Mitigating Summer Overheating of a Primary School Building Based on Dynamic Simulations

Ágnes Marosi – Budapest University of Technology and Economics, Hungary – marosi.agnes@edu.bme.hu
Balázs Nagy – Budapest University of Technology and Economics, Hungary – nagy.balazs@emk.bme.hu

Abstract

Overheating in buildings is a prevalent issue during summer, especially in school buildings due to their design and use. Despite schools being mostly closed during peak summer months, warmer temperatures in May, June, and September exacerbate the situation. We analyzed a primary school building in Budapest, conducting dynamic simulations to evaluate interventions such as flat roof renovations, window shading techniques, passive ventilation strategies, and a comprehensive ‘nearly zero’ energy retrofit. Systematic night-time ventilation proved an effective tool for summer cooling, offering a sustainable, cost-effective solution. The simulations revealed that the current state of the primary school leads to significant overheating. However, the cases revealed that systematic night-time ventilation of the buildings is an effective tool for summer cooling. Additionally, installing shades proved beneficial, installing external overhangs or shades offers practical retrofit options. Conversely, flat roof insulation and energy renovation resulted in slightly worse summer overheating values. Among the solutions, light-colored reflective surface waterproofing performed the best, but further studies with green roof layering are still worthwhile. The study also revealed that a ‘nearly zero’ energy efficiency retrofit focusing solely on thermal insulation and airtightness led to higher indoor temperatures without altering ventilation patterns. This highlights the need for a balanced approach that includes both insulation and ventilation. Combining night-time ventilation with window shading was the most effective strategy to mitigate overheating in schools. These findings can guide energy renovations in educational facilities to enhance comfort and sustainability, ultimately creating a healthier learning environment for students and reducing energy consumption.

1. Introduction

Investigating the summer overheating of school buildings is crucial due to children's increased vulnerability to overheating effects (Hyndman et al., 2023). Additionally, classrooms are often designed with large windows facing east or south to allow natural light, which can lead to increased overheating during peak occupancy hours (Grassie et al., 2022). Classroom conditions are mainly influenced by teachers’ preferences, and research indicates that the comfort needs of adults can differ significantly from those of children (Korsavi et al., 2020; De Giuli et al., 2012; Hellwig et al., 2022).

Examining indoor air conditions in primary schools is a complex task, considering factors such as temperature, humidity, natural ventilation, natural light, acoustics, air quality, and children's satisfaction. It is important to ensure good air quality to create a conducive learning environment. Air cooling systems can alleviate thermal conditions, but inadequate ventilation can cause compromised air quality. In poorly ventilated classrooms the amount of carbon dioxide (CO_2) can rapidly increase over 1200-1500 ppm and reach a level where it can adversely affect the performance of children (Teli et al., 2016; Clements-Croome et al., 2012), and with closed windows and air tightness, this value can rise above 3000 ppm (Bakó-Biró et al., 2008). It has also been found that students can become accustomed to the air conditions in the classroom, making it difficult for them to notice when the air quality worsens (Teli et al., 2016).

On the other hand, open windows and proper natural ventilation during classes lead to increased inner temperatures. Demozzi et al. in their study found a

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Pernigotto, G., Ballarini, I., Patuzzi, F., Prada, A., Corrado, V., & Gasparella, A. (Eds.). 2025. Building simulation applications BSA 2024. bu,press.
https://doi.org/10.13124/9788860462022

