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Запропоновано методику удосконалення системи енергозбереження у вищих навчальних закладах України як складової підвищення результативності діяльності. Запропонована методика базується на розробленій моделі оптимального управління тепловим режимом приміщень з мінімізацією витрат енергії на опалення та енергетичних втрат при підтримці заданого рівня теплового комфорту на прикладі Київського національного університету технологій та дизайну (Україна)

Ключовіслова:теплонадходження,тепловтрати, ABC-XYZ-аналіз, теорія ігор, оптимальний режим теплоспоживання, вищі навчальні заклади

Предложена методика усовершенствования системы энергосбережения в высших учебных заведениях Украины как составляющей повышения результативности деятельности. Предложенная методика базируется на разработанной модели оптимального управления тепловым режимом помещений с минимизацией затрат энергии на отопление и энергетических потерь при поддержке заданного уровня теплового комфорта на примере Киевского национального университета технологий и дизайна (Украина)

Ключевые слова: теплопоступления, теплопотери, ABC-XYZ-анализ, теория игр, оптимальный режим теплопотребления, высшие учебные заведения

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A PROCEDURE FOR OPTIMIZATION OF ENERGY SAVING AT HIGHER EDUCATIONAL INSTITUTIONS

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1. Introduction

At present, energy saving is one of the priority tasks due to the deficit of basic energy resources and the increase in the cost of extraction, as well as global environmental problems. Large consumers of energy resources are educational institutions of various levels, which include higher educational institutions (HEI). According to the National Report on the Status and Prospects of Implementation of the State Energy Efficiency Policy in 2015, the specific energy con-

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sumption (per 1 m²) in Ukraine is almost 3 times higher than in Western Europe, the USA and Canada. Moreover, the specific expenses for utilities (per 1 m²) increase by 25–30 % annually and increased by 3.5 times in recent years. In this case, the cost of heat energy – up to 70 %, electricity – up to 30 % [1]. Inefficient use of energy resources, actual losses of thermal and electric energy leads to the fact that about 25 % of the cost of utilities is a consequence of inefficient use of energy resources and inefficient management of them. The mentioned negative consequences determine the objective need for energy saving, the creation of a system for effective energy saving and rational energy use in universities, which determines the relevance of the study.

2. Literature review and problem statement

Ukraine is paying a lot of attention to energy efficiency issues. Over 1994–2015, Ukraine adopted 13 Laws, 8 Decrees of the President of Ukraine, 44 Decrees of the Cabinet of Ministers of Ukraine. All the mentioned documents relate to various aspects of energy efficiency and energy saving in the economy [2].

The problem of improvement of energy efficiency in Ukrainian universities remains one of the priorities of Ukraine's educational policy. Various international institutions confirm this by their support. Thus, on December 19, 2011, Ukraine and the European Investment Bank (EIB) signed the agreement. The agreement relates to the attraction of a loan for the implementation of the project "Higher Education: Energy Efficiency and Sustainable Development". The loan amount is Euro 160 million. The purpose of the funds is to implement energy efficiency measures in 147 buildings. 7 universities selected in accordance with the criteria of the EIB participate in the project [3].

Experience of HEI in implementation of energy efficiency projects is diverse. There are large-scale events and projects. Here are some of them. The Kyiv National University of Technology and Design implemented a comprehensive scientific and technical program "Energy Efficiency and Energy Saving" [4, 5]. The National Technical University of Ukraine "Kyiv Polytechnic Institute" established a service for energy management and power supply systems based on a virtual station using solar, wind and biomass energy [6]. An educational demonstration center of alternative energy with an active wind turbine installed on the roof, two solar panels on the front of the main building functions in Kharkiv National University named after V. N. Karazin [7]. Some universities (Kherson National Technical University, Lutsk National Technical University, Odessa National Academy of Food Technologies, National University of Water Management and Natural Resources, Zaporizhzhya National University) implemented partial energy saving measures. Among them are: replacement of windows with metal-plastic windows, introduction of autonomous heating system of some buildings, washing of heating systems, optimization of mentioned systems [8–10].

The scientific community also pays great attention to the issues of energy saving and energy efficiency of HEI. This, research [9] presents a structural analysis of energy consumption and energy conservation in the field of education. A base of the modern energy efficiency policy is the integrated energy management system proposed in [10]. Works [11 13] study various technical aspects of energy efficiency improvement and its transition to a new innovative level. Some researchers believe that monitoring energy consumption and energy certification of buildings of higher education institutions should be a base of implementation of an effective energy management system [14]. In some studies, we can see a resource-saving approach by increase in the degree of university autonomy [15] or the use of benchmarking tools in raising a level of energy and resource efficiency of HEI [16].

Paper [17] presents the results of research on energy efficiency and sustainable development in public buildings by leading research institutes in the USA, UK, China, Australia, Italy, Hong Kong Polytechnic University, Delft Technological University, and Tsinghua University. The results of this comprehensive analysis proved that the global environmental problem forced many countries to include a wide range of energy efficiency (EE) strategies to reduce energy consumption in public buildings. Experience of HEI in implementation of energy efficiency projects is diverse. But the most significant and expedient is the use of possibilities of energy marking of buildings and premises of HEI according to the standards of the European Union.

An analysis of three technical reports from leading research institutes in the world [5–7] prove that existing standards (for example, ANSI/ASHRAE/IES 90.1-2013) are typical energy standards for commercial and multi-apartment buildings. But the use of the International Energy Efficiency Code 2015 for both residential and commercial buildings will save energy and energy costs significantly compared to the 2012 version. Thus, a paper [6] evaluates an impact at national and state levels related to energy codes in residential and commercial buildings, describes the methodology used for evaluation, presents impacts from the point of view of energy savings, cost savings for consumers and reductions in CO^2 emissions. Paper [7] proposes to use a new version of the ANSRAE 90.1 standard for the development of commercial energy efficiency standards for commercial buildings. Work [8] shows that to solve the problems of energy efficient construction at mesonic level, it is necessary to introduce principles of bioclimatic design for sustainable architecture and energy efficiency, represent a comprehensive strategy for achievement of efficiency and healthier conditions for urban communities. Works [9–11] propose another approach to solution of problems of energy efficient construction. They invite to solve these issues not by technical procedures, but in general – to build so-called "green buildings". Thus, work [9] proposes an innovative approach to the quality of construction with environmentally friendly technologies, natural building materials, integrated photovoltaic modules, solar collectors, and geothermal heat pumps. As a continuation of this approach, work [10] proposes a use of appropriate green building technologies according to local conditions in Turkey – a heat exchanger of a geothermal centralized heat supply system. As a summary of the most appropriate options for green building, we can point to work [11]. It presents a round table discussion as a result of an investigation on expedience of zero-energy buildings (ZNEs) and their expansion into the market as a more widely used approach for different types and sizes of buildings.

