Static Shading Optimization for Glare Control and Daylight

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Daylight and solar access influence positively building occupants` wellbeing and students' learning performance. However, an excess of sunlight can harm the visual comfort of occupants through disturbing glare effects. This study investigated, through multi-objective optimization, the potential of static shading devices to reduce glare and to guarantee daylight provision in a university building. The results showed that the reduction of disturbing glare was up to more than twice the reduced daylight, which nevertheless, was provided in adequate levels. View out and energy performance were also analyzed. Detailed results of optimal shading types and classrooms layout indications are presented.

Keywords: *Daylight, Visual comfort, Shading, Multi-objective optimization*

INTRODUCTION

Daylight and solar access are important factors for building occupants' comfort and wellness. Studies showed that sunlight and the perception of day-night alternation improve health facilitating the correct entrainment of humans' circadian rhythm (Lockley 2009). Research works proved that daylight increases the workers' satisfaction and productivity (Andersen et al. 2012) and improves the students' learning performance in educational buildings (Heschong 2002). Additionally, studies showed that through a correct design natural light in buildings reduce energy consumption through consistent cut of electric lighting energy and reduction of heating energy also at Northern latitudes (De Luca et al. 2016, Voll et al. 2016) without significant cooling energy increase (De Luca et al. 2018).

On the other hand, an excess of daylight and direct sunlight can significantly decrease the building occupants' visual comfort due to glare effects. A study conducted in a students' studio open space taking into account sun in the field of view, direct sunlight on the desk and monitor contrast found that the space was considered intolerably uncomfortable for many occupied hours (Jakubiec and Reinhart 2016). Field studies conducted in office spaces underlined the importance of the occupant distance from the windows and view direction to control glare (Kong et al. 2018). The studies about the use of shading to eliminate visual discomfort mostly focused on operable internal shades or blinds investigating materials, geometrical configurations and controls (Chan and Tzempelikos 2013, Koo et al. 2010).

There is yet a limited focus in analyzing optimal configurations of building massing and envelope to admit daylight (De Luca 2017), and types of external shading devices to control glare. If on the one hand the static shading glare reduction is smaller compared to the internal operable ones, on the other hand they present the advantages of a constant though reduced view out and higher electric lighting energy reductions because not dependent on occupants' operation (Reinhart 2004). Static shading proved to be an efficient and economic strategy to control daylight distribution (Hans and Voss 2011). Being visual comfort and daylight potentially conflicting performances, they need to be analyzed simultaneously in the early design stages to find optimal and trade-off shading solutions.

Glare analysis

Glare can be caused by an excessive luminous intensity and by the contrast between the different luminance level of the light sources and background. The level of glare is affected also by the location of the main light source inside the field of view of the observer. Two glare levels can be distinguished: discomfort glare which causes eye strain and disability glare which prevents a person to see the surrounding environment (Reinhart 2018). Discomfort glare metrics are based on the glare index which expresses the contrast between a glare source characterized by its size, luminance and position inside the field of view, and the average luminance of the background. According to the glare index, larger and or brighter light sources located in the center of the field of view increase glare, whereas a brighter background attenuates the glare effect (Jakubiec and Reinhart 2012).

Several glare metrics have been developed, such as the Daylight Glare Index (DGI) (Hopkinson 1972) and the Daylight Glare Probability (DGP) (Wienold and Christoffersen 2006). DGI advanced the initial metrics developed for the small sources of electric lighting taking into account large glare sources such as daylight through windows. DGP, which is one the most recent metrics, adds the measure of the scene brightness (saturation effect) as possible visual discomfort source in addition to the contrast used by the previous indices (Reinhart 2018). The DGP index is based on four levels of probability that a person would experience visual discomfort in the specific setting, i.e., imperceptible (DGP ≤ 34 %), perceptible (34 % < DGP ≤ 38 %), disturbing (38 % < DGP ≤ 45 %) and intolerable glare (DGP > 45 %).

