Walery JEZIERSKI • Beata SADOWSKA

ECONOMIC EFFECTS OF CHANGES IN THE REQUIRED THERMAL INSULATION OF BUILDING PARTITIONS IN POLAND

Walery **Jezierski,** Prof. (ORCID: 0000-0001-7829-9733) – *Bialystok University of Technology, Faculty of Civil Engineering and Environmental Sciences*
Beata **Sadowska,** PhD (ORCID: 0000-0003-2866-3685) – *Bialystok University of Technology, Faculty of Civil Engineering and Environmental Sciences*

Correspondence address:
Wiejska Street 45E, 15-351, Białystok, Poland
e-mail: b.sadowska@pb.edu.pl

ABSTRACT: Thermal insulation on the external partitions of the buildings is a very usual strategy to reduce energy demand for heating. This paper presents an original study of the demand for usable energy $Q_{H,nd}$ of a single-family residential building in different climatic conditions (milder conditions – Szczecin, national average – Lodz and more severe conditions – Zakopane) on the thermal transmittance coefficient of selected partitions: external walls, roof, windows and balcony doors, roof windows and doors. They were adopted at three levels, corresponding to the maximum required values, as approved in the Technical Conditions, for periods from 2014, 2017 and 31.12.2020. Based on the results of the computational experiment, three deterministic mathematical models were developed, and the effects of factors on the Y function for the assumed climate conditions were analyzed. Financial savings related to the introduction of stricter requirements for thermal protection of buildings in Poland were determined.

KEY WORDS: demand for usable energy, climate conditions, thermal transmittance coefficient of building partitions, deterministic mathematical model, the economic effect

No. 1(72) 2020 • pages: 107-124 https://doi.org/10.34659/2020/1/7 JEL: C6, Q4, Q5

Introduction

The beginnings of the normalization process for thermal protection of buildings in Poland are connected with the publication by the Publishing House of the Ministry of Reconstruction from 1947 titled "Thermal tables of building structures" (Pogorzelski, 1999). In this document, the thermal conductivity values of the building materials coefficient used for calculating heat transfer coefficients of partitions, as well as the required power of heating devices were included. Then, the PN-57/B-02405 standard provides tabulated *U*-values of frequently used baffles, mainly for heating purposes. The required maximum *U*-values for opaque partitions were introduced in 1968 (PN-B-03404: 1964), due to the requirement of avoiding the water vapour condensation on internal surfaces and based on experience in traditional construction. For walls, this value was 1.47 W/(m^{2}K) in the first and second climate zones of Poland and 1.16 W/(m^{2}K) in the remaining zones (III, IV and V). It corresponded to the specified thickness of the brick wall (two brick wall or one and a half brick wall). The requirement for roofs U_{max} of 0.87 W/(m^{2}K) was supposed to eliminate the risk of snow melting on the roof. In 1982, the PN-/B-02020 standard reduced the required *U*-value of walls to the level of 0.75 W/(m^{2}K) and of roofs to 0.45 W/(m^{2}K), and the requirements were differentiated due to climatic zones. In 1991 U_{max} was reduced for walls to the level of 0.55 W/(m^{2}K) and to 0.30 W/(m^{2}K) for roofs. The number of building parameters regulated by standards, related to the reduction of heat losses (including requirements for windows, heat exchange with the ground, limitation of glass surfaces or air infiltration coefficient) also began to increase.

In 1997, the requirements for thermal protection of buildings were moved from the standards to "Technical conditions that should be met by buildings and their location". In the case of public and industrial buildings, the requirements still concerned the heat transfer coefficient of partitions (U_{max}=0.30-0.50 W/(m^{2}K)). For multi-family residential buildings and collective residences, the limit value of the seasonal heating demand for heating in the standard heating season E_o was determined. In the group of single-family houses, the alternative requirement of U_{max} or E_o was in force.

