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Original Research Article

EFFECTIVENESS OF SCREENS SHADING OPAQUE FACADES IN TERMS OF BUILDING THERMAL MODERNISATION

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A b s t r a c t

Screens used in modernizations of buildings to diversify the facade also provide shade on the walls. The article presents a comparison of the effectiveness of shades with different degrees of shading in terms of energy savings. On summer days, especially when there is a lot of sunlight and air temperatures are above 30°C, the covers reduce the temperature on the outer surface of the wall and, as a result, improve the microclimate of the rooms. Lower temperatures result in less heat accumulated during the day. The results were compared for various masonry materials. Less heat energy accumulated in the wall reduces the energy demand to cool the internal air. Energy savings were estimated over 50 years of building use. A method was proposed to quickly compare the effectiveness of the different shading shields.

Keywords: shading, sunny facades, heat accumulation, energy savings, renovation, thermal modernisation

1. INTRODUCTION

Ventilated facades are often used for architectural reasons in order to obtain the appropriate form of the building (Fig. 1) or to diversify the texture of the facade, also during the modernisation of buildings. For this purpose, for example: wooden lamellas, bent-drawn metal meshes, perforated sheets, stone, concrete, fibre-cement slabs, and even glass plates of various colours are used. These elements shade the surface of the wall. The beneficial effect of shades covering glazed surfaces is known and widely used to prevent overheating of buildings during high temperatures. Empirical tests were carried out on various surfaces of opaque south-orientated walls. The aim of the analyses was to check whether shields shading an opaque wall have a beneficial and significant effect observed on transparent partitions.

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Fig. 1. Examples of covers shading an opaque facade: A – openwork sheets, B – blinds, C – boards, strips, D – boards, E – eaves (photo by M. Siewczyńska)

2. THE INFLUENCE OF SHADING COVERS

The influence of shading elements is widely studied in various aspects in relation to transparent parts of facades.

Active shading control mechanisms help optimise the amount of energy supplied to the building in terms of user comfort and should be adapted to local climatic conditions [1], especially global solar radiation, sky coverage, and global horizontal illumination. These factors are important for the comfort of building users, so they can be omitted from the analyses of the shading of opaque surfaces. The following variables are taken into account in the automation of shading control: climate zone, window-to-wall ratio, building orientation, shading control strategy and its activation threshold. The results of the analyses will be individualised to the analysed building and its location, so providing general guidelines regarding the parameters of the shields is pointless. The analyses may be made easier by the use of parametric design, e.g. using the Rhinoceros and Grasshopper [2, 3] programmes together with Octopus [4] or Ladybugtools [5], in which the shape of covers can be automatically optimised based on the given parameters. Research has shown that horizontal blinds are more effective than vertical ones, and the greatest shade was obtained from mesh-shaped covers (Fig. 2.A) [6] or curved mesh [5] (Fig.

2.B) because the combination of vertical and horizontal shading causes shading even at a low angle of incidence of sunlight [7]. Using parametric programming, it is possible to obtain detailed comparison data of various shapes of window shading covers, optimisation of which allows reducing the energy demand for heating and cooling [8].

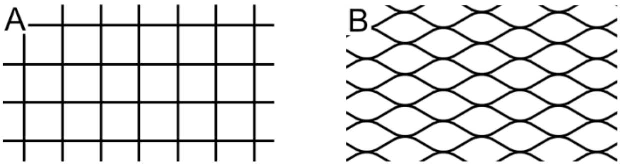

Fig. 2. Cover shape with the highest shading efficiency: A – mesh, B – curved mesh (elaborated by M. Siewczyńska)

External movable shading blinds on windows are the most effective, reducing the cooling demand by up to 60% [9]. Shading elements provide the greatest shade when they are orientated perpendicular to the sun's rays and follow the change in the angle of incidence. This location is also the most optimal from the point of view of solar energy gains [10]. The combination of these two aspects can be used to simultaneously shade the facade and use solar energy to produce energy (Fig. 3).

