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Overheating and daylighting evaluation for free-running classroom designs

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Abstract. Learning performance is strongly related to thermal comfort and lighting conditions of classrooms. Poor facade design can result in high indoor temperatures or insufficient access to natural light. To maintain the required temperatures and illuminance levels in such rooms may require intensive use of artificial lighting and active cooling systems, which are energy-intensive, costly to install, operate and maintain. The purpose of this study was to determine essential parameters and facade design options that ensure overheating prevention and fulfill daylight requirements in classrooms without mechanical cooling. The present study is based on simulations of a parametric room model with variable dimensions and orientations. Facade glazing solutions with optimal combination of solar factor and visible light transmittance were used to minimize overheating risk and maximize natural lighting impact. For east, south and west oriented facades, the effect of horizontal shading was also analysed. Overheating assessment through indoor temperature simulations was conducted with dynamic simulation software IDA ICE, daylighting was simulated with DIVA4 coupled with Grasshopper software. Results show that classrooms without mechanical cooling require in depth analysis to determine satisfying solutions for both overheating and daylighting criteria. The results of this paper can be used for early stage facade design guide for school buildings or similar use free-running buildings.

1. Introduction
The effects of indoor temperature and lighting conditions on schoolwork performance are relatively well researched [1-5]. Studies on lighting conditions show positive effects of natural light availability on performance and visual comfort [4]. Also, daylight utilization is an efficient way to save energy related to electric lighting [6] and heating [7], as its availability corresponds to the period during which buildings are occupied. Thus, daylighting is an important factor in classroom planning and school building design. At the same time excessive direct solar access can cause unwanted glare and solar heat gains that influence occupants’ comfort and building energy use due to cooling need during warm periods [8]. Many studies have found, that higher indoor temperature has negative effect on thermal comfort and learning ability [2, 3, 9]. High indoor temperatures and overheating, specifically in temperate climate regions, are mostly recent problems, arising from paradigm shifts in architectural and energy efficiency related advances on building design [5, 10, 11]. It is essential to assess buildings in early stages of design development to properly ensure sufficient daylighting and prevent overheating. In Estonia, daylight in building is regulated by the standard Daylight in dwelling and Offices [12]. The standard sets different minimum mean Daylight Factor (mDF) values for a series of internal spaces of buildings, of which classrooms are required to guarantee a minimum of 2% mDF. Overheating
assessment for new buildings in the design stage is required by the National Building Code by using temperature excess calculation method, based on dynamic indoor temperature simulations [13]. The present study investigates overheating and daylight performance of classroom and facade design variations for different floor dimensions, window sizes, glazing parameters and shading use. The scope was to find optimal solutions that fulfil daylight and overheating prevention requirements in Estonia.

2. Methods
We have analysed a classroom parametric model through computer simulations to assess indoor temperatures, overheating risk and daylighting. The parameters used in the simulation model creation are shown in Tables 1 and 2. The room model variations included different room widths and depths (5m, 6m, 7m, 8m and 9m) for a total of 25 room size and layout variations. The window layout was varied in accordance to the room width. For the room of 5m 2 windows of width and height 1.9x1.7m (Window-to-Wall-Ratio (WWR) 45.6%) were used, for the room width of 6m 3 windows of 1.466x1.7m (WWR 41.5%) were used, for the room width of 7m 3 windows of 1.8x1.7m (WWR 43.7%) were used, for the room of 8m width were used 4 windows of 1.45x1.7m (WWR 41.1%) and for the larger room width of 9m were used 4 windows of 1.7x1.7m (WWR 42.8%). The floor to ceiling height of the room is 3m for all the room variations. As a passive measure to reduce external heat gains from direct sunlight into the classroom parametric model we used horizontal shading with a depth of 0.9m on top of the windows as an option for east, south and west orientations. Additionally, ground surface with 20% reflectance was modelled outside the room.

Table 1. Room and facade parameter combinations.

| Room dimensions | Envelope | Windows | Window dimensions | Orientation | Glazing g-value | Glazing VT (%) | Shading depth (hor.) |
|-----------------|----------|---------|-------------------|-------------|----------------|----------------|---------------------|
| Depth, m: 5, 6, 7, 8, 9 | Ext. wall: Concrete 150mm | Frame fraction 0.34 | Recess depth 0.25m | E | 0.35 | 0.635 | - |
| Width, m 5, 6, 7, 8, 9 | Exp. polystyrol: 300mm | U<sub>w</sub>, 0.58 W/(m<sup>2</sup>·K) | East/south/west: | | 0.42 | 0.707 | 0.9m |
| | Concrete 50mm | U<sub>ext</sub> 0.60 W/(m<sup>2</sup>·K) | Room width, number of windows- -width/height: | S | 0.35 | 0.635 | - |
| | U<sub>ext</sub>, 0.129 W/(m<sup>2</sup>·K) | East/west with shading: | 5m, 2-1.9/1.7m | W | 0.35 | 0.635 | - |
| | Ext. window perimeter thermal bridge: 0.1W/(m·K) | U<sub>ext</sub> 0.70 W/(m<sup>2</sup>·K) | 5m, 3-1.46/1.7m | | 0.42 | 0.707 | 0.9m |
| | Fixed infiltration: 1.5m<sup>3</sup>/h·m<sup>2</sup> (north) | U<sub>ext</sub> 0.61 W/(m<sup>2</sup>·K) | 8m, 4-1.45/1.7m | N | 0.54 | 0.733 | - |
| | | U<sub>ext</sub> 0.42 W/(m<sup>2</sup>·K) | 9m, 4-1.7/1.7m | |

