global temperatures are rising (Cook et al., 2016). Lechner (2015) reminds that "one of the main reasons for regional differences in architecture is the response to climate". Sustainable design ensures buildings are tailored to maximise their performance, provide good indoor climate, and abide by their local environment. Heating demand gradually becomes a secondary issue even in traditionally heating-dominated climates (Grynning et al., 2014). Reduction of infiltration, lower U-values, highly glazed facades, and high internal heat loads of modern office buildings all contribute to overheating and consequently cooling loads much higher than in conventional leaky buildings. The importance of solar protection devices in reducing cooling loads, ensuring thermal comfort, and mitigating glare in a Swedish cold climate scenario was demonstrated by Wall and Bülow-Hübe (2003). ASHRAE (2017) reads that "the most effective way to reduce the solar load on fenestration is to intercept direct radiation from the sun before it reaches the glazing system". Researchers are in agreement that fenestration design must incorporate solar shading solutions in early building design stages, as it will have an immense effect on energy reduction and improvement of indoor comfort (Dubois, 1997; Haase et al., 2011; Poirazis et al., 2008). Still, the key functions of windows, which are daylighting and visual contact with the outdoor scene, should be preserved.

Solar shading devices can be placed externally or internally. Similarly, devices can be fixed or movable, and, in case of the latter, manually or automatically controlled. Passive shadings are those that do not require energy to function. Externally placed solar shadings are more effective in solar heat gain prevention than internal devices. Moreover, external shadings as fixed elements have higher life expectancy and are less prone to degradation, as opposed to movable ones that can induce operational energy, higher costs and maintenance (ASHRAE, 2017;

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Hammad and Abu-Hijleh, 2010). On the other hand, fixed shadings permanently block a portion of natural daylight, which may cause increased use of electric lights. Furthermore, they reach lower performance efficiencies than automated systems (Bakker et al., 2014).

Many studies debate occupant preferences regarding control systems and often discuss dissatisfaction with automated systems, however, there is no clear consensus about the patterns in which people respond to the indoor climate conditions (Zhang et al., 2018). A field study by Sadeghi et al. (2016) suggests that occupants express higher satisfaction with the indoor climate when they are allowed to adjust the control levels to their liking. The impact of occupant behaviour on building performance has been widely recognised. Simulated energy use can differ as much as three times when compared to the real-life occupant-interactive performance (Delzendeh et al., 2017). Therefore, the energy and daylight simulations should consider user control patterns as they will affect the overall results (van den Wymelenberg, 2012). The subject of human interactions is very complex and dependant on location, cultural inclinations, and acceptable comfort levels that are understandably subjective and varying.

Low solar angles, very common in higher latitudes, are difficult to shade with fixed external shadings, thus necessitate supplementation of vertical window blinds to satisfy comfort functions such as: radiant energy protection, privacy, brightness control (ASHRAE, 2017). Sporadic need for employment of internal blinds means they are typically movable and require a control strategy. Various control types and thresholds of internal blinds operation can be found in literature. A commonly used control measure variable is illuminance since internal blinds are closely associated with visual comfort rather than thermal comfort (van den Wymelenberg, 2012). The reason might be that in reality thermal comfort is harder to evaluate, measure, and also to sense by an occupant, since in a conditioned space the occupant might not be aware of excessive solar gain. Illuminance can be expressed simply in lux on a surface or in terms of glare. Daylight glare probability (DGP) is a method of calculating the likelihood of glare occurrence by analysing illuminances at occupant's eye level (Wienold and Christoffersen, 2006). Its simplified version is an efficient way of predicting visual discomfort caused by extreme brightness or contrasts within a field of view (Wienold, 2009). DGP is expressed as a percentage and values above 40 % are expected to cause disturbing glare that might trigger an occupant to employ blinds. Internal blinds schedule can therefore be driven by DGP and this control method was found to be most accurately representing the average control behaviour in a study by da Silva et al. (2012) comparing different control types and thresholds.