In November 2008, as part of the implementation of the provisions of Directive 2002/91/EC on the energy performance of buildings (EPBD), the Technical Conditions were amended, and an alternative requirement for the maximum value of thermal transmittance coefficient was set for all buildings (U_{max} = 0.30 W/(m^{2}K) for walls and 0.25 W/(m^{2}K) for roofs) or indicator of non-renewable primary energy (*EP*). In another amendment of the Polish regulation of 2013 (PL, 2013), both thermal protection requirements for new buildings ($U \leq U_{max}$ and $EP \leq EP_{max}$) have become obligatory. The maximum values of thermal transmittance coefficient of selected partitions with their validity periods are presented in table 1.

Table 1. Values of thermal transmittance coefficient $U_{C(max)}$ of selected partitions at room temperature t_i≥16°C in Poland

Type of partition	Thermal transmittance coefficient $U_{C(max)}$, W/(m²K), since:		
	01.01.2014	01.01.2017	31.12.2020
External walls	0.25	0.23	0.20
Roofs and ceilings above unheated attic	0.20	0.18	0.15
Windows and balcony doors	1.30	1.10	0.90
Roof windows	1.50	1.30	1.10
Doors	1.70	1.50	1.30

Source: author's work based on PL, 2013.

Issues of choosing the appropriate thickness of thermal insulation in partitions or the optimal thermal transmittance coefficient have been described in many papers (Bogusławski, 1969; Górzyński, 1995; Laskowski, 2005; Pogorzelski, 1998; Robakiewicz, 1998; Rudczyk-Malijewska, 1999; Sanecki, Skoczek, 1966; Stachniewicz, 2002). In the article (Rudczyk-Malijewska, 1999), the practical inability of static methods of thermal insulation of buildings is shown, due to the fact that economic criteria are not included in them.

Although the EBPD Directive imposed the obligation that the minimum energy performance requirements determined by individual European countries should be cost-optimal, it is clear from the report prepared by ECOFYS for EURIMA (ECOFYS, 2007) that threshold *U*-values for individual building elements (roof, floor, walls, windows, etc.) initially did not always coincide with the economic criterion and did not always achieve specific environmental objectives. The optimal *U*-values recommended in (EURIMA, 2007) resulting from the analysis based on cost-effectiveness and POST-Kyoto goals (reduction of CO_2 emissions by 85% by 2050) were in most cases more ambitious than national requirements. These differences depended on the country and the components of the building under consideration. At present, the optimal thickness of thermal insulation for buildings in various climates is increasingly assessed using "cost-optimal" methods (D'Agostinoc et al., 2019; Tzuolisa et al., 2017) or "investment saving" method (PL, 2015).

The problem of optimizing the insulation level of building partitions in heated buildings has been in the scope of Authors' scientific interest since 2016. In the article "Optimal thickness of thermal insulation layer of external walls in current economic conditions" (Jezierski et al., 2016) on the basis of simulation results, the Authors presented optimal thermal insulation layer thickness for external walls in residential buildings with various heating sources and for various macro- and microeconomic parameters (such as the discount rate, VAT tax, as well as unit heat energy prices and thermal insulation costs). The analysis showed that regarding the optimal values of thermal transmittance coefficient U_{opt} for conditions from 2016, tightening the requirements of thermal protection by introducing new reduced U_{max} should not be considered radical. The stricter requirements regarding U_{max} (from 2017 and 31.12.2020), amounting to 0.23 W/(m^{2}K) and 0.20 W/(m^{2}K), respectively, introduced by Polish legal regulations, do not exceed the U_{opt} reduction, calculated using the dynamic method (NPV) when heating the building from the heating network or using electricity; on the contrary, they are almost twice as large as U_{opt}.

However, there are questions – what gives in the real operating conditions of buildings a reduction of the U_{max} requirements by 0.03 W/(m^{2}K) introduced in two subsequent periods of time? Have U_{max} changes for partitions been too slow in recent years? Unfortunately, in the scientific literature, there are no results available for the estimation of energy and economic effects from U_{max} changes for all these divisions. This is an important issue determining the final energy balance of the entire building; hence it should be considered.