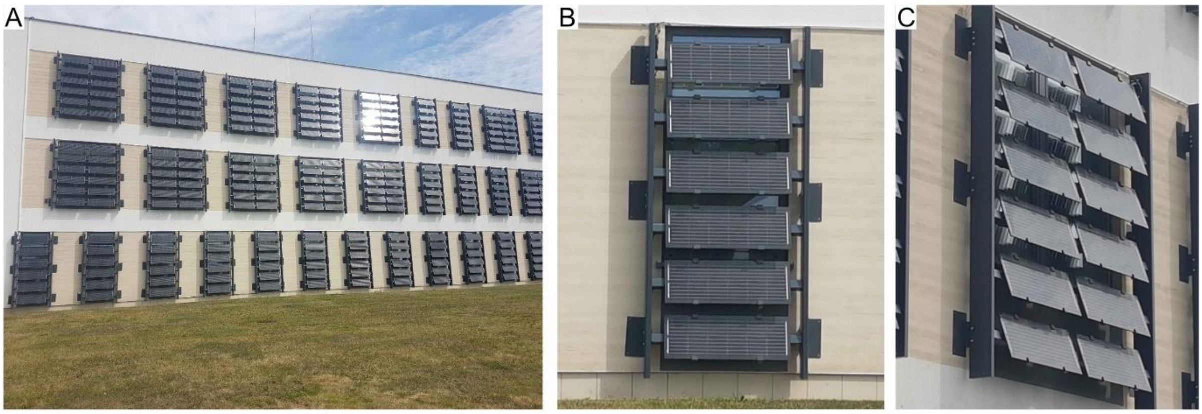

Fig. 3. Connection of shading blinds with photovoltaic panels: A – view of the building, B – view of the spacing of the blinds, C – view of the angle of inclination of the blinds (photo by M. Siewczyńska)

Verification of virtual analyses of the impact of shading elements can be performed by examining the temperature of the wall surface with a thermal imaging camera [11].

Shading screens also reduce air convection right next to the facade, trapping air, creating a buffer zone that is beneficial both in winter (from 7% to 17%) and in summer (from 50% to 60%) [11].

During renovation [12] and thermal modernisation of a building in order to adapt to current requirements that limit the energy demand of the building for heating, cooling, and ventilation, external walls usually require the addition of a thermal insulation layer and external cladding. During thermal modernisation, the form of the building is often renewed to give it a more modern character. Combining these two goals, a ventilated facade can be used, in which thermal insulation consists of a thermal insulation layer and a load bearing wall, while the ventilated air layer and the external facade (in accordance with the heat transfer coefficient according to the PN-EN6946 standard [13]) do not improve the partitions of thermal parameters. The outer layer of the wall, especially the one facing south on sunny days, heats up even more the darker the colour of the facade. The offset of the exterior facade and the air circulation in the air gap reduces the amount of heat that is transferred to the subsequent layers of the wall. If the facade is not ventilated, the heat penetrates to a greater extent into the internal layers of the wall. Shading the facade can be a way to reduce the amount of energy accumulated in the wall.

Shading elements in summer constitute an obstacle to the accumulation of energy in the walls in winter, especially if transparent insulation is used on the facade, which captures sunlight falling at a small angle. In such a situation, screens made of deciduous plants [14] that lose their leaves in the fall are beneficial. Deciduous plants are also used in areas with a warm climate as shading elements [15].

Trees influence the regulation of the local climate by shading and evaporating water from leaves. The effect was demonstrated by comparing the air temperature on a treeless street (42.2°C) with the air temperature in a nearby park (30°C) [16]. The degree of shading and absorption of solar radiation by trees depends on the species and season. Tall vegetation that protects against sunlight can reduce the costs of air conditioning in neighbouring buildings by 30% during periods of heat [17, 18]. They do a better job protecting deciduous trees [19]. Trees should not be planted too close to the building to protect them from affecting the foundation; instead, green walls or pergolas can be used on which leafy plants can climb. Various vertical systems are used , e.g. felt panels, containers or grids. Plants on a large wall surface evaporate, cooling the air, and also retain dust, purifying the air without damaging the top layer of the wall, and constitute a thermal barrier [14, 20].

Limiting the exposure to sunlight on non-transparent partitions requires checking whether it will contribute to saving the energy needed to cool the interior of the building. A method was planned to calculate the gains caused by shading based on measurements of air temperature and surface temperature of the wall from the outside, with known heat transfer resistance of the individual wall layers [21]. Based on the average temperature in the masonry layer, the differences in the thermal energy accumulated for different variants of the shading covers will be calculated.