Climate based dynamic simulation tools are widely used in today's design process and performance evaluations (Kirimtat et al., 2016). Increasing number of studies underline the importance of an integrated daylight and energy performance analysis in a holistic approach that considers interdependency of visual and thermal dynamics in a building (Karlsen et al., 2016; Manzan, 2014; Tzempelikos and Athienitis, 2007). The fundamental correlation between daylight and energy is the use of electric lights. Since every lighting source emits heat, not only does daylighting impact the electrical energy use to power lights but also the demand for heating and cooling. State-of-the-art study on advanced shading systems listed a set of relevant criteria that can be used to make an informed design of a fenestration system (Kuhn, 2017). Those included solar heat gain reduction, thermal comfort, daylighting, visual comfort, view to the outside, etc. More recent studies put emphasis on human comfort in addition to thermal performance, as satisfaction with the indoor environment is linked to higher productivity and well-being of occupants (Day et al., 2019).

This paper presents a comparative study of external solar shadings in a cold Nordic climate. The issue of overheating is a rather new subject matter for heating-dominated climates, in recent years exacerbated by extensive insulation and airtight building envelopes. This study aims to address this gap and analyse passive solar shading solutions, externally fixed to an office room fenestration in the Stockholm weather scenario. Integrated simulation approach was used, including daylight and energy aspects with bespoke schedules governing the operation of internal zone control systems.

2. Method

The study was conducted on a theoretical typical office room – a 'shoebox' model. This reference model (Reinhart et al., 2013) had internal dimensions of 3.6 m × 8.2 m × 2.8 m. There was no outdoor shading context and surface boundary conditions were adiabatic, except for one south-oriented external wall on which a window was placed (Fig. 1). The window-to-wall ratio (WWR) was 84 %, which can be described as a highly glazed façade. WWR was measured against the internal wall dimensions and did not include frames. The modelling was done in

Rhinoceros 3D – a licence-based software, while Grasshopper simulation plugins were open-source, available online for free. The climate data used for annual simulations was an *epw file. It represented a typical meteorological year for Stockholm (Sweden).

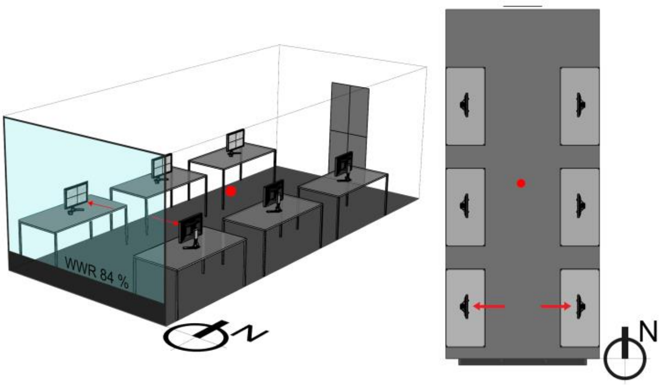


Fig. 1: Reference model (left: perspective view, right: top view)

There are six workstations available within the space of the reference model, but the permanent occupancy was set to four persons with a metabolic heat generation of 120 W person^{-1}. The occupancy time was 8AM to 6PM, seven days a week with summer daylight saving time from April to October. The equipment load was 8 W m^{-2}. Temperature setpoint (target air temperature during occupancy time) and setback (allowed air temperature outside of occupancy time) were 21 °C and 15 °C respectively for heating, and 25 °C and 30 °C for cooling. The external wall construction was an example of a typical highly insulated Swedish lightweight wall with the *U*-value of 0.13 W m^{-2} K^{-1}. The internal walls were also lightweight. Two window solutions were tested, their properties are listed in Table 1. The windows were triple-glazed, argon-filled.

Tab. 1: Glazing types and properties

Glass	Product name	*U*-value (W m^{-2} K^{-1})	*g*-value	τ_{vis}
Clear	Iplus top 3	0.6	0.5	0.7
Selective	Ipasol Ultraselect	0.5	0.26	0.54

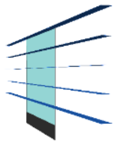
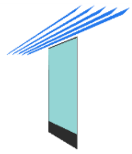
The building had a set constant volume outdoor air supply of 0.35 l s^{-1} per square meter of floor area as is required by the Swedish building code (Boverket, 2011) with additional 7 l s^{-1} per person that meets a bronze criterion of Swedish Miljöbyggnad standard (SGBC, 2020). The system was equipped with a heat exchanger – an enthalpy wheel with sensible heat recovery efficiency of 81 %. Zone conditioning was set to the default EnergyPlus HVAC system called 'Ideal Air Loads'. With this system, all the heating and cooling is airborne, so the air alone has to meet the zone's thermal thresholds and the system is doing so by increasing the flow of air through the heater in a closed loop with no additional outdoor air intake.

