

Analysis of energy efficiency and thermal comfort for an office building complex located in Poland – a case study

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Abstract. This article presents an analysis of energy demand for an office buildings complex located in Gdansk, Poland. The analyses were performed with advanced computer simulations using the Energy Plus software. Simulations were validated by comparing their results with the actual energy consumption data for one of the buildings belonging to the complex and information gathered from complex owner and technical office. The paper includes the effectiveness analysis of using various sources and distribution systems for heating/cooling, use of the phase-change material as internal ceiling layer, reflective glass application and use solar energy produced by photovoltaic glass and PV panels located on the roofs. For each of the variants, thermal comfort analysis was carried out. The aim of the analysis is to examine the time variation and peak load reductions of power demand for the considered variants, indicated as possible to be introduced by the complex owner.

1. Introduction

In Poland the electricity demand is growing each year [1,2]. The growing electricity consumption is also associated with the increasing power peak demand. This is mainly due to the economic development of Poland, as well as due to increasingly higher requirements of building users regarding quality of the internal environment.

One of the most important aspects of the proper and effective functioning of individual buildings as well as large enterprises is proper energy management. Important tasks of such an energy management are rational energy consumption, reduction of power peak demand and choosing appropriate modernization tasks. Nowadays, due to global trends towards sustainable development and increasing requirements of regulations concerning installations of a building, it is necessary to use renewable energy sources, among which solar energy is the most popular in urban areas.

Moreover, an architect should create favorable indoor conditions for people inside every building, among others by providing the thermal comfort conditions [3]. Diversified types of heating, ventilation and air-conditioning (HVAC) installations, as well as development of smart building management systems (BMS) allow dynamic control of a building internal environment.

This article presents an analysis of power peak demand and energy consumption by the existing office building complex located in Gdansk, Poland. The analysis is based on some available real energy consumption data and technical documentation for one of the buildings belonging to the analyzed complex. The research is based on the results of computer simulations for the whole office buildings complex, performed by means the Energy Plus software [4]. A number of simulations is made in order to predict effects of application of phase-change materials (PCM), reflective glass, photovoltaic glass, PV panels as well as different source and distribution systems of chill in air



conditioning system. Analysis focused on thermal comfort, cooling power demand and heating energy consumption.

2. Description of the analysis

In Poland, the current methodology for determining the energy performance of a building [5] requires monthly balance method, based on average values of parameters related to external climate, heat gains and losses, as well as the installations' efficiency.

The analysis was carried out using advanced energy simulations, performed with a minimum one hour calculation step. The computer model of a real office buildings' complex located in Gdansk, Poland, defined by means of the Energy Plus software, is analyzed. Such type of simulations fully reflects the dynamics of changes in external climate conditions and the response of building installations to the environmental thermal loads. All simulations were performed for a full year, using weather data of Typical Meteorological Year (TMY) for Gdansk, Poland [6].

2.1. Subject of the analysis

The subject of the analysis is the existing complex of office buildings located in Gdansk (figure 1). The complex consists of 4 buildings, one of which is under construction (planned commission date – end of 2019). The buildings are characterized by a large office open space areas and significant area of external glass façades. The total office space of the analyzed complex is 98 314,71 m².



Figure 1. Visualization of the completed office buildings complex in Gdansk

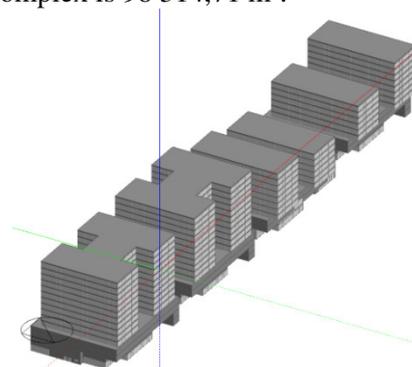


Figure 2. A computer model of the analyzed office buildings complex

The study is based on the real parameters (including building project) and data for one of the analyzed complex buildings. The data included time history of electricity consumption for different purposes, total energy consumption from district heating system, work schedules of individual devices and working hours of the facility. Moreover, air flow of the ventilation system was set according to parameters gathered from technical office of analyzed complex.