Considering the permissible values of the heat transfer coefficient of building partitions in heated buildings set for subsequent periods, one could admit that their implementation will evenly reduce the heat demand for heating for all buildings, as well as for all their locations, despite the fact that they significantly differ in climate conditions. Unfortunately, there is no data on this subject in recent publications. As in the case of U-value, the required by Polish law levels of energy demand are not dependent on climate zones. Such a diversification appeared only in the first version of the program of subsidies for energy-efficient buildings (NECA, 2012) and was removed in the later drafts.

In connection with the above, the aim of this work is to examine the annual demand for usable energy for heating and ventilation $Q_{H,\mathrm{nd}}$ a selected single-family house in different climatic conditions: milder (Szczecin), medium-sized (Lodz) and more severe (Zakopane). The analyzed demand depends on the thermal transmittance coefficient of external walls (U_1), roof (U_2), balcony windows and doors (U_3), roof windows (U_4) and external doors (U_5), adopted at three levels corresponding to the maximum permissible values, as approved in the Technical Conditions for periods from 2014; 2017 and 31.12.2020. The Authors also set out to develop three deterministic mathematical models of this relationship with the estimation of these factors and their effects in different climatic conditions.

Description of the investigated house

The analysis was conducted on a single-family, one-level house, without a basement, with a heated attic and a simple architecture referring to the traditional style. Its usable area is 150,11 m^2 and cubature about 690 m^3. In the plan, the building has a rectangular shape with dimensions of 9.54 m and 11.04 m. It is made in traditional technology, with a gable roof covered with ceramic tiles. The entrance façade is oriented from the north. The schematic diagram of the tested building is shown in figure 1.

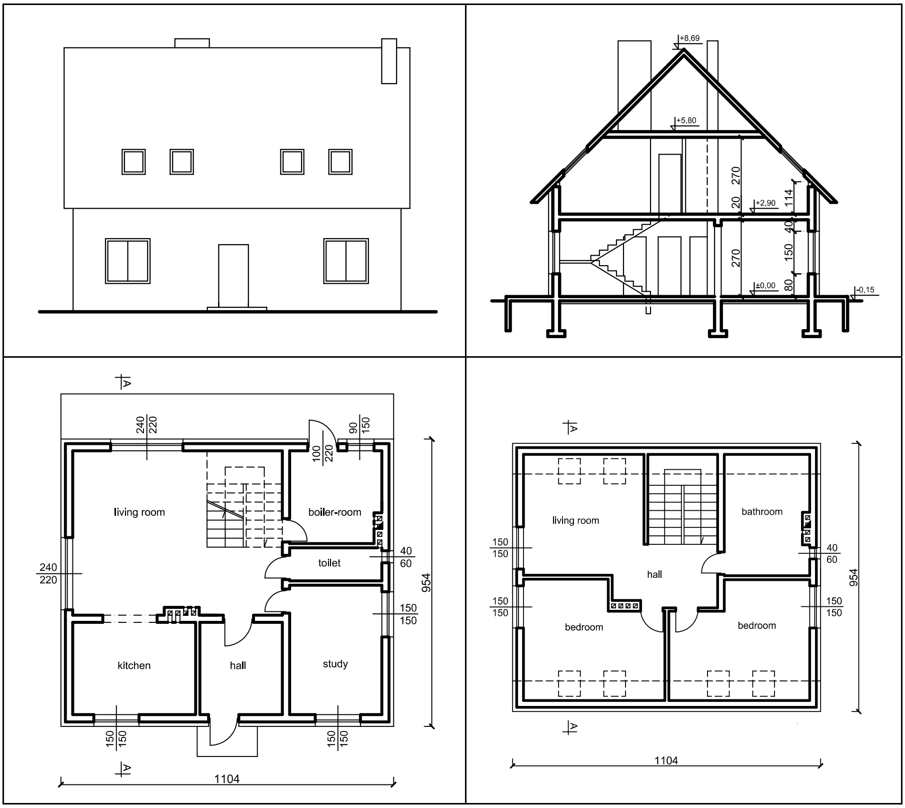

Figure 1. Scheme of the tested single-family house: A – front elevation; B – vertical section; C – ground floor plan; D –plan of a heated attic

Source: author's work.