The lighting load was obtained with Honeybee 0.0.64 Lighting Density Calculator component using default luminous efficacy for fluorescent T5 tubes, medium maintenance factor, and light illuminance level of 300 lux. The resulting lighting density was 6.9 W m^{-2}. The selected 300 lux work plane illuminance threshold is frequently found in recent literature and certifications (SGBC and BRE, 2018; USGBC, 2019) replacing the standard 500 lux threshold. This turn towards a lower required lighting level for an office space is motivated by a technological shift from paper- to computer-based office work (Richman, 2012).

The operation of electric lights was controlled with a manual on/off switch without dimming. Custom schedules were prepared using illuminance results at a sensor point from the annual daylight simulation. The sensor point was located at the centre of the zone at 0.8 m above the floor (marked in Fig. 1). The control can be perceived as automated rather than occupant controlled, as it does not account for real life user's behaviour patterns and reaction time. This manual control type can therefore be called 'active-user', as it is assumed that the user will react to the changing conditions without failure. Even though the method does not reflect realistic user patterns, its advantage is that it is straightforward and allows for comparative analysis of shading solutions and other factors. With this predictable type of control system, which is free of human factor, the resulting on/off schedule can by itself serve as a daylight metric to describe the daylighting quality of the zone. Percentage of occupancy time when the lights are switched on is thereby a reversed indicator of daylight utilisation.

Fixed external shading cases were devised for a south oriented façade, and the selection of solutions with their abbreviations and dimensions can be found in Table 2. Two sizes of each shading type were selected, so that the shading offsets correspond to roughly 40 % and 80 % of the window height. All fixed external shading geometries had a 20 % diffuse-only reflectance (no specular reflections).

Tab. 2: External shading types and depth sizes

Overhang (OH)	Horizontal louvers (HL)	Brise-soleil (BS)
100 cm, 200 cm	5×20 cm, 5×40 cm	100 cm, 200 cm
		

An overhang shading and horizontal louvers shading are both horizontal and have the same total depth and size of the shading elements, the latter is simply divided into smaller sections (e.g. OH: 100 cm = HL: 5 × 20 cm). From a geometrical perspective, those two shading designs intercept equal amount of direct solar radiation falling on the aperture.

Brise-soleil is a shading that is co-planar with the overhang and it has the same capacity to block direct solar radiation as the overhang, but as opposed to one, it is composed not of just one element but of multiple angled louvers that allow air, precipitation, and light to bounce through. The angle of the slats was 45°. The total horizontal offset of the brise-soleil was the same as for the overhangs, however, the resulting total added brise-soleil louvers length was 19 % less than of the overhang, which means less material can be used with BS type of solar shading.

While external shading device is intended primarily to intercept solar rays in order to protect the space from overheating, it can simultaneously provide a better visual comfort for the occupants by lowering the irradiance of the internal surfaces in the proximity to the aperture. To complement the function, internal blinds were provided additionally as a manually operated shading device that was set to active only in occurrence of disturbing glare, when the simplified daylight glare probability (DGP) result was higher than 0.4. DGP was simulated on the eye level of an occupant seated in the nearest workstation from the window, facing their computer screen placed against east or west wall side (marked in Fig. 1). For each design option a single internal blinds schedule was then obtained considering only the higher DGP value from the two occupant positions results. This method is straightforwardly based on probability of glare occurrence, which could mimic behaviour of an active user, but may not reflect real life occupant control patterns and does not account for passive user scenarios. When the blinds are down, the electric lights have to be switched on, as the blinds do not allow enough daylight to meet the lighting control illuminance threshold, they only manage to reduce the glare probability to an acceptable non-disturbing level. Furthermore, active blinds obstruct the view to the outside during the occupancy hours. This is a performance indicator describing the quality of the fenestration design as it carries information about the visual comfort occurrence. It was therefore used as an analysis metric to assess the visual quality of the space.

