

Article

Efficiency of Solar Shading Devices to Improve Thermal Comfort in a Sports Hall

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Abstract: Thermal environment in sports facilities is probably one of the most important parameters, determining the safety and performance of athletes. Such facilities, due to the required operating temperature and physical activity of users, are a serious challenge for both investors and administrators, especially in summer. The additional criterion of low energy consumption in extremely airtight and well-insulated passive buildings often results in overheating of the interior, creating considerable economic and operational problems. The significant need to reduce solar gain during periods of high outdoor temperatures for low-energy buildings prompts a variety of design solutions. Sun shading systems, as an indispensable element of glazed surfaces, are designed to control the amount of solar radiation reaching the building interior, at the same time creating a favorable microclimate inside. This article analyzes the effects of sun shading, which have actually been applied and modified on the southern façade of a passive sports hall in Słomniki. Measurements of the thermal conditions in the hall were the starting point, on the basis of which a model of the object was created in the DesignBuilder program. Using simulation analyses, thermal conditions arising with the use of different variants of internal and external shading devices were studied in the program. The results presented in the article show that in a well-insulated hall of large volume, appropriately selected external shading devices are only able to reduce the access of sunlight to the rooms. External brise-soleils are able to limit the access of solar radiation to the rooms by up to 30%, but this is not enough to guarantee internal thermal comfort. Internal blinds do not affect the interior microclimate significantly and do not protect protection from overheating. Momentary differences in PMV values for different patterns of closing the blinds do not exceed 0.2.



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Keywords: thermal comfort; solar protection; overhangs; passive building; overheating; sports hall

1. Introduction

Decreasing conventional energy resources and the significant need to protect the climate by reducing the greenhouse effect have necessitated the demand for energy-efficient building designs. The term “energy-efficient buildings” does not cover any technical specifications for the building envelope and energy demand. These buildings are generally defined as “very highly energy efficient” and interpreted in each member state according to local conditions and regulations. The passive house standard introduced in Germany is based on a list of precise technical requirements. The most well-known criterion of all the requirements on this list is a low energy demand for heating of 15 kWh/(m²·year). It is also required to provide thermal comfort in winter and summer with a permissible limit of 10% of the time in the year with an indoor air temperature above 25 °C [1]. Therefore, an interdisciplinary approach to the design process of structural elements and installations and the use of all possible passive measures to protect the building from overheating is strongly recommended in such buildings [2]. Passive protection measures include, but are not limited to, the use of the building’s accumulation properties, night ventilation of the interior, and the use of shading devices, which is further discussed within this article.

1.1. Thermal Comfort in Sports Facilities

In periods of high outdoor temperatures and strong sunlight, it is extremely difficult to maintain thermal comfort in passive buildings where, in addition, the metabolic rate of users is significantly increased. In sports halls, the thermal environment is probably one of the most important parameters determining the safety and performance of athletes [3]. An integrated approach to thermal conditions in sports halls can influence not only well-being but promote physical activity and healthy lifestyles. The literature review proves that only a small number of publications of studies on thermal comfort in sports facilities are available. In addition, there is a lack of standards for the indoor environmental parameters to be maintained in sports halls or a general standardization of the measurement procedure to be used in these spaces. So far, published measurement results have focused mainly on monitoring thermal conditions according to thermal comfort indices. The subject of research conducted by Kisilewicz and Dudzińska [4] was a passive sports hall in Krakow. The authors analyzed the phenomenon of overheating of the building in summer when the hall was not used, and the ventilation system was switched off. Based on the microclimate parameters measured, it was found that 33% (90% in extreme conditions) of the hall users would be dissatisfied with the conditions in the facility. The study concluded that the indoor air temperature could be lowered by using available passive measures to protect the building from overheating, such as solar shades, throughout the day. The authors of the article also suggested intensive cooling of the interior of the hall at night through gravity or mechanical ventilation to discharge the internal heat capacity of the building. Rajagopalan and Luther [5] searched for solutions to improve the comfort parameters in a sports hall connected to an aquatic center in Australia. The studies conducted by the researchers included the performance of natural and hybrid ventilation (assisted by exhaust fans), evaluation of CO₂ content, and overall interior thermal conditions. Due to the high levels of thermal discomfort observed during the summer, a number of energy-efficient solutions were considered to reduce overheating without mechanical cooling and, at the same time, maintaining high indoor air quality. The study showed that at high values of outdoor air temperature, it is difficult to achieve thermal comfort conditions among users with elevated metabolic rates. In order to limit overheating of a sports facility with a large volumetric capacity, the authors of the publication suggest, among other things, using a simple and effective solution, i.e., night ventilation of the building. Bugaj and Kosiński [6] also pointed out the difficulties in maintaining appropriate climatic conditions in sports facilities with high user activity. This article presents a detailed study of the microclimate, carried out in a tennis hall located in Olsztyn. The authors found that the lack of thermal comfort in the hall can result in health and economic problems, but its achievement is not always possible. It was pointed out that clothing and velocity of airflow play an important role in the thermal sensitivity of a person who is active in sport. The study showed that increasing the air velocity in the arena was the fastest way to improve indoor thermal comfort. On the other hand, in all interval training exercises, such as playing tennis, strenuous physical exertion is interrupted by rest, which greatly limits the use of high air velocities.

The authors of another publication focused their attention on comparing objective measurements of thermal comfort and subjective thermal sensations of room users. Revel and Arnesano [7] researched the perception of the thermal environment in a gym and a swimming pool in Italy. They compared objective measurements of the microclimate with subjective evaluation of thermal conditions obtained from questionnaires. Measurements included air temperature, mean radiant temperature, air humidity, and air velocity to assess PMV (predicted mean vote). The subjective evaluation included the use of questionnaires regarding the perception of the thermal environment on a seven-point scale of thermal sensation. The authors concluded that the PMV index could be used to assess thermal conditions in sports facilities. The same team analyzed temperature distribution and thermal comfort parameters in sports facilities to balance energy consumption [8,9]. It was shown that PMV/PPD indices could be used to evaluate the actual thermal sensation in sports facilities and to make informed decisions on energy conservation.

On the other hand, Zhai et al. [10] and Zora's team [11] searched for the relationship between comfort temperature and physiological responses during exercise. The former studied the effect of airflow velocity on thermal comfort for high metabolic values. The authors reported that for elevated activity levels between 2 and 6 met, it is possible to improve thermal comfort conditions for any temperature up to 26 °C by increasing airflow velocity in the zones in use. Zora et al. studied the thermal behavior of athletes in relation to thermal comfort and exercise intensity. They evaluated the relationship between the thermal comfort analysis index PMV (predicted mean vote) and the exercise parameter RPE (rating of perceived exertion), which shows exercise intensity and exhaustion level.

1.2. Shading Devices As Passive Protection Against Overheating

The available literature on sports facilities has not analyzed the issue of solar shading and its effect on interior thermal conditions. Exposing airtight low-energy buildings with large glazed areas to solar radiation can result in overheating of the interior and thus impairing the performance of athletes. Excessive solar gain causes an increase in indoor air temperature, consequently contributing significantly to the cooling load in the summer. Thus, by reducing solar gains through the use of appropriate shading devices, energy savings in the building, as well as improved indoor climatic conditions, can be achieved, which play a fundamental role in athlete performance and health.

Regulation of the amount of light and energy supplied is achieved by, among others, shading wings, horizontal overhangs (brise-soleils), blinds, or roller blinds located on the inner or outer side of the glazing. Many factors influence the efficiency of solar protection shields, but the most important is the place of installation and size of the shield, g_n coefficient determining the total permeability of solar energy for the type of glazing, f_c coefficient determining the reduction in radiation due to the applied solar protection devices, as well as thermal insulation of the window shade and the window itself. Horizontal overhangs, most often used on south façades, are very effective in this respect. Light catchers with different geometry and varying overhang and distance from the top edge of the window allow for passive control of solar gains penetrating through the windows. Properly selected horizontal overhangs block a significant part of solar energy in summer, acting as a passive cooling system and protecting rooms from overheating. In winter, on the other hand, with the low angular height of the sun, it should not overly limit heat gain from solar radiation through windows.

Authors of national and international publications, when looking for effective strategies for passive protection against overheating, often refer to shading systems. As an example, Sivasankar et al. [12] attempted to research various shading strategies. According to the authors, the most effective method of reducing indoor air temperature in summer is primarily to block solar radiation from migrating into the building interior. Shading minimizes solar gain and effectively cools the building, thus dramatically affecting the energy efficiency of the building. Based on the analysis, shading can reduce the peak cooling load in buildings, providing energy savings of 10 to 40%. With appropriate solar shading, it is possible to reduce the indoor air temperature by about 2.5 to 4.5 °C. Authors Valladares-Rendón and Shang-Lien Lo [13] came to similar conclusions, finding that systems of horizontal external shading devices (overhang) effectively reduce the penetration of solar radiation into the interior, reducing the energy demand for cooling. The researchers, using eight building models created in Taipei City, analyzed various scenarios of horizontal overhangs used. Among other things, it was shown that shading systems designed on the building's exterior façades and roof could lead to mitigation of urban heat island effects by reducing the outdoor solar factor and is the most effective passive strategy for reducing indoor overheating.

According to Evioli et al. [14], buildings with large glazed surfaces are prone to thermal and visual discomfort as a result of excessive direct solar radiation. To avoid excessive solar gain and glare problems for occupants, it is necessary to use appropriate solar mitigation solutions such as reflective coatings or movable sunshades. Shading

devices must be selected depending on the building location and the exposure of the glazed façades. The article evaluates the effectiveness of 29 shading devices used in an existing glazed office building in southern Italy. The objective of the analysis was to identify solutions that improve thermal comfort while maintaining adequate levels of indoor lighting intensity. The analyses were repeated for different building orientations to obtain general information. Based on the tests, the authors concluded that internal blinds should be avoided because their thermal comfort benefit is significantly lower than that of external blinds. The results suggested that external blinds are most effective on glazed south-facing façades and much less effective when installed on the west side. In addition, Bellia et al. [15] analyzed the effect of external sunshades on the energy demand of an office building in Italy. The study included horizontal shades on the south façades and louvers on the east-west façades. Simulations were repeated for three different locations. The results suggested that depending on the location, building orientation, and appropriate shading devices, energy consumption could be reduced by up to 20%.

An article [16] evaluated thermal comfort in zero energy buildings in the U.K. Simulations were carried out for different depths of external shading over windows on all façades. As expected, additional solar protection on the south, east, and west façades significantly improved thermal comfort conditions. Bazzocchi et al. [17] in their study analyzed and optimized solar shading systems in a low-energy nursery school in Florence. In their study, the authors found that the use of automatic horizontal blinds with a control system allows for better energy efficiency of the building by about 5–6%, compared to a fixed form of solar protection. In turn, Śliwińska, Nowak et al. [18] noted that the use of shading in the form of an awning is able to significantly reduce the operational temperature in the room. However, on hot days it does not provide sufficient stability of the internal temperature, especially in buildings characterized by low thermal mass. Fedorczak-Cisak et al. [19] pointed out that the current architectural trend, including the exposure of glass façades on the south side, is flawed due to the high cost of sun protection and cooling systems and the lack of the required level of thermal comfort. The research was conducted in an experimental building of the Lesser Poland Laboratory of Building Energy Efficiency (MLBE), in which various high-efficiency heating, cooling, and ventilation devices operating under the supervision of an integrated control system were used. The authors confirmed through their research that appropriate shading elements could reduce the cooling costs of the building but do not ensure thermal comfort.