3. TEMPERATURE ON THE SURFACE OF A WALL EXPOSED TO SUNLIGHT

The research was carried out in Poznan in summer on a day when the air temperature was above 30°C and the sky was cloudless. The temperature of the external surface of the wall exposed to the sun behind the shading covers was collected. Examples of shading degrees are shown in Fig. 4.

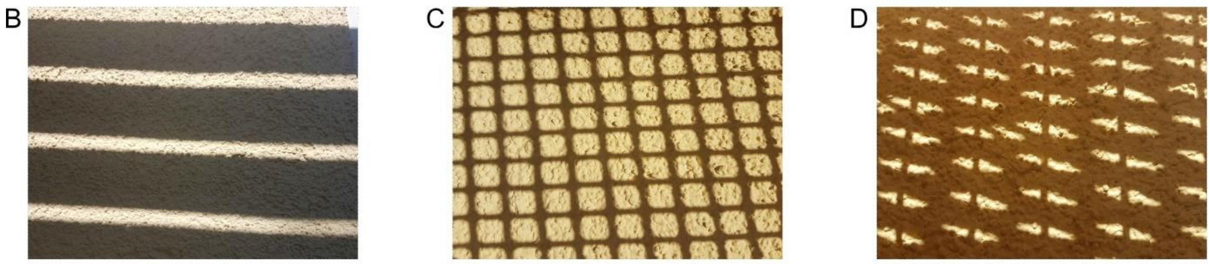

Fig. 4. Examples of shading degrees (Table 1): B – 75%, C – 37% and D – 82% (photo by M. Siewczyńska)

Due to the different orientations of the walls, the measurements were repeated three times a day and then the highest value was selected at a given point. In selected points, six temperature measurements were made using a pictometer (BP25), giving results with an accuracy of 1.5°C, and then the arithmetic mean and standard deviation of the average multiplied by the Student-Fisher coefficient were calculated. The value of the standard deviation of the average was lower than the accuracy of the temperature metre, so the error was assumed to be 1.5°C. The results are shown in Table 1.

Table 1. Average temperatures in the shaded part of the sun-lit wall (behind the cover) (elaborated by M. Siewczyńska)

Variants of shading elements	The highest average surface temperature [° C]
comparative surface – yellow lamb-like plaster (A)	54.2±1.5
comparative surface behind a cover of wooden boards with a shading level of 75% (B)	42.6±1.5
comparative surface behind a plastic grid cover with a shading level of 37% (C)	49.0±1.5
comparative surface behind a wicker mesh cover with a shading level of 82% (D)	42.9±1.5
comparison surface behind a partially transparent black glass cover (E)	43.6±1.5
comparison surface behind a light beige stone plate cover (F)	34.1±1.5
clinker tile exposed to sunlight for 5 hours (G1)	61.4±1.5
shaded clinker tile (G2)	31.8±1.5
dark brown surface of the external window blind (H1)	60.8±1.5
dark brown surface of the external window blind shaded by the leaves of a climbing plant (H2)	41.5±1.5

The outside air temperature read from a thermometer standing in the shade was 33±0.5°C. The pictometr used to measure surface temperature also reported the local air temperature. Its average value during all measurements was 35.2±1.5°C.

The air temperature inside the building measured with a thermometer was 29.5±0.5°, and the average of the measurements was 29.6±1.5°C.

The temperature of the sun-heated surface (A, G1 and H1) ranged between 54.2°C and 61.4°C. The temperature of the shaded surface (B, C, E, E, F, G2, H2) ranged from 31.8°C to 49.0°C.

Figure 5 shows the structure of the wall analysed, and the material parameters are given in Table 2. The assumed heat transfer resistance on the external side is 0.04 m^2K/W and on the internal side 0.13 m^2K/W. The calculated heat transfer coefficient was 0.23 W/m^2K (homogeneous wall without leaks on the warm side of the insulation and with PVC connectors).