Table 1. Comparison of the results of computer simulation of energy consumption, made with Energy Plus software with real values.

	Actual use [kWh]	Simulation [kWh]	Absolute difference [kWh]	Relative difference [%]
Cooling	168 568.36	167 354.67	- 1 213.69	- 0.72
Int. Lighting	350 830.63	360 022.39	9 191.76	2.62
Int. Equipment	564 306.17	560 694.61	- 3 611.56	- 0.64
Fans	813 125.94	748 726.37	- 64 399.57	- 7.92
Pumps	57 102.08	57 907.22	805.14	1.41
Humidification	145 107.47	132 968.01	- 12 139.46	- 8.37
Sum (electricity)	2 099 040.65	2 027 673.27	- 71 367.38	- 3.40
Heating	1 211 413.24	1 154 476.82	- 56 936.42	- 4.70

Firstly, a calibration of the computer model (figure 2) was performed, comparing simulation results to the real energy consumption data. Electricity consumption was calibrated on the basis of hourly readings, while heating energy consumption was compared to monthly energy bills. Table 1 presents comparison of the annual electricity and heat consumption obtained from simulations (variant 0) with the actual values. Worth mentioning fact is that the computer model of the analyzed building was accepted by the complex owner. It was assumed that other buildings of the complex are characterized by the same parameters of the energy model (thermal insulation, installations, working hours schedule etc.).

The research does not cover the first floors of the analyzed buildings, which are used for different purposes (space types): car parking area, restaurants, gyms and swimming pool. This is due to the lack of data concerning the actual energy consumption for these parts of analyzed buildings.

2.2. Description of simulation variants

The following variants were analyzed in the study:

- variant 1: application of phase-change material (PCM) as internal layer of ceilings

The use of PCM as internal ceilings layer has been analyzed. It was assumed, that PCM was encapsulated in plasterboards. The material phase change temperature range was between 22 and 24 °C.

- variant 2: use of the reflective glass [7] on the external façade

It is assumed use of reflective glass on the exterior façade of the buildings. Reflective glass is coated with a metal oxide in order to obtain solar control and reduce solar energy penetration. The glass assumed in the simulations [8] is characterized by a lower value of light transmittance (L_T) and lower solar heat gain coefficient (SGHC) value than real elevation glass of the analyzed complex.

- variant 3: application of photovoltaic glass on the front elevation

It is assumed use of photovoltaic glass [9], for electricity production (figure 3). It was assumed that the photovoltaic modules constitute 15 % of front façade, (oriented to the southwest) glazing area for the all buildings of complex. The nearest area of the analyzed complex as well as its individual buildings do not generate shadings on the front façade. The total area of photovoltaic modules is 917,42 m². Analysis takes into account the lower natural light transmittance (L_T) and lower solar heat gain coefficient (SGHC) value..



Figure 3. An example of the existing photovoltaic glass use.

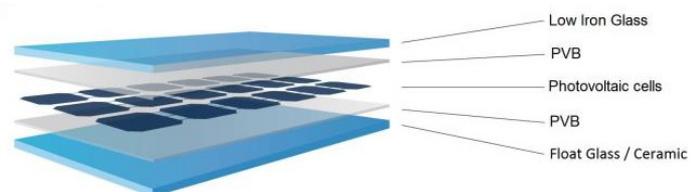


Figure 4. Typical photovoltaic glass construction.

- variant 4: use of photovoltaic panels on the roof of the analyzed complex

It is assumed use of photovoltaic panels installation on the available roof area of the complex. The available roof area for solar installation is 4 600.68 m², which is 39.67% of total roof area of the complex. PV panels are oriented directly to the south, inclined at 30 degrees to maximize electricity production during summer. The arrangement of the solar installation assumed shading minimization generated by individual panels. Total area of used PV panels [10] is 1 155.29 m².