significant, 16—22 % performance loss caused by thermal discomfort (Demozzi et al., 2022).
A great emphasis has to be placed on the design of the division of windowpanes to achieve effective natural ventilation. Hellwig shows that classroom air change rates can be improved by separating the opening for supply air and exhaust air horizontally, 2 rows of tilt windows work best (Hellwig, 2010).
The other important factor of the indoor environment is natural light. Children need an adequate amount of natural light, 500 lux (EN 16798-1:2019) for studying so it is important to find the proper shading methods to let enough diffuse sunlight in but blocking solar radiation as much as possible. This standard also specifies requirements for indoor environmental parameters. The mentioned standard specifies four categories for the classification of expectations, with different, progressively lighter threshold values for each category in terms of expected temperature, air quality, and comfort expectations. Retrofits belong to category III. The thermal comfort level of an examined building can be evaluated by the satisfaction levels of the users. Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) values reflect the human comfort level and the percentage of dissatisfied users. These values can aid in calibrating simulation settings more accurately.
In the Hungarian practice, energy renovations typically focused on winter conditions only: achieving air tightness and applying thermal insulations on walls and roofs, choosing windows with good insulating parameters, and installing modern heating systems according to the National regulations that follow the EU directive of nearly zero energy consumption (2010/31/EU 2010). Summer overheating is not considered in most of the cases. Eight schools in the district of the examined school in Budapest have been retrofitted in the past 10 years, but the issue of solar protection or ventilation after school hours has not been taken into account in either case. Cooling, shading, and water-retention potential of vegetation and green roofs have not been considered in retrofitting policy either, despite studies showing their potential (Gómez et al., 2021).
This study investigates and suggests passive solutions to prevent schools from overheating during warmer months.

2. Methodology

2.1 Introduction and Modeling of the Building

The subject of the investigation is a 2-storey primary school building with 16 classrooms located in Budapest suburbs. The building was originally built in 1960 with brick walls, reinforced concrete frames, and reinforced concrete beam/block slabs. Fig. 1 and Fig. 2 show the 3D model and floor plans of the building.

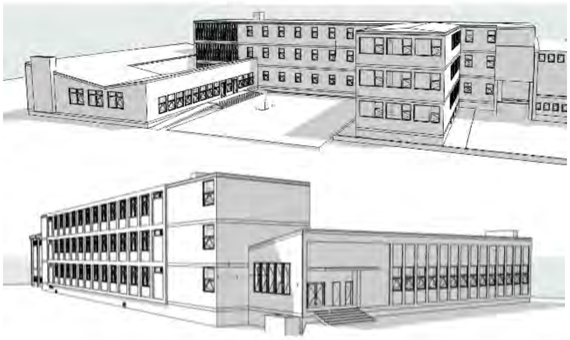

Fig. 1 – BIM model of the building using Archicad 26

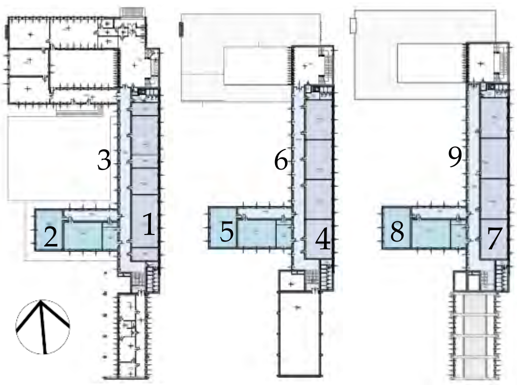

Fig. 2 – Floor plans of the building, from left to right: ground floor, first floor, second floor. The subject of this investigation: eastern classrooms, southern classrooms, and the corridor with the service areas are highlighted in different shades of blue

We chose this building for our examination because the layout is typical for Hungarian schools: 2 blocks of classrooms facing east and south connected by a corridor on one side. The service areas and stairs are located at the end of the corridors which connect the classroom area to the offices, teachers' rooms, and the gym.
We used WUFI Plus software for the hygrothermal dynamic simulation of the building. First, the BIM model of the school building was modeled in

Archicad and then converted into a Sketchup file. In Sketchup, we used a WUFI plugin and arranged the main settings. We divided the school building into 10 zones and defined their relation to each other and the outside air and ground. The Sketchup file then was saved in a WUFI-compatible format and was ready to use. Fig. 3 shows the model of the block of classrooms in WUFI.

