Rocznik Ochrona Środowiska

Volume 23 Year 2021 ISSN 1506-218X pp. 458-469

https://doi.org/10.54740/ros.2021.031 open access

Received: 16 June 2021 Accepted: 27 July 2021 Published: 06 December 2021

Changing Energy and Exergy Comfort Level after School Thermomodernization

Nadia Buyak[*]
Department of Heat Engineering and Energy Saving,
National Technical University of Ukraine
"Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine
https://orcid.org/0000-0003-0597-6945

Valeriy Deshko
Department of Heat Engineering and Energy Saving,
National Technical University of Ukraine
"Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine
https://orcid.org/0000-0002-8218-3933

Inna Bilous
Department of Heat Engineering and Energy Saving,
National Technical University of Ukraine
"Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine
https://orcid.org/0000-0002-6640-103X

[*]*corresponding author's e-mail: korovaj.te@gmail.com*

Abstract: Increasing the level of thermal resistance of the building envelope in combination with the choice of heat source is an urgent task. It is important to take into account changes in the cost of energy over time. Thermal modernization, in its turn, allows to increase the level of thermal comfort, which is not taken into account and evaluated in practice, although the relevant standards for comfort conditions and categories of buildings to ensure comfort have been introduced in Ukraine. This paper analyzes the change in the level of comfort after thermal modernization, determines the category of the building to provide comfortable conditions, as well as identifies the change in the average radiation temperature of the fences, as one of the main factors of PMV change in these conditions.

Keywords: energy need, PMV, mean radiant temperature, comfort temperature, thermomodernization

1. Introduction

Improvement of the energy efficiency in buildings is an important and complex public task. Particular attention should be paid to increasing the energy efficiency of public buildings, the level of thermal comfort, which is regulated by the relevant requirements (Zare et al. 2018) and is widely covered in recent studies

(Deshko et al. 2020, Deshko et al. 2016, Hurnik et al. 2017, Dylewski et al. 2012). In addition, the human factor is taken into account by determining the level of use and the degree of occupancy of the building (Rodrigues et al. 2017), which creates the need to consider economic, environmental (Javid et al. 2019), energy and social factors in assessing and making decisions during thermal modernization of the building. Starting from the end of 2020, all new buildings should be highly energy efficient after thermal modernization (Moran et al. 2020). Similarly, this requirement is relevant for all public buildings from the end of 2018. In order to determine the energy performance requirements of buildings for nZEB, the EU countries had to use a cost-optimal methodological framework to assess cost-effective minimum energy consumption levels of building / building elements / building materials performance requirements (Moran et al. 2020).

This methodological system estimates the total costs (or life cycle costs) of buildings / building elements / building materials and their corresponding impact on primary operating energy needs for heating, cooling, ventilation, hot water, and lighting systems.

It is clear that thermal modernization can increase the energy performance and energy efficiency of existing buildings and reduce their energy demand. However, its effect on the level of thermal comfort has only recently been studied (Park et al. 2020). The application of modern economic approaches will reveal the economic potential of thermal modernization in the construction stock, and the use of modern models of thermal comfort will assess the impact and opportunities to increase the level of thermal comfort. Modern economic approaches have been developed to show the example of Sweden's economic potential for thermal modernization in the housing stock using 3 main methods, namely: 1) full investment costs and energy savings (complete approach), 2) approach that takes into account the cost of improvements related to energy efficiency and energy saving (respectively) and 3) an approach that corresponds to the approach of improvement, but additionally assigns a residual value to each building element (reduction approach) (Streicher et al. 2020).