The house's walls were made of cellular concrete and foamed polystyrene. The insulation of the roof was mineral wool and gypsum board on the attic side. The floor on the ground consists of a concrete foundation on gravel ballast, 10 cm thick foamed polystyrene, PE film and floor layers on a concrete foundation. Windows and external doors are made of PVC. Ventilation is natural. A natural gas boiler, panel radiators located under windows with thermostatic valves, central and local regulation, pipes with good insulation located in heated rooms are used in building.

The method of usable energy demand calculation

The usable energy demand for space heating and ventilation $Q_{H,nd}$ [kWh/year] describes the energy balance of a building, taking into account heat gains and losses in an annual period. The calculation of $Q_{H,nd}$ of the selected building was carried out according to the methodology (PL, 2015) in force in Poland from 27.02.2015. It is the sum of the $Q_{H,nd,s,n}$ demand for each of the heated zones in the building and for each of the months of the year and is determined according to formulas (PL, 2015):

$$Q_{H,nd,s,n} = Q_{H,ht,s,n} - \eta_{H,gn,s,n} \cdot Q_{H,gn,s,n} , \tag{1}$$

$$Q_{H,ht,s,n} = Q_{tr,s,n} + Q_{ve,s,n} , \tag{2}$$

$$Q_{tr,s,n} = H_{tr,s} (\theta_{int,s,H} - \theta_{e,n}) t_m 10^{-3}, \tag{3}$$

$$Q_{v,e,s,n} = H_{ve,s} (\theta_{int,s,H} - \theta_{e,n}) t_m 10^{-3}, \tag{4}$$

$$H_{tr,s} = \sum [b_{tr,i} (A_i U_i + \sum l_i \Psi_i)], \tag{5}$$

$$H_{ve,s} = \rho_a c_a \sum_{l,k} V_{ve,k,n} , \tag{6}$$

$$Q_{H,gn,s,n} = Q_{sol,H} + Q_{int,H} , \tag{7}$$

$$Q_{sol,H} = \sum C_i A_{oi} I_i F_{sh,gl} F_{sh} g_{gl} , \tag{8}$$

$$Q_{int,H} = q_{int} A_f t_m 10^{-3}, \tag{9}$$

where:

A_f – the useful floor area,
A_i – the area of element *I* of the building envelope,
A_{oi} – the surface area of window or door opening,
$b_{tr,i}$ – the reduction factor for the adjacent unconditioned space,
C_i – share a glass plane surface area to the total area of the window,
F_{sh} – reducing factor due to shading from the external partitions,