Most scientific studies on energy efficiency of premises offer either certain programs [12–18] or implementation of certain organizational and technological energy saving measures [19–23]. Thus, paper [12] proposes a comprehensive program for saving retro-commissioning of large office buildings built before 1980 and modernization of

29 measures for their upgrading. The most effective, from the point of view of some researchers, is a use of alternative energy sources. Thus, in paper [13], there is an estimation of potential energy saving and economic efficiency of solar energy and daylight illumination options for the project of the reconstruction of the Richland School of the United States. In practice, Ukrainian HEI also have similar experience in creation of energy management services and energy supply systems based on the use of solar, wind and biomass energy from the virtual station [14], a training and demonstration center for alternative energy with an active wind turbine installed on the roof, two solar panels on the facade of the main building [15].

The Pacific Northwest National Laboratory (USA) developed a benchmark for a use of energy from various banking institutions [16], which can be considered as a prototype for similar buildings, as a result of the analysis of daily energy usage profiles in bank buildings. A paper [17] proposed efficient electrical equipment with more efficient, lower power consumption and lower costs than existing electrical equipment for University Technology Malaysia. Paper [18] proved that it is necessary to create a scientific schedule for dispatching of energy supply and use on the basis of implementation of the multiple optimization model AGC and Energy to ensure safe and reliable operation of the University's energy system. A work [19] proposed a comprehensive scientific and technical program "Energy Efficiency and Energy Conservation" based on a resource-saving approach and an increase in the degree of autonomy of HEI or a use of benchmarking tools [20] for increase in the level of energy and resource efficiency of HEI. Some works propose specific organizational and technological measures: increasing a use of solar photovoltaic systems for alternative power supply [21], a use of energy-saving lighting [22]; creation of automation products and services to reduce cost of electricity in colleges and universities [23].

But the issues about possibility of optimization of energy saving and energy use in Ukrainian university buildings remained uncertain. The reason for this may be, firstly, in most cases, technical obsolescence of buildings, due to the fundamental impossibility of their energy reorganization. Secondly, objective difficulties of a use of advanced energy saving technologies and equipment due to high costs involved, which makes relevant studies inappropriate. An opportunity to overcome mentioned difficulties can be an innovative approach to the use of existing premises. For example, using multicriteria factor analysis of energy efficiency of buildings of HEI [24] or multi-purpose optimization model of energy saving dispatching by coordination of energy consumption during peak load [25].

Thus, there is a lack of consistency between existing theoretical and practical approaches for determination of the most appropriate energy management and energy saving systems for buildings of the domestic HEI. Difficulties arise in ranking of factors that have the greatest impact on the level of energy efficiency of HEI. That is, many problems remain unsolved, debatable and require additional study. All this suggests that it is expedient to develop a methodology for optimization of the energy saving of Ukrainian HEI.

3. The aim and objectives of the study

The aim of present study is to develop a methodology for optimization of energy consumption and improvement of energy efficiency in HEI. The mentioned methodology is a set of methods, which give possibility to choose an optimal mode of heat consumption and load of auditorium during a heating period.

We solved the following tasks to achieve the objective:

– development of a comprehensive methodology for diagnostics and substantiation of an optimal energy consumption regime in HEI during a heating period;

– selection of a set of diagnostic methods for evaluation of the actual state of a balance of heat loss and heat supply for each HEI premise;

– substantiation of the expediency of a use of the modified ABC/XYZ matrix analysis for making a managerial decision on optimal use of HEI premises in the educational process during a heating period.

4. Substantiation of the method of selection of an optimal mode of energy consumption in HEI premises

4. 1. Integrated scheme of diagnosis taking into account the index of thermal comfort

The program for reduction of energy consumption by educational institutions and educational institutions commenced with Order No. 147 of the Ministry of Education and Science of Ukraine of 26.02.2010. The aim of reforms in the field of energy consumption and energy efficiency improvement of HEI is to reduce budget expenditures for the payment of energy resources for educational institutions and educational institutions of Ukraine [26].

The main documents regulating energy consumption in HEI are: Law of Ukraine "On Energy Saving" [27]; General provisions on the procedure for the standardization of specific expenditures of fuel and energy resources; DSTU 2339-94 "Energy Saving: Key Provisions" [28]; DSTU 2155-93 "Energy Saving: Methods for Determination of Economic Efficiency of Energy Saving Measures" [29]; DSTU 2420-94 "Energy saving: terms and definitions" [30].

A base of the proposed approach is an indicator of thermal comfort criterion – PMV (Predictive Mean Vote) criterion proposed by ASHRAE, the American Society of Heating, Cooling and Air Conditioning Engineers. According to a paper [31], a forecasted average rate (PMV) is an indicator by which an average sensitivity to the temperature of a large group of people is forecasted based on a body temperature balance. We achieve the temperature balance when a heat produced by our body is equal to a loss of our body's heat into the environment. The international standard ISO7730 introduced PMV [31].

According to ISO7730, which regulates parameters of a microclimate in residential and public buildings, a complex indicator, which characterizes thermal conditions in a room, may be resulting temperature. The following dependence determines the resulting temperature:

$$T_{SU} = b_1 T_r + b_2 T_a, \quad (1)$$

where Ta is indoor temperature, °C; Tr is radiation temperature of a premise °C; $b1$, $b2$ are coefficients equal to 0.5 at the speed of air in a premise below 0.2 m/s or 0.4 and 0.6, respectively, at an air speed from 0.2 to 0.6 m/s.