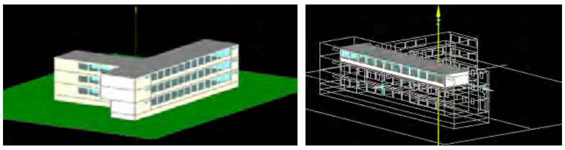

Fig. 3 – Model of the building in WUFI

2.2 Setting up the Model in WUFI

The building's location was determined using coordinates, and data from a weather station based in Budapest was utilized. The weather file contained complex weather data for 2020, such as temperature, relative humidity, solar radiation, driving rain, and wind.

The simulation was set for a whole year but only the data from 01.05. to 24.06., the last few weeks of the school year were analyzed in this research.

We divided the building into 10 zones. There are 3 main zones on each floor, (ground floor, 1st and 2nd floor):

- eastern classrooms (zone 1, 4, 7),
- southern classrooms (zone 2, 5, 8)
- corridor (zone 3, 6, 9)
- zone 10 is the basement.

We set the materials of building structures from the WUFI database according to the architectural documentation not only on the outside structures but on the inside as well, because the heat storage capacity is an important factor in overheating calculations.

Flat roof layers were set according to the present state, with 2 possible retrofit options – a minor and a complete renovation. A preset green roof layering was chosen from the WUFI database. Green roofs can retain water, which plays a key role in night cooling and can be calculated in WUFI but the material properties need to be carefully selected (Baniassadi et al., 2018).

A wide range of window parameters can be set manually or from the WUFI database. For shading, we can choose window overhang or sunscreen devices with 3 options. In sunscreen settings, both the closing factor and shading factor can be determined. The shading effect of the surroundings, in this case, a few trees near the eastern façade, was not considered. The trees only impact the ground-floor classrooms, which are not the most affected areas of this study.

The window blinds in some scenarios were selected with actual products in mind such as light fabric roller blinds and Venetian blinds. These blinds block direct sunlight while allowing natural lighting to filter through. The shading factor was set to 0.2 in each case, (1 – no shading, 0 total shade). Closing factor was set differently in each of the 3 cases keeping in mind that a fully closed shade can block natural ventilation. The software limitations prevent an accurate calculation of reduced natural ventilation, potentially impacting results during school hours.

At present, the building lacks external shading, so the 2005 scenario is calculated accordingly.

The internal load was calculated based on the ISO 7730:2005 standard, preset in the WUFI database, in which heat, moisture, and CO2 emissions are assigned to a given action, and a given age (child or adult). In this case: sitting activity during the classes and standing or a light walk during the breaks (child sitting activity, moisture: 33 g/h; convective heat: 56 W; radiant heat: 28 W; CO_2: 40 g/h; human activity: 1.2 met).

The calculation was based on an average school day with 45-minute lessons and 15-minute breaks from 8.00 to 13.00, a lunch break, and then afternoon classes until 17.00, from Monday to Friday. After school hours the internal loads and ventilation were set to zero. The values were set as accurately as possible to model the actual usage.

Setting the amount of natural ventilation was a difficult task. We assumed that the windows are mostly open in summer to maintain fresh air and keep CO_2 levels low, so after a few trial simulations we set natural ventilation to 3 ACH or 4 ACH during classes.

The settings for summer internal air velocity (here: a light draught, 0.4 m/s) and summer clothing (clo=0.5) were also considered. (1 Clo is a fully dressed person, 1 clo = 0.155 m^2K/W for adults). These settings affect satisfactory values (PMV and PPD).

All simulation scenarios had the same settings for the internal loads and occupancy.

