dr inż. Anna Dudzińska[1)*)]
ORCID: 0000-0003-1349-6108
dr inż. arch. Ewelina Panasiuk[2)]
ORCID: 0000-0001-8848-3542

Ways to reduce overheating in a passive standard school building

Sposoby ograniczania przegrzewania budynku szkoły w standardzie pasywnym

Abstract. Thermal gains from indoor heat sources and the tight envelope of passive buildings, combined with high outdoor temperatures, can lead to overheating and thermal imbalance of the human body. Heat pumps together with ground heat exchangers favorably shape thermal comfort in summer. This study examines whether the use of modifications to the construction and location solutions adopted in a passive school building in Budzów could sufficiently reduce overheating in summer, thus eliminating the need for building services. Through simulation in DesignBuilder, the conditions that arise for various modifications of the exterior and interior insulation systems used in the school were considered. Also analyzed were various possibilities for the orientation of the selected classroom in relation to the cardinal directions. Rotations of the school building model by 90°,180° and 270° respectively, were done. Simulations were carried out for the two-month period between May 1 and June 31. The results presented showed that the mechanical ventilation system, in combination with a source of cooling in the form of a ground heat exchanger and heat pump, can effectively reduce discomfort in summer on its own. The other suggested modifications to the building, despite the fact that they reduce the amounts of weighted measures of discomfort due to overheating, relative to other adopted options, were not as effective as ground cooling. In order to objectively assess comfort conditions, this study proposes a different and very simple way of estimating the measure of discomfort associated with overheating.

Keywords: thermal comfort, overheating, discomfort, heat pump, passive school

Streszczenie. Instalacja pompy ciepła wraz z wymiennikami gruntowymi korzystnie kształtuje komfort cieplny w pomieszczeniach latem. W artykule sprawdzono, czy zastosowanie w szkole w standardzie pasywnym w Budzowie modyfikacji przyjętych tam rozwiązań konstrukcyjnych i lokalizacyjnych mogłoby wystarczająco ograniczyć przegrzewanie obiektu latem, eliminując w ten sposób potrzebę stosowania systemów chłodzenia. Stosując analizy symulacyjne, w programie Design Builder, rozpatrywano warunki, jakie powstają w przypadku różnych modyfikacji systemów osłon zewnętrznych i wewnętrznych zastosowanych w szkole. Analizie poddano także różne możliwości orientacji wybranej klasy względem stron świata. Dokonano obrotu modelu budynku szkoły, odpowiednio o 90°, 180° i 270°. Symulacje przeprowadzono w okresie dwumiesięcznym, tj. 01.05 – 31.06. Zaprezentowane w artykule wyniki wykazały, iż system wentylacji mechanicznej skutecznie ogranicza przegrzewanie pomieszczeń latem jedynie w połączeniu ze źródłem chłodu w formie gruntowego wymiennika ciepła i pompy ciepła. Pozostałe sugerowane modyfikacje budynku nie są tak efektywne jak chłodzenie gruntowe. W celu obiektywnej oceny warunków komfortu, w artykule zaproponowano odmienny i bardzo prosty sposób szacowania miary dyskomfortu, związanej z przegrzewaniem.

Słowa kluczowe: komfort cieplny; przegrzewanie; dyskomfort; pompa ciepła; pasywna szkoła.

Thermal comfort in educational facilities directly affects perception and learning performance, ensuring pleasant, safe and effective learning. Rapidly progressing unfavorable climate changes force the search for appropriate technological solutions to design sustainable and energy-efficient buildings. In connection with the constantly modified requirements for energy consumption, the issue of thermal comfort in schools during the summer is being addressed and analyzed with increasing frequency [1 – 9]. Reducing the amount of energy consumed should in no way reduce the level of safety and comfort of users.