We can calculate radiation premise temperature as:

$$T_r = \frac{\sum S_i T_i}{\sum S_i}, \quad (2)$$

where *Si* is an area of an internal surface of fences and an external surface of heating devices, m²; *Ti* is temperature of an internal surface of fences and an external surface of heating devices, °C.

The proposed diagnostic approach consists of a series of interconnected, sequential stages aimed at obtaining a quantitative and qualitative evaluation and substantiation of an optimal heat consumption mode (OHCM) (Fig. 1).

The objective of optimization of a thermal mode of a building with a combined heating system is to minimize total energy consumption for heating and energy losses while maintaining a given level of thermal comfort. According to this concept, we propose the following algorithm.

4. 2. Determination of criteria for estimation of a heat balance of HEI premises

Complex diagnostics of the existing heating mode begins with determination of static and dynamic states of research objects by calculation of two components of heat balance of all premises of HEI (auditorium, offices, laboratories, etc.):

$$Q_{suppl}=Q_{loss} \quad (3)$$

where

$$Q_{suppl}=Q_{dev}+Q_{dom}+Q_{peop}+Q_{sun}. \quad (4)$$

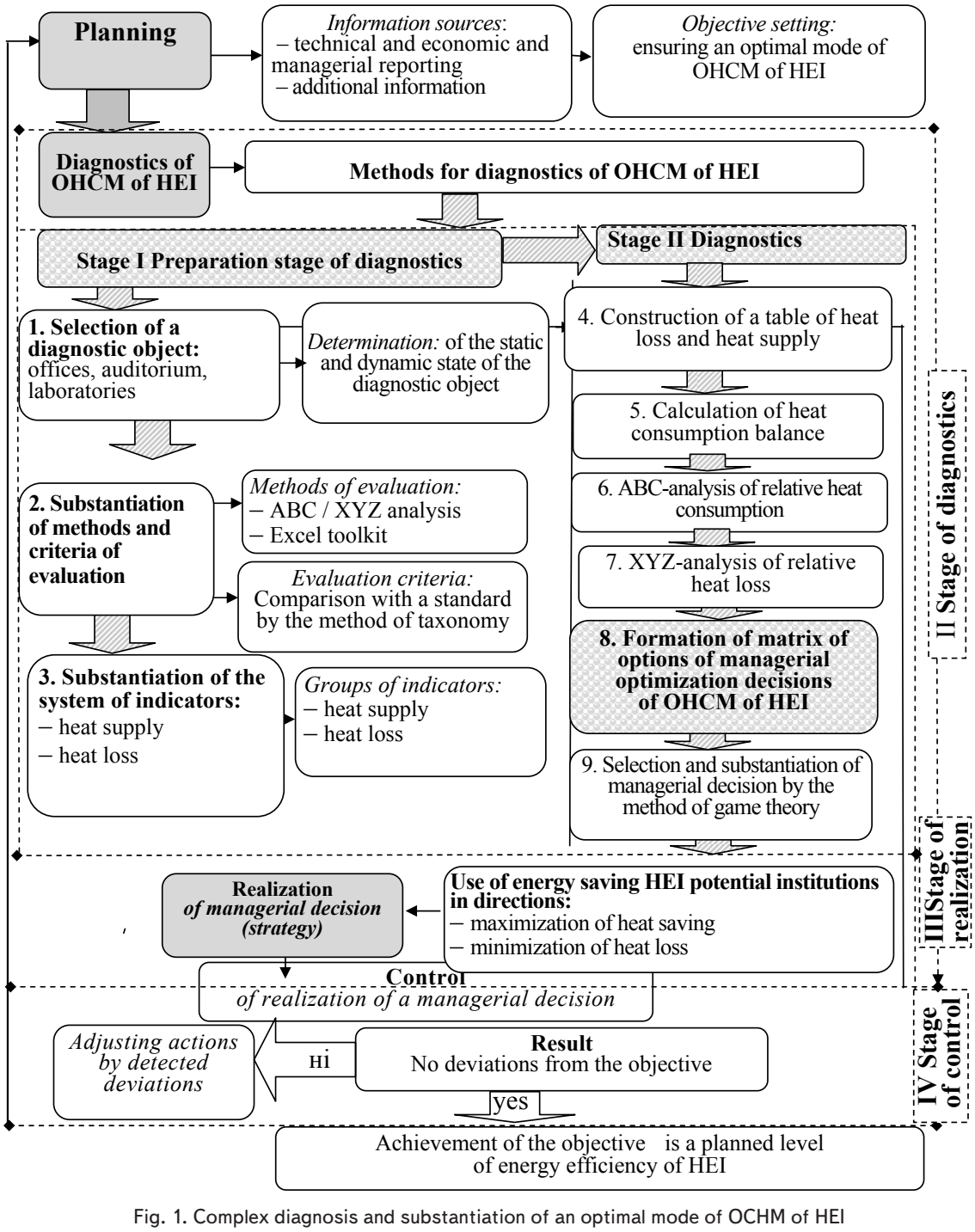

Fig. 1. Complex diagnosis and substantiation of an optimal mode of OCHM of HEI

Q_{suppl} is total heat supply; Q_{dev} is heat supply from heating devices; Q_{dom} is heat supply from domestic sources; Q_{peop} is heat supply from people; Q_{sun} is heat from solar energy through light gaps.

$$Q_{loss}=Q_{ext.enc}+Q_{vent}, \quad (5)$$

where $Q_{ext.enc.}$ is heat loss of a building through external enclosing structures.

We can determine the required total heat supply basing on existing building codes and rules (BCaR) and the indicator of thermal comfort PMV:

$$Q_{suppl}=q_i\times V\left(T_r-T_{ext}\right)\times\vartheta\times10^{-3}, \quad (6)$$

where V is a volume of a premise, m^3; q_i are regulatory expenses of heat energy for heating; ϑ is duration of a heating period, h; t_{in} is estimated temperature inside a premise °C; t_{out} is average temperature of outside air during a heating period, °C.