A building is a complex energy system. And the issues of energy consumption are investigated starting from the heat source and ending with enclosing structures, however, the requirements for thermal comfort are set by a human, which is reflected in the following works (Dovjak et al. 2015, Deshko et al. 2020, Deshko et al. 2016). Thermal comfort models that are developed by Fanger (Fanger 1973) formed the basis of the ISO 7730 standard. They are based on energy balance for the human body. An exergetic approach is being developed not only to assess the destruction of exergy in enclosures (Choi et al. 2020), but also to determine the exergy spent on the mechanism of human thermoregulation (Dovjak et al. 2015, Prek & Butala 2017, Shukuya 2018, Deshko et al. 2019). The possibilities of adaptation of the human body to environmental conditions is generalized by adaptive models and relevant studies that also reflect the importance of environmental conditions (Dinesh et al. 2021, de Dear et al. 2020, Vellei et al. 2017, Rijal et al. 2020, Hellwig et al. 2019). The most recent studies (Sayadi 2020) that evaluated the thermal modernization of buildings show that it is necessary to take a comprehensive approach to the system as a whole to improve the energy efficiency of the building. Given the growing demands for thermal comfort, it is necessary to take into account both the social aspects (PMV and exergy consumption of human body) and the application of life cycle analysis of the building. The purpose of the study is to analyze the impact of thermal modernization on the level of human energy and exergy thermal comfort and economic assessment of changes in the heat source in combination with fences.

2. Materials and methods

The choice of heat source in combination with fences is carried out using the method of cash flow, which allows to take into account the change in the cost of energy and money over time:

$$B = \sum_{\tau=0}^{n} \frac{B_\tau^{\mathrm{ot}}}{(1+E)^\tau} + \sum_{\tau=0}^{n} \frac{B_\tau^{en}(1+l\cdot\tau)}{(1+E)^\tau}) + I_0 + I_{\mathrm{iz}} + I_{\mathrm{ha}} \quad (1)$$

where:
B_τ^{en} – annual energy costs, UAH,
B_τ^{ot} – other costs, UAH,
I_0 – capital costs for the purchase of heat generating equipment, UAH,
I_{iz} – costs aimed at improving the thermal protection of the building, UAH,
I_{ha} – the cost of purchasing heating appliances, UAH,
l – coefficient that takes into account the increase in energy prices,
n – time for which the integrated discounted costs are determined, years,
E – discount rate, selected according to the level of inflation, type of financing,
B – net present value of costs.

Function B is also called the integral value function of the system – it is the net present value of costs. This function allows you to take into account the change in the cost over time of energy l, take into account the discounting with E and take into account the efficiency of the heating system ε. The discount rate is chosen according to the interest rate on bank deposits.

The level of thermal comfort is based on the Fanger method, which is presented in the ISO 7730 standard and which is based on the equations of human heat balance:

$$PMV = (0.303 \cdot e^{-2.1 \cdot M} + 0.028) \times [(M - W) - H - E_c - C_{res} - E_{res}] \quad (2)$$

where:
M – metabolism level, W/m^2,
W – effective mechanical work, W/m^2,
H – sensitive heat losses, W/m^2,
E_c – heat transfer by evaporation from the skin, W/m^2,
C_{res} – heat transfer by convection, during respiration, W/m^2,
E_{res} – heat exchange by evaporation during respiration, W/m^2.

The Fanger model, namely the PMV index, is based on a large number of experiments, but it does not take into account the mechanism of thermoregulation, which has a rather large influence in the calculations of human heat transfer. It also helps to assess the acceptability of environmental conditions to ensure the thermal comfort for a human. The exergy approach to creating comfortable conditions is to determine the value of human body exergy consumption (HBExC). HBExC is calculated according to the approach proposed by M. Shukuya (Shukuya 2018). Finding the minimum consumption of exergy and the corresponding value of indoor air temperature will ensure that the indoor air temperature at which the thermoregulatory mechanisms will be activated the least, and therefore the body will work in the best conditions. Therefore, this algorithm is presented in the paper.