Due to the progressive global warming, Szagri and al. [20] create a heat sensitivity map that includes dynamic simulations based on building typology. As part of the publication, the authors performed dynamic simulations of nursing homes to investigate the effects of building types and construction methods on summer overheating. The potential factors influencing the risk of overheating of the building were analyzed, such as the design, the number of stories of the building, the shape of the roof, building materials, the degree of glazing and shading. Using dynamic simulations has been established main parameters that play a major role in reducing indoor air temperature in summer. The research shows that the increase in the number of night air exchange rates significantly decreased the temperature in the rooms. According to the authors, the operation of roller shutters also has a significant impact on the reduction in discomfort.

In Poland, the investment cost of building meeting passive standards requirements is still very high. The modern materials with appropriate thermal parameters together with the installation systems are relatively expensive as they are still not widely common. Despite the subsidies offered, the fact of the long payback period makes this kind of solution to be not popular among investors. Investors who decide to meet the passive standard of the building are looking for simple architectural and construction solutions being at the same time energy efficient. In passive buildings, there are always cost-effective mechanical ventilation systems connected with natural nighttime ventilation to reduce the risk of overheating. The ground heat exchangers, additionally recommended in the construction of low-energy facilities, generate additional investment and operating costs; therefore,

investors are still skeptical about this solution. Despite the fact that mechanical ventilation was designed in the analyzed object, it was not working during the measurement time, and night ventilation was not applied due to safety reasons. Thus, the method of exploitation of the examined building was far from the design assumptions and recommendations for passive construction regarding the protection of the building from overheating. Therefore, it was checked whether the usage of the shading devices in airtight, large-volume passive buildings is a sufficiently effective method in reducing the cooling load and shaping thermal comfort in the space. Are the hall's microclimate parameters determined by its energy "passivity", or maybe an interdisciplinary approach to the issue regarding the usage of available passive means of protecting the building against overheating should be applied? This article investigates the effects of actually applied and modified sunshades on the southern façade of a low-energy sports hall. The author answered the question of the appropriate modifications of the sun shading systems are capable enough to reduce the internal solar gains and to keep the comfortable internal thermal conditions.

2. Object and Methodology

2.1. Passive Sports Hall in Słomniki

The analyzed object with passive energy standard is a sports hall in Słomniki. The building's orientation is in accordance with passive building principles, with the longitudinal axis of the building in the east-west direction (Figure 1a,b). The sports hall with a total usable area of 1755.06 m² has one overground story. The building holds a multi-purpose arena with a 22 × 44 m pitch with stands for approximately 240 spectators, which is the subject of the analysis in this article. Technical and storage rooms, which do not require access to daylight, are located under the stands. The social facilities are located in a separate, lower part of the building on the south side.

The main material used for the walls is 25 cm thick silicate blocks, insulated from the outside with 30 cm thick expanded polystyrene (EPS). The heat transfer coefficient of external walls, conforming with the passive house requirements, is 0.1 W/(m²·K). Silicate blocks are construction materials with favorable accumulation and ecological values. High volume density and thermal conductivity allow for the obtainment of high heat capacity and high value of heat diffusion coefficient. Detailed material properties of the external wall sports hall are presented in Table 1.

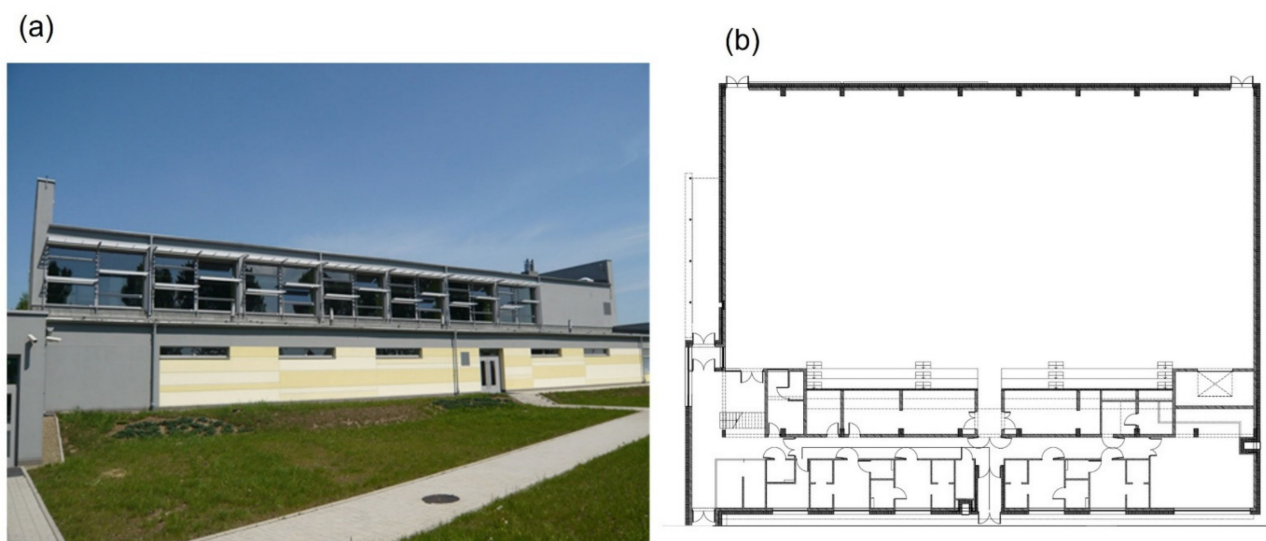


Figure 1. Passive hall in Słomniki, south façade (a) (author's archive), and ground floor plan (b) [23].

Table 1. Material properties of the external wall [21,22].

External Walls	Thickness (m)	Density ρ (kg/m ³)	Thermal Conductivity λ (W/(m·K))	Specific Heat c (J/(kg·K))	Heat Capacity C (MJ/m ³ ·K)
Interior plaster	0.015	1000	0.40	840	0.84
Silicate blocks	0.25	1900	0.80	880	1.67
Expanded polystyrene (EPS)	0.30	15	0.04	1400	0.02
External plaster	0.02	1800	0.82	840	1.51

On the south side, the analyzed sports hall arena gets illumination through a line of windows with an area of 85 m², and on the north side, the area of the hall's glazed partitions is 65 m². Wooden triple-glazed windows are installed in the hall, and the chambers are filled with argon. The heat transfer coefficient of the whole set is 0.8 W/(m²·K) [23].

On the south façade, immovable external brise-soleils consisting of separate vertical slats were mounted horizontally (Figure 1a). The building additionally uses electric internal blackout blinds.

In accordance with the premises of passive construction, a supply and exhaust ventilation system with heat recovery was designed and implemented in the hall. The air handling units were equipped with recuperators allowing for heat recovery from the exhaust air with maximum efficiency of 72%.

In the passive hall, high air-tightness of external walls was confirmed by pressure test in accordance with PN-EN 13829-2002 [24]. During the tests, a final result $n_{50} < 0.6$ 1/h was obtained.

2.2. The Criterion for Ensuring Thermal Comfort

Thermal comfort is defined as a state of equilibrium between the amount of heat generated in the body during metabolic processes and the heat losses released to the environment mainly by radiation, convection, and conduction [25]. Heat exchange in the human-environment relationship results from a number of interacting factors involved in shaping the thermal balance of the body. The sense of comfort is therefore determined by a number of environmental parameters affecting the intensity of heat exchange, such as indoor air temperature, indoor air humidity, or the radiation temperature of surrounding surfaces. All factors related to the building user, which include physical activity and thermal insulation of clothing, are extremely important for the perception of environmental conditions (Figure 2).

When assessing the conditions of the indoor environment, it is possible to rest on the primary indices of thermal comfort: PMV and PPD based on the European standard PN-EN ISO 7730:2006 [26]. PMV (predicted mean vote), i.e., statistical index of feeling warm, predicts the mean evaluation of a large group of people defining their thermal sensations in the Fanger's seven grade scale [25] (Figure 2). For appropriate use of the PMV model, the parameters involved in the calculation of the index need to be within certain limits according to EN ISO 7730 [26]. It should be added that researchers Humphreys and Nicol [27] consider that the validity intervals stated in this standard contribute largely to the biases in PMV. Bandwidths of comfort parameters matching correct PMV are narrower than that stated in EN ISO 7730. According to the researchers, the current intervals are too large, and near the extremes, there is not sufficient data to confirm the validity. The authors consider PMVs free from bias, inter alia, if the activity level is $\text{met} < 1.4$. With increased activity, for example, 1.8 met, the feeling of heat is overestimated by one scale unit. However, the same researchers say that by taking the database worldwide as a single distribution, PMV is free from serious bias.

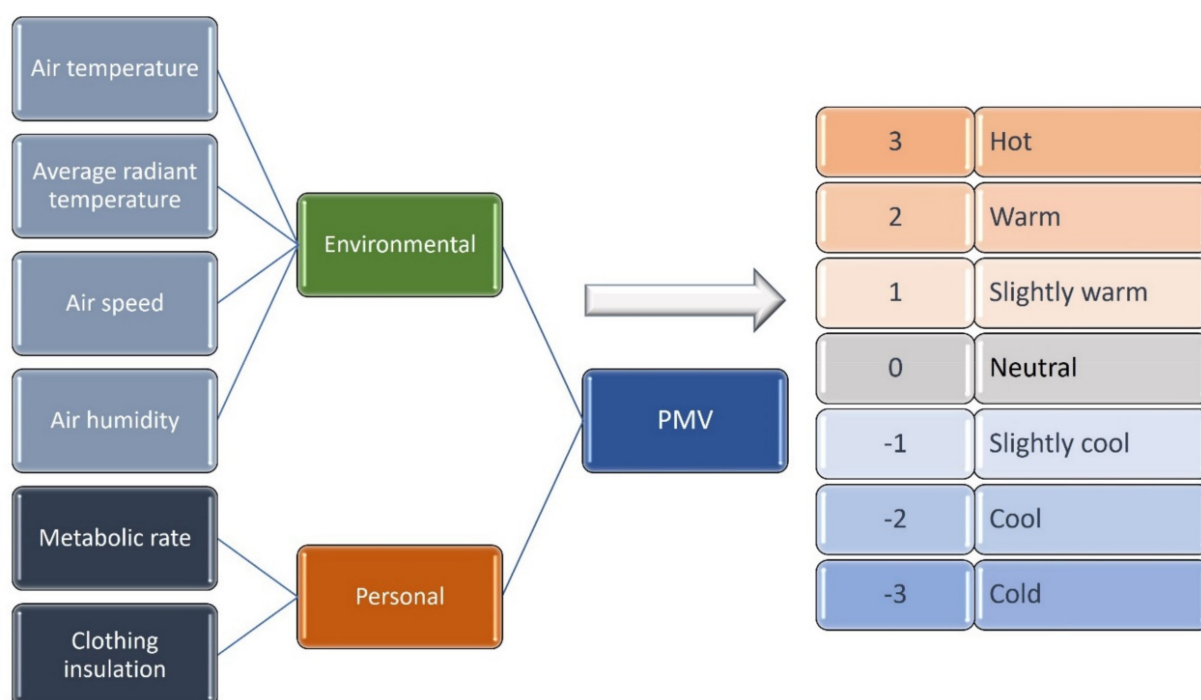


Figure 2. Parameters used in the predicted mean vote (PMV) calculation and relation to thermal sensation scale.