Fig. 5. Construction of a comparative wall, layers in order from the outside: 1 – external thin-layer plaster, 2 – EPS polystyrene, 3 – aerated concrete masonry, 4 – internal cement-lime plaster (elaborated by M. Siewczyńska)

Table 2. Wall material parameters (elaborated by M. Siewczyńska)

Layers	Layer thickness d [m]	Heat conduction coefficient λ [W/mK]	Density ρ [kg/m^3]	Specific heat c_p [J/kgK]
1 – external thin layer plaster	0.003	1.0	1800	1500
2 – EPS polystyrene	0.10	0.042	11	1460
3 – aerated concrete masonry	0.24	0.14	500	1000
4 – internal cement and lime plaster	0.02	0.82	1850	840

4. TEMPERATURE DISTRIBUTION IN THE WALL CROSS-SECTION

The graph of temperature change in the wall cross section was calculated using the formulas [22]:

$$\upsilon_e = t_e - U\,R_{se}\,(t_e - t_i) \tag{4.1}$$

$$\upsilon_1 = t_e - U\,(R_{se} + R_1)(t_e - t_i) \tag{4.2}$$

$$\upsilon_2 = t_e - U\,(R_{se} + R_1 + R_2)(t_e - t_i) \tag{4.3}$$

$$\upsilon_3 = t_e - U\,(R_{se} + R_1 + R_2 + R_3)(t_e - t_i) \tag{4.4}$$

$$\upsilon_i = t_e - U\,(R_{se} + R_1 + R_2 + R_3 + R_{si})(t_e - t_i) \tag{4.5}$$

where:
t_e – external air temperature,,
t_i – internal air temperature,,
U – wall heat transfer coefficient,
R_{se} – heat transfer resistance on the external side of the wall,
R_1, R_2, R_3 – heat transfer resistances of 1, 2 and 3 wall layers, respectively,
R_{si} – heat transfer resistance on the internal side of the wall,
υ_e – temperature on the surface of the external wall
υ_1, υ_2, υ_3 – temperature at the junction of successive wall layers,
υ_i – temperature on the surface of the internal wall,
assumed $t_e = 33°C$ and $t_i = 29.5°C$ for comparative calculations.

The temperature of the external air measured in the shade is significantly different from the temperature of the air in contact with the wall surface. Due to this difference, subsequent calculations were made with the assumption that the bending of the graph caused by air convection on the exterior surface of the wall is 0.1°C due to the small value of R_{se}. The graphs in Figure 6 show values that exclude areas outside the thickness of the wall because they are not needed for further analysis.