Glare analysis is particularly important in educational and work premises because the occupants cannot change seating position and view direction. Using computer simulations, glare is assessed at the height of the eyes and in the view direction of the occupant in a seating position at approximately 1.2 m. Input of the simulations are the interior surfaces, the glazed areas and the external obstructions, the materials reflectance and the visible transmittance values. Glare simulations are performed for a single moment (point-in-time) using a specific sky condition or a climate based sky, or for the entire year. The point-in-time simulation output is the fisheye view presenting the luminance values (cd/m^2) and the glare assessment through the metric used (Figure 1). Annual glare simulations require the additional inputs of the statistical weather data and occupancy hours. The output is a chart showing the visual discomfort levels for each hour of the year.

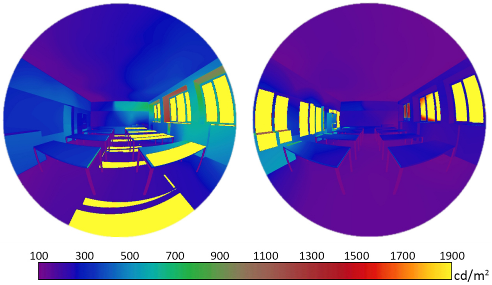


Figure 1
Point-in-time glare assessments in one classroom of the study using a clear sky with sun at 11 a.m. on April 4 – DGP 32 % (left) and at 11 a.m. on January 4 – DGP 43 % (right).

Daylight analysis

Daylight availability metrics date back to the end of 19th century. One of the most used metrics is the Daylight Factor (DF) which predicts interior natural light levels as a ratio of exterior illuminance. DF is a simple metric to use through formulas and computer simulations. Its reliability is limited because it considers only the geometrical characteristics of the room surfaces, glazed areas and external obstructions and the materials' reflectance and glazing transparency. Climate based daylight metrics such as Daylight Autonomy and Useful Daylight Illuminance have been developed to accurately predict through computer simulations the annual percentage of time during which an interior point meets the daylight threshold, using also the building orientation and statistical weather data (Reinhart et al. 2006, Nabil and Mardaljevic 2006).

Spatial Daylight Autonomy (sDA) is a recently developed annual daylight metric introduced in the method LM-83-12 and adopted by leading international standards such as LEED (Illuminating Engineering Society 2013). sDA assesses annual daylight availability as the percentage of occupied floor area where the illuminance threshold of 300 lux is reached for at least 50 % of the time (sDA300/50%) between 8 a.m. and 6 p.m. regardless of the function of the building. LM-83-12 requires minimum 55 % of sDA300/50% to consider a room acceptably daylit.

Daylight is simulated on a horizontal plane (simulation grid) located at the desk height of approximately 0.75 m using sensor points. Other inputs of the annual daylight analysis are the room surfaces of floors, walls, ceiling, window glass and frames, main furnishing and the external obstructions, their reflectance and visible transmittance values, the illuminance threshold (lux), the occupancy hours and the annual weather data.

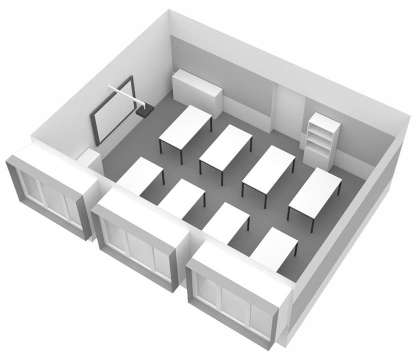
This study investigated through multi-objective optimization the potential of different types of external static shading devices to improve visual comfort while guaranteeing adequate daylight provision in two classrooms of Tallinn University of Technology (TalTech). The study was conducted using two simulation planes to provide useful information for the classrooms' layout. View out and energy performance using the shadings are also presented. The novelty of the study lies in the assessment of glare, to control together with daylight through static shading, for the entire room area and multiple views instead than for a single view as in existing literature.

METHODS

The study was conducted through three-dimensional modeling of the classrooms and buildings, measurement of the optical properties of the interior materials, parametric modeling of the shading devices, daylight modeling, multi-objective optimization, view out and energy modeling. The building used in the study is the Academy of Architecture and Urban Studies of TalTech located in Tallinn, Estonia (Lat. 59°26'N Lon. 24°45'E).