3. Description of the research model

The object of this study is a specialized school №64, Kyiv, built in 1973. The average heat transfer coefficient of the walls significantly exceeds the normative heat transfer coefficient U = 0.3 W/m^2·K and equals U = 1.3 W/m^2·K. The total wall area is 2814 m^2. We suggest to insulate the external walls. Additional thermal insulation will reduce excessive heat loss through the walls and improve the appearance of the building. For the insulation material we choose mineral wool boards, 0.2 m thick and 30 kg/m^3 thick. The average heat transfer coefficient of the windows of the building exceeds the estimated standard heat transfer coefficient U = 1.33 W/m^2·K and equals U = 2.05 W/m^2·K. The total window area is 1251.53 m^2. It is suggested to replace existing metal-plastic windows with double-glazed windows with energy-efficient spraying. The average heat transfer coefficient of the roof significantly exceeds the standard heat transfer coefficient U = 0.2 W/m^2·K and equals U = 0.58 W/m^2·K. The total roof area is 2251 m^2. Modeling of changes in the level of thermal comfort before and after thermal modernization is possible under the room model and due to the determination of the average radiation temperature. The object of the study was a typical study room located on the second floor of the building in block B, size 10×10 m with three window openings, size 2.05×2.1 m. The model of the study room is shown in Fig. 1. The glazing ratio is 0.3. This model was created in the software product sketchUp and all engineering systems were added, namely, the simulation was performed by EnergyPlus software. Table 1 shows the basic characteristics of the research model and Table 2 presents the characteristics of the internal and external environment.

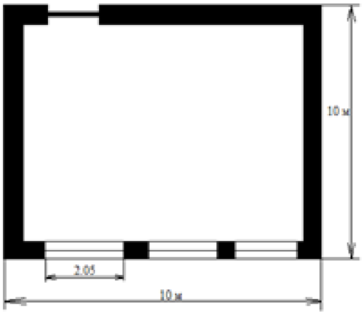

Fig. 1. Room model

Table 1. Basic Characteristics of the Research Model

External Wall Area F_z, m^2	17.4
Window Area F_v, m^2	12.6
Thermal resistance of the outer wall R_z, m$^2\cdot$°C/W	0.77
Thermal resistance of the window R_v, m$^2\cdot$°C/W	0.40
Air exchange n, hr^{-1}	1.0

Table 2. Characteristics of internal and external environment

Outside Temperature T_0, K	273
Relative Environment Humidity φ_0, %	78
Relative Room Humidity, φ_v, %	50
Air Pressure, Pa	101325
The average power of solar radiation on a vertical surface W/m^2	30

Also, the metabolic rate was 70 W/m^2, because in this room the main activity is sedentary work, which is typical for educational institutions and the thermal resistance of typical clothing combinations, respectively, is 0.155 m$^2\cdot$K/W (Zare et al. 2018).

4. Results and discussion

4.1. Cash flows for the system before and after thermal modernization

As a result of complex thermal modernization of the building, the percentage difference of the calculated value of specific energy consumption, EP, from the maximum allowable value, EPmax is 20%. The energy efficiency class after thermal modernization, established by the ratio corresponds to the class – "B" and before – class “E”. The increasing of thermal resistance of the walls will be considered in conjunction with a change in the source of heat supply. Currently, the appropriate microclimate in the room is created through the use of a centralized heating system. As an alternative, one can choose autonomous gas heating, a system with a heat pump installation. Table 3 shows the change in the cost of energy over time through the use of appropriate coefficients, considering the cash flows for the selected alternatives before and after thermal modernization. An optimistic and average statistical forecast will be considered.

Table 3. Possible scenarios of energy price changes

l, %	Gas	Electric
Optimistic	0	0
Medium	15	8

The results of cash flow calculations for the system before and after thermal modernization are presented in Fig. 2. Cash flow graphs, as integrated discounted costs, when using district heating, gas boilers and heat pump before and after complex thermal modernization (Figure 2a) will determine the complex payback period of the proposed alternatives compared to the existing option.