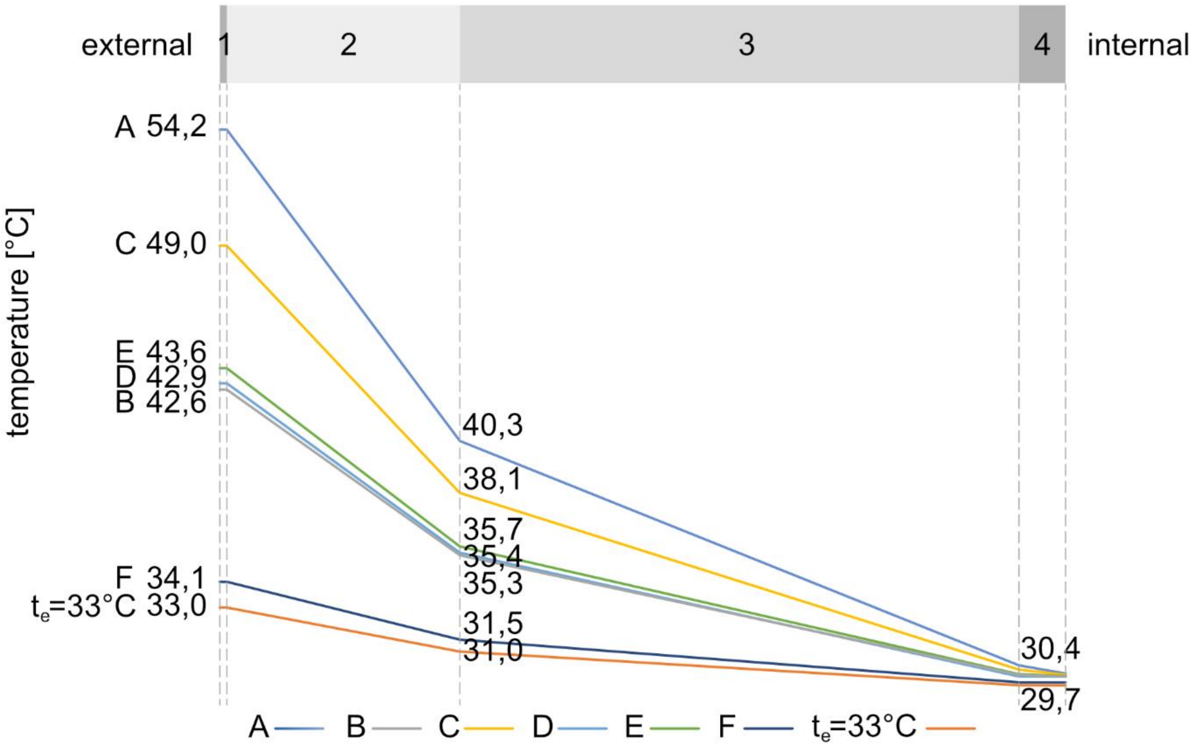

Fig. 6. Temperature change graph in the wall cross-section: A – comparative surface – yellow lamb-like plaster, B – comparative surface behind a cover made of wooden boards with a shading degree of 75%, C – comparative surface behind a cover made of a plastic grid with a shading degree of 37%, D – comparative surface behind a cover made of wicker mesh with a shading degree of 82%, E – comparative surface behind a cover made of a partially transparent black glass plate, F – comparative surface behind a cover made of a light beige stone slab and comparatively for $t_e = 33°$ C (elaborated by M. Siewczyńska)

5. THERMAL ENERGY ACCUMULATION IN THE MASONRY LAYER

Based on the calculated temperatures at the contact surface (υ_2 and υ_3) of the wall layer, the accumulation of this masonry layer was calculated using the formula [23]:

$$Q = F\, d\, \rho\, c_p\, T \tag{5.1}$$

where:
Q – accumulated portion of heat,
F – wall area,
d – thickness of the wall layer,
ρ – density,
c_p – specific heat,
T – average temperature of the wall layer,
assuming the wall area F = 9 m^2 and the data from Table 2. The results are presented in Table 3 in order from the highest to the lowest average temperature of the masonry layer. The error in the result was calculated using the logarithmic differential method.

Table 3. Heat accumulation in the masonry layer of the analysed wall (elaborated by M. Siewczyńska)

Variant	Average temperature of the masonry layer T [°C]	Accumulated portion of heat Q [kWh]
A	35.4±1.5	10.6±0.4
C (37%)	34.1±1.5	10.2±0.4
E (glass)	32.8±1.5	9.9±0.5
D (82%)	32.7±1.5	9.8±0.4
B (75%)	32.6±1.5	9.8±0.5
F (plate)	30.6±1.5	9.2±0.5

The largest difference in the value of heat accumulation is between variant A (comparison area without a shading cover) and F (cover made of a light beige stone plate) and is less than 1.5±0.5 kWh. The area with the lowest shading percentage (37%) has the lowest efficiency. Openwork covers with a shading level of 75% and 82% and black glass gave comparable results.

To check the influence of the masonry material on the accumulation efficiency, the calculations were repeated for the same external temperatures, the internal temperature reduced to 21°C and three variants of masonry structures: aerated concrete, hollow ceramic block and silicate with the parameters given in Table 4. The accumulation results are given in Table 5.

Table 4. Parameters of compared masonry materials (elaborated by M. Siewczyńska)

Masonry material	Heat conduction coefficient λ [W/mK]	Density ρ [kg/m^3]	Specific heat c_p [J/kgK]
aerated concrete	0.14	500	1000
hollow ceramic block	0.30	770	880
silicate	0.54	1500	880

Table 5. Heat accumulation in the masonry layer of three wall variants (elaborated by M. Siewczyńska)

–	Accumulated portion of heat Q [kWh]		
Variant	aerated concrete wall	hollow ceramic blocks wall	silicate wall
A	8.7±0.5	10.8±0.6	19.9±1.2
C (37%)	8.3±0.5	10.4±0.6	19.4±1.2
E (glass)	7.9±0.5	10.1±0.6	18.9±1.2
D (82%)	7.9±0.5	10.0±0.6	18.8±1.2
B (75%)	7.8±0.5	10.0±0.6	18.8±1.2
F (plate)	7.2±0.5	9.4±0.6	17.9±1.2

In 2023, there were approximately 30 days [24] with temperatures above 30°C in the period from June 19 to September 18. Assuming 30 days per year with a temperature above 30°C with 12 hours of solar heating and 50 years of building use, thermal energy savings for the indoor air cooling system were estimated. The results are given in Table 6. The highest efficiency was achieved for a silicate wall, followed by a hollow ceramic block wall, and the lowest value was achieved for aerated concrete.