- variant 5: change of chill distribution system from fan coils to cooling beams [11]

This case was analyzed in order to compare those two most commonly used systems. It was assumed that priority of the system is cooling, but room heating is also possible (4 pipe installation system). In the assumed installation scheme, the heating elements were water convectors, and not hot air supply as in variant 0.

- variant 6: change of chill source from air-cooled chillers to water cooled

This variant assumed chill source change from air-cooled aggregates to dry liquid coolers, which were connected to the water-glycol mixture installation. The variant implied significant changes in the hydraulic system of the HVAC installation.

3. Simulation results

In subsection 3.1 the energy demand and cooling power for the analyzed variants of buildings complex were analyzed, while in subsection 3.1 thermal comfort was considered.

The results concerning time variation of power demand and thermal comfort are presented for extreme summer and winter week periods. In each figure (from figure 5 to figure 8) working hours were shown by grey background. The extreme weeks were selected from the TMY weather data for Gdansk, Poland. The Extreme Summer Week (ESW) was chosen on the basis of the highest average temperature of external air. Similarly, an Extreme Winter Week (EWW) was selected considering the lowest average temperature of external air. ESW lasts from 12th to 18th July, while EWW – from 10th to 16th December. Calculations of the electricity yield by means solar installation were performed in accordance with [12].

3.1. Energy demand results

The energy demand for different purposes obtained from the energy simulations, is summarized in Table 2. Each of the considered variants was compared with the base one (variant 0).

Table 2. Comparison of energy consumption results obtained for the analyzed variants.

	Variant 0 [kWh]	Variant 1 [kWh]	Variant 2 [kWh]	Variant 3 [kWh]	Variant 4 [kWh]	Variant 5 [kWh]	Variant 6 [kWh]
Cooling	927 592.87	853 453.28	785 238.58	823 030.74 ^a	704 088.68 ^b	788 232.74	719 594.09
Int. Lighting	2 046 267.06	2 046 267.06	2 107 119.83	2 049 193.15	2 046 267.06	2 046 267.06	2 046 267.06
Int. Equip.	2 990 732.74	2 990 732.74	2 990 732.74	3 014 576.02	3 070 210.35	2 990 732.74	2 990 732.74
Fans	3 908 200.41	3 884 049.47	3 660 744.94	3 894 364.83	3 519 681.49	2 712 113.35	3 908 200.41
Pumps	298 816.86	296 500.16	273 448.22	297 309.11	258 986.68	327 281.80	583 737.53
Humidif.	715 784.42	554 465.82	682 702.71	712 332.94	663 844.29	636 090.83	715 784.42
Sum (electricity)	10 887 394.36	10 625 468.53	10 499 987.02	10 790 806.79	10 263 078.55	9 500 718.52	10 964 316.25
Heating	6 160 098.76	6 139 094.12	6 626 522.81	6 179 328.85	6 160 098.76	6 635 229.02	6 160 098.76

^a The value of cooling energy demand reduced by energy yield from photovoltaic glass.

^b The value of cooling energy demand reduced by energy yield from photovoltaic panels.

The most advantageous, in terms of electricity consumption, was variant 5, i.e. cooling beams as a chill distribution source. This variant results in reduction of cooling energy demand by 15.02% and lower electric energy consumption by fans by 30.60%. Total annual electricity consumption has been reduced by 12.74%.

Variant 6, i.e. change of chill source from air-cooled chillers to water cooled ones, has lower cooling energy demand than variant 5. Modification in the installation HVAC schema led to a change in energy consumption structure (see Table 2). Total annual electricity consumption is higher than in the base variant 0.

The lowest value of cooling energy demand gave variant 4, i.e. use of photovoltaic panels on the roof of the analyzed complex. This variant assumes use of energy produced by photovoltaic panels for

cooling the buildings. The PV panels produced 223 504.19 kWh of electricity per year. Variant 4 reduced cooling energy demand by 24.10%.