Building and classrooms model

The classrooms 46 of 45.9 m^2 southerly oriented and 41 of 52 m^2 easterly oriented, which have the same windows and tables layout, were selected to analyze glare and daylight for different orientations and opposite buildings' height and distance (Figure 2). The classrooms were located at a height of 13.25 m. Detailed three-dimensional models were realized in Rhinoceros (McNeel 2021) including tables, cupboards, cork wall boards and the main appliances as projector and whiteboard. The relevant surrounding buildings were also modeled (Figure 2).



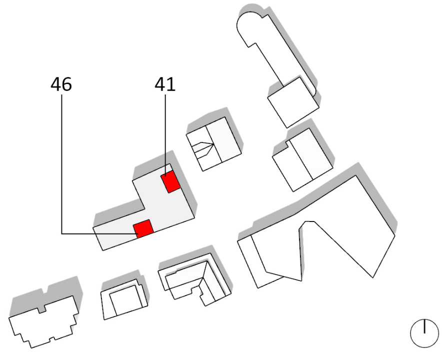


Figure 2
The Academy building with location of the classrooms used in the study and the surrounding buildings. Grayscale rendering of classroom 46.

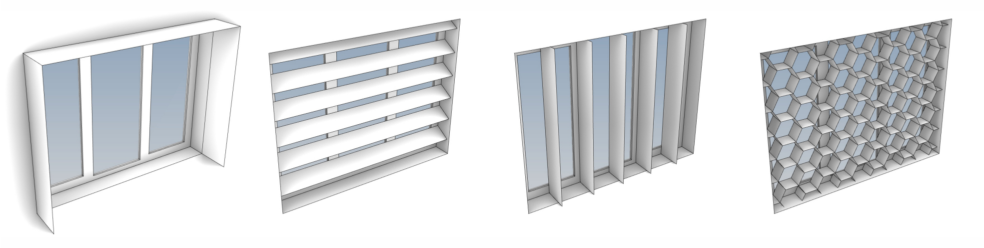


Figure 3
The shading device types overhang with vertical fins, horizontal louver, vertical louver and hexagonal pattern (from left to right).

Figure 4
The reflectance measurement equipment 3nh - Spectrophotometer YS3060.

Surface	R (%)	VT (%)
Walls int./Ext./Cork pan.	80/30/60	-
Floor/Ceiling	24/20	-
Table top/Legs	83/5	-
Whiteb. screen/Frame	86/10	-
Projector bracket/Body	80/5	-
Window frame-Glazing	84	77

Table 1
The interior surfaces reflectance (R) and windows visible transmittance (VT) values.

Material characterization

The optical properties of the interior surfaces and windows were measured to realize a reliable daylight model and to obtain accurate occupant visual comfort and daylight availability predictions. The light reflectance (R) of the opaque surfaces was obtained using the calibrated equipment 3nh - Spectrophotometer YS3060 (Figure 4). The visible light transmittance (VT) of the two-pane glazing was calculated as the ratio of the vertical illuminance measured with the window closed and open, which constitutes a simple method to approximate VT (Reinhart 2018). The VT measurements were conducted using the calibrated Luxmeter MSC-15. The R and VT values are presented in Table 1.

Shading parametric models

For the study four different shading device types were modeled: overhang with vertical fins; horizontal louver; vertical louver; and hexagonal pattern (Figure 3). For each type an algorithm was realized in Grasshopper (Rutten 2021) to generate the shading using different parameters.

The overhang with vertical fins shading only parameter was the depth, variable from 0 m to 2 m. The parameters of the horizontal louver were the slats spacing starting from 0.1 m to the full window height (no slats), the depth from 0 m to 0.3 m and the rotation with hinge on the top edge of the slat from 0° (open) to 89° downward (closed). The parameters of the vertical louver were the slats distance from 0.1 m to the window width (no slats), the depth from 0 m to 0.3 m and the rotation with hinge on the internal edge from -89° (closed cw) through 0° (fully open) to +89° (closed ccw). The parameters for the hexagonal pattern shading were the radius of the aperture from 0.1 m to the window width (no shading), and the depth from 0 m to 0.3 m.