The study of shading designs integrated daylight and energy simulations into one workflow aiming to assess the fenestration performance in a more holistic approach. Annual daylight simulations were carried out using Radiance, while annual glare as DGP was calculated with Daysim analysis software, which is based on Radiance. Thermal modelling and energy simulations were performed in EnergyPlus. The geometries were modelled in Rhinoceros and Grasshopper, while the simulation setup was done in the Grasshopper environment using Ladybug and Honeybee plugin tools. The chart in Figure 2 illustrates the workflow method applied in this study. For the two workstations considered in glare analysis, the higher DGP result for a given hour was kept, consolidating two lists into one. Seeing from the chart, two types of results can be obtained: with and without internal blinds employment. When internal blinds were used, daylight-based lighting schedules had to be adapted to include electric lighting operation for the hours during which blinds were down. Having the operational schedules ready, energy simulation is the last step of the simulation workflow.

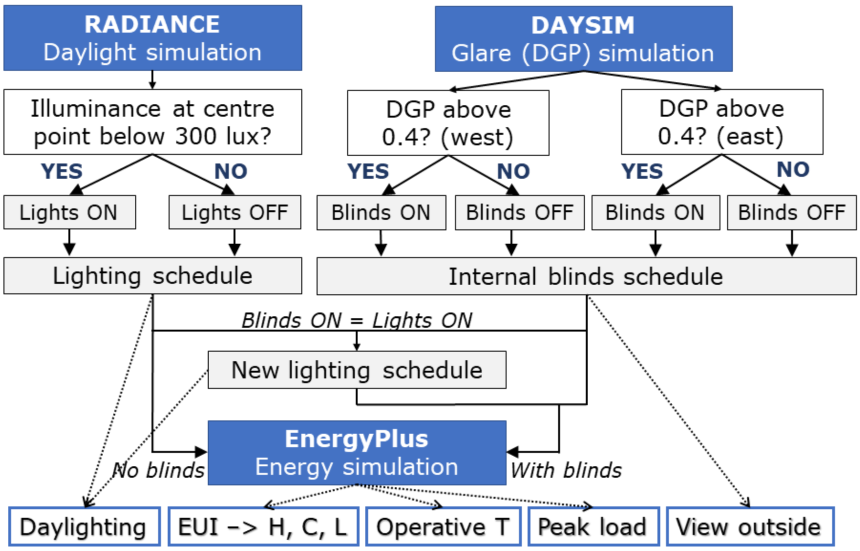


Fig. 2: Simulation workflow

The outputs of the analysis – listed at the bottom part of the chart in Fig.2 – are performance metrics that quantify and help describe the quality of design with regard to: daylight (daylighting), energy use intensity for heating cooling and lighting (EUI), thermal comfort (operative temperature), visual comfort (view outside), and system sizing (peak load).

3. Results

Figure 3 shows results of yearly electric lights use in the occupancy time (3 650 h annually) for investigated external shading cases, distinguishing between clear and selective glass type, as well as comparing the impact of internal blinds operation. Increased use of electrical lighting can be noticed for study cases where blinds schedules were implemented. In those cases, higher daylighting was often achieved by a fenestration design that featured an external shading device.