Variant 3, i.e. the photovoltaic glass applied on the front elevation, produced electricity more evenly throughout the year than variant 4. The total amount of the produced electricity was equal to 95 534.28 kWh per year. This variant only slightly affected the interior lighting conditions in the rooms of the analyzed buildings.

Most of the analyzed variants had similar energy demand for heating. The most advantageous is variant 1, i.e. application of PCM as internal layer of ceilings. However, the achieved reduction is very small (by 0.34%) that this variant cannot be considered as profitable. The highest heating demand was obtained for variant 2, i.e. use of reflective glass. The increase of heating demand by 7.57 % was caused by a reduction of solar gains in the heating period.

The internal equipment energy consumption for the analyzed variants, except of variants 3 and 4, were equal. These variants' results take into account the additional electricity consumption by auxiliary drivers of the solar installation. In addition, for variants 2 and 3 the energy consumption for internal lighting was increased due to lower light transmission through windows.

The hourly cooling power demand history for ESW period is shown in figure 5. In addition, the power production output by means of photovoltaic glass (sol_3) and PV panels (sol_4) has been shown.

The analysis showed that the all considered variants applied in order to reduce cooling peak demand were effective, but to different extent.

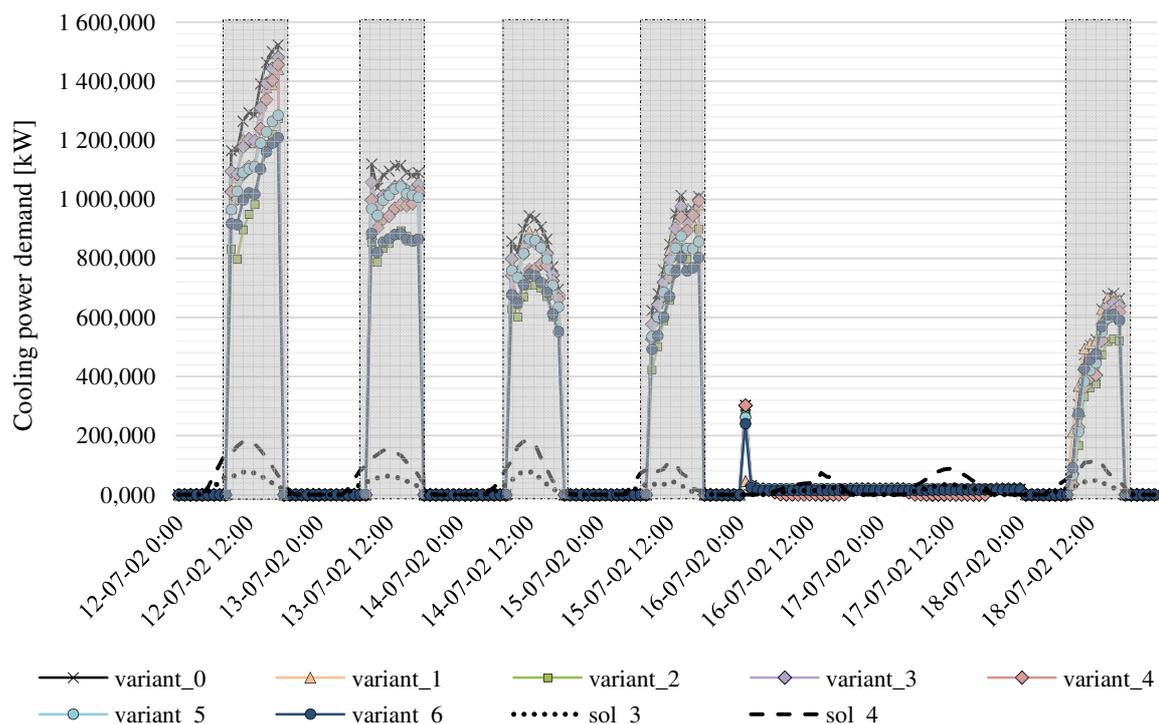


Figure 5. Cooling power demand distribution of the analyzed variants for the ESW period.