$F_{sh,gl}$ – shading reduction factor for movable shading devices,
g_{gl} – the total solar energy transmittance factor of the transparent part of the element,
q_{int} – internal heat sources,
$H_{ve,s}$ – the total heat transfer coefficient by ventilation of the building or building zone *s*,
$H_{tr,s}$ – the total heat transfer coefficient by the transmission of the building or building zone *s*,
I_i – the value of solar energy in the considered month on the plane in which there is a window,
$I_{,k}$ – the reduction factor for the adjacent unconditioned space,
l_i – the length of linear thermal bridge *k*,
$Q_{H,gn,s,n}$ – the total heat sources in the heated zone *s* in the *n*-th month of the year,
$Q_{H,ht,s,n}$ – the total heat transfer from the heated zone *s* in the *n*-th month of the year,
$Q_{int,H}$ – the sum of internal heat sources,
$Q_{sol,H}$ – the sum of solar heat sources from solar radiation through windows or door opening,
$Q_{tr,s,n}$ – the total heat transfer by transmission from the heated zone *s* in the *n*-th month of the year,
$Q_{v,e,s,n}$ – the total heat transfer by ventilation from the heated zone *s* in the *n*-th month of the year,
t_m – the number of hours in a month,
U_i – the thermal transmittance of element *I* of the building envelope,
$V_{ve,k,n}$ – the airflow rate through the heated space,
$\eta_{H,gn,s,n}$ – the dimensionless gain utilization factor in the heated zone *s* in the *n*-th month of the year,
$\theta_{e,n}$ – the average external temperature,
$\theta_{int,s,H}$ – the average internal temperature of the heated building zone,
$\rho_a c_a$ – the heat capacity of air per volume,
Ψ_i – the linear thermal transmittance of linear thermal bridge *k*.

Based on the presented formulas (1) – (9) and methodology (Pl, 2015), the Authors selected five input variables and developed an algorithm for calculating the demand for usable energy (figure 2) when changing the values of selected factors according to the plan of the computational experiment. This algorithm was the basis for developing an original computer program in Microsoft Excel.

It was assumed that the determination of the annual demand for usable energy for heating and ventilation $Q_{H,nd}$ of the analyzed building would be carried out successively taking into account the climatic conditions for each of the adopted building locations.

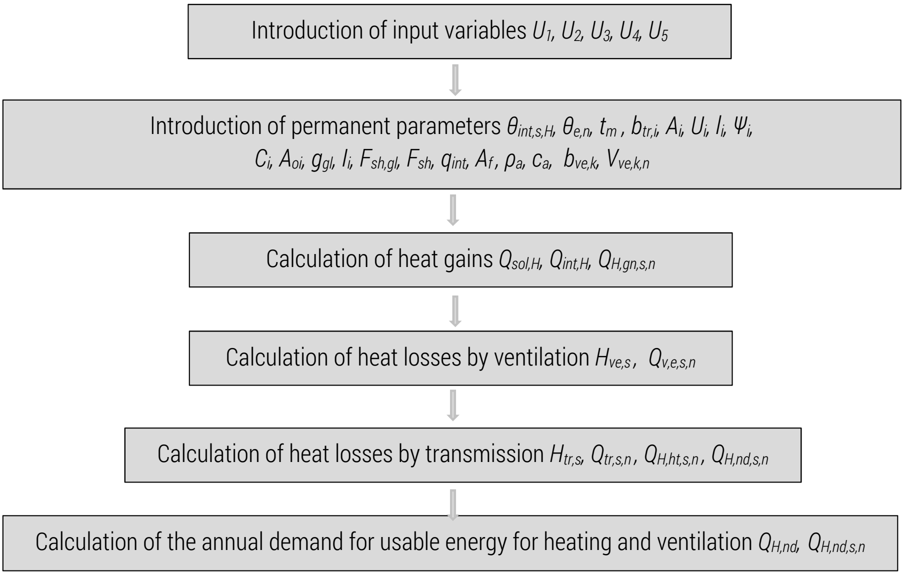

Figure 2. Block diagram for calculating the annual demand for usable energy for heating and ventilation of a selected building

Source: author's own work based on PL, 2015.

Mathematical model of the usable energy demand of a selected residential building

As a research method, mathematical modelling was used, which allows mathematical dependencies to describe the functioning of the tested object, determine the output parameters and the optimal values of the input parameters of the object (Gutenbaum, 2003). The use of mathematical modelling allows to abandon physical modelling, minimize the number of sampling, and reduce the labor intensity of the study. The main component in such a system is the mathematical model.

Mathematical models are appropriate and effective tools to perform the analysis of a test object provided that the developed formulas are short and use the most important factors describing the process or property being investigated, and they are important for recipients of information about the tested object (Gutenbaum, 2003).