In recent years, there has been an increase in interest in heat pumps and ground heat exchangers, but due to high investment costs, these systems are still used sporadically. The aforementioned systems favorably shape thermal comfort in summer, but also the operation of a heat pump involves a significant expenditure of electricity. Consequently, through a high input factor, it significantly increases the primary energy demand. Another aspect is the environmental and ecological assessment of buildings and the modern tendency to the simplest possible solutions in construction.

Due to the aforementioned economic and ecological considerations, it was checked whether, if ground cooling had not been used in the school located in Budzów (realized in the passive building standard), modifications to the construction and location solutions adopted

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[1)] Politechnika Krakowska, Wydział Inżynierii Lądowej
[2)] Politechnika Krakowska, Wydział Architektury
[*)] Correspondence address:
anna.dudzinska@pk.edu.pl

there, could have reduced overheating in the summer. In order to check the effectiveness of the selected solutions, a comparison was made between the so-called reference variant, in which ground cooling was used, and a modified variant, taking into account the adopted modifications. A thermal comfort analysis was carried out in Design Builder based on the standard Fanger PMV index. The duration of overheating was then evaluated, but also its intensity using a single-value weighted measure of discomfort proposed by the authors.

Passive standard school in Budzów

The school building is a two-story, non-basement building with an area of about 800 m^2, arranged on a north-south axis, located in Budzów, Lower Silesia (Photo). The main material used for the walls is 25 cm thick silicate blocks, characterized by high heat capacity. The walls were insulated with 32 cm thick polystyrene foam, which made it possible to achieve a heat transfer coefficient for the building envelope of $U \cong 0{,}1$ W/(m^{2}K).

The building, of mixed construction, was founded on footings 40 cm thick and 80 and 100 cm wide. Reinforced concrete ceilings, reinforced unidirectionally, 20 cm thick, were used. The ceiling of reinforced concrete structure, reinforced unidirectionally, with a thickness of 25 cm. The rooms on the east and west sides were illuminated by a band of windows measuring 900 x 1900 mm. The installed windows have double-glazed insulating glass units. The heat transfer coefficient of the entire set meets the condition $U \leq 0{,}8$ W/m^{2}K, and the total solar heat transmittance (SHGC) is equal to $g = 0{,}63$ [10].

Assumptions in the Design Builder program

A model of the school was created in the simulation program Design Builder. The geometry of the building, its location, the partition structure, the heating system, detailed occupancy schedules, the operation of lighting and all other installation systems of this building were taken into account. On the basis of observations during earlier measurements at the school, the metabolic rate of children was set at 108 W/m^2, and a clothing insulation level of 0,5 (characteristic of summer) was assumed. The illumination intensity was assumed to be 300 lux. For modeling the school, suspended lighting was assumed with parameters as follows:

- normalised power density – 5,0 [W/m^2 – 100 lux];
- return air fraction – 0,54;
- radiant fraction – 0,42;
- visible fraction – 0,18.

The modeling assumed that artificial lighting was used from 7:00 to 15:00, depending on the needs of the users. Gains from indoor electrical equipment (computer, printer, projector) of 5 W/m^2 were included in the analysis.

First, the external and internal shielding systems used at the school were modified. Due to the highly questionable, extremely short length of the light breakers (equal to 0,4 m), their overhang was increased to 1,24 m and the validity of the adopted solution was evaluated. Another modification also concerned the effect of internal blinds on reducing hours of discomfort. It was checked whether interior blinds play a significant role in shaping the interior microclimate and protecting against solar radiation. Or do they only allow smooth adjustment of the intensity of incoming light to darken the interior and possibly protect against glare. Subsequent modifications to the basic model:

- variant 1: baseline (without modification); light breakers of the Overhangs type with an overhang of 0,4 m, shading blinds located on the inside of the window, covered during the operating hours of 7: 00 – 15: 00, when the temperature inside reaches 24°C;
- variant 2: overhangs type light breakers with an overhang of 1,24 m, other assumptions as above;
- variant 3: overhangs type light breakers with an overhang of 0,4 m, blinds uncovered at all times;
- variant 4: overhangs type light breakers with an overhang of 0,4 m, shading blinds located on the inside of the window, covered during the hours of use of 7: 00 – 15: 00, when the intensity of solar radiation >100 W/m^2.