The shadings were located on the exterior of the window frame inside the window recess of 0.22 m, except the overhang with fins which was attached to the building façade. The overhang had two fins for the south facing room and only the one toward south for the east facing room as recommended by rules-of-thumb. The windows were 2.28 m and 2.35 m (w), and 1.71 m and 1.74 m (h) in size in classrooms 46 and 41, respectively. Custom components were created and used in the parametric model for the glare and daylight simulations, the multi-objective optimizations, the view out and the energy assessments.

Daylight model

The daylight model was realized using the software ClimateStudio in Grasshopper (Solemma 2021). ClimateStudio is based on the validated daylight simulation software Radiance (Ward 1994) and the novel path tracing technology which allows daylight simulations hundreds or thousands of time faster than previous Radiance-based software without compromising the accuracy. The daylight model presented two sections, one for glare and the other for daylight availability simulations. Both used as inputs the classrooms' three-dimensional models and the materials definition realized using the measured interior surfaces' optical properties. For the surrounding buildings and ground were used standard reflectance values, i.e. 35 % and 20 %, respectively. The material used for the shading was a metal with reflectance 49.8 %. Additional inputs were the statistical annual weather data of Tallinn in *epw* format, the occupancy schedule from 8 a.m. to 6 p.m. during weekdays, which are the hours during which lessons take place in the classrooms and as well those recommended by the Estonian building regulations for energy and daylight analysis of educational buildings.

The simulations were conducted using grids of points spaced 0.5 m, with two offsets from the walls and windows, approx. 0.5 m and 1 m, to analyze the performance of different classroom used areas. For glare simulations the grid was located at 1.2 m and presented 8 view directions for each grid point, for a total of 1320 and 768 in room 46 and 1496 and 832 in room 41, for grid offsets 0.5 m and 1 m, respectively. ClimateStudio performed annual hourly glare simulation for every view. The output was the spatial discomfort glare (sDG) based on the metric DGP, i.e., the fraction of views which present a DGP level above 0.38 (disturbing glare) for more than 5 % of the occupied hours (Figure 5). The 5 % exceedance time in glare assessments is defined in the European daylight standard EN 17037 (CEN 2018).

For daylight availability simulations the grid was located at 0.75 m from the floor, and was constituted by single points with the normal facing upward. Among the several daylight metrics available in ClimateStudio, sDA300/50% was used as introduced by LM-83-12 (Figure 5). Although the current Estonian daylight standard requires daylight assessments through DF, sDA was used because existing literature proved that DF is not reliable to predict daylight levels in Estonia (Sepúlveda et al. 2020). The main Radiance parameters used in the simulations were: - ab 6 - lw 0.01 -ad 1. The path tracing parameters were: sample rays per sensor per pass 64 and max number of passes 100.

Multi-objective optimization

Multi-objective optimization was used to investigate optimal trade-off shading configurations to reduce glare while guaranteeing daylight availability. The software used was Opossum, a model-based optimization tool for Grasshopper (Wortmann 2017). The

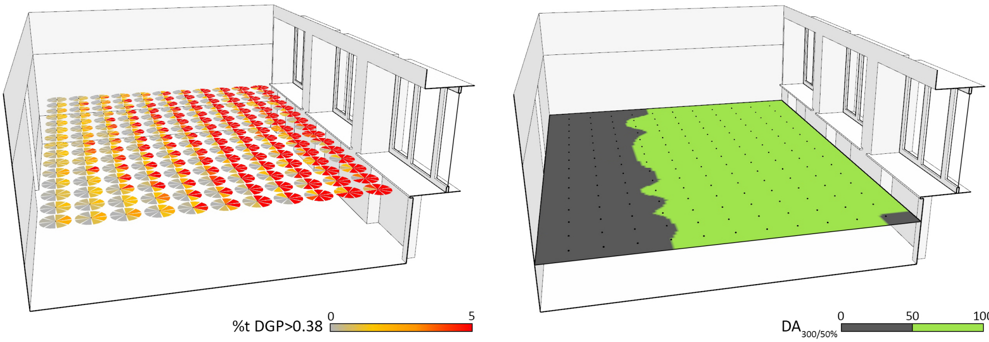


Figure 5
The analysis grid for glare simulations with views (left) and for daylight availability (right) in classroom 46 (0.5 m from walls), as generated by ClimateStudio with results visualization.

algorithm used was RBFMOpt (Radial Basis Multi-Objective Optimization). The objectives were the minimization of sDG and the maximization of sDA through minimization of the result of the subtraction of the simulation result from 1 (1=100 % of the sensor points receiving DA300/50%). The parameters of the shading devices were used as the variables of the optimization process.