2.3 Scenarios of the Research

We examined the following scenarios and combinations within the current research:

- Original building (1960) as reference
- Present case (2005)
- Flat roof renovation
  - light surface
  - dark surface
  - green roof
- External shading
  - window overhang
  - schedule
  - reduce overheating
  - radiation limit
- Night ventilation
  - 2 ACH
  - 6 ACH
- Nearly zero retrofit
  - nearly zero
  - nearly zero + night ventilation
  - nearly zero + window overhang
  - nearly zero + night ventilation + shade

2.3.1 Present case scenario (2005)

The first scenario was run with the basic settings of the building in its present state. In 2005 the building underwent a basic renovation focusing on increasing energy efficiency according to the regulations of that time. The walls were insulated with 5 cm of EPS and the windows were replaced with PVC windows with 2-layer insulating glazing (U_w = 1.4 W/m²K). We have named this scenario '2005' after the year of the most recent renovation.

We generated a simulation of the original, 1960 building as a reference to make the effects of the 2005 minor renovation more visible.

For data comparison, we used the ODH_{26} indicator (Overheating Degree Hours over 26 °C [Kh/a]) which sums up the parts of the operative temperatures above 26 °C. This is a simple method for analyzing the received data set and detecting trends. In each of the simulations, we aggregated these values by zone so we got a series of values that can be easily compared (Fürtön et al., 2022).

2.3.2 Cases of flat roof renovation

We examined three possible cases of flat roof renovation. If the waterproofing of the roof is in good condition the layers in the roof and the slab might be dry, so there is a possibility to keep the old layers and add new layers of thermal insulation and waterproofing. The present bituminous layers have dark surfaces, so in the three cases, we examined a dark surface and a light surface, reflective waterproofing as a closing layer, and also calculated for an extensive green roof. WUFI has options for setting the value of the absorption coefficient of shortwave radiation on surfaces (0-1), so we set those to 0.8 for dark surfaces; 0.2 for light surfaces; and 0.6 for green roofs.

2.3.3 Cases of external shading

In the 'window overhang' scenario, the dimensions of the shades were determined by a solar exposure test to maximize efficiency in both summer and winter. Solar heat gain can be advantageous during the winter months but has negative effects during the summer.

In the 'schedule' setting scenario, the schedule of the blinds was based on the hours exposed to direct sunlight and was considered pulled down to varying degrees hour-by-hour. The solar transmittance of the shade fabric and the percentage of closedness can be determined in a daily profile setting. The downside of this setting is that it does not take into account the solar radiation values, i.e. it considers the shade closed even if the sun is not shining.

In the 'reduce overheating' setting scenario the shade is considered pulled down when the maximum temperature set for the zone (27 °C) is exceeded. We set this simulation with a light-surfaced reflective textile blind in mind.

With the 'radiation limit' setting we set the solar radiation threshold value to 400 W/m² after which the shades are closed and block direct sunshine.

2.3.4 Cases of night ventilation

In these scenarios, we examined the effect of night ventilation. Lower temperature outside air cools the building's inner structures in the night, which helps regulate indoor temperatures. Using the building's heat storage capacity is an effective passive cooling method. The division of the windowpanes is the key to natural ventilation in classrooms. A row of tilt windows in the uppermost section seems to be a feasible solution for security concerns. Setting the amount of the exact air change rate is difficult in a simulation of natural ventilation. We set 2 ACH and 6 ACH air change rates in our scenarios from 21.00 to 6.00 at night. Night cooling must be monitored daily or must be completely automated because, with unexpected drops in night temperatures, overcooling can occur. (Pellegrini et al., 2012).

In our simulation, we found that with a 6 ACH air change rate in some cases, the inner temperatures fall below 20 °C in the morning hours, but as the children arrive it quickly rises to 23-24 °C. Also, strong winds, rain, or storms can cause problems. With monitored temperature data and motorized control, it is possible to determine the number of windows needed in each room for night ventilation, and thus optimal night cooling is achieved.

We should note that during heatwaves, the temperature of the air at night is much higher in densely populated urban areas, so night ventilation might not be as effective during those periods.