Table 2. Simulation input parameters.

| Schedules | Internal gains | HVAC systems | Daylighting |
|-----------|----------------|--------------|-------------|
| Internal gains | Ventilation | Occupancy | Lighting / Equipment | Temp. setpoint | Supply air temperature | CAV air exchange | Reflectance values (%) |
| 00:00-07:00 – 0.0 | 00:00-08:00 – 0.036 | 35W/m<sup>2</sup> | 5.0W/m<sup>2</sup> +21°C | >+16°C | 4.2 | Walls 50 |
| 07:00-17:00 – 1.0 | 08:00-12:00 – 0.8 | 2.1W/m<sup>2</sup> ooc. | 12.0W/m<sup>2</sup> | … | (without cooling) | 1/(s·m<sup>2</sup>) Shading 35 |
| 17:00-00:00 – 0.0 | 12:00-13:00 – 0.5 | 1.0 MET | 0.85±0.25 CLO | +25°C | | Ceiling 70 |
| | 13:00-16:00 – 0.8 | | | | | |
| | 16:00-00:00 – 0.036 | | | | | |

2.1. Overheating and indoor climate class assessment
The overheating assessment was done according to Estonian Building Code regulations. Indoor temperature simulations were conducted with well validated building simulation software IDA ICE [14] (Figure 1). Hourly-mean indoor temperature values were used to calculate temperature excess (DH) over a set base temperature. The allowed cumulative temperature excess in case of classrooms is 100K and the base temperature 25°C. The simulation periods for school buildings are set from 1<sup>st</sup> of May to 15<sup>th</sup> of June and 15<sup>th</sup> of August to 30<sup>th</sup> of September. For outdoor climate input, Estonian test reference year
is used, which is based on 30 year measurement data consisting of outdoor air temperature, relative humidity, wind velocity, direct and diffuse solar radiation [15].

Figure 1. Examples of indoor temperature calculation model in IDA ICE (left) and daylight factor calculation model in Grasshopper using DIVA4 (right).

Aside from the overheating intensity assessment, we calculated the cumulative hours for the cooling period during which the room temperature was in bounds of specific thermal environment class according to the standard EVS-EN 15251 ‘Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics’ [16].

2.2. Daylight factor simulations

The parametric model of the classroom was built using the software Grasshopper for Rhinoceros and the analysis was carried out with daylighting design plug-in DIVA4 (Figure 1), which performs simulations through validated software Radiance [17]. Through the daylight analysis parametric model it is possible to assign reflectance (R) values to interior elements of the room (i.e. floor, wall, ceiling, external shading and ground) and visible transmittance (VT) values to the glazed surface of windows, set the simulation grid, select the simulation parameters, run the simulations and record result data. The R values used in the simulations were the same for all the classroom variations and are standard values recommended for Daylight Factor calculations, presented in Table 2. The daylight parametric model permits to associate in different ways the glazing VT values and use or not of the shading device. This procedure has been necessary to match the room variation parameters used for energy efficiency studies. Different combinations of glazing VT and use of shading has been used for the different orientations in consideration of Estonian overheating requirements. Because Daylight Factor analysis do not take into account windows orientation, daylight simulation combinations refer solely to glazing VT and use of shading. The combinations are presented in Table 1. The grid used for the simulation has a size of 0.2m, was located at 0.75m from the floor and occupies 80% of the floor area. The main Radiance parameters used in the simulations are: -aa .1 -ab 5 -ad 1024 –ar 256. As required for DF simulation the CIE overcast sky model was used. The Daylight Factor simulations were performed automatically for all the classroom size and parameters variations through an automation function of the parametric model and the values of mDF were recorded for each iteration.

3. Results and discussion

Results of overheating and daylight factor are presented for different orientations due to the different glazing g-value, VT and shading described in methods section. For each orientation a figure is composed, how rooms with different WFR and dimensions respond to requirements studied. Rooms are ordered by the decreasing value of WFR, cumulative time is shown firstly, overheating secondly and daylight factor results thirdly. The color-coded cumulative graph shows duration in percentages during which the hourly room temperature values stayed between the limits of a specific indoor climate class (IC), ranked from I (best) to IV (worst) according to the standard [16]. Overheating hours and mean daylight factor values are marked as green squares, if both criteria are met and as red if one or both of
the criteria do not meet the requirements. Room result figures are divided to left and right by shading use.