Leaving aside inflation, at current electricity prices, the profit is significant. The calculated results relate to the wall area of a room with dimensions of 3 m x 3 m, so the profit will be even greater on the scale of the entire wall on the south side.

Table 6. Thermal energy savings for the cooling system over 50 years of use compared to a wall without shading covers (A) (elaborated by M. Siewczyńska)

–	Saving thermal energy Q [kWh]		
Variant	aerated concrete wall	hollow ceramic blocks wall	silicate wall
C (37%)	6617±0.5	6245±0.6	9236±1.2
E (glass)	13616±0.5	12850±0.6	19005±1.2
D (82%)	14464±0.5	13650±0.6	20189±1.2
B (75%)	14824±0.5	13991±0.6	20692±1.2
F (plate)	25768±0.5	24318±0.6	35967±1.2

6. OPTIMISATION OF THE DEGREE OF COVERS SHADING

The angle of incidence of sunlight in Poznan [25] during spring and summer varies in the range of 37°÷61°. The optimal setting of the shading blinds is between 29° and 53°. The closer the angle to 29°, the greater the solar energy gain in autumn and winter, with a favourable degree of shading in spring and summer. The simulation of the width of the illuminated strip on the wall between the blinds for the blind angles of 29° and 53° is shown in Figure 7.

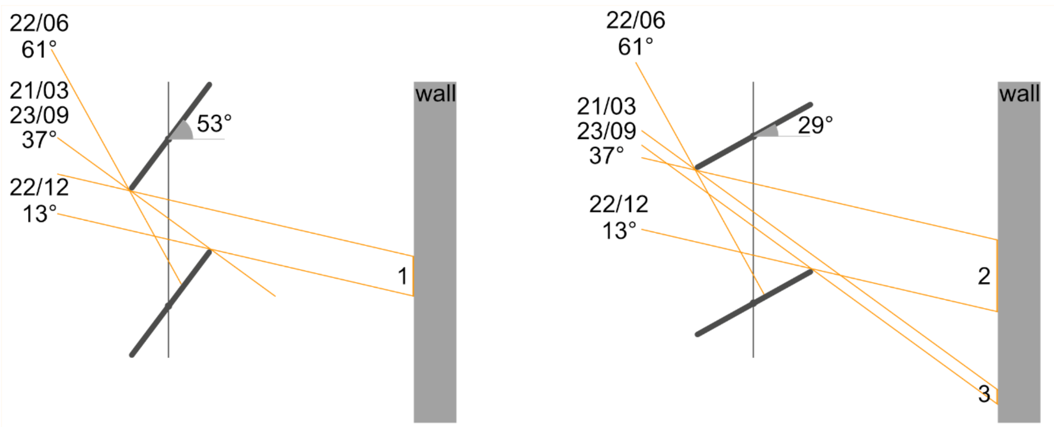

Fig. 7. Optimal angles of inclination of shading elements in Poznan: 1 and 2 – strips illuminated in the autumn-winter period, 3 – strips illuminated in the spring-summer period (elaborated by M. Siewczyńska)

Variants of various shapes of covers, modelled three-dimensionally or parametrically, can be imported in the form of a three-dimensional virtual model, together with a building model with a specific location and orientation, into programmes that simulate sunlight, e.g. on the Forma platform by Autodesk, and use artificial intelligence tools to check the effectiveness of the designed solutions. In the daylight analysis potential is used a cloudy sky model in September 21. The backlight is predicted using technology ray tracing. The analysis result determines how much light reaches the facade from the sky in percentage terms. A value below 15% means difficulties in providing the appropriate amount of daylight through the windows. This analysis is used to determine the size of windows that provide access to daylight inside a building, but it can also be used to compare the effectiveness of screen shading.