Accordingly, we can define heat supply from heating devices (for additional heating) as a difference between the required total heat supply and heat supply from other sources:

$$Q_{dev}=Q_{suppl}-Q_{dom}-Q_{peop}-Q_{sun}. \quad (7)$$

We can define heat supply from domestic sources (lighting devices, computers, refrigerators, copying machines, etc.) by formula:

$$Q_{dom}=\Sigma N\times\tau_a\times Z_a, \quad (8)$$

where ΣN is total installed capacity, respectively, lighting, computers, refrigerators, copying machines, kW; τ_a is actual operating time of the equipment during working days of a heating period, h; Z_a is actual duration of a heating period, day.

We determine heat supply from laboratory equipment (thermostats, ovens, driers, heat exchangers) for each type separately by the formula:

$$Q_{le}=10^{-3}\alpha\cdot F\times\left(t_{ext}-t_{surf}\right)\times\tau_a\times Z_a, \quad (9)$$

where F is heat loss surface of a corresponding equipment, m^2; α is coefficient of heat loss from a surface to the environment 14÷18 W/m^2·°C; t_{surf}, t_{ext} is actual temperature on a surface of equipment and indoor temperature at premise, respectively, °C.

We determine the volume of heat supply from people for each category separately (employees, students) depending on a professional orientation of an institution and a type of work (light, moderate, hard) according to formula:

$$Q_{peop}=\left(q_{emp}\times n_{emp}\times t_{emp}\times z_o+q_{st}\times n_{st}\times t_{st}\times z_o\right), \quad (10)$$

where q_{emp} is heat supply from the first employee of HEI; in connection with the absence of norms we accept: q_{emp} heat release from the 1st employee, 125 W per hour (light work); q_{st} heat release from students, 90 W per hour; t_{emp}, t_{st} are times of stay of employees and students in an institution, hours per day.

We determine heat supply through transparent enclosing structures of solar radiation taking into account the orientation of facades by eight rumbs by the formula:

$$Q_{sun}=q_{wind}\times k_F\times\sum A_{Fk}\times J_k, \quad (11)$$

where τ_F is a specific heat power from solar radiation in dependence on the orientation of a window, W/m² (Table 1); k_F is a coefficient, which takes into account a presence of sunscreen elements on a window; ΣA_{Fk} is a total area of glassed windows, m^2; J_K is average intensity of total (direct and dispersed) solar radiation on horizontal and vertical surfaces under conditions of cloudiness in Kyiv for a heating period, kW·h/m^2 (accepted in accordance with Table 1).

Table 1

Intensity of total solar radiation on horizontal and vertical surfaces under conditions of cloudiness in Kyiv, kW·h/m^2

Window orientation	North-East	East	South-East	South	South-West	West	North-West	North
q_{wind}	190	250	240	240	350	470	370	0

Source: DSTU B V.2.2-21: 2008. Method for determination of specific heat loss for heating of buildings

We determine heat losses of a building under actual conditions through external enclosing structures by the formula:

$$Q_{ext.enc.}=0{,}024\times D_d\times\sum 1/R_i\times A_i\times n, \quad (12)$$

where D_d is a degree-day of a heating period

$$D_d=\left(t_b-t_{heats}^{av}\right)\times Z, \quad (13)$$

where t_b is indoor air temperature in a premise, °C, it corresponds T_{SU} – an indicator of thermal comfort in public spaces. When actual temperature differs from the calculated one we take actual temperature; t_{heats}^{av} is actual average temperature of outside air during a heating period, °C; Z_a is duration of a heating period (actual), days; A_i are areas of elements: walls, windows, coverings, overlays, doors, etc.; n is a correction coefficient, which takes into account the dependence of a position of an external surface of a building. For external walls, windows, coverings, combined with overlays n=1. For other cases, we should accept a value of n in correspondence with building and architectural standards; R_i is heat transfer resistance m^2·C/W of walls, windows, stained-glass windows, coatings, overlays, etc., it should correspond to project data or calculation in accordance with building and architectural standards for the actual construction (wall thickness, building material, insulation, etc.) and taking into account a coefficient of heat technical homogeneity.

We determine heat losses of a building due to ventilation air exchange taking into account infiltration by formula:

$$Q_{vent}=6{,}7\cdot10^{-3}\times L_b\times c_s\times p^{av}\times d_d, \quad (14)$$

where c_s is specific heat of air, 1 kJ/kg·°C; L_b is air exchange in premises of concrete purpose buildings, m^3/person; ρ^{av} is average density of infiltrated air during a heating period, which we determine by formula:

$$p^{av}=353/\left[273+0{,}5\times\left(t_b-t_{heats}^{av}\right)\right]. \quad (15)$$

The exchange of air in educational institutions should be at least 5 m^3/person per 1 m^2 of a calculated area (F_p). The

estimated F_p area is equal to the sum of areas of all premises located in a building except for corridors, tambours, transitions, ladder cells, elevator mines, as well as premises intended for a placement of engineering equipment and engineering networks.

4. 3. Substantiation of the methodology of evaluation and diagnostics of the actual state – a balance of heat losses and heat supply

4. 3. 1. Stage 1 "Preparation stage of diagnosis"

We offer the combined approach to simultaneous use of 2 diagnostic methods:

1) ABC/ XYZ analysis – to diagnose the actual state – a balance of heat loss and heat supply for each room;

2) a theory of games – to choose an optimal mode of use of premises during a heating period.

Substantiation of the methodology of evaluation. We will base obtaining conclusions about the expediency of making a managerial decision regarding an option of a use of a room under study during a heating period on the analysis of modified ABC/XYZ matrix (Fig. 2).

Heat saving				
	A	AX	AУ	AZ
	B	BX	BУ	BZ
	C	CX	CУ	CZ
		X У Z		
		Heat loss		

Fig. 2. Matrix of diagnostics of use of premises of HEI during a heating period

We can divide ABC and XYZ methods between groups by the so-called Pareto (20/80, "thumb") method, according to which a fifth (20 %) of a total number of objects usually gives approximately 80 % of results. Accordingly, contribution of the remaining 80 % is only 20 %. The essence of Pareto's principle is to divide objects by degree of return. Then to pay attention to those only that have little impact. ABC analysis is one of the methods of rationalization. We can use it for all functional areas of activity. To optimize energy consumption, we can use it to detect heat supply and heat loss of premises. Those premises where heat supply is the lowest, and heat loss is the highest, belong to the group C. Those premises where heat supply is the highest, and the heat loss is the lowest – to the group A.