2.3.5 Cases of ‘nearly zero’ energy renovation

To reach the nearly zero energy efficiency goals we added additional subsequent thermal insulation on the walls and on the flat roof. We also replaced the existing windows with new, triple glazed thermal insulating low-e coated glazing and insulating frames and thermally insulated the basement slab of the ground floor from the basement side. We set the U value of the structures to safely meet the current Hungarian regulations which entered into force in autumn 2023, shown in Table 1. (176/2008. Gov. decree 2023).

Table 1 – Thermal transmittances (U; W/m²K) for structures in present, planned, and for ‘nearly zero’ regulation conditions

	U present (W/m²K)	U planned (W/m²K)	U regulation (W/m²K)
exterior walls	0.465	0.194	0.24
flat roof	0.349	0.139	0.17
unheated basement slab	0.782	0.159	0.26
windows	1.4	0.8	1.1

3. Results

3.1 Results of Present Case Scenario (2005)

According to the first two simulations of models 1960 and 2005, a 60 % reduction in the heating energy demand can be observed, but in addition, the results show a significant, 210-420 % increase in the ODH_{26} indicator. The results of the ODH_{26} for the zones and the average ODH_{26} value for the overall building are shown in Fig. 4.

Observing the results by zones, it is visible that the zones representing the Eastern classrooms, especially on the first and second floors (zones 4 and 7), experienced the highest temperatures and overheating due to intense morning solar radiation. These are followed by the classrooms of the southern block (zones 8 and 5). Shading these zones’ windows to limit the incident solar radiation would be certainly necessary to avoid overheating in summer conditions.

In contrast, the ground floor areas benefitted from the cooling effect of the basement, showing lower temperatures and ODH_{26} values. This tendency showed in every further simulation, so we concentrated our investigations mainly on the two most affected eastern zones: 4 and 7.

Interestingly, in the 2005 scenario, zone 4 was the most affected, while in the 1960 case zone 7 had the worst results in the case of the ODH_{26} indicator, the effect of the previous renovation is visible on the results.

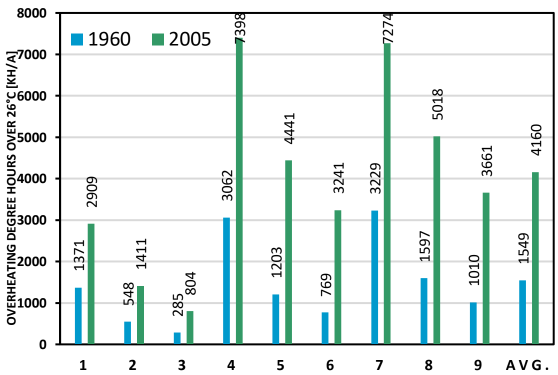

Fig. 4 – ODH_{26} values of zones in 1960 and 2005 case scenario

WUFI generates diagrams of operative temperatures as a function of the exponentially weighted running mean of the outdoor temperature according to EN 16798-1:2019 standard. The diagram shows that the majority of operative temperatures in zone 4 in the current, 2005 scenario are above the acceptable boundaries, shown in a red continuous line (see Fig. 5). Compared to the reference building, thermal insulation prevents building heat loss in winter but can result in overheating in summer.

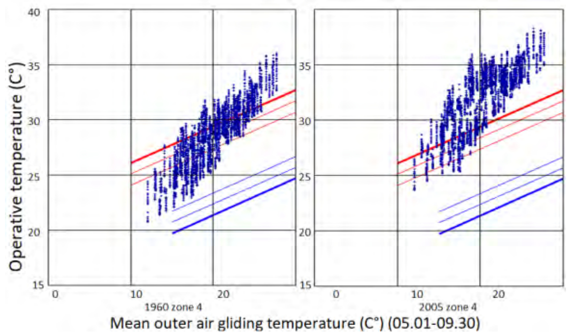

Fig. 5 – Zone 4 operative temperatures in 1960 (left) and 2005 (right) scenarios from 01.05. – 09.01. in the adaptive temperature range according to EN 16798-1:2019 standard

3.2 Results of Flat Roof Renovation Scenarios

In all flat roof renovation scenarios, a slight rise in temperatures can be observed. Understandably, the temperatures in the 2nd floor zones (7, 8, 9) rise the most, because the thicker thermal insulation prevents heat loss through the flat roof. The simulation indicates that choosing a light, reflective material for the flat roof reduces the heating of the surface, thus decreasing overheating (see Fig. 6).