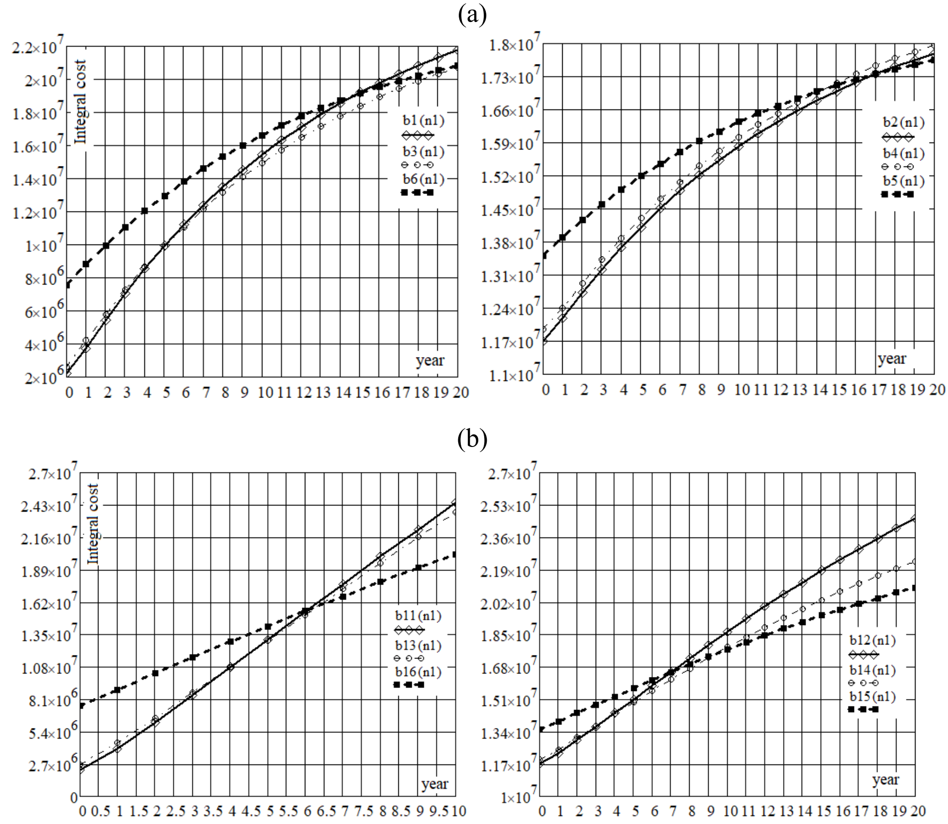

Fig. 2. Cash flows for the system before and after thermal modernization:

b1, b2, b3, b4 ,b5, b6 – integrated discounted costs with the use of central heating before and after thermal modernization, gas boiler before and after thermal modernization and heat pump after and before thermal modernization, UAH;
b11, b12, b13, b14, b15, b16 – integrated discounted costs, using district heating before and after thermal modernization, gas boiler before and after thermal modernization and heat pump after and before thermal modernization, taking into account the changes in energy costs over time, UAH.

Therefore, according to Fig. 2, the complex payback period is defined as the intersection of one heat source with another. Figure 2 presents the impact of the energy cost changes. When we do not take into account changes in the cost of energy, this leads to higher costs and longer payback periods than when we take into account this indicator. Significant changes in the discounted payback periods indicate that the change in the cost of energy over time plays a significant role and must be taken into account. In conclusion, after a comprehensive thermal modernization, it would be appropriate to change the source of the heating system, which will lead to greater savings and faster payback. Hence, comparing Figures 2a and 2b, we can conclude that the change in the cost of energy over time affects the payback period. Taking into account the growth rate of energy prices, the discounted payback period is reduced by almost 2 times.

4.2. Influence of thermal modernization on the level of thermal comfort

Currently, the world is wondering how to achieve efficient energy use and not to reduce the thermal comfort of buildings. Hence, this issue is so important and requires a comprehensive approach to its solution.