The PPD index (predicted percentage of dissatisfied) defines the predicted percentage of dissatisfied as the percentage of people evaluating the examined thermal environment as definitely negative. In addition, consideration should be given to minimizing the local thermal discomfort, which is influenced by, e.g., drafts, temperature asymmetry, vertical temperature difference, or perceived floor temperature, also defined in PN-EN ISO 7730 or in national regulations. In thermal comfort conditions, for a class with medium requirements (category II according to EN 16798-1 [28]), the PMV should be between -0.5 and $+0.5$, which corresponds to 10% PPD.

In the case of existing buildings, the quality of the internal environment can be determined in the simulation program on the basis of measurements or calculations of the basic and derived physical parameters and then calculating the values of the appropriate indicators for comparison with the standard requirements [29]. The instrument used to measure the thermal microclimate in the analyzed hall building was an integrated digital meter BABUC A (Figure 3), meeting the requirements of PN-EN ISO 7726 [30]. The measurement results were used to validate the simulation model of this building.

2.3. Simulation Model in DesignBuilder Program

In this article, DesignBuilder software was used to simulate the effects of internal and external shading on thermal conditions in the sports hall. DesignBuilder is a visual modeling tool for overall building performance simulation software based on the EnergyPlus engine. The core of the simulation in the EnergyPlus program is a model of the building that is based on fundamental heat balance principles. According to EnergyPlus Engineering Reference [31], the air heat balance is given by:

$$C_z \frac{dT_z}{dt} = \sum_{i=1}^{N_{sl}} Q_i + \sum_{i=1}^{N_{surfaces}} h_i A_i (T_{si} - T_z) + \sum_{i=1}^{N_{zones}} m_i C_p (T_{zi} - T_z) + m_{inf} C_p (T_{\infty} - T_z) + Q_{sys} \quad (1)$$

where:

$C_z \frac{dT_z}{dt}$ rate of energy storage in air (W)

$\sum_{i=1}^{N_{sl}} Q_i$ sum of the convective internal loads (W)

$\sum_{i=1}^{N_{surfaces}} h_i A_i (T_{si} - T_z)$ convective heat transfer from zone surfaces (W)

$$\sum_{i=1}^{N_{zones}} m_i C_p (T_{zi} - T_z) \text{ heat transfer due to interzone air mixing (W)}$$

$$m_{inf} C_p (T_{\infty} - T_z) \text{ heat transfer due to infiltration (W)}$$

$$Q_{sys} = m_{sys} C_p (T_s - T_z) \text{ air systems output (W)}$$

The theoretical basis of DesignBuilder is, therefore, the law of conservation of energy, which considers the process of heat exchange in the building. In calculating the energy consumption, this approach considers the influence of many external conditions, such as meteorological conditions, the thermal insulation of the envelope, the operation of the installations, indoor equipment, and the activities of users. It is worth emphasizing that at present, it is the most modern and most advanced tool designed for simulation calculations.



Figure 3. Digital microclimate meter Babuc A (author's archive).

A model of the entire sports arena building, Figure 4, was created in DesignBuilder; however, the simulation analyses focused on the arena itself and the active occupants. In the model, the parameters, structures, and installations of the object were taken into account, as well as the schedules of people present. Due to the nature and purpose of the

analyzed facility, the metabolic activity called “exercise/sport”, available in the program library database, was chosen. This value gives the volume of the heat flux produced by the human body, and in the assumed case, it is 300 W/person [26,32]. The value of the athlete’s metabolic rate assumed for the simulation reflects the activity observed during the measurements. It should be kept in mind that the analyzed hall is a place for practicing different sports with different activity and associated metabolic intensity (200–464 W/m²) [33]. A clo coefficient value of 0.4 was assumed for the users of the analyzed hall practicing sports in light clothing.



Figure 4. South façade of passive sports hall building in Słomniki generated in the DesignBuilder program.

Due to the lack of precise information in the design documentation, the required illuminance was based on the standard [34] equal to 400 lux. Suspended lighting was assumed for modeling the hall (Figure 5a), selecting the “Best practice” suggested option with the most favorable parameters from the DesignBuilder library. Lighting characteristics:

- Normalized power density—3.3 (W/m²—100 lux);
- Radiant fraction—0.42;
- Visible fraction—0.18.

The exterior louvers on the south façade are composed of separate vertical slats. In the simulation model, it was only possible to select full shades with an overhang of one meter, permanently mounted (Figure 5b).

In the modeling, it was assumed, guided by the actual use of the hall at the time of the measurements, that the interior blinds are closed regardless of indoor and outdoor conditions between 9:00 a.m. and 3:00 p.m. every day of the week except Saturdays. Parameters of internal blinds assumed in the program:

- Solar radiation transmittance—0.05;
- Solar radiation reflection—0.35;
- Thermal conductivity $\lambda = 0.1$ W/(mK).

The program includes detailed characteristics of transparent and non-transparent building partitions. The heat transfer coefficient of external walls is $0.1 \text{ W}/(\text{m}^2\text{K})$, and of windows is $0.8 \text{ W}/(\text{m}^2\text{K})$.

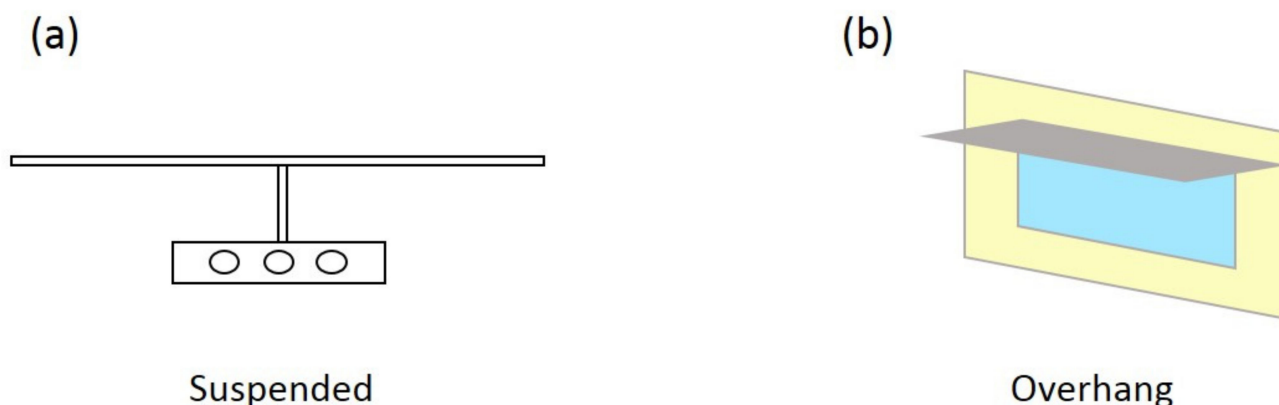


Figure 5. The type of lighting (a) and the type of external light-breakers (b) adopted in the DesignBuilder program for the hall in Słomniki [32].

In accordance with the design, a simplified description of the mechanical ventilation system was introduced into the model. When modeling the HVAC system, DesignBuilder allows one to choose from two simulation algorithm options: Simple and Detailed. The choice of option depends on the level of knowledge available about the installation. The simple option was adopted in the model due to the lack of detailed data regarding the HVAC system. During the research in the period of 29.06.–01.07. mechanical ventilation was not activated, therefore in the basic variant, reflecting the actual conditions during the measurements, this option was turned off.

The model of the building also takes into account the operation of air infiltration and gravitational air exchange, reflecting the real image of the object used during the day when the windows are open. For modeling natural ventilation in the hall, the option “calculated” was adopted in the program, making it possible to enter information about the percentage of the window opening in each area separately in any given time interval. The calculated model of air exchange used in the program takes into account the difference in indoor and outdoor temperatures, the distribution of wind pressure on each façade, and the pressure difference between zones in the building.

The created simulation model was validated. For this purpose, weather data were obtained from IMGW (Institute of Meteorology and Water Management) in Cracow, which is the meteorological station closest to Słomniki, located approximately 24 km away toward the north. Looking for the degree of dependence between the results obtained by measurements and simulations, first of all, the correlation coefficient was calculated, taking values in the range $[-1,1]$. Comparing the results of indoor air temperature measurements during the summer 29.06.–01.07. with the results of the model obtained by simulation for the same period, the value of the correlation coefficient equal to 0.94 was obtained (Figure 6).

A correlation coefficient value in the range of $0.7 \leq r_{xy} < 0.9$ indicates a very high correlation in the statistical analysis [35]. Additionally, the standard error of estimation was assessed to be $\pm 0.371 \text{ }^\circ\text{C}$. Therefore, it was further assumed that the model of the passive sports hall in Słomniki made in the DesignBuilder program could be used for further analysis.

Figure 7 presents a graphical scheme of the experimental simulation analysis of the sports hall in Słomniki.

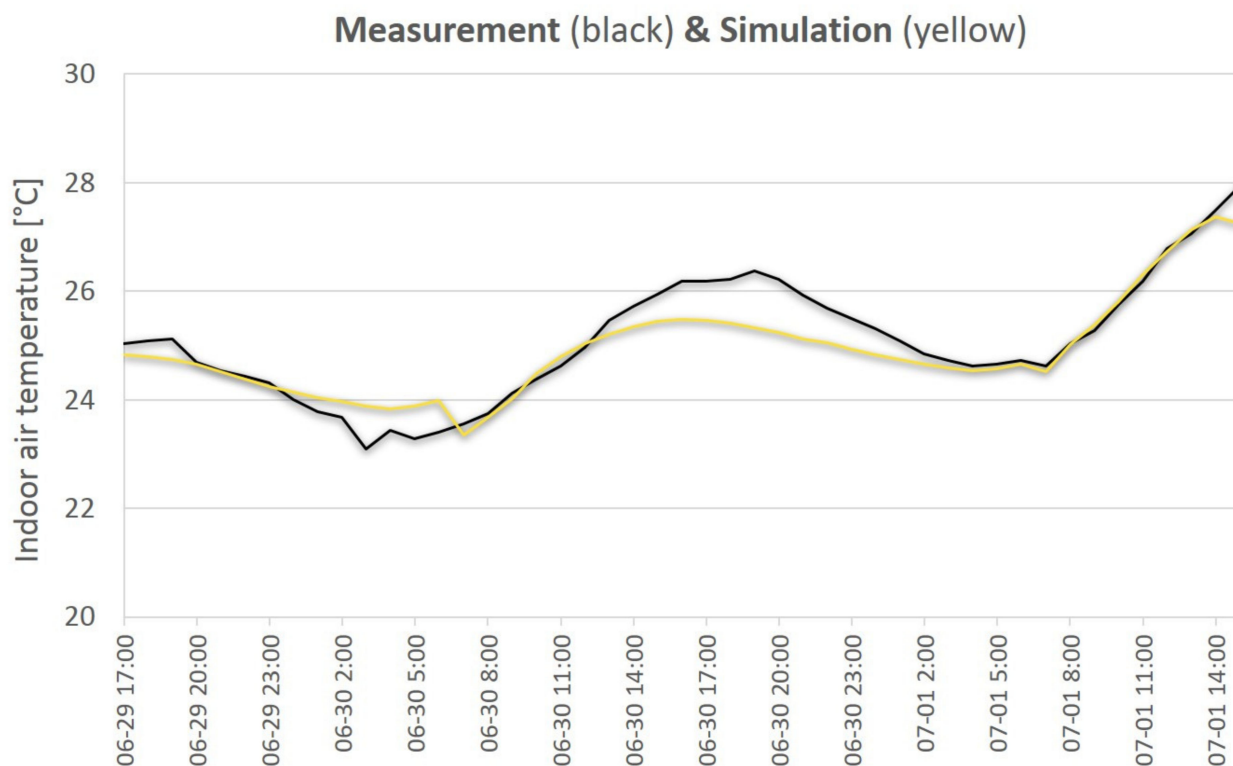


Figure 6. Indoor air temperature distribution during the summer measurement and the values obtained from the simulation model for the studied sports arena.