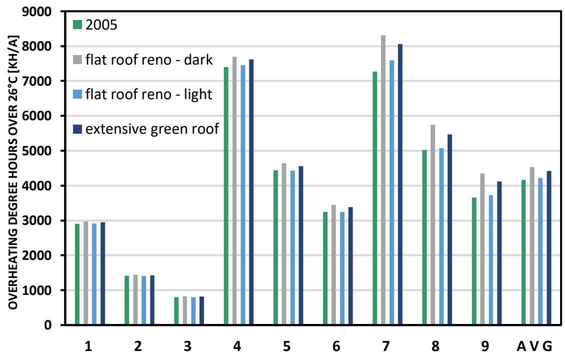

Fig. 6 – ODH_{26} in 3 different flat roof renovation scenarios compared to the present state in zones 1–9, and overall performance of the building

Temperature data of Table 2 of the external surfaces of the roof also show a significant, 24 °C difference in the best and worst cases. The internal surfaces have slightly different values in maximum temperature, as the result of the building's heat storage capacity and the lack of night ventilation. This issue will be discussed in the night ventilation scenarios. The cooling effect of green roofs was not considered in the present study; therefore, further investigations are needed. The results indicate that selecting reflective or light-colored materials for roof surfaces can significantly reduce heat absorption and improve indoor thermal conditions. Green roofs offer additional benefits and should be considered for their cooling potential and water retention capabilities.

Table 2 – Max. temperatures of the surfaces of the flat roof

	inner surface temp (max).	**outer surface temp (max.)**
2005	38 °C	67 °C
green roof	38.4 °C	54.4 °C
dark surface	38.3 °C	64.8 °C
light surface	37.5 °C	43 °C

3.3 Results of Shading Scenarios

The effect of external window overhangs reduced the value of the ODH_{26} indicator notably to 45-71 % in the zones, and 60 %. in zone 7. The scheduled shading scenario also showed positive results, but its effectiveness depends on accurately predicting solar radiation patterns. The "reduce overheating" setting, where shades close based on indoor temperatures, provided the best results, balancing natural light and thermal comfort. Every shading solution were effective in reducing overheating, but it is difficult to say which setting depicts the actual operation best (see Fig. 7), our research shows that any kind of external shading can be beneficial as it effectively reduces internal temperatures by blocking direct sunlight and should be integrated into the building design. When selecting window shades, it is important to consider both the amount of natural light and the natural ventilation of rooms.

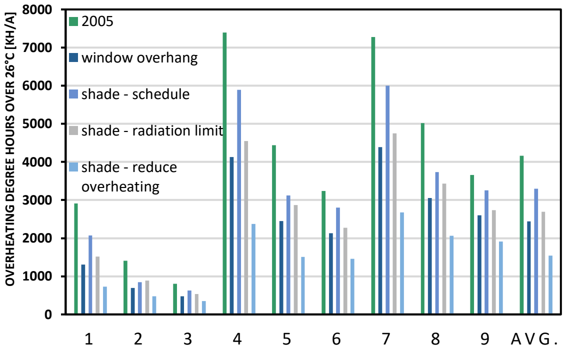

Fig. 7 – ODH26 of shading scenarios compared to the 2005 phase in zones 1–9, and overall performance of the building

3.4 Results of Night Ventilation

Night ventilation proved to be a highly effective passive cooling method. Both 2 ACH and 6 ACH scenarios showed significant reductions in ODH_{26} values. The 6 ACH scenario, although more effective, sometimes resulted in overcooling, indicating the need for monitored or automated control systems to optimize ventilation rates and prevent discomfort. Implementing night ventilation systems with automated controls can optimize indoor temperatures without compromising comfort. This method is cost-effective and sustainable, reducing reliance on active cooling systems. Further research is needed to optimize night cooling in schools, but the potential of this kind of passive cooling is promising.