Energy and view out models

Energy simulations were performed without and with the Pareto-optimal shading types with the best performances using the energy tools of ClimateStudio based on the software EnergyPlus (NREL 2019). The simulations parameters are presented in Table 2.

Zone settings		Envelope properties			
People density	0.2 (p/m^2)		EW	IW-F-C	W
Lighting density	7 (W/m^2)	U_t	0.14	A	0.9
Heat./Cool. setp.	21/25 (°C)	W-VT 77%		W-SHGC 0.4	

Table 2
Energy simulation parameters. EW = external walls, IW = internal walls, F = floor, C = ceiling, A = adiabatic, W = window, VT = visible transmittance, SHGC = solar heat gain coefficient, Ut (W/m2K).

The scope was to investigate the effect of the different shading devices on the energy performance. The occupancy schedule, the climatic data and the daylight setpoint were the same used for the daylight model. The view out allowed by the shadings was analyzed through the Sky Exposure Factor (SEF) using the plug-in Ladybug Tools (Sadeghipour and Pak 2013). The SEF metric calculates the visible portion of the sky from points of surfaces as a ratio of the sky hemisphere visible without any obstruction.

RESULTS

The results of the study are presented in three sections. In the first the optimal types of shading devices to reduce glare and provide adequate daylight are presented and the performances are discussed. In the second the influence of the shadings on the view out is presented. In the third the energy consumption variations using the shadings are analyzed.

Optimal shading devices

To find the optimal trade-offs allowed by the different types of shading multi-objective optimization was used for each shading type in the two classrooms 46 and 41 using the two simulation grids as presented in the section Methods. To compare the performance, the Pareto front solutions of each shading type were used because these represented the optimal trade-offs of glare protection and daylight availability. The most performative shading types of each classroom were those which permitted the largest sDG reduction and at the same time an sDA of minimum 55 %.

Taking into account classroom 46 the sDG and sDA in the actual condition (no shading) were 38.4 % and 99.4 % respectively, using the simulation grid at 0.5 m offset from the walls, and 41.7 % and 100 % respectively, using the grid with 1 m offset from the walls. The results are presented in Figure 6. The two most performative shading types were the horizontal louver and the overhang with vertical fins. Considering the simulation grid with the maximum extension,

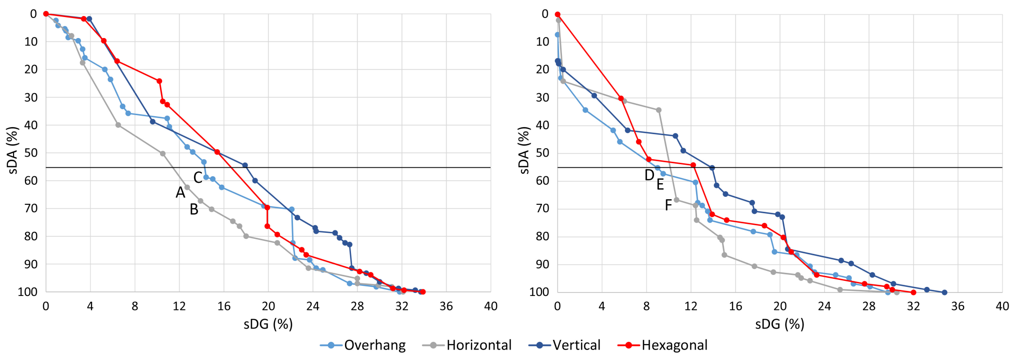


Figure 6
Plots of the Pareto front trade-off solutions of the shading devices of classroom 46 for analysis grid with distance from walls 0.5 m (left) and 1 m (right).

the best shading was a horizontal louver (A) which reduced the sDG to 12.7 % while guaranteed an sDA of 62.4 %. The geometrical parameters of the slats were 0.13 m spacing, 0.14 m depth and 4.8° rotation. The second best performance was recorded also for the type horizontal louver (B) characterized by the slats parameters of 0.14 m spacing, 0.14 m depth and 3.5° rotation. This shading allowed to reduce sDG to 13.9 % and at the same time to provide an sDA of 67.3 %. The third most performative shading was of the type overhang with fins (C) which allowed to reduce sDG to 14.4 % while guaranteed an sDA of 58.8 %. The depth of the shading was 1 m.