4. 3. 2. Stage 2 "Diagnostics"

The proposed methodology for the formation of OHCM of HEI involves implementation of calculations using Excel toolkit.

Algorithm of calculations: we choose a group of analyzed premises of HEI (auditorium, offices, laboratories, etc.). We determine a period for which we will make an analysis (for example, a heating period from November to March). We calculate a value of heat saving as a difference between heat supply and heat loss in each of premises. We put the data into the calculation table. We sort the table from larger to smaller based on the specific heat savings value. We calculate a share of each of ABC groups as a cumulative result. We determine groups: 0...80 %="A", 80...95 %="B", 95...100 %="C". As a result, we get the data: "A" group – premises, which give 80 % of a total amount of heat saving; "B" group – premises, which give 15% of a total amount of heat saving; "C" group – premises, which give 5 % of a total amount of heat saving.

Similarly, we carry out XYZ analysis. Its purpose is to find out those premises where heat loss is the greatest. The result of this analysis is obtaining the coefficient of variation (deviation). The coefficient of variation, expressed in %, shows how large were the deviations in heat loss by type (enclosing structures, ventilation) for the analyzed period. The quotas for XYZ analysis groups are as follows: "X" group – 0...10 %; "Y" group – 10...15 %; "Z" group – 15...100 %.

The algorithm of calculations is as follows: the comparison of indicators of matrix-vectors of heat loss with a conditional vector model determined by the method of multidimensional spaces (taxonomy).

1. We construct the matrix of heat loss:

estimation of the level of heat loss by types:

$$Q_{\text{loss}} = \left[Q_{\text{ext.enc}\,j}; Q_{vent\,j}\right]. \quad (16)$$

2. We give the matrix a dimensionless standardized form:

estimation of the level of heat loss by types:

$$q_{loss} = \left[q_{\text{ext.enc.}\,j}; q_{vent\,j}\right], \quad (17)$$

where

$$q_{loss\,j} = \frac{Q_{loss_j}}{\overline{Q}_{loss}}. \quad (18)$$

3. We compose a vector-standard, where "0" index is the best value in columns:

estimation of the level of heat loss by types:

$$q_{loss0} = \left[q_{\text{ext.enc.0}}; q_{vent0}\right]. \quad (19)$$

We select the best value in columns on the basis of the principle of "stimulator – destimulator". That is, stimulators – are those indicators, best values of which is chosen as the maximum, and those, best values of which by the minimum – destimulators.

4. We determine the multidimensional Euclidean distance from the standard vectors to each object under study:

$$L_{loss\,j} = [(q_{\text{ext.enc}_j} - q_{\text{ext.enc0}})^2 + (q_{ventj} - q_{vent0})^2]^{1/2}. \quad (20)$$

5. We determine an average arithmetic multidimensional Euclidean distance

$$\overline{L}_{\text{loss}} = \frac{1}{n} \cdot \sum_{j=1}^{N} L_{\text{loss}\,j}, \quad (21)$$

where N is quantity of the premises.

We carried out further processing of statistical information by calculation of average square deviations of multidimensional distances of heat loss for each premise by the formula:

$$\sigma_{\text{loss}} = \frac{1}{n} \cdot \left[\sum_{j=1}^{n} \left(L_{\text{loss}\,j} - \overline{L}_{\text{loss}}\right)^2\right]^{1/2}. \quad (22)$$

This indicator serves as the basis for ranking by XYZ-analysis.

6. The method of game theory determines the maximum possible volume of heat saving/minimum heat loss. To apply it, there must be 2 conditional players. In our case, the first player (player A) – is a need to maximize heat saving while spending the least resources. The second player (player B) – is a need to minimize heat loss to the maximum. As can be seen from this statement of the problem, the strategy of players is in antagonism – the diametrically opposite direction. The solution to the pair of such dual tasks is as follows:

Player A (maximization of heat saving for a minimum of expended resources) selects a strategy in accordance with the principle of maximin by the formula:

$$\max_{pi}\left\{\min\left(\sum_{i=1}^{n}a_{i1}x_i,\sum_{i=1}^{n}a_{i2}x_i\ldots\sum_{i=1}^{n}a_{in}x_i\right)\right\}. \quad (23)$$

Player B (minimization of heat loss at maximal volume) on the principle of minimax:

$$\min_{pj}\left\{\max\left(\sum_{j=1}^{m}a_{j1}y_j,\sum_{j=1}^{m}a_{j2}y_j\ldots\sum_{j=1}^{m}a_{jn}y_j\right)\right\}, \quad (24)$$

where xi is a probability of selection of i-th strategy of heat saving, yj is a probability of selection of j-th strategy to reduce the heat loss.

5. Results of the practical application of the proposed methodology for calculation of optimal energy consumption

Table 2 shows the results of the conducted ABC/XYZ-analysis on the example of the Building 4 at the Kiev National University of Technology and Design (KNUTD).

Next, we combine both calculations and analyze the results. Now each of premises has values of groups from ABC analysis and from XYZ analysis (Fig. 3).

Fig. 4 shows the results of the taring of premises of building 4 at KNUTD.

Table 2

Generalization of the results of ABC/XYZ-analysis of rooms of building 4 at KNUTD

Group	Quantity	Total heat supply/ heat loss	Description (criterion)
ABC – analysis			
A	35	192,188	>3,800
B	50	102,456	>400; <3,800
C	89	–36,772	<400
XYZ – analysis			
X	45	85,920	<4 %
Y	102	155,788	>4 %; <7 %
Z	27	16,163	>7 %

We propose selection and substantiation of an optimal mode of heat consumption as follows. During a heating period, we load category premises maximally according to the principle of obtaining a required working area in descending order: AX, then BX, AY, then CX, BY, AZ. Since the task of finding an optimal version of a use of premises during a heating period has a multidimensional appearance, we propose to solve it using the method of game theory.