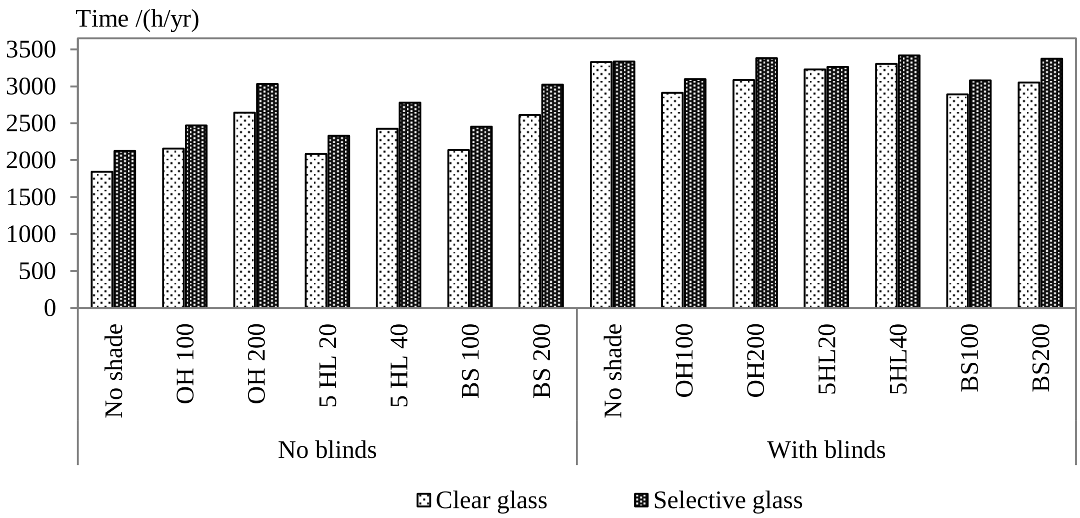


Fig. 3: Electric lighting use derived from daylight availability

Visual comfort expressed by "view to the outside" in Figure 4 indicates the annual availability of view to the outside during occupancy, enabled through low glare probability that entails that the internal blinds can remain open. The visual comfort and consequently the view availability improved dramatically with an external shading device. The graph in Fig. 4 presents percentage of the occupancy time when a) electric lights are required, thus low values are desired, b) occupants have an unobstructed view to the outside – higher values are desired. Noticeably, a given size of horizontal louvers shading compared to an overhang yielded higher artificial lighting use and also provided less hours with view to the outside, which indicates more frequent use of internal blinds with higher glare occurrence. Overhang and corresponding brise-soleil performed equally in that respect. Brise-soleil reduced the use of electric lights when compared to the respective overhang shading only by 1 %.

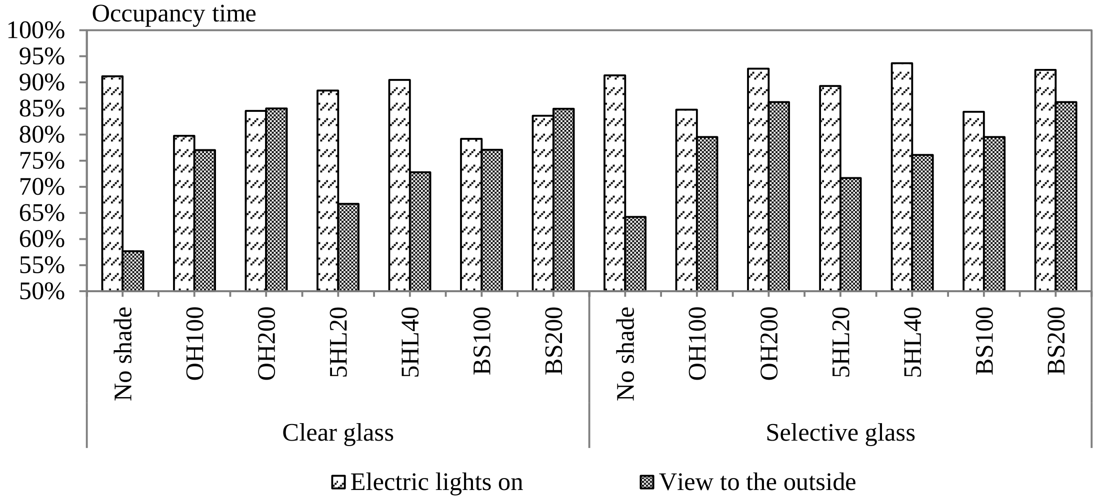


Fig. 4: Share of annual occupancy time with electric lights and view availability

Figure 5 compares the EUI for base cases of unobstructed windows without an external shading device. These cases were simulated with and without glare-driven internal blinds. When blinds were included, the energy results increased for all three energy use segments. The total EUI with internal blinds was higher than without internal blinds operation by 47 % and 41 % for clear and selective glass, respectively.