Considering the simulation grid with the largest distance from walls and windows, the most performative shading type was the overhang with vertical fins with two configurations. The first (D) had a depth of 1.19 m and permitted to reduce glare in the classroom so that only 9 % of all the views recorded a disturbing glare (sDG) and at the same time guaranteed a daylight provision of sDA 55.2 %. The second (E) had a depth of 1.24 m and allowed a reduction of sDG to 9.5 % and an sDA of 57.3 %. The third most performative shading was a horizontal louver (F). It allowed a reduction of sDG to 10.7 % and at the same time guaranteed an sDA of 66.7 % using the slats geometrical parameters of 0.25 m spacing, 0.21 m depth and 13.9° rotation angle.

Taking into account classroom 41 the sDG and sDA without shading were 18.8 % and 85.0 % respectively, using the analysis grid at 0.5 m from the walls, and 21.1 % and 91.4 % respectively, using the grid at 1 m from the walls. The most performative shading types were the overhang with fin, the hexagonal pattern and the vertical louver. The results are presented in Figure 7. Considering the grid closer to the walls, the first and the third best shading types (G-I) were overhang with fin which allowed to reduce the sDG to 6.6 % and 6.8 % while guaranteed an sDA of 55.6 % and 56.7 %, respectively. Their depths were 0.60 m and 0.61 m, respectively. The second best shading (H) was of the type hexagonal pattern with an aperture radius of 0.46 m and a depth of 0.3 m. It allowed to reduce sDG to 6.8 % as the third best shading of type overhang with fin but allowed slightly more daylight provision with an sDA of 58.3 %.

Considering the grid at 1 m from the walls, the three most performative shading types were all overhang with fin (J-K-L). They permitted to reduce the sDG to 2.9 %, 3.5 % and 3.9 %, respectively, while they allowed an sDA of 57.7 %, 58.6 % and 61.5 %, respectively. Their depth were 0.75 m, 0.71 m and 0.67 m, respectively. For classroom 41 and considering the small grid, two other shadings had performance similar to the third best. A hexagonal pattern shading (M) with 0.1 m of aperture radius and 0.07 m of depth reduced sDG to 4 % and allowed an sDA of 62.5 %. A vertical louver (N) with slats spacing of 0.9 m, a depth of 0.24 m and a rotation of 58.7° CCW reduced the sDG to 4.1 % while allowed a sDA of 55.8 %.

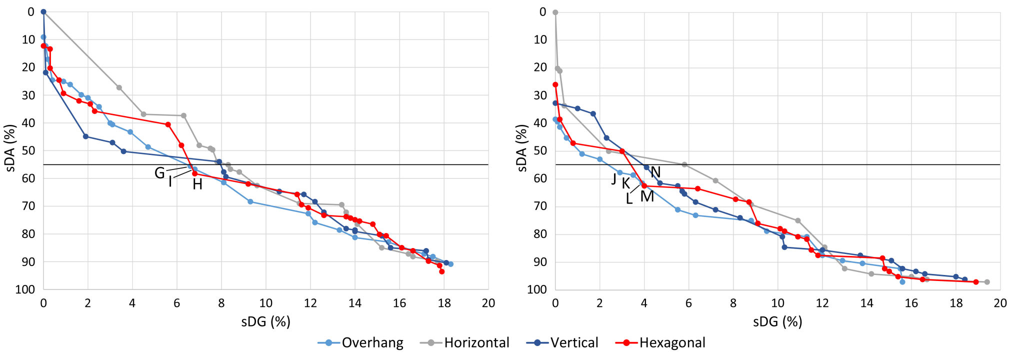


Figure 7
Plots of the Pareto front trade-off solutions of the shading devices of classroom 41 for analysis grid with distance from walls 0.5 m (left) and 1 m (right).