Table 3 presents the obtained cooling power demand and resulting power reduction for the analyzed variants during the highest cooling demand period (i.e. between 4 p.m. and 5 p.m. on 12th July). The biggest reduction, by 313.91 kW (20.62%), was obtained for variant 6.

Table 3. Comparison of peak power cooling demand of the analyzed variants.

Variant 0	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5	Variant 6
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Cooling power demand [kW]	1 522.64	1 440.77	1 272.43	1 480.81	1 456.04	1 284.56	1 208.72
Absolute difference [kW]	-	- 81.86	- 250.21	- 41.83	- 66.60	- 238.08	- 313.91
Relative difference [%]	-	- 5.38	- 16.43	- 2.75	- 4.37	- 15.64	- 20.62

3.2. Thermal comfort analysis

For each of the considered variants thermal comfort conditions were analyzed, based on Predicted Mean Vote values (PMV index). There are four internal environment categories [13]. For the analyzed buildings complex the 2nd category of internal environment was assumed (standard expectations, recommended for new and modernized buildings). The value of PMV index should be in the range of:

$$-0.5 < PMV < +0.5$$

Within a few hours of building operation time it is acceptable to lower the category of internal environment to the 3rd category.

The time histories of the PMV index are shown for the ESW period in figure 6 and for the EWW period in figure 7. The presented results concern the corner room, for which, due to glazing façades of both outer walls, it is the most difficult to maintain thermal comfort. The complex does not have working weekends, hence the analysis of PMV index distribution does not concern 16th and 17th July (ESW period) and 10th and 11th December (EWW period). Simulations by means the Energy Plus software performed thermal comfort calculations accordance with [14].

In figure 6 it can be seen that during the working hours the PMV index values oscillate within the recommended limits of thermal comfort. The best PMV index values were obtained for variant 2, i.e. use of reflective glass. It may be observed that the assumed internal air temperature for the summer period (24 °C) is correctly selected. Solar radiation, which is reduced in variant 2, has a large influence on the room thermal comfort..

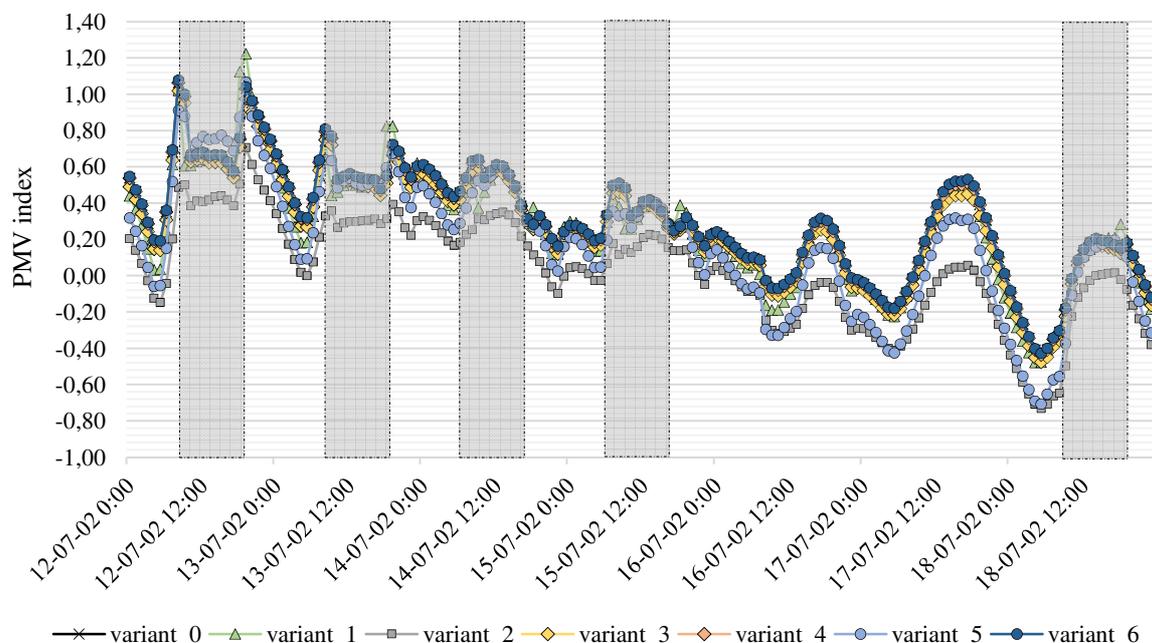


Figure 6. The time histories of the PMV index for ESW period.