For east orientation (Figure 2) rooms without shading and with WFR over 0.23 are overheated and rooms with width of 5m also do not meet the overheating requirement. Same rooms gain 1 to 2% more time out of II IC class compared to rooms, which stay below 100Kh line. All the rooms without shading are well lighted as mDF is over 2%. It is seen, that as the WFR increases and floor plan has more width and less depth, classrooms are both more naturally lighted and overheated. If shading is added and glass g-value increases from 0.35 to 0.42, room air temperature hours in III and IV IC class decrease up to 3%. Most of the rooms are underneath the overheating requirement line, only half of the rooms meeting the daylight factor criteria. Only 6 rooms, compared to 10 in the initial situation, of 25 met both criteria.

![Figure 2](image)

**Figure 2** Simulation results for east oriented classrooms: indoor climate class (IC) cumulative time during cooling period, temperature excess (DH) and mean daylight factor (mDF) without (left) and with (right) shading.

![Figure 3](image)

**Figure 3** Simulation results for south oriented classrooms: indoor climate class (IC) cumulative time during cooling period, temperature excess (DH) and mean daylight factor (mDF) without (left) and with (right) shading.
In south orientation (Figure 3) without shading all rooms basically are overheated and properly naturally lit. Up to 10% of the time, air temperature in classrooms does not meet II IC class. After adding shading, only 2 to 3% of the time room air temperature is out of II IC class. While all the rooms now meet the overheating criteria, only 8 rooms of 25 have mDF over 2%.  

For west orientation (Figure 4) 20 of 25 rooms meet both criteria without cooling, while room air temperature varies from 5 to 8% out of II IC class. Adding horizontal shading and optimized g-value of 0.42 similarly to east, all the rooms are underneath the overheating criteria, while 13 rooms with higher WFR do not meet daylight criteria. Classroom air temperatures IC classes for being out of II class also decreases between 3 to 5% of the time.

![Figure 4](image) Simulation results for west oriented classrooms: indoor climate class (IC) cumulative time during cooling period, temperature excess (DH) and mean daylight factor (mDF) without (left) and with (right) shading.

![Figure 5](image) Simulation results for north oriented classrooms: indoor climate class (IC) cumulative time during cooling period, temperature excess (DH) and mean daylight factor (mDF) without shading (left) and for all facades, WFR correlation with DH and mDF (right).

As it is unnecessary to block direct sunlight on north facade (Figure 5), room results are presented only for the initial situation without shading. It is seen by the green squares that all the rooms meet both...
overheating and daylight factor criteria. Rooms with higher WFR have 1 to 2% more cumulative hours out of II IC class. Room DH values are more constant compared to higher mDF as the WFR increases.

For east, south and west orientations, rooms with wider width and shorter depth dimensions received more daylight. For north oriented facade, all the analysed cases fulfilled the overheating and daylight requirements. IC class percentages indicate that room air temperature is mainly affected by internal gains of students, electrical equipment, lighting and supply air. Results are shaped less from the direct sunlight and as the WFR increases, more diffuse lighting enters the room. Similar distribution of results is seen on south façade with shading, but the balance gap between DH and mDF is clearly smaller for maintaining both criteria requirements. On the east and west façade results are more spread out, but still parallel as WFR increases. The room air temperature is less time out of II IC class for all south, east and west orientations if shading is added to the windows of the classrooms. Right side of Figure 5 with all the façades and simulated classrooms together shows why DH and mDF should be calculated together during the building design process.

4. Conclusion
The aim of this study is to determine whether the school building classrooms could be designed without active room cooling units and cooled ventilation supply air. Passive cooling methods, like decreasing window glass g-value and external shading decrease the amount of sunlight into the rooms, may cause poorly conditions for natural lighting as a result. Therefore, both overheating and daylight parameters must be analysed jointly. Results show that as window-to-floor ratio increases, the room receives more daylight but also becomes more vulnerable to temperature rise and overheating. In the other hand, with increasing depth, overheating risk lowers and daylight level decreases.

Parametric study shows that horizontal shading is more helpful on the southern façade. Adding shading to eastern and western facades with modified window parameters, distribution of classrooms meeting both temperature excess and mean daylight factor requirement changes and for west it also decreases. The easiest balance between two criteria is on the north façade due to low amount of direct sunlight. Adding shading reduces the number of hours out of indoor climate class II, while temperature excess method illustrates more efficiently the intensity of overheating. In addition, temperature excess overheating method results correlates well with daylight result distribution.

Designing low-energy school buildings without active room cooling units or cooled mechanical supply air ventilation, facade design is critical to ensure thermal comfort and lighting conditions that directly affect students’ performance. As school buildings are not used during summertime, it is possible to design classrooms to meet both overheating and daylighting requirements without the need for mechanical cooling systems. However, proper design requires skillful analysis of suitable combination of room dimensions, window sizes, glazing parameters and shading options to meet both overheating and daylight requirements.

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