Grid		46 reduction (%)			41 reduction (%)				
0.5		A	B	C	G	H	I		
	sDG	66.9	63.8	62.5	64.9	63.8	63.8		
	sDA	37.2	32.3	40.8	34.6	31.4	33.3		
1		D	E	F	J	K	L	M	N
	sDG	78.4	77.2	74.3	86.3	83.4	81.5	81.0	80.1
	sDA	44.8	42.7	33.3	36.9	35.9	32.7	31.6	38.9

Table 3
Reduction of sDG and sDA obtained through the shadings analyzed (A-N) for the two classrooms using the two analysis grids.

Table 3 summarizes the shading devices performance for glare reduction and consequent decrease of daylight which was anyway adequate according to the most advanced standards. In classroom 46, due to its southerly orientation, the most performative shadings were the horizontal louver (A), which reduced annual glare by 66.9 % and daylight by only 37.2 % when the large grid was used, and the overhang with fins (D), which reduced glare by 78.4 % and daylight by a much lesser 44.8 % when the small grid was used. In classroom 41, due to its easterly orientation, the most performative shadings were the overhang with fin and the vertical louver, with close performances. However, the first was the most performative using both the large and the small grid (G-J) reducing glare by 64.9 % and by 86.3 % and daylight by a much lesser 34.6 % and 36.9 %, respectively.

Thus evidence showed that using static shading the reduction of visual discomfort outperformed the decrease of daylight availability. Results also showed that the analysis grid, representing a possible tables' layout, further from the walls presented higher glare and daylight without shading, being the further sensors closer to the windows, but also recorded the larger glare reduction using the shadings.

View out analysis

The view out analysis as well as the energy analysis were used in the study to evaluate the influence of the shading devices on other aspects of occupant comfort and building performances. For the view out analysis SEF was calculated for the same sensor points as for the glare simulations (Figure 8), using both analysis grids. The average SEFs of the classrooms without shading and with the 14 most performative shadings analyzed were compared (Table 4).

Grid	46 av. SEF (%)				41 av. SEF (%)					
0.5	ns	A	B	C	ns	G	H	I		
	6.1	3.5	3.8	3.36	6.3	4.8	4.5	4.8		
1	ns	D	E	F	ns	J	K	L	M	N
	6	3.1	3.1	3.6	6	4.4	4.5	4.6	4.4	4.1

Table 4
Average Sky Exposure Factor (SEF) values without shading (ns) and with the shadings analyzed (A-N) for the two classrooms using the two analysis grids.

In classroom 46 using the larger analysis grid (0.5) the three most performative shadings (A-B-C) reduced the view to the sky by values between 38.5 % and 44.8 %. Similar reductions, between 40 % and 48.3 %, were recorded when the smaller analysis grid was used (1) and with the related most performative shadings (D-E-F). In classroom 41 the reduction of SEF was between 24.1 % and 28.7 % when the large grid was used (0.5) with the related optimal shadings (G-H-I), and was between 23.3 % and 31.6 % when the smaller grid was used (1) and the related most performative shadings (J-K-L-M-N). The smaller SEF reduction in classroom 41 was due to the possibility to use smaller and more open shadings because the easterly orientation caused smaller visual discomfort.

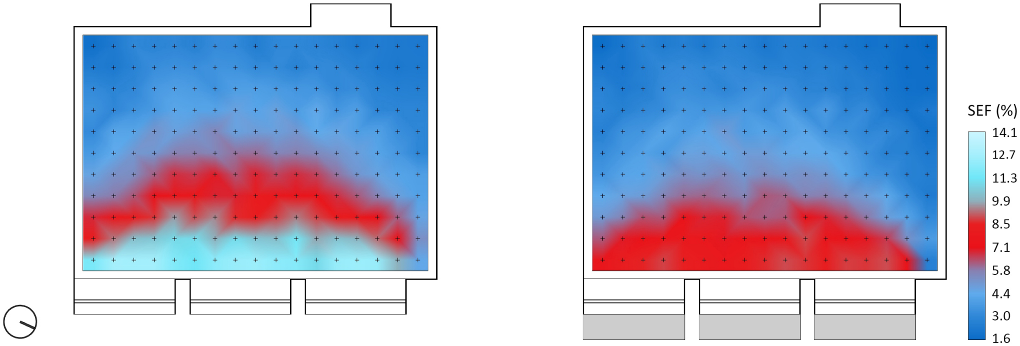


Figure 8
Sky Exposure Factor analysis in classroom 41 without shading (left) and with the shading overhang with fin G (right).