In the test, the annual demand for usable energy for heating and ventilation of the tested building $Q_{H,nd}$ was chosen as a function Y, depending on the following thermal transmittance coefficients: of external walls U_1 (factor X_1), roof U_2 (factor X_2), windows and balcony doors U_3 (factor X_3), roof windows U_4 (factor X_4) and external doors U_5 (factor X_5). The demand for usable energy for heating and ventilation of the building has a physical meaning, it is measurable and unambiguous. The selected factors result from the purpose of the study. They are measurable, controllable, independent, unambiguous and consistent, that is, they meet the basic requirements of mathematical modelling (Gutenbaum, 2003).

Table 2. Averaged climate characteristics for the heating season in selected cities in Poland

Group of climatic conditions	City	The energy of solar radiation on the plane with the window S orientation ΣI_i, kWh/(m^2 month)	The average monthly external temperature θ_e, °C	The sum of hours of the heating season Σt_m, h
I	Szczecin	48188.5	4.49	5808
II	Lodz	46763.7	2.70	5328
III	Zakopane	63734.3	1.99	6048

Source: author's work based on PL, 2008.

Unfortunately, the factor of climatic conditions mentioned in the study was not taken into account as the sixth factor in the model, because it is presented with a set of various climate indicators (table 2), which are difficult to combine with a comprehensive indicator. Therefore, a decision was made to develop and compare three mathematical models of the dependence on five factors for each of the three groups of climatic conditions: for Szczecin (I) – $Q_{I,H,nd}$ ($Y_{I,i}$); Lodz (II) – $Q_{II,H,nd}$ ($Y_{II,i}$) and Zakopane (III) – $Q_{III,H,nd}$ ($Y_{III,i}$).

It was assumed that the desired dependency $Y = f(X_1, X_2, X_3, X_4, X_5)$ could be described by the second-degree polynomial in the form:

$$Y=a_0+a_1X_1+a_2X_2+a_3X_3+a_4X_4+a_5X_5+a_{12}X_1X_2+a_{13}X_1X_3+a_{14}X_1X_4+a_{15}X_1X_5+ a_{23}X_2X_3+a_{24}X_2X_4+a_{25}X_2X_5+a_{34}X_3X_4+a_{35}X_3X_5+a_{45}X_4X_5+a_{11}X_1^2 +a_{22}X_2^2+a_{33}X_3^2+a_{44}X_4^2+a_{55}X_5^2 \quad (10)$$

To obtain data for the description of this dependency, a 5-factorial calculation experiment was carried out according to the second-degree plan (table 4). A compositional symmetrical three-level plan, consisting of 26 trials (Korzyński, 2006) was applied. For the calculation of Y_i value in 26 lines of the plan, the author's program developed in Microsoft Excel was used.

The ranges of variability, according to the adopted objective of the study, for each of the considered factors have been adopted three levels corresponding to the maximum values specified in Polish regulations in force from 2014, 2017 and 31.12.2020 (table 1). For factors X_1 and X_2 this range turned out to be narrow and was only 0.03 W/(m^{2}K). The larger range was for the remaining factors (0.2 W/(m^{2}K)). Nevertheless, U_i values were chosen, approved in the Technical Conditions that buildings and their location should satisfy for the above-mentioned time periods. These ranges of the variability of factors allowed the Authors to check the sensitivity of the examined function and obtain useful information for those who are working on the regulations regarding the value of the U_{imax} coefficients tested before approving the thermal protection requirements of buildings for a new time period.

Thus, selected factors were adopted at levels (table 3): X_1: 0.20(-1), 0.23(0), 0.26(+1); X_2: 0.15(-1), 0.18(0), 0.21(+1); X_3: 0.90(-1), 1.10(0), 1.30(+1); X_4: 1.10(-1), 1.30(0), 1.50(+1) and X_5: 1.30(-1), 1.50(0), 1.70 W/(m^{2}K) (+1). The principle of experimental planning regarding the symmetrical ranges of variability for all factors forced the Authors to deviate from the maximum values according to the Technical Conditions of 0.25 (X_1 = + 0.6667) and 0.20 (X_2 = + 0.6667 W/(m^{2}K)) and change them at 0.26 and 0.21 W/(m^{2}K) respectively. However, this did not pose any problem with modeling, because the new increased range covers previous values.