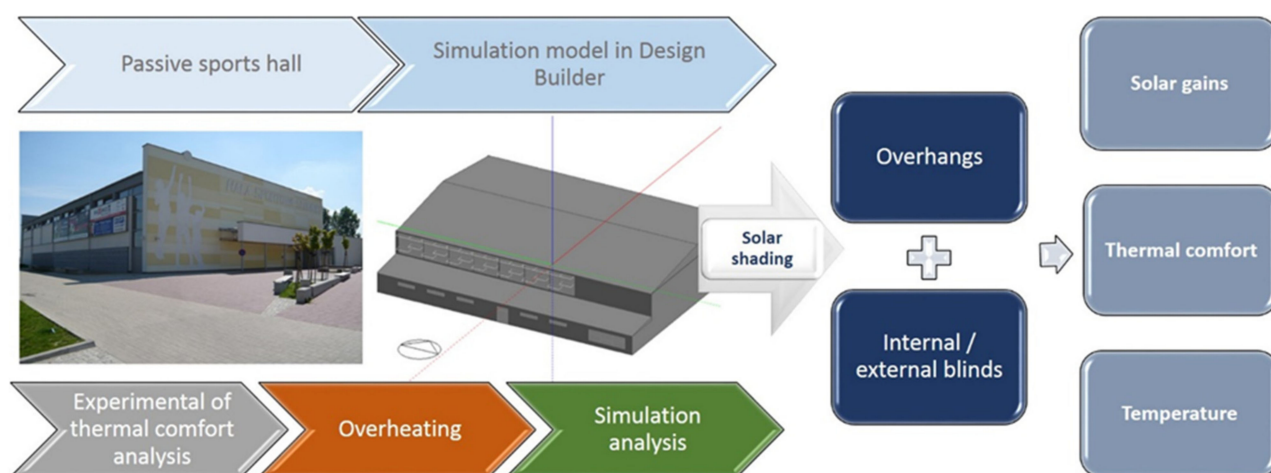


Figure 7. Graphical scheme of the experimental simulation analysis of the sports hall in Słomniki.

3. Results of Thermal Comfort Analysis

3.1. Experimental Analysis

Summer thermal comfort measurements were conducted during a period of high thermal load in late June and early July (3 days) 2012. Measurement data were recorded at 10 min time intervals. During the third day of the study, i.e., 01.07., a sports competition was held in the hall. On the first and second day of measurements, the hall was not used.

Detailed measurement conditions of the sports hall in summer are presented in Table 2. As already mentioned, due to the proximity of meteorological station Kraków Balice, data on outdoor air temperature, as well as humidity and wind speed values, not included in

the table, were obtained from the IMGW Institute of Meteorology and Water Management during the study days.

Table 2. Measurement conditions in the sports hall during the three-day summer period.

Date	Maximum Outdoor Air Temperature (°C)—Meteorological Station Kraków Balice	Closed Internal Roller Blinds	Tilted Windows N (25% of Total Window Opening)	Tilted Windows S (15% of Total Window Opening)
29 June Friday	27.5	Yes	7.00–9.00	7.00–9.00
30 June Saturday	31.6	No	7.00–9.00	7.00–9.00
1 July Sunday	33.3	Yes	7.00–9.00 and 15.00–19.00	7.00–9.00 and 15.00–19.00

The location of the measuring device on the mezzanine floor was dictated by the safety of the meter and the possibilities resulting from the way the facility is used. The location of the sensors could not interfere with the schedule of the sports activities taking place. It was verified that the difference in height between the level of the hall floor in Słomniki, where the classes occurred, and the location of the device could have some small effect (± 0.5 °C) on the final results of the analyses. However, this was the only possibility to conduct measurements during the normal operation of this facility.

The calculated values of environmental parameters and comfort indices are summarized in Table 3.

Table 3. Summary of average results of thermal microclimate and thermal comfort measurements in the hall during the period of high outdoor air temperature.

Environmental Parameter	Average Value
Indoor air temperature t_a (°C)	25.1
Radiation temperature t_r (°C)	25.8
Operative temperature t_o (°C)	25.3
PMV (-)	2.6
PPD (%)	93.1

The resulting mean PMV was several times greater than the highest acceptable thermal comfort index of +0.5, confirming the intense overheating of the room. The mean value of the predicted percentage of unsatisfied PPD exceeded 90%.

The average calculated indoor air temperature during the study period was 25.1 °C. The highest measured temperature was 27.9 °C. The average value of the radiant temperature of the surrounding surfaces was 25.8 °C, and the average operative temperature was 25.3 °C.

Polish formal requirements for thermal conditions inside buildings [36] (Section IV, Chapter 4, §134) provide a design temperature, used in the design of gymnasiums, of 16 °C. However, there are no explicit guidelines for the range of thermal comfort of athletes. It is obvious that intense physical exertion (from 300 W/person upward) is more beneficial at lower air temperature [37], but this issue is not clearly defined. According to the CIBSE Guide [38], for sports activities in a multi-purpose hall, the optimal operative temperature may be between 12 and 18 °C depending on the type of activity. In turn, the authors Trianti-Stourna et al. [39] came to the conclusion that desirable indoor conditions for sports hall facilities are temperature between 18 and 20 °C. The available sources lack consistency and unambiguously specified categories of sports, metabolic values, and corresponding thermal comfort temperature. The analysis of indoor conditions for the assumed level of metabolism and insulation of clothing made it possible to establish a range of indoor thermal comfort using the algorithm formulated by Fanger. It was finally assumed that indoor air temperature in the hall, which is comfortable for active users of the hall in summer, is within the range of 14–18 °C. From the obtained measurement results, it should

be concluded that the range of comfortable temperature in the hall was exceeded to a considerable degree.

The results of measurements clearly show that large energy gains related, among others, to placing transparent partitions mainly on the southern side (which are in accordance with the assumptions of passive construction) and gains from people and devices, while extremely desirable in winter, constitute a significant heat load for the building in summer. In the literature, researchers often refer to shading devices as an effective way to reduce overheating. However, the study shows that in the case of the analyzed hall, the shading used in the building is insufficient to maintain thermal comfort in the summer. Using the DesignBuilder simulation program, it was checked whether changing the parameters and dimensions of the applied shading could reduce the discomfort during high thermal load.

3.2. Simulation Variants and Results

Rooms overheated in summer pose considerable economic and operational problems. Sunshades are one of the simplest possible architectural and construction solutions to rationalize energy use and reduce discomfort in summer. However, the effectiveness of the used and widely advertised protection against excessive solar radiation depends on many factors related to, among others, the location, size, and technical characteristics of the shading device. Therefore, looking for solutions to reduce the discomfort in the sports facility in Słomniki, the effects of sun shading, which have actually been applied and modified on the southern façade, were examined. However, the type of glazing was not changed.

Simulations were performed for the following versions:

- Variant 1: Overhangs brise-soleils were used (Figure 5b) with an overhang of 1 m, and shading roller blinds located on the inner side of the window, assuming the following output parameters:
 - Solar energy transmittance of the blind—0.05;
 - Solar energy reflectance of the blind—0.35.
- Variant 2: no brise-soleils; shading roller blinds located on the external side of the window, with the parameters as above.
- Variant 3: Overhangs with a range of 2 m, shading roller blinds placed on the inner side of the window, with the same parameters as above.
- Variant 4: Overhangs with a reach of 1 m, shading roller blinds located on the internal side of the window, with the following parameters:
 - Solar energy transmittance of the window shade- 0.1;
 - Solar energy reflection of the window shade- 0.5.
- Variant 5: Overhangs with an overhang of 1 m, shading roller blinds located on the external side of the window and parameters:
 - Solar energy transmittance of the window shade—0.00;
 - Solar energy reflection of the window shade—0.35.

The simulations were carried out for a period of a month from 15 June 2012 to 15 July 2012 due to the occurrence of the highest outdoor temperatures during this period. The adopted period of analysis, which is much shorter in relation to the entire summer season, allows for more precise observation of internal conditions on charts and a more precise assessment of the impact of individual modifications. It should be added that although the simulation period includes the summer break, the school hall is often used in the afternoon or evening hours (7–10 p.m.) by people from outside the school who rent it. On Sundays, it is not uncommon for sports competitions to take place, which involves a high thermal load on the hall at that time.

The analyses initially maintained the assumptions used to validate the model, consistent with the actual use of the facility at that time (Section 2.3). It was determined that the blinds are closed between 9 a.m. and 3 p.m., every day of the week except Saturdays. Windows are tilted at the weekend as assumed for validation (Table 3). From Monday to

Thursday, the north windows are opened from 7 to 9 a.m. and 7 to 10 p.m., and on the south side from 7 to 10 p.m.

In the simulations for the use of sunshades, mechanical ventilation is turned off (as it was during the study). In this way, during periods of high outdoor air temperatures, an attempt is made to limit the influx of warm air into the hall while reducing the energy expenditure to drive the ventilation.

Because of the assumed weekly cycle of use of the hall and for the sake of clarity of the results, the following diagrams show only the selected weekly period 29.06–5.07 with high values of the indoor air temperature. However, the statistical measurements in the tables are given for the whole month period of simulation.

The distribution of solar gains for the selected week is shown in Figure 8. The highest daily solar gains can be observed in variant 2, in which the external brise-soleils were removed. On Saturday 30.06, when the window blinds were not closed as per the schedule of hall use (according to the observations made during the study), there was a significant increase in the total solar gains to about 18 kW—(red circle in Figure 8) compared to the other days, during which the highest value per day was 11 kW.