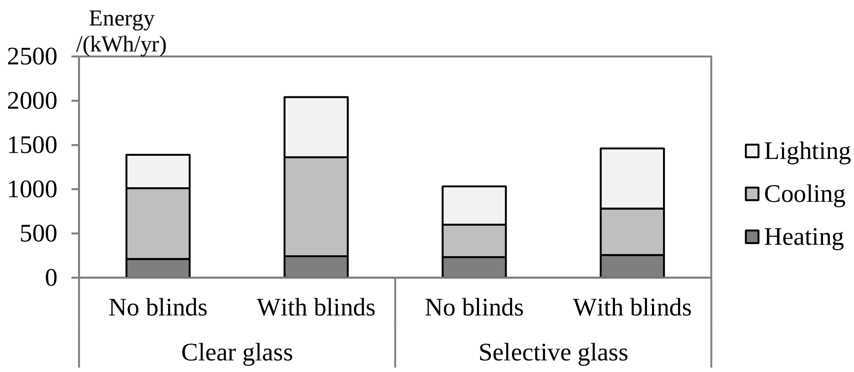


Fig. 5: Annual energy use for cases without an external shading

Considering annual energy use for the cases with external shadings and internal blinds being implemented, it can be seen from results in Fig. 6 that the window benefited from any external shading device regardless of the type of glass as the EUI decreased compared with the base cases (no shade). A large shading size on the clear glass window was better than the small, whereas for the selective glass window the difference with respect to the shading size was insignificant. The horizontal louvers type of shading yielded higher energy use than the corresponding overhang or a brise-soleil due to glare-induced high lighting load and extra internal solar gain added by radiation reflected from the louvers.

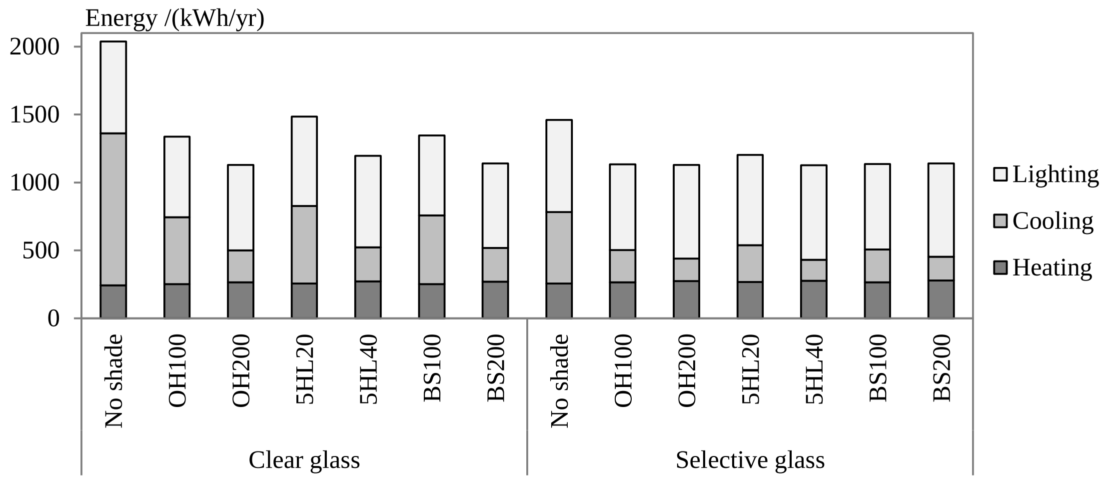


Fig. 6: Annual energy use for external shading cases with internal blinds operation

Thermal comfort metric is presented as a percentage of occupancy time when operative temperatures (equal to the average of mean radiant temperature and air temperature) exceeded the temperature setpoint of 25 °C (Fig. 7). Notably, external shadings improved summertime thermal comfort by means of operative temperatures, and even more effectively when combined with a selective glass window. Additionally, cooling peak loads and solar heat gains were minimised with selective glass cases, especially together with external shadings. System size assessed from cooling peak loads would transpire to be almost identical for large shading with clear glass and as for a small shading with selective glass cases.