The simulation was performed for a typical room located on the south and north sides. The next step was to insulate the walls, roof and replace the old windows with new energy efficient ones. It is proposed to replace window constructions with double-glazed windows with selective coating. After that, re-simulation was performed. The calculation of thermal comfort indicators for the variable hourly average radiation temperature during the before and after thermal modernization for the North and South walls was carried out in Mathcad. The PMV values for the heating period are shown in Figure 3. PMV varies from -0.7 in the cold months to 0.2 in the off-season. Changes in the thermal resistance of the barriers can increase the PMV, and, therefore, improve human heat by about 0.1. The S orientation wall is characterized by larger fluctuations of PMV, which is due to the inflow of solar radiation and as a consequence of the increase in the variation of the room radiant temperature.

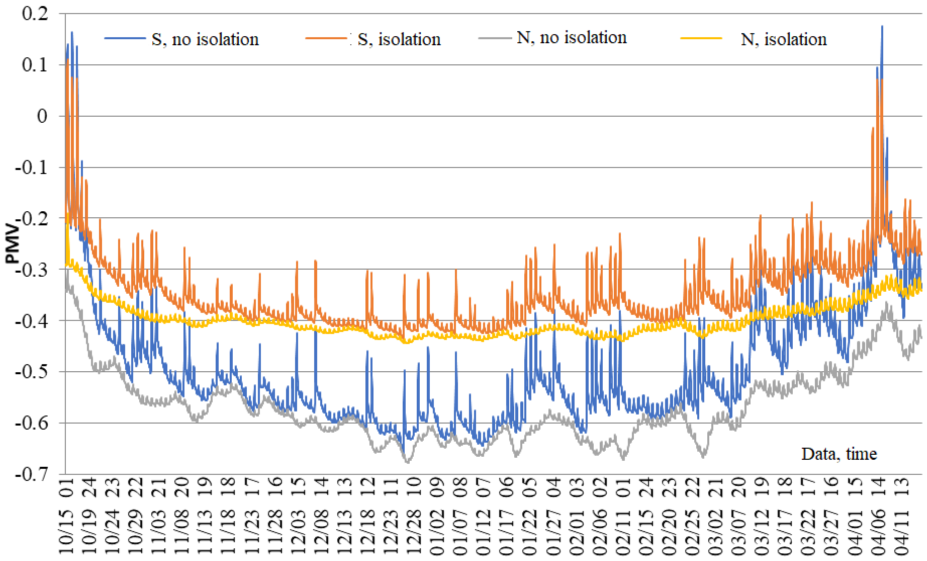

Fig. 3. PMV value for the heating period

Figure 4 shows the change in the average radiation temperature for January (a) and March (b), before and after thermal modernization for the wall of North and South orientation. It is established that the increase of the thermal resistance of enclosing structures allows to increase the average radiation temperature of the room by an average of 2°C. The southern orientation of the wall provides an increase in the average radiation temperature to 1.4°C compared to the Northern. This increase in the average radiation temperature will reduce the temperature in the room without reducing the level of thermal comfort.

Also, the EnergyPlus software calculated energy consumption of this room on the south and north orientation before and after insulation. Energy consumption for Southern orientation after insulation decreased by 32%, and for Northern – by 30%, which indicates the appropriateness of insulation of the building. According to DSTU B EN 15251:2011, different categories of the internal environment are established based on different criteria for PMV and PPD, which are defined respectively (Zare et al. 2018). This research concludes that this building has a third category of comfort, i.e., an acceptable average level of expectations can be used for existing buildings, but for a comfortable living, and, especially, for teaching children, this is not enough. Therefore, this work suggests to conduct a comprehensive thermal modernization of the building, and our research also shows how it was possible to bring this building to the II category of comfort – this is a normal level of expectations to be met for new buildings and renovations.