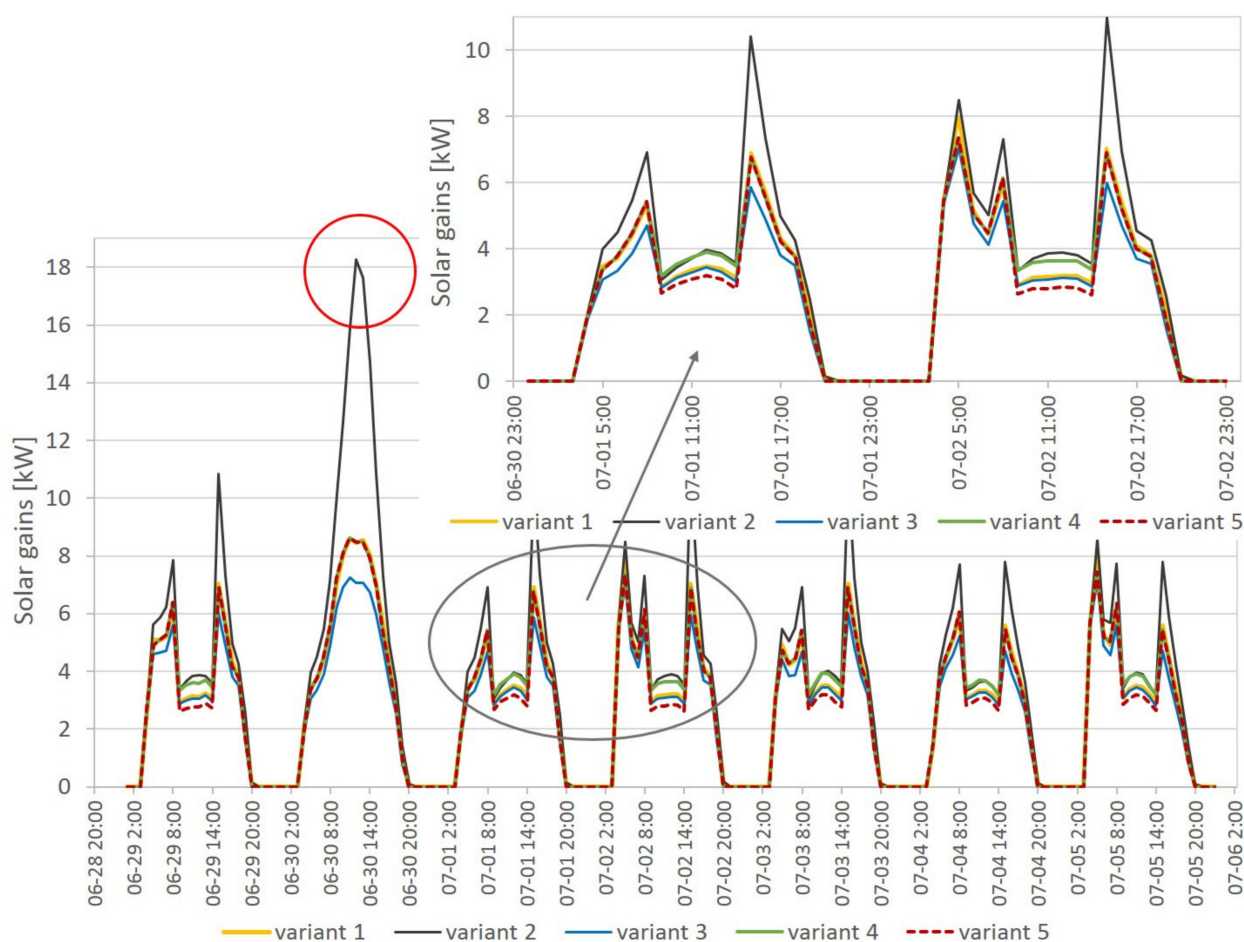


Figure 8. Solar gains output for the selected week.

As expected, the lowest values of gains can be observed in variant 5, where, apart from the brise-soleils, impermeable sun blinds located on the external side of the window were used. In the morning hours (7–9 a.m.) and in the afternoon (after 3 p.m.), when the roller blinds are not closed, the lowest gains are observed in variant 3, where the outreach of the brise-soleils was increased to 2 m. In Figure 8, it can be seen that there is a difference in gain of 1.3–6.4 kW between the period when the internal blinds are used, i.e., 9 a.m.–3 p.m. (Sunday–Friday), and the hours when they are not used.

Analyzing the entire monthly period (Table 4), it can be concluded that variant 2, without the external breakers applied, is associated with the highest solar gains, 2607.7 kWh. Variant 5, in which a “double” external cover was applied (breakers + impermeable blinds on the external side), comes out most favorably from the point of view of protection against excessive solar gains in summer but only between 9 a.m. and 3 p.m. Outside these hours, the least amount of energy, amounting to 1868.2 kWh, can be seen in variant 3. In the variant with breakers with an overhang of 2 m, the total monthly gains are 28.4% lower compared to variant 2. Variant 5, on the other hand, has energy gains that are 23.1% less than model 2. Focusing only on external breakers, variant 1 (1 m overhang breakers) provides 6.8% more total gains than variant 3 (2 m overhang breakers). This difference is, therefore, completely disproportionate to the cost of this cover and its impact on the aesthetic value of the façade.

Table 4. Monthly (15.06–15.07) internal profits for the adopted variants of the simulation.

Variants of the Simulation	Internal Gains (kWh)			
	Solar	Lighting	People	Σ
Variant 1	2053.2	191.1	236.3	2480.5
Variant 2	2607.7	183.7	236.3	3027.8
Variant 3	1868.2	199.5	236.3	2304.0
Variant 4	2108.3	195.3	236.3	2539.9
Variant 5	2004.6	195.4	236.3	2436.4

Small differences in heat gains from lighting result from the fact that the hall was used mostly in the evening hours (7–10 p.m.) and only then illuminated by artificial light. The hours of closing the roller blinds assumed in the model, based on the information obtained, are independent of people being in the facility. They are operated by a technical employee who is present in the hall. So, between 9 a.m. and 3 p.m., even though the internal blinds are used, the lighting is not switched on (except on Sunday).

Considering the sum of internal gains for the whole month (Table 4), in the hall building equipped with roller blinds and brise-soleils with a 2 m overhang, its value is 2304.0 kWh. The highest total gains from radiation, lighting, and people are 3027.8 kWh and are obviously related to the situation when no blinds were installed.

The arithmetic mean values of indoor air temperature are similar for all five simulation variants (Table 5). The difference between variant 2, where the indoor air temperature is highest (23.2 °C), and variant 5, where the indoor temperature is lowest (22.6 °C), is only 0.6 °C. Averaged over the monthly simulation period, the radiant temperature is in the range of 22.8–23.5 °C, and the difference between the adopted modifications is 0.7 °C.

Table 5. Mean values of indoor air, radiation, and operative temperatures for the monthly analysis period of the five adopted variants of the simulation.

Simulation Variants	Indoor Air Temperature t_a (°C)	Radiation Temperature t_r (°C)	Operative Temperature t_o (°C)
Variant 1	23.1	23.3	23.2
Variant 2	23.2	23.5	23.3
Variant 3	22.8	22.9	22.9
Variant 4	23.0	23.2	23.1
Variant 5	22.6	22.8	22.7

In Figure 9, it is possible to observe the distribution of air temperature in the hall for the selected week and analyzed variants of window shading. Figure 9 additionally added the upper limit of optimal operative temperature for cooling season equal 26 °C, in accordance with PN-EN ISO 7730: 2006 [26], for low activities of users up to 70 W/m². As the graph shows, the disproportion between the thermal comfort limit temperatures, depending on

the users' metabolic rate, can be as high as 8 °C. It can be seen that microclimatic conditions, which are a considerable discomfort for athletes, may still be comfortable for inactive users.

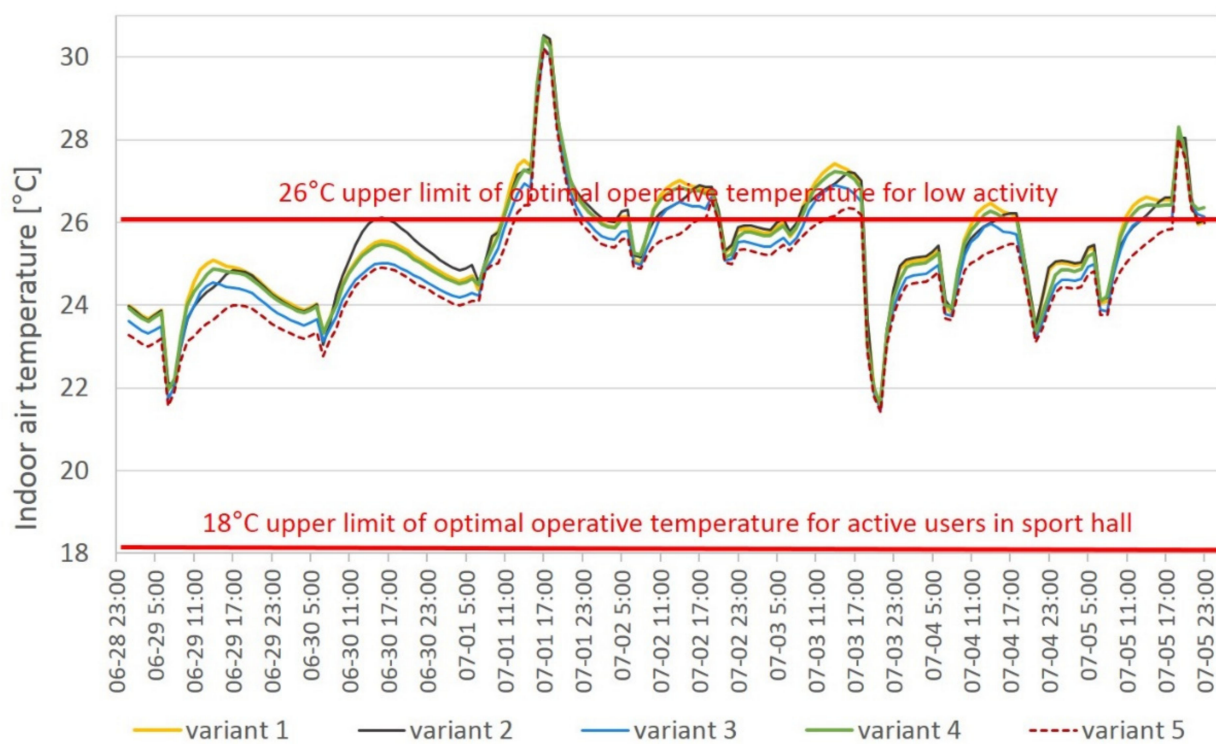


Figure 9. Indoor air temperature distribution for the selected week.

The differences of 0.0–1.2 °C depend on the hourly interval and the day of the week and the related thermal loads of the building. The red dashed graph (variant 5) is characterized by the lowest values of internal temperature in relation to the remaining options. The greatest disproportion in values occurs between 1 p.m. and 3 p.m. due to the use of shading at that time.

The variability and irregularity in the way the hall is used have a decisive influence on the course of the internal temperature. An additional comparison of changes of indoor temperature and solar gains (Figures 10 and 11) for the initial variant 1, in which the presence of people was not taken into account, explains the reason for these discrepancies. From Sunday to Monday, between 9 a.m. and 3 p.m., the blinds are closed, so the solar gains are then only 3 kW. On Saturday, the interior shades are not used, hence the significant jump to a value of 8.5 kW in the baseline variant and up to 18 kW in the case of variant 2, without brise-soleils, Figure 8.

The significant rise of temperature on 01.07. at 3 p.m. is connected with the assumed tilting of windows on the southern side at that time and the gains from the inflow of warm air from outside (Figure 12). On the other hand, the decrease in temperature inside the hall on 03.07. at about 7 p.m. is connected with the inflow of cooler outside air.

It should be added that the shading simulations use the window opening schedule assumed from the research, which is independent of the outside temperature. Airing in the morning and evening hours is a constant activity, not related to the presence of people. Analyses show that for hot summer days, natural ventilation should be avoided. Opening windows when outdoor temperatures are higher than indoor temperatures results in significant deterioration of indoor thermal conditions. Therefore, the following analyses present simulation variants in which the scheduled window opening is made dependent on the outdoor conditions. If the outdoor air temperature T_{out} is higher than the indoor air temperature T_{int} ($T_{out} > T_{int}$), the windows will be closed.