AX – high level of heat saving and low level of heat loss	AY – high level of heat saving and average level of heat loss	AZ – high level of heat saving and high level of heat loss
BX – average level of heat saving and low level of heat loss	BY – average level of heat saving and average level of heat loss	BZ – average level of heat saving and high level of heat loss
CX – low level of heat saving and low level of heat loss	CY – low level of heat saving and average level of heat loss	CZ – low level of heat saving and high level of heat loss

Fig. 3. Taring of expedience degree of a use of HEI premises in a heating period

4–0708; 4–1418; 4–0322; 4–0815; 4–1003b; 4–060; 4–0212; 4–1218; 4–0315	4–0502a; 4–1008; 4–1108; 4–0208; 4–0203; 4–0324; 4–1004a; 4–0803; 4–0508; 4–1312; 4–0406; 4–1411; 4–1101; 4–0214; 4–0206; 4–0408; 4–0403; 4–0313; 4–0412; 4–0814; 4–0314; 4–1204; 4–0312	4–0113; 4–0809; 4–0702a
4–0306; 4–1107; 4–1007a; 4–1306; 4–0205; 4–0303; 4–0710; 4–1420; 4–0703a; 4–1304; 4–0908; 4–1105; 4–0506; 4–0906; 4–1214; 4–1208; 4–0218; 4–1011; 4–1012	4–1409; 4–1005; 4–0320; 4–0805a; 4–0610a; 4–0704; 4–0706; 4–1407; 4–0612; 4–1206; 4–1209; 4–0910; 4–0606; 4–0416; 4–1402; 4–0901; 4–0914; 4–1412; 4–0802; 4–1007; 4–0507; 4–0601; 4–0210; 4–0309; 4–1010	4–0814a; 4–0410; deputy dean; 4–0603; 4–0204
4–0503; 4–1406; 4–1408; 4–0211; 4–1202a; 4–1202; 4–0404; 4–0305; 4–0316; 4–0305a; 4–1216; 4–1220; 4–0301; 4–0307; 4–0302; 4–0308; 4–0310; 4–0407; 4–0304	4–1414; 4–1003; 4–1416; 4–1102; 4–1212; 4–0401a; 4–1308; 4–0216; 4–0311; 4–1003a; 4–1403; 4–0608; 4–0805; 4–1405; 4–1103; 4–0705; 4–0804; 4–1111; 4–1210; 4–0326; 4–0810; 4–1203; 4–1401; 4–0712; 4–1201; 4–0812; 4–0504a; 4–1109; 4–0806; 4–0207; 4–1207; 4–0808; 4–0605; 4–0401; 4–1301; 4–0409; 4–1303; 4–1001; 4–0501; 4–0902; 4–1006; 4–0701; 4–1106; 4–0414; 4–1307; 4–0905; 4–1004; 4–0318; 4–0801; 4–0907; 4–0201; 4–0610; 4–0209	4–1208a; 4–1310; 4–0904; 4–0502; 4–1002; 4–1104; 4–0912; 4–0903; 4–1305; 4–1205; 4–0702; 4–0402; 4–0405; 4–0602; 4–0202; 4–0703; 4–0104

Fig. 4. Results of the taring of premises of building 4 at KNUTD

While solving a maximin/minimax problem by the theory of game at formation of the optimal program of heat saving and additional heat of premises, a university may receive guidelines for optimal loading of premises, which simultaneously makes possible obtaining a maximum of heat saving and a minimum of heat loss. We carried out the visualization of the conducted ABC/XYZ-analysis by cluster analysis (Fig. 5).

Fig. 6 shows premises that, for example, entered the first cluster (AX).

We propose to carry out identification of each room by the value of heat saving/heat loss with the help of discriminatory analysis tools (Fig. 7, Table 3).

Each received discriminant function describes a dependence of the required additional heat of a premise from inherent values of heat saving/heat loss and indicates that it belongs to one of the nine clusters of heat saving (Fig. 5). Further construction of the optimal plan for loading premises is as follows.

We determined the required volume of auditorium – offices – for a heating period. We had to compare the

volume step-by-step: first, with the area of AX premises, if this volume is not enough, we had to add AY category, then – BY and so on in the order of the transition from green to red (fig. 4). After determination of premises, we had to substantiate the optimal variant of heating/additional heating by a sign of maximization of heat saving (all OY)/minimization of loss (all OX). To do this, we inserted actual data on the infrastructure of premises involved to each of the discriminant functions received. These indicators are: area, number and types of equipment, seats (for auditorium), number of employees (for offices), etc. Next, we put obtained calculated values of heat supply and heat loss into Excel table of heat loss and heat supply (Fig. 7, Table 3). We solve the resulting matrix using the theory of games.

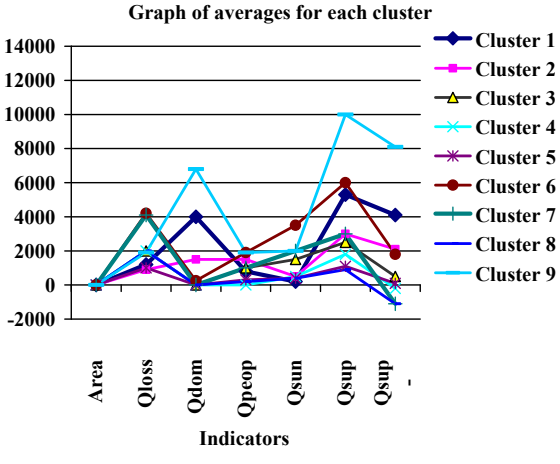

Fig. 5. Visualization of the results of ABC/XYZ analysis of rooms of building 4 at KNUTD with the help of cluster analysis

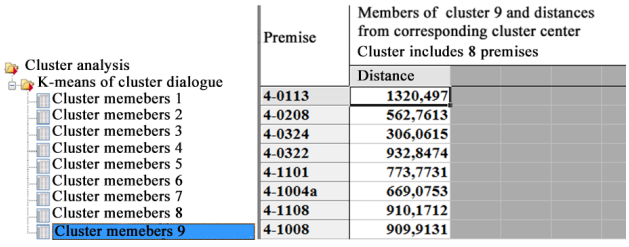

Fig. 6. Premise of the ninth cluster (AX) – listing of STATISTICA program 10 (fragment)