Figure 7 shows that the all considered variants have similar PMV index values for the EWW period. During buildings working hours, the obtained PMV index values are below recommended

values of thermal comfort. The analysis included the following parameters related to human physiology: typical office work ($M = 70 \text{ W/m}^2$) and common clothing set during winter period ($I_{cl} = 1.0 \text{ clo}$). This led to the conclusion that indoor air temperature in the winter period (assumed as $22 \text{ }^\circ\text{C}$, which was given by the building administrator) is too low.

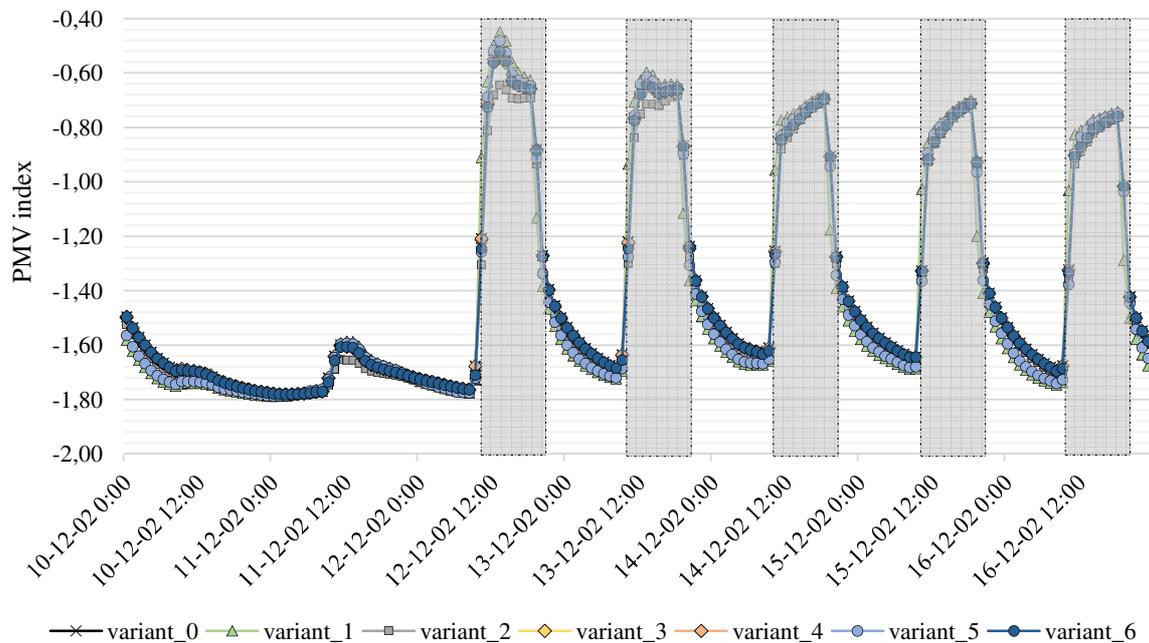


Figure 7. The time histories of the PMV index for EWW period.

Hence additional simulations were done for the increased air temperature ($24 \text{ }^\circ\text{C}$) to analyze thermal comfort during the EWW period. In figure 8 it can be seen that, for each variants, thermal comfort has improved comparing to the previous analysis (see figure 7). It can be concluded that higher internal air temperature is required in order to meet thermal comfort requirements for buildings with glass exterior façades than for ones with masonry walls. Mean radiant temperature (which, in this case, is much lower than air temperature) had significant influence in the PMV index results. The total heating demand, for the EWW period, increased from 4.77 to 6.99 % (depending on the variant).