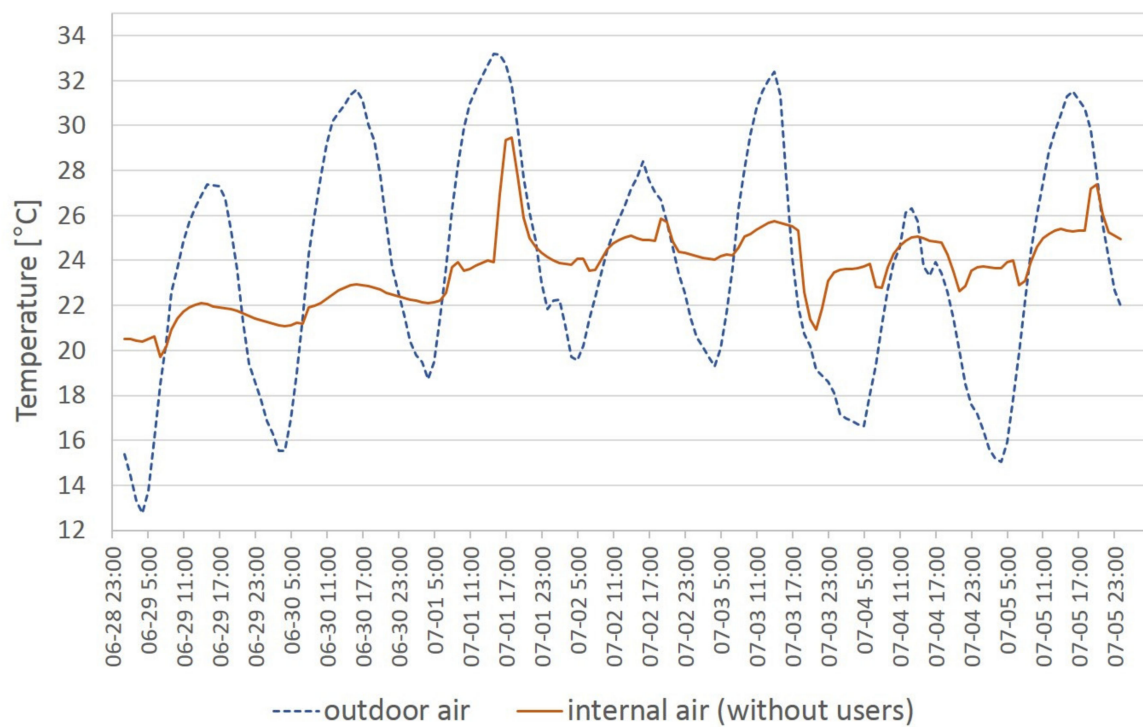


Figure 10. Distribution of indoor and outdoor air temperature during the selected week (without taking into account heat gains from people).

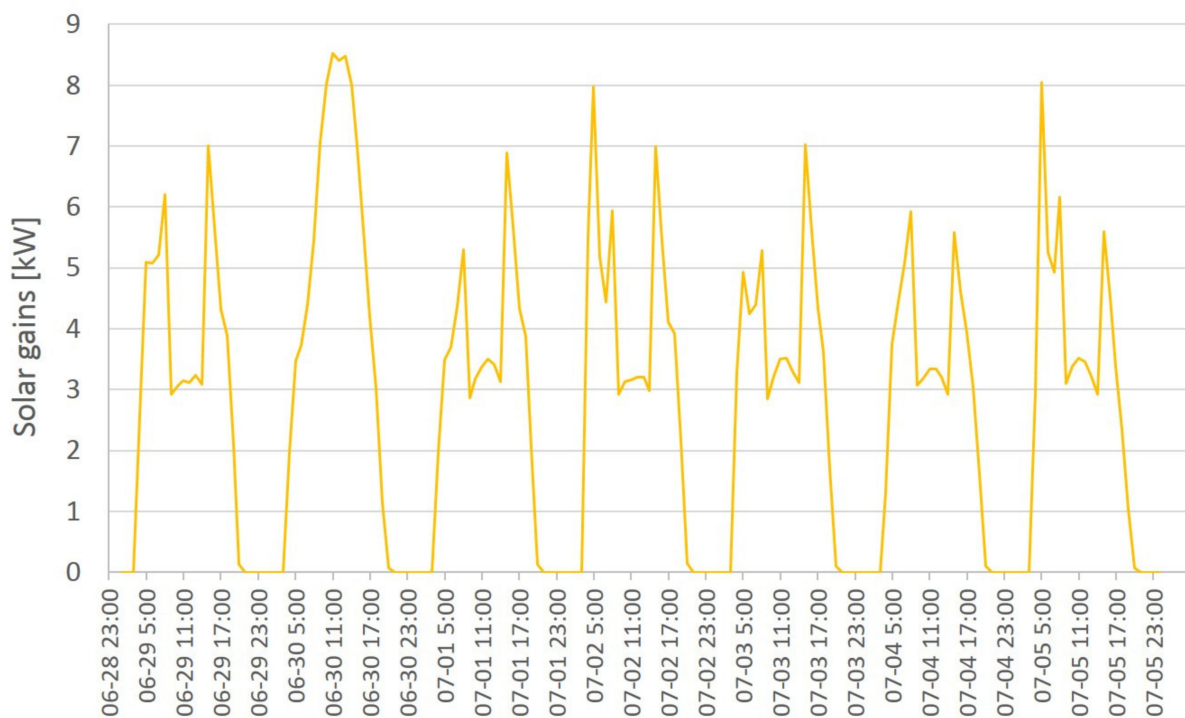


Figure 11. Distribution of solar gains for the selected week (without taking into account heat gains from people).

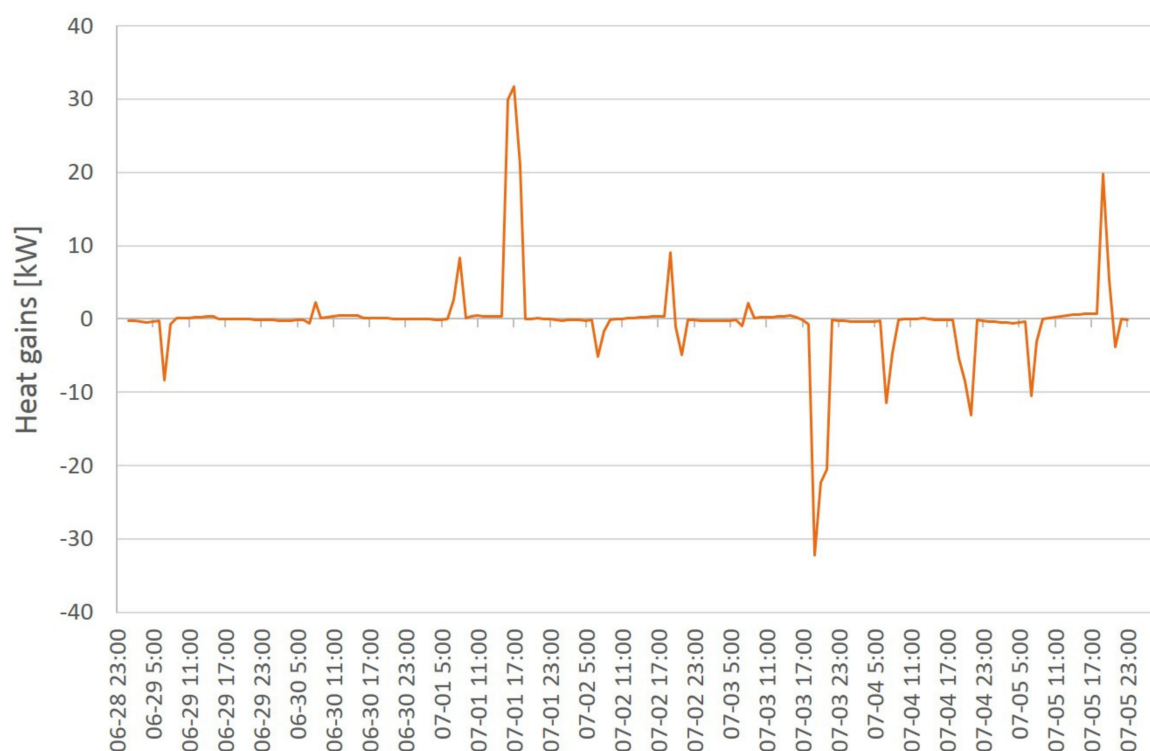


Figure 12. Distribution of heat gains from outdoor air for the selected week.

The adopted variants of shading the windows of the building were analyzed according to the criterion of the number of hours with the internal air temperature in the range of 14–18 °C and the temperature above the thermal comfort limit of the athlete. In each considered case, the number of hours with the air temperature above the thermal comfort limit of the athlete (18 °C) is absolutely dominant in relation to all hours in a month (95.8–98.8%).

Only 1.2–4.2% of all 744 h falls within the comfortable temperature range of 14–18 °C. Only the fifth variant, with the use of brise-soleils and impermeable blinds located on the outside, is slightly more favorable. In this case, the number of hours with air temperature within the thermal comfort range is higher by 3% than in the worst case, i.e., variant 1. Changing the parameters of the roller blinds in variant 4 increased the number of hours within the thermal comfort range almost two-fold, in comparison with the basic variant 1, but those effects are still insignificant and practically imperceptible for the user.

The distribution of PMV values for the selected weekly simulation balance is presented in Figure 13. The graph for three selected days has been additionally enlarged for a more detailed analysis of the adopted variants.

The lowest values of PMV are found for variant 5 (dashed red graph), the highest for variant 2 (gray graph). The difference in PMV values for the extreme variants is about 0.2. The use of brise-soleils and the location of the blinds on the outside, and the complete reduction in solar transmittance proved to be the most effective. As with temperature, modifying the characteristics of the blinds in variant 4 did not significantly increase the number of hours of thermal comfort.

The number of hours for which conditions fall within the thermal comfort range for variant 2 and variant 1 is the same, at only 4 h. Only the number of hours with $PMV > 2.0$ (Table 6) differs slightly for each variant. Even in the most favorable option, i.e., variant 5, in which the number of hours falling within the range $-0.5 < PMV < +0.5$ is the highest (24 h), it constitutes only 3.2% of all 744 h in a month. Therefore, it can be concluded that in the best variant, only one day in a month is fully comfortable, and during the other days, the users experience strong discomfort due to overheating of the building.