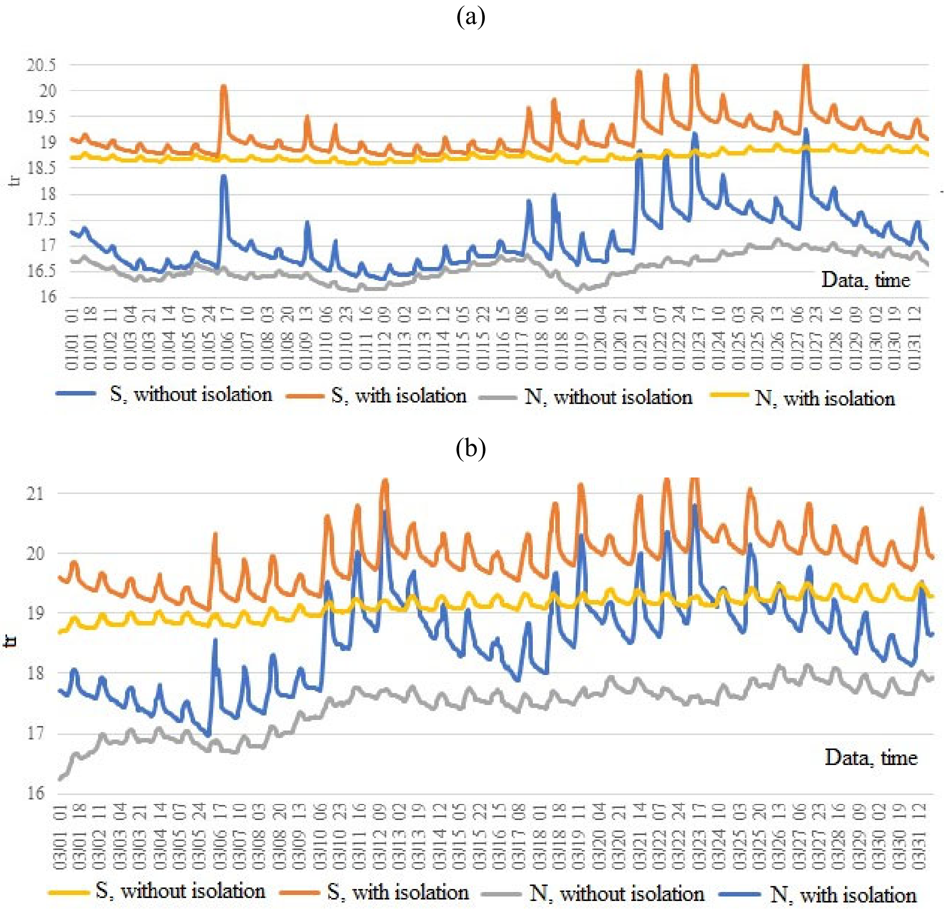

Fig. 4. Changes in the mean radiant temperature in january (a) and march (b)

4.3. Human body exergy consumption

The human body exergy consumption (HBExC) was determined for the average, maximum and ambient temperature. In Fig. 5 the value of exergy consumption by the human body for a room with an external wall of N and S of orientation before and after thermal modernization is presented. The corresponding PMV and HBExC values are also plotted. The trends in PMV change are the same as for HBExC. For the selected model HBExC varies from 3.43 to 3.97 W/m^2. Finding the minimum of this function indicates the conditions when the consumption of exergy on the thermoregulatory mechanism is minimal. However, the lowest HBExC values do not correspond to the PMV values which are the closest to 0.