Classification functions for Sigma clusters – restrictions of parameterization

Effect	1 p=,0460	2 p=,0172	3 p=,1782	4 p=,0920	5 p=,2299	6 p=,0920	7 p=,1609	8 p=,1379	9 p=,0460
Constant	-51,3146	-272,299	-13,9109	-21,7765	-5,38582	-28,5299	-6,24713	-16,8747	-56,1812
F_p	1,0936	2,845	0,4389	0,3324	0,17393	0,1328	0,00839	-0,0044	0,1003
$Q_{loss.enc}$	0,0010	0,005	0,0008	0,0009	0,00010	0,0001	0,00007	0,0001	0,0013
$Q_{loss.vent}$	-0,0023	0,001	-0,0049	-0,0020	-0,00354	-0,0106	-0,00449	-0,0032	-0,0059
Q_{dom}	0,0033	-0,002	-0,0004	0,0065	-0,00011	0,0001	0,00021	0,0069	0,0129
Q_{peop}	0,0003	-0,001	0,0010	0,0012	0,00098	0,0019	0,00117	0,0008	0,0008
Q_{sun}	-0,0009	-0,001	-0,0006	0,0003	-0,00037	0,0003	-0,00012	-0,0005	-0,0010

Fig. 7. Results of discriminant analysis - listing of STATISTICA10 program

The so-called "saddle" point is a pair of optimal strategies (*Ai*, *Bj*), which is optimal in terms of the theory of games (the maximum possible volume of heat saving/minimal heat loss). If it exists – in this case, a number $a=b$ is called the (net) price of the game (the bottom and the upper price of the game coincide). This means that the matrix contains an element that is minimal in its line and at the same time maximal in its column. If there is no saddle point – the matrix solution is implemented using mixed strategies.

Here is an example of game results for 4-0113 auditorium (Table 4). This auditorium belongs to AZ category and cluster 9.

Table 3

Identification of premises, which belong to a cluster by signs of the amount of heat saving/heat loss

		Heat loss		
		X	Y	Z
Heat saving	A	$Q_9=-56.1812+0.1003F_s+0.0013Q_{loss.enc.}-0.0059Q_{loss.vent}+0.0129Q_{dom}+0.0008Q_{peop}-0.001Q_{sun}$	$Q_8=-16.9949-0.0044F_s+0.001Q_{loss.enc.}-0.0032Q_{loss.vent}+0.0069Q_{dom}+0.0008Q_{peop}-0.0005Q_{sun}$	$Q_3=-13.9109+0.4389F_s+0.0009Q_{loss.enc.}-0.0049Q_{loss.vent}-0.0004Q_{dom}+0.001Q_{peop}-0.0006Q_{sun}$
	B	$Q_6=-28.5299+0.1328F_s+0.0001Q_{loss.enc.}-0.0106Q_{loss.vent}+0.0001Q_{dom}+0.0019Q_{peop}+0.0003Q_{sun}$	$Q_4=-21.7765+0.3324F_s+0.0009Q_{loss.enc.}-0.002Q_{loss.vent}+0.0065Q_{dom}+0.0012Q_{peop}+0.0003Q_{sun}$	$Q_1=-51.3146+1.0936F_s+0.001Q_{loss.enc.}-0.0023Q_{loss.vent}+0.0033Q_{dom}+0.0003Q_{peop}-0.0009Q_{sun}$
	C	$Q_7=-6.24713+0.00839F_s+0.00007Q_{loss.enc.}-0.00449Q_{loss.vent}+0.00021Q_{dom}+0.00117Q_{peop}-0.00012Q_{sun}$	$Q_5=-5.38582+0.17393F_s+0.0001Q_{loss.enc.}-0.00354Q_{loss.vent}-0.00011Q_{dom}+0.00098Q_{peop}-0.00037Q_{sun}$	$Q_2=-272.299+2.845F_s+0.005Q_{loss.enc.}+0.001Q_{loss.vent}-0.002Q_{dom}-0.001Q_{peop}-0.0006Q_{sun}$

Table 4

Matrix of optimization of heat saving/heat loss for 4-0113 auditorium

		Value of heat loss			a=min(*Ai*)
		X	Y	Z	
Value of heat saving	A	21.986	24.412	–29.129	**–29.129**
	B	–81.761	35.229	–2.619	–81.761
	C	–29.208	–21.239	–178.525	–178.525
b=max(*Bi*)		21.986	35.229	**–2.619**	

The largest of the smallest elements of lines is **–29.129**, this is the lower price of the game; it corresponds to the first line, therefore, the maximin's strategy of the first player is the first. The smallest of the largest elements of columns is **–2.619**, this is the upper price of the game, it corresponds to the third column, hence, the second player strategy minimax is the third. That is, the price of the game is within **–29.129 <P4-0113< –2.619.**

We solve this task by the mixed strategy method, where A1, A2 are strategies of "A" player, and p1, p2 are probabilities (frequencies) with which the strategies are applied respectively, and p1+p2=1. Similarly, B1, B2 are strategies of "B" player, and q1, q2 are probabilities with which the strategies are applied, respectively, and q1+q2=1. Previously, we excluded the second column and the third line from our analysis as potentially inactive strategies. Thus, we convert the payment matrix into a dimension of 2×2, and its solution in the general form looks as follows:

$$-29.129 \cdot p_1 + (-81.761) \cdot (1 - p_2) =$$
$$= 21.986 \cdot q_1 + (-2.619) \cdot (1 - q_2).$$

The calculated game price is 23.239. Calculations confirm that we need additional heat supply at the appropriate volume for heating of 4-0113 room for exploitation of it in a heating period. Due to the fact that 4-0113 room is in the fourth group of light yellow color in accordance with the principle of "traffic light" – premises of this group are more energy-efficient than groups of green color. But it must be included to the plan of workload in connection with the production necessity – the lack of sufficient volume of an energy saving auditorium for classes. The estimated price of the game is 23.239. Its negative value indicates an excess of heat losses over heat supply.