Another important element of energy-efficient buildings, besides shielding, is their proper orientation. The recommended orientation of passive buildings with respect to the sides of the world is to place the longitudinal axis of the building in the east-west direction [11]. The school building in Budzów is realized almost exactly on the north-south axis. In view of the contradiction between the guidelines and the adopted solution, various possibilities for the location of the selected classroom in relation to the world sides were analyzed. A 90°, 180° and 270° rotation of the

Passive School Building in Budzow
Szkoła w standardzie pasywnym w Budzowie

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school building model was made, respectively. Thus, the analyzed eastern classroom became, in successive rotations, a southern, western and northern classroom.

The program for modifying the school building did not take into account changing the type of construction material of the partitions and thus increasing the thermal capacity of the interior, since the material used there to fill the frame of the structure is silicate brick with a relatively high density and thermal conductivity.

Weighted measure of discomfort as a tool for estimating overheating

EN 15251 [12] defines the assessment of overall thermal comfort conditions in several ways. For example, the percentage of hours outside the PMV or temperature limit ranges is given, or alternatively the degree-hour criterion or the weighted PPD criterion is used. In order to objectively assess comfort conditions, the article proposes a different from the above-mentioned and very simple way of estimating the measure of discomfort associated with overheating. The time during which the PMV exceeds a certain range during the use of the facility is multiplied by an appropriate weighting factor, appropriate to the degree to which the range is exceeded. In this way, not only the duration of discomfort, but also its intensity can be included in a single-value evaluation. The detailed algorithm for the calculationis as follows:

1. weighting factor kc equals 0 when PMV is within the recommended, thermal comfort range: -0,5 < PMV < +0,5;
2. the weighting factorkcis taken in accordance with Table 1, depending on how much the maximum comfort interval is exceeded;
3. the products of the weighting factor kc and the number of hours for all ranges are summed. For simplicity, it is assumed that the conventional (informal) unit of measurement is the hour.

Table 1. Calculating the weighting factor for a measure of overheating discomfort
Tabela 1. Sposób obliczania współczynnika ważenia w przypadku miary dyskomfortu związanej z przegrzewaniem

PMV	Weighting factor kc
-0,5 < PMV <+0,5	0
+0,5 < PMV <+1,0	1
+1,0 < PMV <+1,5	2
+1,5 < PMV <+2,0	3

Weighted measures of discomfort for the adopted alternatives were estimated as follows:

- variant 1: (9 • 1,0) + (0 • 2,0) + (0 • 3,0) = 9,0 h;
- variant 2: (15 • 1,0) + (15 • 2,0) + (2 • 3,0) = 51,0 h;
- variant 3: (16 • 1,0) + (18 • 2,0) + (4 • 3,0) = 64,0 h;
- variant 4: (22 • 1,0) + (15 • 2,0) + (11 • 3,0) = 85,0 h.

Results of thermal comfort analysis

The calculated hours of thermal comfort and discomfort are summarized in Table 2. Taking into account the number of hours in Fanger's thermal comfort interval -0,5 < PMV< + 0,5, the most favorable is variant 1 – the initial variant, which assumes a consistent overhang of the breakers of 0,4 m and lowered interior blinds. When the length of the aluminum outer cover was increased to 1,24 m, the number of hours in the comfort range decreased by 5 h and amounted to 105 h. The same result was obtained for the variant with the blinds exposed. The least number of hours in the comfort compartment was obtained for variant 4, in which lowering the blinds depended on the intensity of the radiation.