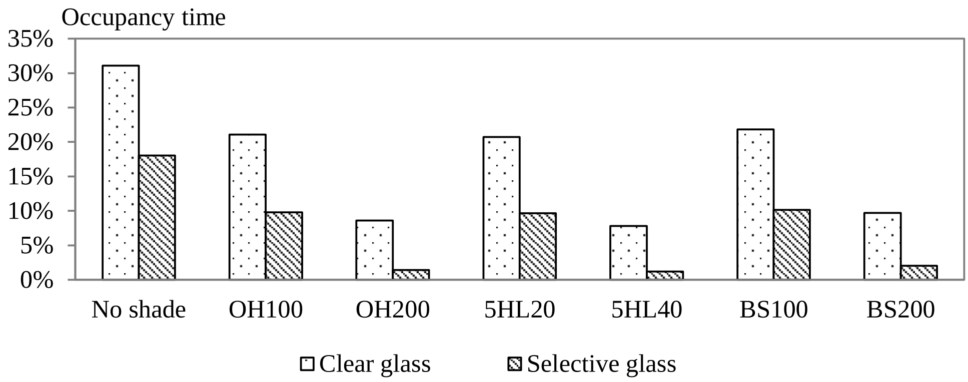


Fig. 7: Percentage of occupancy time with operative temperature exceeding 25 °C

4. Conclusions

The study intended to test, via computer simulations, various external shading geometries and glazing types placed on a south-oriented ‘shoebox’ office room aperture in a Nordic climate of Stockholm. It was done using means of integrated daylight and energy simulation approach. The main focus was the assessment of overheating issues in a modern highly insulated office space with a high thermal load. The study shows that interdependence of light, glare, and solar heat gain in buildings is a complex phenomenon that ought to be approached holistically, in an integrated manner. Its impact can be significant hence should be accounted for in performance assessments through routine implementation of integrated daylight and energy simulations. Other findings of this study were grouped into categories and listed.

Operational inferences:

- Internal shading systems, as glare protection, hinder both daylight and energy building performance.

- Occupant interaction with internal shading systems affects building performance assessments and should be accounted for, to avoid erroneous design inferences. More empirical studies on occupant interaction with building systems are needed.
- Building energy performance assessments require real-life operational schedules such as daylight-driven lighting or glare-driven blinds schedules for increased reliability.
- The authors claim that preparation of schedules for energy assessments, based on independent simulations of daylight and glare, is a complicated and time-consuming task, which highlights the need for more integrated and efficient simulation tools and workflows.

Fenestration design inferences:

- In a highly-glazed and well-insulated office in a Nordic climate, external shadings reduce overheating and improve occupant comfort, including visual comfort.
- In the absence of an external shading device, selective glass is a preferred glazing choice for a south-oriented window in the studied case, seeing as it reduces the annual energy use and improves occupant comfort.
- While external shadings were found inconsequential to the heating demand as they permit low-angle winter solar radiation, internal blinds increased the heating demand. The reason is that lower solar angles are likely to cause unwanted glare, which is mitigated by internal blinds, but consequentially, useful winter solar gains are also reduced.
- Brise-soleil type of external shading geometry is superior to a solid overhang due to higher daylight penetration, lesser material use, and more advantageous tilt angles for potential active solar integration on the building facade.
- Clear-glass window with a large overhang provided higher visual comfort (fewer glare occurrences), while an aperture with selective glass and a small overhang was more effective for summer thermal comfort (reduced overheating), albeit the same energy and daylight performance of these two cases.
- Overhang and horizontal louvers are two different shapes of external shading that intersect solar radiation equally; however, louvers pose a higher risk of glare, which impacts the operation of internal blinds and consequently worsens the energy and daylight building performance.

Future research on summer overheating in Nordic climates is highly encouraged, as it was shown that excessive solar radiation can negatively impact energy use and indoor comfort in a conventionally heating-dominated climate. The use of external solar shadings is not engrained in classic or modern Nordic architecture, but as was shown in this study, it might become essential from the standpoint of sustainable design. Moreover, there is a potential opportunity in utilizing external shading surfaces for active solar building integration (e.g. photovoltaic systems), which should be an interesting area for further exploration.

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