Energy analysis

The energy simulations were performed for the main types of consumption which can be influenced by the external static shading, i.e., heating, cooling and electric lighting (Figure 9). The results showed that the use of the shading caused a small increase of total energy consumption in comparison with the much larger visual comfort increase. In both classrooms the 14 most performative static shading types analyzed (A-N) increased the heating energy and decreased the cooling energy due to reduced solar gains, and increased the electric lighting consumption due to reduced daylight.

In classroom 46 the average increase of total energy was 8 %. The average increase of heating energy was 9.8 %, the average decrease of cooling energy was 70.5 %, and the average increase of electric lighting was 8.3 %. In classroom 41 the average increase of total energy was 2.5 %. The average heating and electric lighting energy increase was 2.6 % and 4.9 %, respectively and the average cooling energy decrease was 25.5 %. Being heating the largest consumption, the difference of energy increase between the two classrooms was due to the smaller solar gains of classroom 41, due to its easterly orientation.

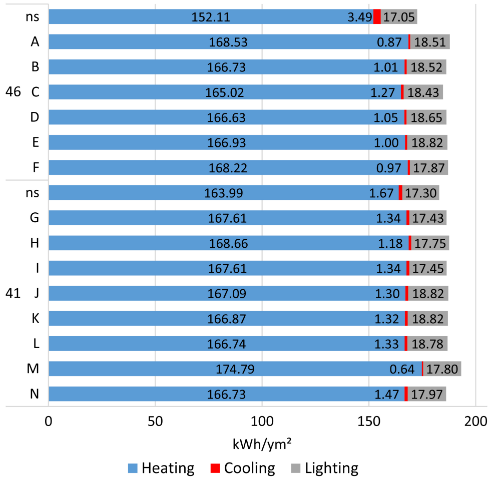


Figure 9
Energy simulation results for the classrooms without shading (ns) and with the shadings analyzed (A-N).

CONCLUSION

The research investigated the potential of static shading to reduce visual discomfort and to guarantee adequate natural illumination in two classrooms of TalTech Academy of Architecture and Urban Studies with different orientations. Parametric variations of four types of shading (overhang with fins, horizontal and vertical louver, hexagonal pattern) were used to minimize disturbing glare and maximize daylight autonomy through multi-objective optimization. View out and energy analyses were used to further evaluate the optimal shadings. Two analysis grids with different offsets from the walls were used to obtain useful information for the classroom tables' layout.

The results showed that the shadings allowed a reduction of disturbing glare by up to 78.4 % and 86.3 % and at the same time reduced daylight availability of 44.8 % and 36.9 % in the southerly and easterly oriented classrooms, respectively. Nevertheless, adequate daylight levels were provided. Thus the study proved the potential of static shading in improving visual comfort while guaranteeing daylight provision. However, the most performative shadings reduced the average view out by 48.3 % and 26.6 %, and increased the energy consumption by 7.9 % and 2.3 % in the two classrooms, respectively.

The outcomes also showed that using the smaller grid, which represented a compact tables' layout, the shadings performed better in reducing glare. Moreover, the shadings horizontal louver and overhang with fins were the most performative for the southerly oriented classroom and the latter also for the easterly oriented classroom together with the vertical louver.

Future work will analyze classes with different sizes and orientations and will use multi-objective optimization of pairs of performances between glare, daylight, view out and energy. The resulting sets of data will be used to develop prediction formulas to be applied as the basis of a coupled method to inform design decisions about optimal shading types and sizes for specific room sizes, orientation and layout, during the early design phase.

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