Following the authoritative criterion of the weighted measure of discomfort, it can be noted that the least favorable variant is for the situation when the interior blinds are uncovered when the school is in use, and the length of the breakers is consistent with reality and equal to 0,4 m. The result obtained for the third model is 20% higher, with respect to the variant one, identical in terms of the overhang of the breakers, but with the blinds lowered.

The different usage schedules for indoor blinds assumed in variants 1 and 4 yielded identical discomfort measures. Both temperature restriction in variant 1 and radiance-dependent control in variant 4 yielded 51 h weighted measures of discomfort.

Increasing the overhang of the external light-breakers to 1,24 meters in model two reduced the number of weighted hours of discomfort by 8% compared to the first baseline variant. The slight disproportion in the number of weighted hours of discomfort is due to the pattern of covering the interior blinds from 7 a.m. to 3 p.m. adopted, which is identical for both variants. In addition, due to the trajectory of the sun during the day and its height during the summer, the breakers on the eastern elevation only reduce the access of radiation in a very limited time range [13].

The magnitude of the disparity obtained between the variants is also influenced by the type of double-glazed composite glazing unit used, with a total solar heat transmittance (SHGC) of g = 0,63. The glazing of the triple-glazed passive window, is coated with a low-emissivity coating to reduce heat loss by radiation. This solution makes it possible to capture gains from solar radiation and reduce heat loss through the windows [14]. The energy transmit-

Table 2. Hourly distribution of the PMV index for the adopted simulation variant
Tabela 2. Godzinowy rozkład wskaźnika PMV w przypadku przyjętych wariantów symulacji

Simulation variants	Number of hours in				Weighted measure of overheating discomfort [h]
	the thermal comfort range -0,5 < PMV<+0,5	the range +0,5 < PMV <+1,0	the range +1,0 <PMV <+1,5	the range +1,5 < PMV <+2,0	
Variant 1	110	15	15	2	**51,0**
Variant 2	105	15	13	2	**47,0**
Variant 3	105	18	17	4	**64,0**
Variant 4	100	15	15	2	**51,0**

tance, determines what fraction of solar radiation reaches the interior of the building [15]. The type of glazing used in the school under study, with a relatively high value of this coefficient, is necessary to obtain solar gains in winter. In the summer, on the other hand, it can be a serious impediment to reducing the then undesirable solar radiation. Figure 1 summarizes the calculated solar gains in the classroom for the four variants assumed here.

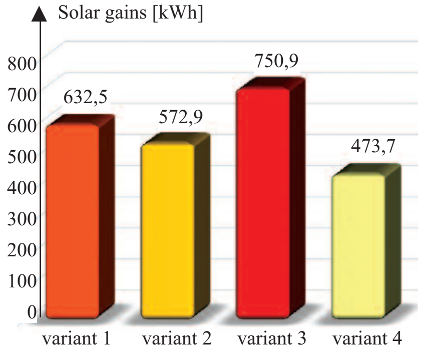

Fig. 1. Solar gains for the entire two-month period and the four assumed variant
Rys. 1. Zyski solarne w przypadku całego okresu dwumiesięcznego i czterech założonych wariantów

In the modeling, the highest solar gains generated over the entire two-month period equal to 750,9 kWh apply to the obvious situation with the interior blinds uncovered, and are as much as 37% higher compared to the most favorable option four. The lowest value, equal to 473,7 kWh, applies to the situation when covering the blinds depended on the amount of radiation (option four). The result obtained is the result of covering the blinds from the early morning hours in connection with reaching the required intensity level of 100 W/m^2. Although variant one obtained a higher sum of solar gains than option four, the number of the weighted measure of discomfort for both cases is identical. The discrepancy is due to the fact that the solar gains are calculated for a full two-month period, and the other parameters apply only to the usable period. In the case of increasing the length of the teardrops in model 2, the sum of gains is 572,9 kWh, which is 9% lower with respect to variant 1. The difference in solar gains between the least favorable case with exposed apertures and the baseline variant is almost 16%.