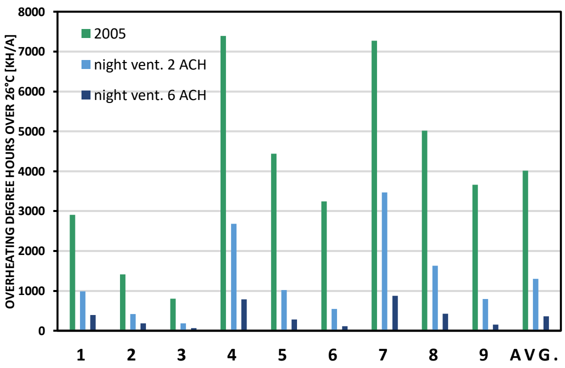

Fig 8 – ODH_{26} of night ventilation compared to the 2005 phase in zones 1-9, and overall performance of the building

3.5 Results of Nearly Zero Scenario

In each zone of the building, we can see a jump in the ODH_{26} indicator values (Fig. 8). Unlike before, the temperature of the rooms on the ground floor increased most dynamically, due to the insulation of the basement slab. The nearly zero energy retrofit, focusing on enhanced thermal insulation and airtightness, led to higher indoor temperatures across all zones. This retrofit, while improving winter energy efficiency, exacerbated summer overheating issues. The results underscore the necessity of incorporating ventilation strategies alongside insulation to maintain thermal comfort year-round.

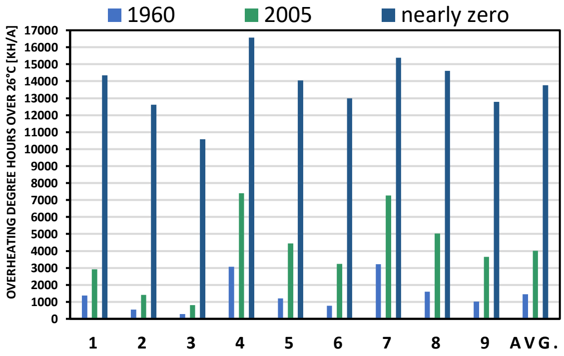

Fig. 8 – ODH_{26} of nearly zero renovation compared to 2005 and 1960 in zones 1–9, and overall performance of the building

Based on the results presented in Fig. 9, the worst-performing eastern zone 4 is already in the temperature range of 33 – 37 °C by June and does not follow the external temperature fluctuations. The building cannot cool down and will become unusable during warmer months without shading and unchanged ventilation habits. Increasing the thickness of thermal insulation changed the trend: the zones positioned in the middle of the building became the most affected by overheating. This phenomenon has been observed in other studies too (Szagri et al., 2019).

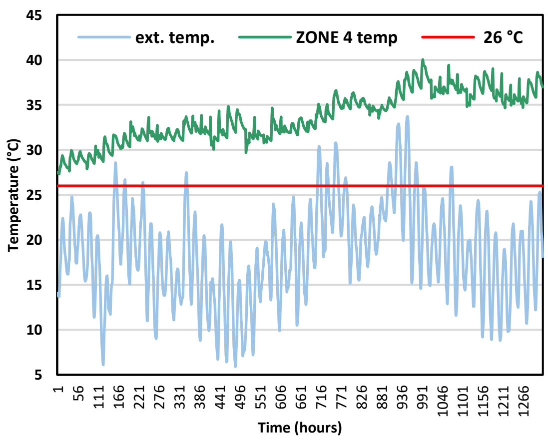

Fig. 9 – Hourly temperatures of zone 4 in nearly zero scenario (05.01-06.24)

We examined the effect of the formerly presented scenarios with the 'nearly zero' settings. Based on the ODH_{26} results, by blocking solar radiation in summer, indoor temperatures are more favorable than without shading. With night ventilation, we can achieve results similar to the previous scenarios. By combining the two solutions, we can create very favorable conditions in the classrooms (see Fig. 10).