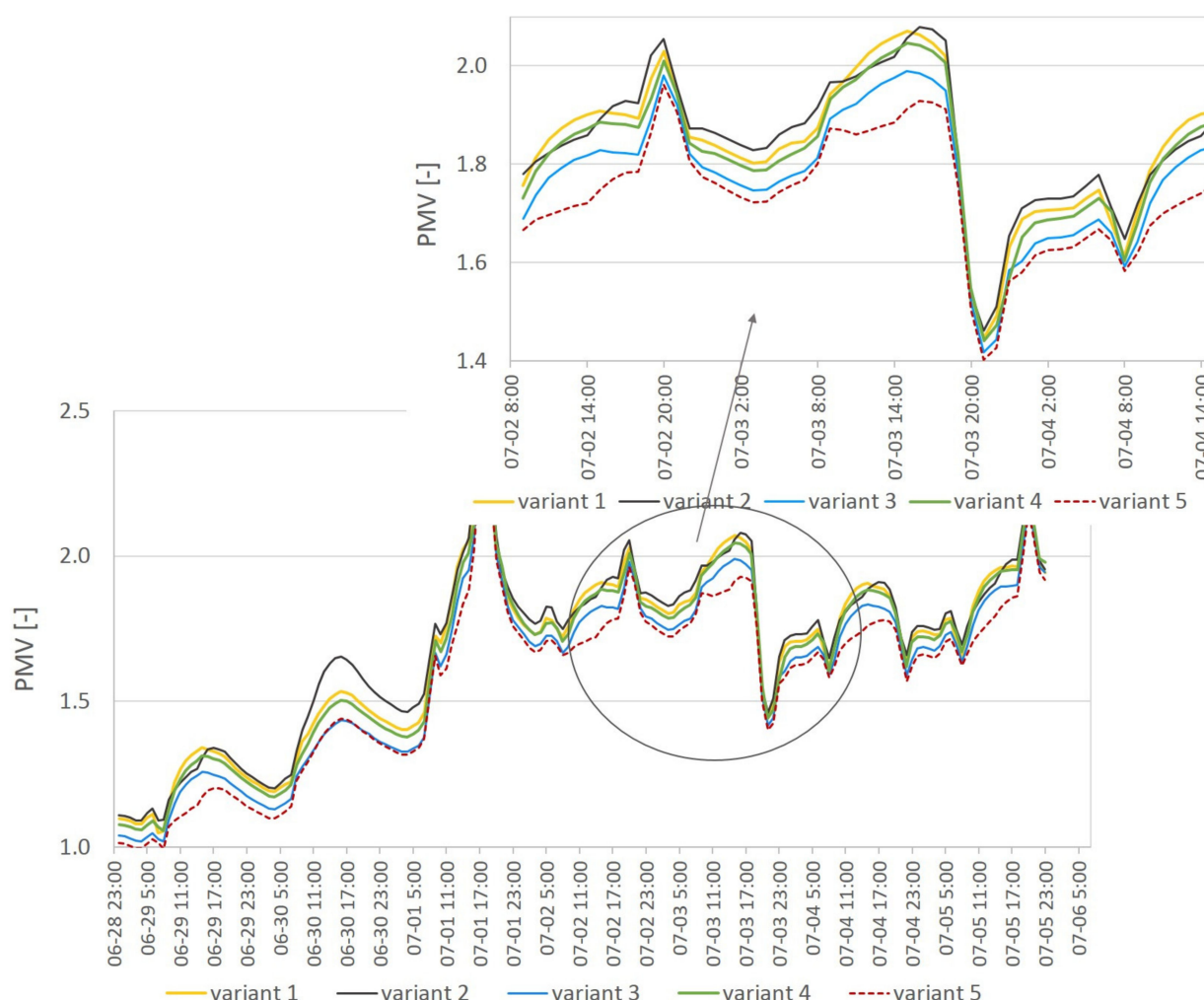


Figure 13. Distribution of PMV values for the selected week.

Table 6. Hourly distribution of the PMV index for the adopted simulation variants.

Simulation Variants	Number of Hours in the Thermal Comfort Range	Number of Hours with PMV > 0.5	Number of Hours with PMV > 2.0
Variant 1	4	740	96
Variant 2	4	740	104
Variant 3	11	733	67
Variant 4	5	739	96
Variant 5	24	720	41

In view of the results obtained and the clear discomfort for all sunshade variants used, additional simulations were performed. The irrational schedule of closing the roller blinds, independent of the conditions assumed on the basis of the interview, raised significant doubts. Therefore, in subsequent analyses, the way of using the roller blinds was made dependent on the values of the indoor temperature and the intensity of solar radiation. The following variants were adopted:

- Variant 1: assumptions as in point 3.2, roller blinds closed 9 a.m.–3 p.m. (except Saturdays)—this option has been included here only in order to be able to compare the applied modifications with the actual use of the facility;
- Variant 2—blinds closed when indoor air temperature > 18 °C;
- Variant 3—blinds closed when indoor air temperature > 21 °C;

- Variant 4—blinds closed when solar radiation intensity $> 100 \text{ W/m}^2$;
- Variant 5—blinds closed when solar radiation intensity $> 200 \text{ W/m}^2$.

The solar radiation intensity values considered in the analysis were determined based on data from the Institute of Meteorology and Water Management IMGW and literature. In summer, the typical range of variation in the intensity of radiation on the horizontal plane is from 100 to 800 W/m^2 [40]. The range of values $100\text{--}400 \text{ W/m}^2$ was analyzed, and the corresponding hours during the summer analysis period were examined. It was found that the protection against excessive gains makes sense only from the early morning hours, so in the detailed simulations, the threshold values of 100 W/m^2 (already present at around 4 a.m.) and 200 W/m^2 (around 6 a.m.) were kept.

The distribution of the indoor air temperature for the chosen week is presented in Figure 14. Generally, it should be stated that making the shading control dependent on the ambient conditions did not obtain the expected significant improvement of the conditions in the hall. Individual variants also differ little from each other. The momentary differences in the obtained results are very small and amount to a maximum of 0.7°C .

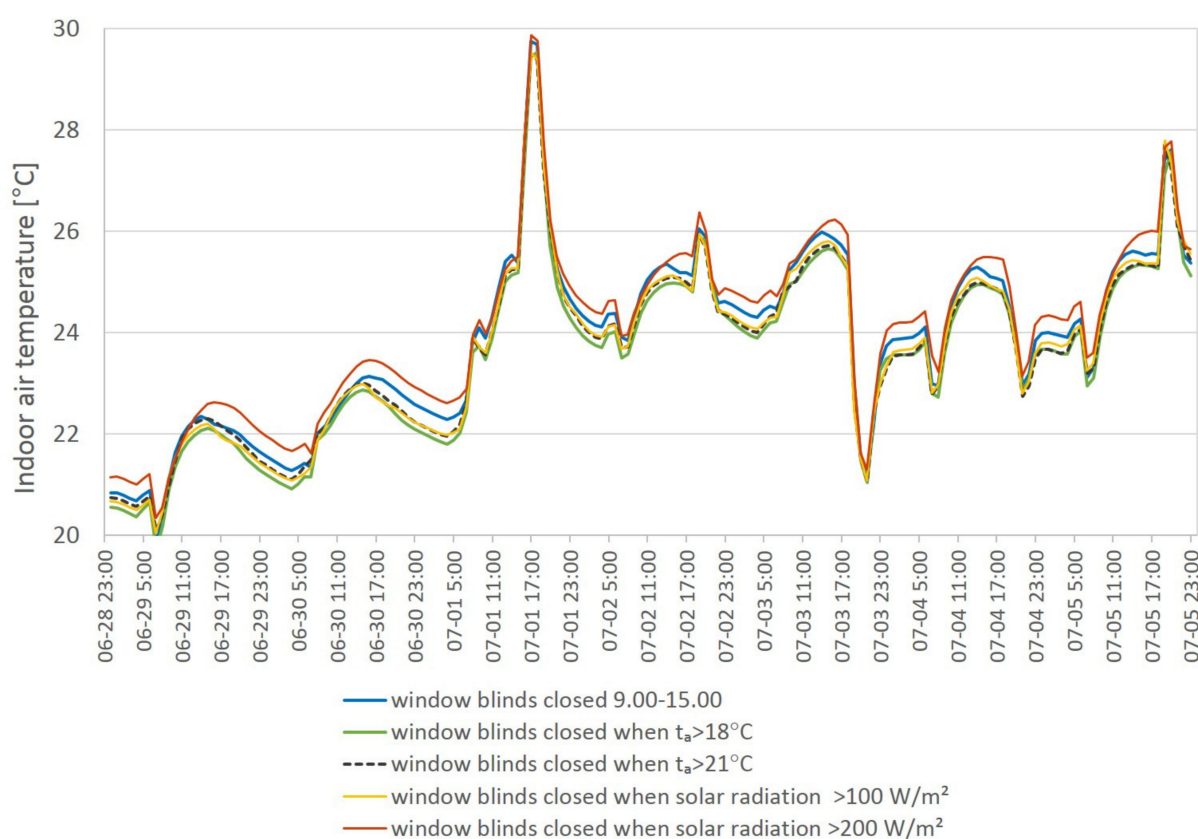


Figure 14. Distribution of indoor air temperature for the selected week.

The variant, in which closing the blinds was conditioned by the maximum value of solar radiation intensity equal to 200 W/m^2 , is the least favorable for the analyzed summer period and generates the highest temperatures in the hall (orange graph Figure 14). Two out of the five applied variants practically overlay in weekly distribution. The yellow graph (irradiance $> 100 \text{ W/m}^2$) and the gray dashed graph ($t_a > 21^\circ\text{C}$) do not show significant mutual differences in the course of the temperature in the hall but are more favorable in relation to the initial variant. The blue graph, reflecting the actually applied shading schedule from 9 a.m. to 3 p.m., is not, as can be seen in Figure 13, the best solution for limiting direct radiation. The lowest temperatures are observed in variant 2 (green graph) when the blinds are closed at $t_a > 18^\circ\text{C}$. It is worth noting again, however, that the

differences in internal temperature values between all the variants are negligible and not perceptible for the hall user.

The analysis of indoor conditions for the assumed variants also concerns the indicator of the predicted mean PMV, Figure 15. On its basis, it would be necessary to resign from the fixed schedule of closing the indoor blinds (blue figure) and make their use dependent on the indoor air temperature (green figure = upper limit of the athlete's comfort range).

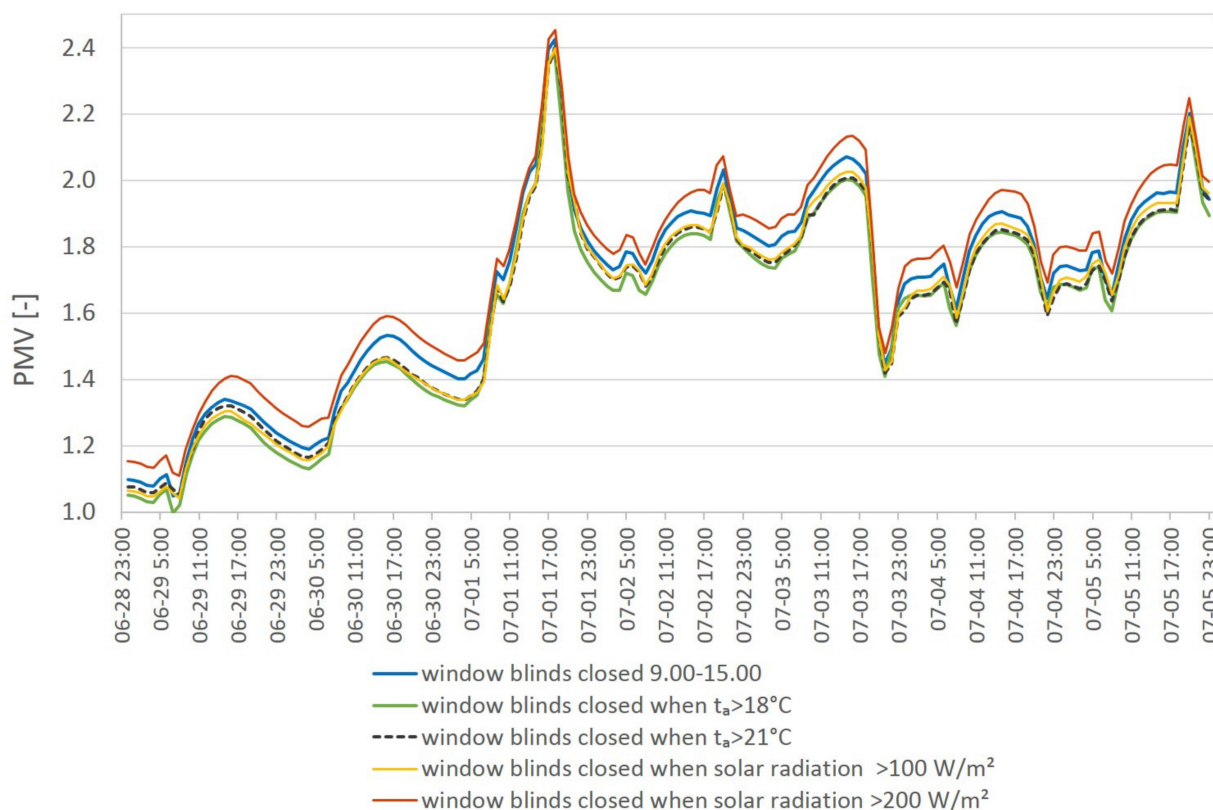


Figure 15. Distribution of the predicted average assessment index for the selected week.