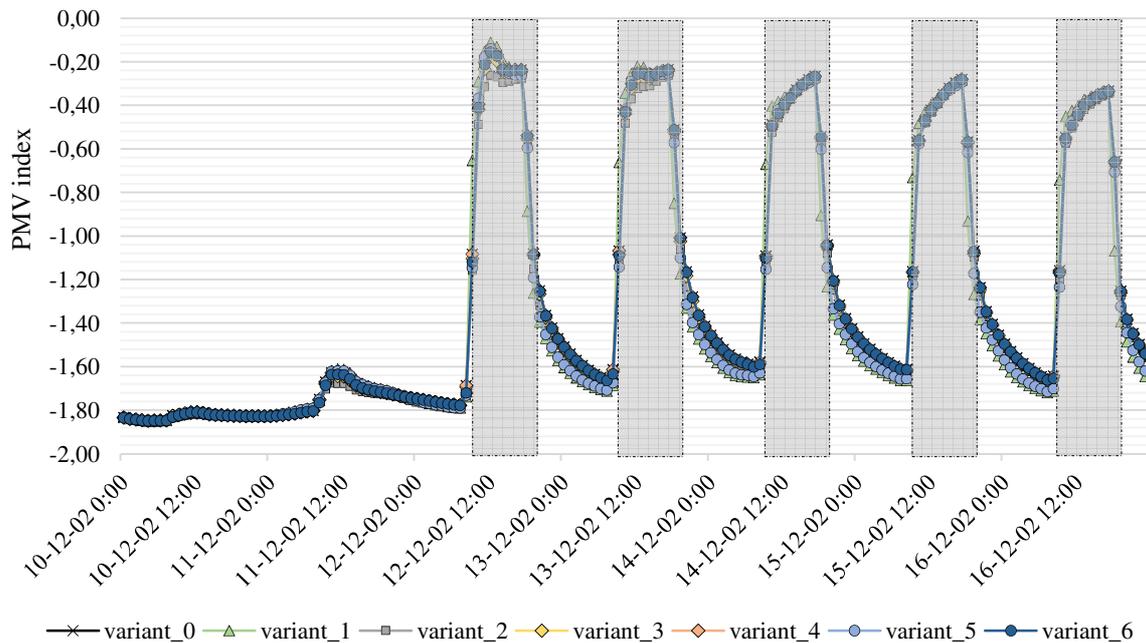


Figure 8. The time histories of the PMV index for EWW period for higher internal air temperature adjustment.

4. Conclusions

The results of the analysis performed lead to the following conclusions:

- The use of advanced computer simulations for large public buildings has been demonstrated in order to select the most appropriate construction and HVAC installation solutions.
- The computer simulation is an effective tool for selecting the proper solution of HVAC system at the designing stage of building project.
- In order to check the profitability of modernization variant for an existing building, the analysis should be extended by appropriate economic analyses.
- The analysis showed a potential for using solar energy in urban areas, using both photovoltaic glass façade and PV panels on the building roof.
- All considered modernization variants resulted in cooling power demand reduction during summer period. Reduction of power peaks is one of the most important issues for proper building energy management.
- The need of limiting solar radiation causing uncontrolled inner heat gains during summer has been demonstrated. Reducing the adverse effects of solar radiation leads to improvement of thermal comfort and reduction of energy consumption during summer.
- Using cooling beams instead of fan coils in chill distribution system (variant 5) was shown to be the most advantageous in the study performed. This variant results in reduction of cooling energy demand by 15.02%, while total electricity consumption was reduced by 12.74%. However, it should be noted that cooling beams may perform well only up to a certain limit value of inner heat gains.
- Any proposed modernization variant should be assessed in terms of meeting the required internal environment conditions, because providing thermal comfort is a priority for spaces intended for permanent stay/work of people.

5. References

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