6. Discussion of results of making up an optimal plan for premises loading in a heating period

The obtained results made possible to make certain comparisons after we proposed an approach and made calculations in accordance with it.

Namely: as a result of calculations, we obtained a summary matrix of the optimal loading plan for premises during a heating period (Fig. 8). We constructed the plan in two coordinates. There is a value of the required specific heating of premises (the upper price of the game for each cluster – category of a premise) on OY axis. There is a value of specific heat loss of premises (lower price of the game for each cluster – category of premises) on OX axis.

The obtained matrix makes possible to make substantiated decisions on the order of loading of premises at the current moment due to the combination of two calculation values "The value of the required specific additional heating" and "The value of specific heat loss". In addition, construction of a forecasting matrix for future will give us possibility to develop a perspective plan for loading of the auditorium and make an optimal schedule of classes.

Advantages of the study in comparison with analogues is a possibility of step-by-step composing of an optimal plan for loading of premises in a heating period. 4 groups of premises got into the plan. At the first stage, we include to the plan premises of the group of dark green color. Premises of this group are most energetically saving.

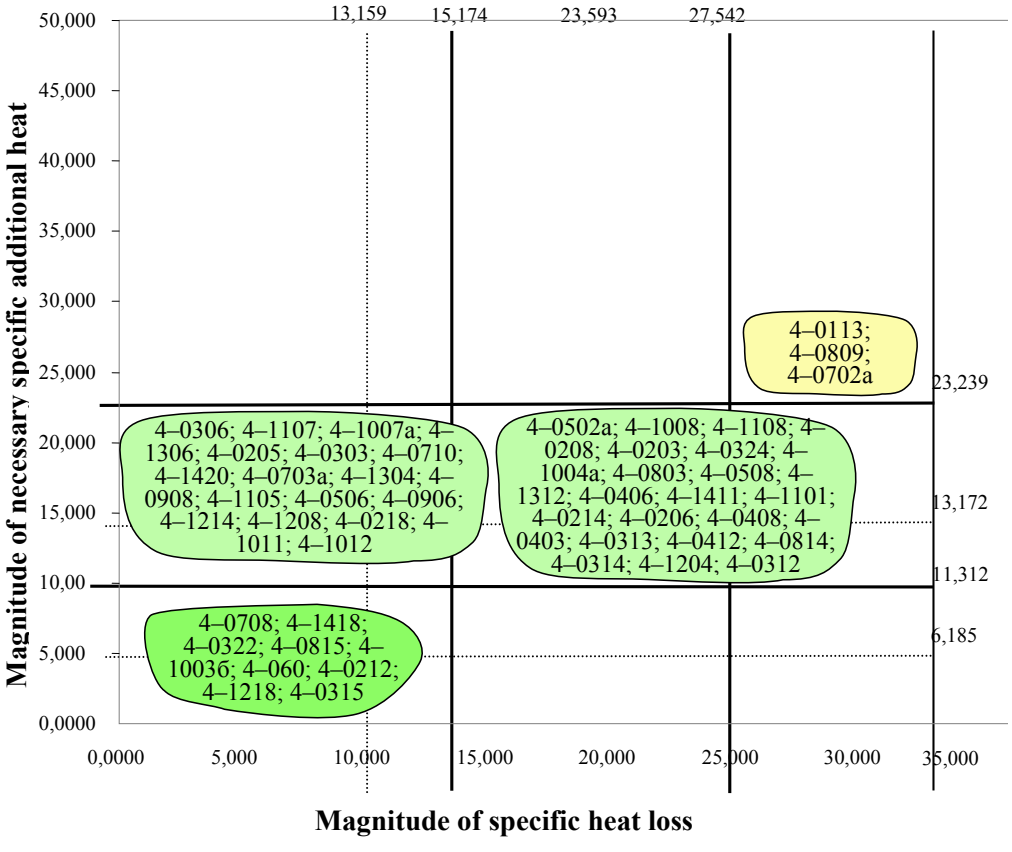

Fig. 8. Matrix of the optimal plan for loading of premises in a heating period of building 4 at KNUTD

At the second step – premises of two groups of light green color. These rooms are less energy-efficient, but enough to use them during a heating period with minimal cost of heating. And at the end, at the third stage, if the auditorium is not enough, we load premises from light yellow color. The premises of this group are more energy expensive than the previous groups. But we have to include them into the plan of loading in connection with production necessity – the lack of sufficient amount of energy-saving auditorium. So far, an alternative method of composing of a plan for loading of auditorium during a heating period was operation-based – according to a schedule of an educational process. This method remained after Soviet times, it is anachronistic, and very energy-consuming due to the high cost of energy carriers.

Disadvantages of the study may be complexity and high work coefficient of energy audits conduction for construction of a balance between heat loss and heat supply.

Development of the study may be development and substantiation of a methodology for identification of those groups of premises of HEI, for which is expedient not only to use them during a heating period, but also to carry out measures on insulation (internal and external).

7. Conclusions

1. We proposed a complex methodology of substantiation of an optimal mode of energy saving mode in HEI during a heating period. The methodology includes the sequence of the following actions: the preparation stage of diagnostics (selection of an object of diagnosis, substantiation of methods, criteria and indicators of evaluation) and diagnostics (construction of heat loss and heat supply table, calculation of heat balance, ABC analysis of relative heat consumption, XYZ analysis of relative heat loss). The substantiation of an optimal mode of energy consumption is formation of a matrix of options for managerial decisions for optimization of OHCM of HEI, selection and substantiation of managerial decision by the method of game theory.

2. Diagnostics for estimation of heat supply and heat loss balance of each HEI premise as the first stage of the developed methodology is based on a use of a combination of the following methods: ABC analysis, XYZ analysis and game theory. Balance calculation is the taring of premises for the actual state of heat supply/heat loss.

3. Making of the managerial decision on optimal use of HEI premises in the educational process during a heating period, as the second stage of the developed methodology, is the so-called "traffic light" of the modified ABC/XYZ matrix. The "traffic light" works in the following way. Premises of dark green color are the most energy-efficient and should be used primarily. And then we should load auditorium in the sequence as the color shifts from green to red.

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