Due to the smallest number of weighted hours of discomfort obtained with the 1,24 meter-long breaker variant, further analysis of the lump turnover was carried out for such a shield length.

The hourly distribution of the predicted average rating index, along with a weighted measure of overheating discomfort, is detailed in Table 3. The most hours in the comfort range were calculated in the eastern class (105 h), while the least in the northern class (85 h). The difference between these variants is 19%. The southern and western classes have almost identical values of hours in Fanger's comfort range, 91 h and 90 h, respectively.

Table 3. Hourly distribution of the PMV index for the adopted simulation variant
Tabela 3. Godzinowy rozkład wskaźnika PMV w przyjętych wariantach symulacji

Simulation variants	Number of hours in				Weighted measure of overheating discomfort [h]
	the thermal comfort range -0,5 < PMV <+0,5	the range +0,5 < PMV <+1,0	the range +1,0 < PMV <+1,5	the range +1,5 < PMV <+2,0	
Estern class	105	15	13	2	**47,0**
Southern class	91	15	11	0	**37,0**
Western class	90	14	11	1	**39,0**
Northern class	85	14	10	0	**34,0**

The highest values are for the eastern class (47 h) and the western class (39 h), which is associated with the highest number of hours of discomfort. The northern class (34 h) and the southern class (37 h) are the most favorable. The percentage variation among the received measures of discomfort for the assumed cases, ranges from 17 – 28%, with the upper limit concerning the disparity between the eastern and northern classes.

The lowest discomfort value was obtained when the tested classroom was located on the north side. Additional analysis showed that for this solution there is no need for interior blinds, and the measure of discomfort when uncovered is virtually identical to the option with the blinds down. In addition, constant access to natural lighting provides increased concentration and a pleasant learning atmosphere, while reducing operating costs. Due to the lower on the north façade, solar gains during the winter, passive educational buildings around the world are using alternative solutions. In an exemplary passive Montessori school near Munich [16], oriented along the east-west axis in accordance with passive building principles, spacious classrooms were located on the south side while administrative, sanitary and technical rooms were located on the north side.

The slight differences between the variants are due to the use of blinds during the period of use. While the low discomfort values for the northern class are not surprising, the result for the southern class might be surprising at first glance. The explanation comes from Figure 2, which illustrates the well-known apparent movement of the sun across the sky and its penetration into the interior for different seasons. During the winter month (e.g., December), the sun moves low over the horizon. The horizontal exterior shades used are not a barrier to the gains from solar radiation desired at that time. In summer (e.g., June), the sun shines much higher, so the breakers cause the amount of solar radiation reaching the building to be significantly reduced [17, 18, 19].

Figure 3 illustrates the distribution of shading of the analyzed class, depending on the orientation of the building. One sample day of 11.06 was selected from the considered two-month period.

It can be seen that the greatest shading at 10:00 occurs in the northern and western classes. In the southern class, despite the fact that at this time the sun shines intensely on this side of the elevation, the number of hours of discomfort is lower than, for example, for the eastern class, which is due to the height of the sun explained above and the effectiveness of the breakers in this case.

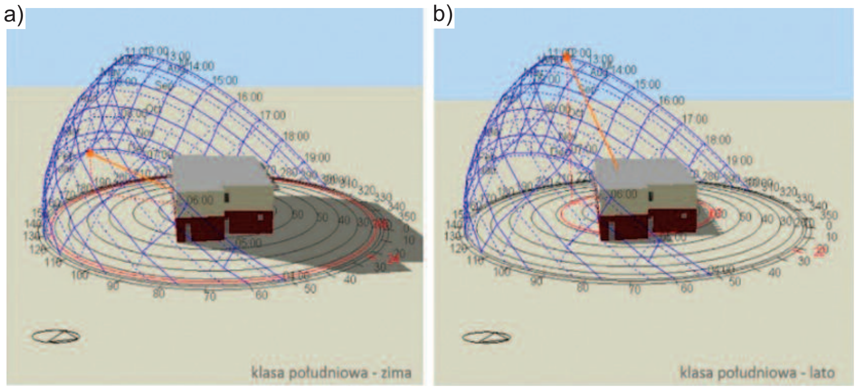

Fig. 2. Sun positioning for the southern class at 12:00 pm: a) in winter; b) in summer
Rys. 2. Usytuowanie słońca w klasie południowej o godz. 12.00: a) w zimie; b) w lecie