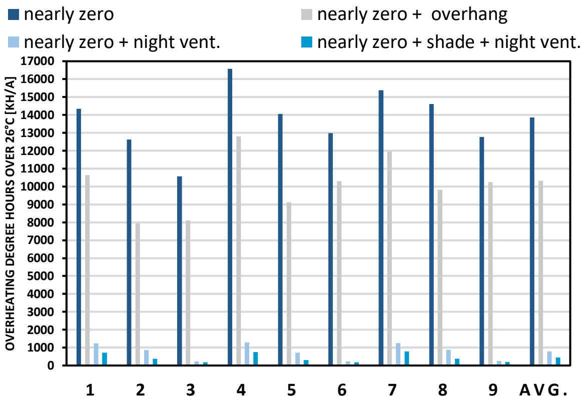

Fig. 10 – ODH_{26} of scenarios for possible nearly zero solutions

4. Conclusion

Due to global warming, children's school environment needs to be revived nationwide. This study demonstrated the effectiveness of various interventions to mitigate summer overheating in a primary school building in Budapest. Our findings align with research indicating buildings should be protected against summer overheating. Designers must prioritize this in energy renovations.

The examined school is prone to overheating in its present state and this tendency is likely to worsen.

In each simulation, the eastern classroom block on the 1st and 2nd floor consistently experienced the highest levels of overheating. This is due to the combination of high internal loads in the classrooms and the intense morning solar radiation on the eastern façade. The dynamics of overheating depend on the thickness of the thermal insulation applied to the walls and flat roofs.

The degree of warming slightly increases in all cases. of flat roof renovation scenarios. Of the solutions listed, waterproofing with a light-colored, reflective surface proved to be the best. Further studies of the cooling effect of green roofs need to be conducted.

There was a significant improvement in every case when applying external shades. The best results came with the reduce overheating setting, where the screen closes to a given percentage when the defined maximum temperature is reached in the classroom. Also, a more affordable but effective solution can be achieved with the combination of window overhangs and internal curtains.

The results of the 2005 energy renovations do not meet the current 'nearly zero' energy expectations. The calculations showed that by refurbishing the thermal envelope to meet the 2024 requirements the warming indicators deteriorate very significantly.

Nighttime ventilation proved to be the best solution in all scenarios. Even the smallest amount of air change rate can be used as a powerful tool in mitigating overheating. It can be combined with any of the examined scenarios.

In 'nearly zero' energy cases it is impossible to cool down buildings without nighttime ventilation.

In our calculations we proved that the current design and operation of the school is not sustainable. Installing air conditioning in classrooms may effectively cool the temperature, but it can lead to poor air quality and high CO_2 levels due to the lack of ventilation.

Currently, the windows of school buildings are closed during non-school hours for security reasons. of night ventilation offers a long-term profitable solution. The maintainers must be informed of its potential so that solutions can be found at the system level. The results of this study can also provide a basis for the modernization of similar school buildings.

Buildings cannot be always cooled to a comfortable level by passive means during heatwaves. The solution can be found by developing hybrid systems. It is recommended to prioritize passive solutions or renewable energies even in systems with mechanical cooling.

These findings can guide future energy renovations in educational facilities to enhance comfort, sustainability, and the overall learning environment for students.

Acknowledgements

The research reported here was supported by TKP2021-NVA-02 project. Project no. TKP2021-NVA-02 has been implemented with the support provided by the Ministry of Innovation and Technology of Hungary from the National Research, Development and Innovation Fund, financed under the TKP2021-NVA funding scheme.

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