It is worth noting that none of the adopted variants significantly improves the microclimate conditions inside the hall, and the momentary differences in PMV values in individual cases are so small (max. 0.2) that even the best option will not reduce the thermal discomfort.

4. Discussion of Results

The criterion of low energy consumption in extremely airtight and well-insulated passive buildings often results in overheating of the interior, creating considerable economic and operational problems. Sports facilities are spaces with specific microclimate requirements due to the required operating temperature and physical activity of users. Ensuring thermal comfort is particularly important there because it can affect the performance and health of athletes. Looking for simple solutions to reduce overheating, shading devices were analyzed, which mainly require knowledge and diligence at the building design stage.

Most of the aforementioned sports buildings are multi-purpose arenas where several activities with varying metabolic rates are performed. Thus, determining a thermal environment that is equally comfortable for all athletes and spectators is difficult and may lead to an overestimation of thermal sensation for some athletes. This article analyzed conditions for lower-activity athletes. Therefore, it can be assumed that the feeling of discomfort in members of the other group would be even greater.

The analyzed sports hall in Słomniki is in line with the assumptions of passive building with the longitudinal axis of the building in the east-west direction; nevertheless, the summer solar gains through vertical glazing on the south façade pose a risk of overheating. The external brise-soleil used in the hall is able to limit the sunlight to the rooms, but not enough to guarantee thermal comfort inside.

The analysis shows that the lowest monthly total solar gains occur in the case of the application of brise-soleils with a range of 2 m and amount to 1868.2 kWh (variant 3), and the highest, occurring in variant 2, in which no brise-soleils were applied, amount to 2607.7 kWh. Reducing the range of brise-soleils to 1 m, however, increases gains from radiation only by 6.8%. If no brise-soleils are used, the value of unwanted energy in summer increases by 28.4% in relation to the variant with brise-soleils. Reduction in solar gains does not translate into a significant improvement of thermal conditions in the analyzed object. The difference in average values of indoor air temperature for the variants used is small and amounts to 0.1–0.6 °C. These relatively small differences are the result of thermal gains from the inflowing outside air, dominating the balance.

Analyzing the number of hours with a temperature exceeding the upper limit of the athlete's thermal comfort of 18 °C, it can be seen that each of the adopted options gives bad results (more than 95% of the time out of comfort conditions). A maximum of 4.2% of the number of hours of the entire month falls within the thermal comfort range. However, keeping the operation of the building in accordance with the measurements, it is not surprising to find that the most advantageous solution is the use of brise-soleils and impermeable blinds located on the exterior side. In this case, the number of hours with air temperature within the thermal comfort range is slightly higher compared to the baseline variant. However, the PMV values for all variants deviate significantly from the thermal comfort range. In the most favorable fifth variant (brise-soleils + blinds), there is the highest number of days in the comfort range, but it accounts for only 3.2% of the total time of the analyzed month. This result is completely inadequate in relation to the costs incurred for the blinds themselves and is not even perceptible to the user.

Based on the results obtained, it can be concluded that common interior shades alone do not play a significant role in shaping the microclimate inside and protecting against solar radiation. However, the shades located on the inner side allow smooth adjustment of the intensity of the incoming light, so they can be taken into account by the designers as a cheap way to darken the interior, protect against glare, or as an element of modern decoration.

It should also be added that mechanical ventilation was designed in the examined building, whose task was to provide fresh air at the required and controlled level, regardless of external conditions. In practice, it could be concluded that the way the examined building was actually used was far from the design assumptions. During the measurements, the available mechanical ventilation was not used, which have influenced the obtained results of measurements and simulations. An effective measure to reduce overheating of passive buildings is also night ventilation. In the hall in Słomniki, an attempt was made to reduce excess energy by opening windows in the early morning and evening, but this was not sufficient to cool such a large volume of the building. Night ventilation was not implemented due to the risk of burglary. The conducted separate analyses about the influence of ventilation on thermal comfort show that the predicted mean value in option without night ventilation is 0.2–0.7 higher compared to the option with night cooling. Intensive natural ventilation makes it possible to lower the maximum temperature at night by 4 K, compared to the variant without night ventilation. In the case of natural ventilation by night, indoor air temperatures are lower by 0.4–1.7 K during the day compared to the option with mechanical ventilation by night. The effects of night mechanical ventilation of a large-volume hall are weaker compared to natural night ventilation. This is due to the relatively low mechanical power of ventilation in relation to the entire volume of the interior. Mechanical ventilation intensity was related to the expected number of users, not the volume of the interior. The maximum ventilation capacity is 9000 m³/h, which corresponds to the volume air exchange rate of 0.9 h^{−1}. Night natural ventilation is more

effective in removing excessive energy gains in the analyzed building due to the average number of air changes at the level of approximately $2\text{--}4\text{ h}^{-1}$. Analyses of the impact of nighttime cooling on the thermal capacity of the building by intensive ventilation are also the subject of separately published articles [1,41].

In the case of the analysis of the sports facility in Słomniki, the adaptive thermal comfort model, included in the American standard ASHRAE 55 [42] and the European standard PN-EN 16798-1:2019-06 [28], was not considered. This model assumes that the level of thermal comfort will vary depending on the external climate. It also takes into account the ability of users to control the parameters of this comfort and to adjust the insulation of their clothing [43]. The adaptive model is applicable to rooms without mechanical cooling, where internal thermal conditions are regulated by opening windows. According to studies conducted in the United States [44] and the United Kingdom [45], users of such facilities are willing to accept less favorable conditions or actively adapt to them. However, users are characterized by low physical activity, close to sedentary, and metabolism of $1.0\text{--}1.3\text{ met}$ [28]. Due to the higher activity level of the sports hall in Słomniki and the mechanical ventilation system used there, this facility cannot be analyzed according to the adaptive criterion. In the currently widely promoted low-energy buildings, a mechanical ventilation system is designed, which theoretically excludes the adaptive concept of thermal comfort. The application of scientific research to actual building trends is, therefore, still difficult to directly transform into the design and operational practice [46]. In the planned buildings, however, an indirect approach can be used, with hybrid ventilation, combining mechanical with natural ventilation, to try and optimize thermal comfort, air quality, and energy savings. Nevertheless, in buildings with mixed ventilation, relying on an adaptive approach is only possible where all the criterion requirements allow it.

The analyses carried out clearly show that sun shades should be suggested to designers as one of several ways to reduce overheating in summer. However, on their own, they do not play a sufficient role in shaping the thermal comfort, and only in combination with other solutions, which are the subject of analysis of separate publications by the author, can they provide the expected results.

5. Conclusions

Conducted simulations concerning the influence of sunshades on shaping thermal comfort in a passive sports hall in summer enabled the formulation of the following conclusions:

- Due to the very high level of user's activity of a sports hall, thermal comfort conditions require a low operative temperature. Obtaining such conditions throughout the summer period by using only passive solutions is practically impossible, even in the temperate climate of Central Europe. The window cover solutions analyzed in the article only partially improve the internal conditions in the hall. At the same time, they are indispensable as part of all activities in this area;
- External brise-soleils are able to limit the access of sunlight to the rooms by up to 30%, but this is not enough to guarantee thermal comfort inside. Increasing the range of the brise-soleils by 1 m reduces gains from radiation only by 6.8%. The angle of inclination of these covers is constant for all year; therefore, the impact of the overhang on lowering the temperature inside the summer is limited;
- The building should be protected from the south by external brise-soleils with appropriately selected overhang. Due to different angles of incidence of the sun's rays (depending on the season of the year, time of the day, and intensity of sunlight), at the stage of designing the building, one can take into account the use of movable lamellas, enabling adjustment of the inclination of the window shade depending on the angle of radiation;
- Reduction in solar gains does not translate into a significant improvement of thermal conditions in the analyzed object. The difference in average values of indoor air temperature for the variants used is small and amounts to $0.1\text{--}0.6\text{ }^{\circ}\text{C}$;

- Overhangs and shading roller blinds used together in the most favorable fifth variant provide the most days in the comfort range, but it accounts for only 3.2% of the total time of the analyzed month. This result is completely inadequate in relation to the costs incurred for the blinds themselves and is not even perceptible to the user;
- Internal blinds do not play a significant role in shaping the interior microclimate and protecting from solar radiation. Temporary differences in PMV values for different patterns of closing the blinds (depending on the internal temperature or radiation intensity values) amount to a maximum of 0.2. However, they should be taken into account in design as a simple way to shade the interior and protect it against glare;
- The design of the building and its installations should take into account the possibility of natural night ventilation to reduce the accumulated excess solar and internal energy gains. In buildings with a large cubature of rooms (e.g., sports hall), opening windows in the early morning and evening is not sufficient to cool such a large volume of the facility and effectively reduce overheating;
- The way the examined building was actually used was far from the design assumptions, which have influenced the obtained results of measurements and simulations. Due to the positive daily energy balance in the effectively insulated partition of the building, even with a massive structure, its thermal capacity was not sufficient to prevent the building from overheating, as night mechanical or natural cooling was not used;
- Ground heat exchangers, recommended in low-energy public utility construction, are not used in the hall. This solution generates both additional investment and operating costs; therefore, investors still approach such a solution with skepticism. As can be seen from many studies and analyses, the mentioned installations favorably shape the thermal comfort in summer, but the operation of the heat pump is also associated with considerable input of electricity. Another aspect is the environmental and ecological assessment of buildings and their installations, as well as contemporary trends for the simplest possible solutions in the building industry while maintaining the principles of sustainable development. Due to the aforementioned economic and ecological considerations, investors often back off from expensive installations while accepting the increased risk of overheating the interior;
- According to Fanger's comfort scale, conditions observed in the sports hall building should be defined as a hot environment out of the thermal comfort range. When using the adaptive comfort approach, the conditions could be assessed a bit more gently. Due to the higher activity level of the sports hall in Słomniki and the mechanical ventilation system used there, this facility cannot be analyzed according to the adaptive criterion. Thermal adaptation in sports building and intermittent use conditions is not yet recognized in the available bibliography. It must be stated that there is no specified objective method for thermal comfort evaluation in sports buildings.

It is not known what heat discharging scenarios have been considered at the design stage and to what extent building users have been trained in the operation of the hall. Without close cooperation of the designers and users, advanced passive buildings would be poorly managed and would raise dissatisfaction of users. An interdisciplinary approach to the process of designing structural elements and installations and the use of all possible passive measures to protect the building from overheating is strongly recommended. As a continuation of the addressed problem of overheating of sports facilities and beyond, among other things, analyses of other passive means of protection using the heat accumulation properties of buildings and night ventilation of the interior are planned, as well as analyses of building orientation in relation to the main assumptions of passive construction. Future articles are also planned to analyze the impact of various design and material solutions on reducing summer discomfort (e.g., ground heat exchangers, thermally activated ceilings).

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