The results obtained confirm the validity of passive building design assumptions, also from the point of view of protection against overheating. Orientation of the school building with the longest axis along the north-south line is less favorable in terms of the number of hours of discomfort, compared to the east-west location. A hypothetical 90° change in the orientation of the block would yield 17% fewer weighted hours of discomfort. From the information consulted, it appears that the location of the school in Budzów is a consequence of the unfavorable shape of the plot.

In order to check the combined effectiveness of the selected solutions, the so-called reference variant, which uses ground cooling, was compared with a modified variant that takes into account the changes suggested in the article. The new model, equipped with mechanical day and night ventilation, takes into account the rotation of the building mass by 90° in a southerly direction and the extension of external light breakers to a length of 1,24 m. In both variants, shading blinds are located on the inside of the window, covered during the use hours of 7:00 to 15:00, when the interior temperature reaches 24°C.

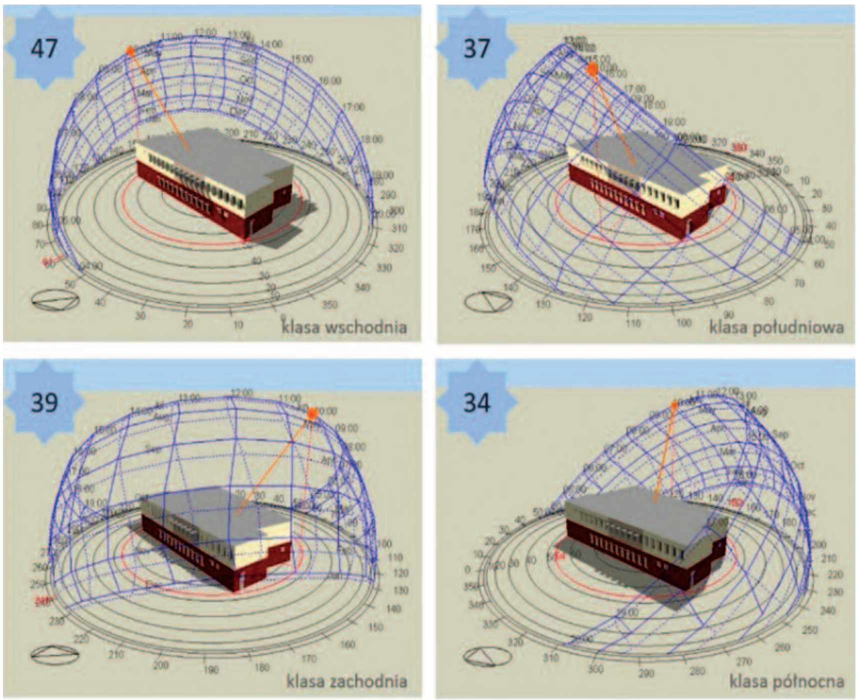

Fig. 3. Distribution of shading and calculated weighted measures of overheating discomfort for different building orientations on the 11.06 at 10 am
Rys. 3. Rozkład zacienienia oraz obliczone ważone miary dyskomfortu związane z przegrzewaniem w przypadku różnej orientacji budynku 11.06. o godz. 10.00

Table 4 summarizes the number of hours calculated from the simulations, the number of hours in the ranges of the predicted average rating index and measures of overheating discomfort. In the range closest to Fanger's upper comfort limit, the reference variant has 40% fewer hours, compared to the modified model. For both cases compared here, there are no PMV values above 1,5. The number of hours in the thermal comfort range for the reference variant is 45% higher than in the modified model. The weighted measure of discomfort is almost four times higher for the new model than for the case reflecting actual school use, at 37 h.