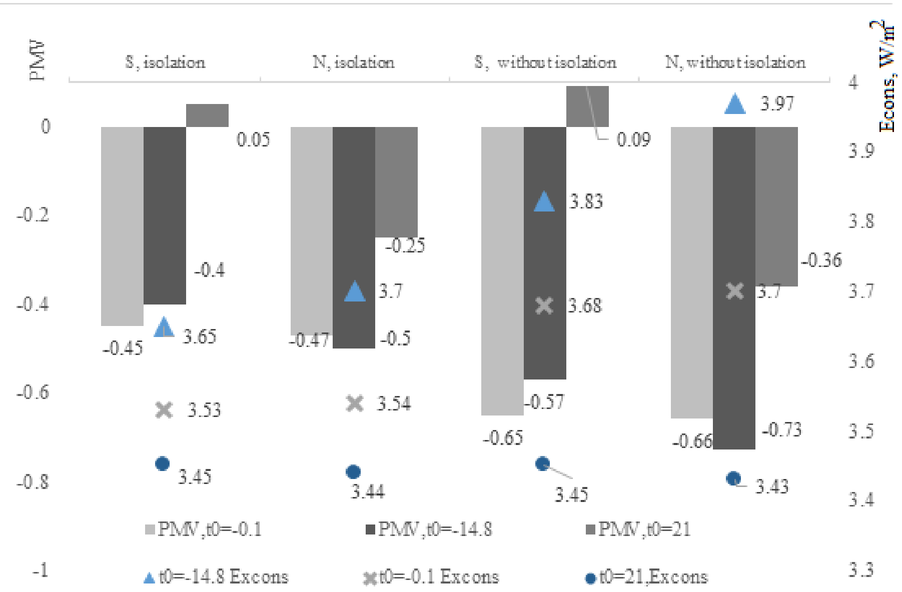

Fig. 5. Change of HBExC, PMV in winter for southern (a) and northern orientation (b) for main temperature point

5. Conclusions and further study

The paper presents a method of choosing a heat source on the example of the school, under different scenarios of changes in energy costs over time. In addition, the dynamic aspect of comfort conditions indicates a change in building category and the possibility of using energy-saving modes. PMV has been found to vary from -0.7 in the cold months to 0.2 in the off-season. Changing the thermal resistance of the barriers can increase the PMV, and, therefore, improve human heat by about 0.1. The wall of the S orientation is characterized by larger fluctuations of PMV, which is due to the inflow of solar radiation and as a consequence of the increase in variation of the room radiant temperature. Based on the calculation of PMV, it is established that this building has a category of comfort III – this is an acceptable average level of expectations to be used for existing buildings, but for a comfortable stay, and, especially for teaching children, this is not enough. Therefore, this paper proposes to carry out a comprehensive thermal modernization of the building, to achieve the second category of comfort-a normal level of expectations to be met for new buildings and renovations. Therefore, in this paper it was proposed to conduct a comprehensive thermal modernization of the building, due to which the category of the building changed to the second category of comfort – this is a normal level of expectations to be met for new buildings and renovations.

References

Choi, Wonjun, Ryozo, Ooka & Masanori Shukuya. (2020). Unsteady-state exergetic performance comparison of externally and internally insulated building envelopes. *International Journal of Heat and Mass Transfer, 163*: 120414.

de Dear, R., et al. (2020). A review of adaptive thermal comfort research since 1998. *Energy and Buildings, 214,* 109893. DOI: 10.1016/j.en-build.2020.109893

Deshko, V., & Buyak, N. (2016). A model of human thermal comfort for analysing the energy performance of buildings. *Eastern European Journal of Advanced Technology, 4*(8), 42-48.

Deshko, V., Buyak, N. &Voloshchuk, V. (2019). *Reference state for the evaluation of energy efficiency of the system "heat source-human-building envelope"*. ECOS 2019-Proceedings of the 32nd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems. 2287-2300.

Deshko, Valerii, Bilous, Inna, Buyak, Nadia & Shevchenko, Olena (2020). *The Impact of Energy-Efficient Heating Modes on Human Body Exergy Consumption in Public Buildings*. IEEE 7th International Conference on Energy Smart Systems (ESS), 201-205. DOI: 10.1109/ess50319.2020.9160270

Dinesh, Kumar Shahi, Hom Bahadur, Rijal, Genku, Kayo & Masanori, Shukuya. (2021) Study on wintry comfort temperature and thermal improvement of houses in cold, temperate, and subtropical regions of Nepal. *Building and Environment, 191*(3). 107569.