The daylight analysis potential on the Forma platform was carried out for four different shading element shapes (Fig. 8) of a building located in Poznan, orientated with the shielded wall facing south. On the wall without covers, a lighting potential of 36÷37% was achieved, while behind the covers (in order from left to right) in the first variant, when the covers were moved 50 cm from the wall:

- 12÷18%,
- 9÷17%,
- 17÷19%,
- 13÷21%.

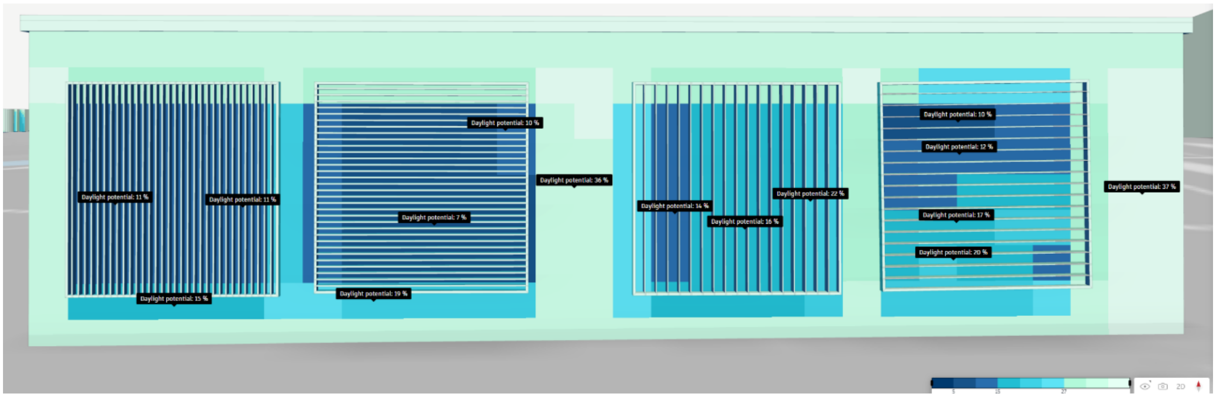

Fig. 8. Example analysis of daylight potential on the Form platform of four types of covers modelled in Archicad (second variant: distance of 15 cm from the wall) (elaborated by M. Siewczyńska)

In the second variant, when the covers were located at a distance of 15 cm from the wall, slightly more favourable results were obtained:

- 11÷15%,
- 7÷19%,
- 14÷22%,
- 10÷20%.

The most effective was a shading elements made of horizontal slats of 2 cm x 10 cm spaced every 10 cm, offset 15 cm from the wall.

7. CONCLUSIONS

Based on measurements of the surface temperature of the wall exposed to sunlight with various variants of shading screens, the temperature distribution in the analysed wall was calculated. Based on the average temperature in the masonry layer, the thermal energy accumulated in the southern wall of the sample room was calculated for 12 hours on a sunny day. The values were related to the results for the wall without covers. The energy savings needed to cool the indoor air due to the use of shading covers were estimated. The analysis results allow to draw the following conclusions:

- shades covering opaque facades save energy needed to cool the air inside the building,
- the cover providing 37% shading turned out to be ineffective,
- partially transparent black glass gave savings similar to 75% and 82% shading elements,
- the greatest efficiency was achieved by shading with a stone slab with small gaps between the slabs,
- movable shutters allows to adjust the degree of shading of the wall surface, which allows to adjust the area shaded in summer without limiting heating in the period from autumn to spring,
- shading the clinker surface and the dark brown window blind resulted in a reduction of the surface temperature by approximately 25°C on average,
- the highest efficiency of saving thermal energy needed for the cooling system was achieved for a silicate wall, followed by a ceramic brick wall, and the lowest value was achieved for aerated concrete,
- using a virtual three-dimensional building model and various shield variants, it is possible to initially estimate which variant has the best efficiency.

The savings calculated theoretically in the next step of the investigation should be verified by measuring the actual energy consumption needed to cool the building's internal air.

The estimated benefits caused by shading the facade in the summer should be balanced with the losses caused by thermal bridges [26] caused by the installation elements of the blinds.

To conduct an in-depth analysis of the impact of shading on opaque partitions, the authors of the article point out the need to conduct research covering the entire year and to link the measurements with monitoring energy consumption as a function of outdoor temperature.

Furthermore, it can be considered to analyse reduce the amount of rainwater supplied to the exterior wall.

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