Summary and conclusions

As a consequence of the above analysis, it can be concluded that a mechanical ventilation system only in combination with a cooling source in the form of a ground heat exchanger and heat pump is effective in reducing discomfort in summer. The other suggested modifications, despite the fact that they reduce the amounts of weighted measures of overheating discomfort, relative to other adopted options, are not as effective as ground cooling.

The high solar energy transmittance values of passive glazing generate unwanted significant solar gains in summer, which interior screens cannot sufficiently cope with during usable periods. In addition, this popular security system limits the availability of daylight and prevents visual contact with the outside environment therefore it must be properly selected and prudently applied. After all, constant access to natural lighting ensures increased concentration and a pleasant learning atmosphere, while reducing operating costs. In the case of schools, adequate lighting intensity is crucial to ensure optimal learning conditions and contributes to the overall comfort and efficiency of education. External light breakers, on the other hand, limit the access of the sun's rays to the interior, but their effectiveness is strongly dependent on the time of year, the time of day, the location of the block in relation to the sides of the world and the intensity of sunlight. Adopted in

Table 4. Hourly distribution of the PMV index for the adopted simulation variant
Tabela 4. Godzinowy rozkład wskaźnika PMV w przyjętych wariantach symulacji

Simulation variants	Number of hours in				Weighted measure of over-heating discomfort [h]
	the thermal comfort range 0,5<PMV<+0,5	the range +0,5<PMV<+1,0	the range +1,0<PMV<+1,5	the range +1,5<PMV<+2,0	
Reference variant	165	9	0	0	**9,0**
Modified variant	91	15	11	0	**37,0**

the analyses, a threefold increase in the cantilever overhang on the eastern elevation resulted in a reduction in total solar gain of only 9% and a reduction in the weighted measure of discomfort of 8% compared to the baseline variant.

Orienting the block with the longest axis along the east-west line is the most favorable solution in shaping thermal comfort. Protected by appropriate external and internal shielding, rooms located on the south side generate fewer hours of discomfort than rooms located on the east and west sides.

North orientation is associated with the fewest hours of discomfort in summer, but also with limited direct sunlight. In accordance with practices already used in passive construction, going beyond the scope of room overheating discussed here, it is suggested to place sports, administrative or technical rooms, for example, on the north side.

However, evaluating the considered solutions in a slightly different way, it should be noted that in the guidelines created by the Passive Building Institute in Darmstadt regarding the design of passive buildings [20], a period of interior overheating of no more than 10% per year is allowed. In this context, the proposed modifications to the school building would be sufficient to maintain acceptable operating conditions in the interior.

It is worth mentioning that, increasingly, the adaptive comfort model is being used to assess thermal conditions in buildings with hybrid ventilation. According to it, during a long period of increasing outdoor air temperature, the human body adapts slowly to these conditions, and the range of comfortable conditions shifts toward higher temperatures. This type of approach can only be used if building occupants have the ability to adjust their clothing or open windows in accordance with changing environmental conditions. Taking into account the adaptation of users, a more lenient assessment of microclimate makes it possible, once the requirements are met, to accept conditions treated according to the Fanger criterion as overheating. Although the adaptive method of determining thermal comfort has its limitations, it should be used wherever possible. The synergy of the indoor environment, controlled by the occupants in response to the prevailing external conditions, and the low energy consumption of passive buildings is becoming an indispensable part of the idea of sustainable development. Taking into account the body's thermoregulatory capabilities and using the basic principles of heat exchange with the environment, it is possible to ensure user comfort with minimal operating costs.

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