Dovjak, M., Shukuya, M. & Krainer, A. (2015). Connective thinking of building envelope – Human body exergy analysis. *International Journal of Heat and Mass transfer, 90*, 1015-1025. DOI: 10.1016/j.ijheat-masstransfer.2015.07.021.

Dylewski, R. Adamczyk, J. (2012). Economic and ecological indicators for thermal insulating building investments. *Energy and Buildings, 54*, 88-95. DOI: 10. 1016/j.enbuild.2012.07.021.

Fanger, P. (1973). Assessment of man's thermal comfort in practice. *British Journal of Industrial Medicine, 30*, 313-324.

Hellwig, Runa T., et al. (2019). A framework for adopting adaptive thermal comfort principles in design and operation of buildings. *Energy and Buildings, 205,* 109476. DOI: 10.1016/j.enbuild.2019.109476

Hurnik, M., Specjal, A., Popiolek, Z. & Kierat, W. (2017). Assessment of single-family house thermal renovation based on comprehensive on-site diagnostics. *Energy and Buildings, 8*, 378-400. DOI:10.1016/j.enbuild.2017.09.069

Javid, Atiye Soleimani, Aramoun, Fereshteh, Bararzadeh, Masoomeh & Avami, Akram (2019). Multi objective planning for sustainable retrofit of educational buildings. *Journal of Building Engineering*. DOI: 10.1016/j.jo-be.2019.100759.

Moran, Paul, O'Connell, John & Goggins, Jamie. (2020), Sustainable energy efficiency retrofits as residenial buildings move towards nearly zero energy building (NZEB) standards. *Energy and Buildings*. DOI: 10.1016/j.en-build.2020.109816 .

Park, Ji Hun, Yun, Beom Yeol, Chang, Seong Jin, Wi, Seunghwan, Jeon, Jisoo & Kim, Sumin. (2020). Impact of a passive retrofit shading system on educational building to improve thermal comfort and energy consumption. *Energy and Buildings*. DOI: 10.1016/j.enbuild.2020.109930.

Prek, Matjaž, Butala, Vincenc. (2017). Comparison between Fanger's thermal comfort model and human exergy loss. *Energy, 138*, 228-237. DOI: 10.1016/j.energy.2017.07.045

Rijal, Hom B., Yoshida, K., Humphreys, M.A. & Nicol, J.F. (2020). Development of an adaptive thermal comfort model for energy-saving building design in Japan. *Architectural Science Review*, 1-14. DOI: 10.1080/00038628.2020.1747045.

Rodrigues, Carla, Freire, Fausto. (2017). Building retrofit addressing occupancy: An integrated cost and environmental life-cycle analysis. *Energy and Buildings, 140*, 388-398. DOI: 10.1016/j.en-build.2017.01.084.

Sayadi, S. (2020). Dynamic Exergy-Based Methods for Improving the Operation of Building Energy Systems.

Shukuya, M. (2018). *Exergetic aspect of human thermal comfort and adaptation*. Sustainable Houses and Living in the Hot-Humid Climates of Asia. Springer, Singapore, 123-129.

Streicher, Kai Nino, Mennel, Stefan, Chambers, Jonathan, Parra, David, Patel & Martin K. (2020). Cost-effectiveness of large-scale deep energy retrofit packages for residential buildings under different economic assessment approaches. *Energy and Buildings*, 109870. DOI: 10.1016/j.en-build.2020.109870.

Vellei, M., Herrera, M., Fosas, D., Natarajan, S. (2017). The influence of relative humidity on adaptive thermal comfort. *Building and Environment, 124*. 171-185. DOI: 10.1016/j.buildenv.2017.08.005

Zare, S., Hasheminezhad, N., Sarebanzadeh, K., Zolala, F., Hemmatjo, R., & Hassanvand, D. (2018). Assessing thermal comfort in tourist attractions through objective and subjective procedures based on ISO 7730 standard: A field study. *Urban climate, 26*, 1-9.