Table 3. Natural and standardized values of selected factors

factor level $\dot{X}_i$	U_1, W/(m^{2}K) (X_1)	U_2, W/(m^{2}K) (X_2)	U_3, W/(m^{2}K) (X_3)	U_4, W/(m^{2}K) (X_4)	U_5, W/(m^{2}K) (X_5)
bottom (-1)	0.20	0.15	0.90	1.10	1.30
meddle (0)	0.23	0.18	1.10	1.30	1.50
upper (+1)	0.26	0.21	1.30	1.50	1.70
range of factor change ΔX_i	0.03	0.03	0.20	0.20	0.20

Source: author's work.

The above-mentioned natural values of factors $\dot{X}_1$, $\dot{X}_2$, $\dot{X}_3$, $\dot{X}_4$, $\dot{X}_5$ and the corresponding standardized values (in brackets) of normed values X_1, X_2, X_3, X_4, X_5 are presented in table 3. The transition from natural $\dot{X}_i$ to normative values X_i (Korzyński, 2006) is expressed by the following formula:

$$X_i = \frac{\dot{X}_i - \frac{\dot{X}_{i,max} + \dot{X}_{i,min}}{2}}{\frac{\dot{X}_{i,max} - \dot{X}_{i,min}}{2}}, \quad (11)$$

where:
$\dot{X}_i$, $\dot{X}_{i,max}$, $\dot{X}_{i,min}$ – are the current, maximum and minimum natural values of the *i*-th factor, respectively.

Table 4. Planning matrix and calculation results of $Q_{I,H,nd}$ $(Y_{I,i})$, $Q_{II,H,nd}$ $(Y_{II,i})$, $Q_{III,H,nd}$ $(Y_{III,i})$.

No	U_1 X_1	U_2 X_2	U_3 X_3	U_4 X_4	U_5 X_5	$Q_{I,H,nd}$ [kWh] $Y_{I,i}$	$Q_{II,H,nd}$ [kWh] $Y_{II,i}$	$Q_{III,H,nd}$ [kWh] $Y_{III,i}$
1	0.20 -1	0.15 -1	0.90 -1	1.10 -1	1.70 +1	6490	7204	8645
...	...	...	...	...	...	...	...	...
26	0.23 0	0.18 0	1.10 0	1.30 0	1.70 +1	7627	8418	10109

Source: author's work.

Based on the results of $Q_{I,H,nd}$, $Q_{II,H,nd}$, $Q_{III,H,nd}$ calculations (table 4), using the method of least squares (Durakovic, 2017), three mathematical models were developed in the form of regression equations for the dependence of $Y=f(X_1,X_2,X_3,X_4,X_5)$:

for Szczecin:

$$\hat{Y}_I=7558,15+403,00X_1+274,88X_2+381,11X_3+90,78X_4+ 68,89X_5+2,25X_1X_2+3,25X_1X_3+2,13X_2X_3+1,84X_1^2+1,84X_3^2 \quad (12)$$

for Lodz:

$$\hat{Y}_{II}=8343,84+430,38X_1+293,38X_2+405,72X_3+96,56X_4+ 73,44X_5+2,38X_1X_2+3,25X_1X_3+2,25X_2X_3+1,66X_1^2+1,66X_3^2 \quad (13)$$

for Zakopane:

$$\hat{Y}_{III}=10020,03+520,11X_1+354,61X_2+490,16X_3+116,50X_4+ 88,89X_5+3,00X_1X_2+4,50X_1X_3+3,00X_2X_3+1,88X_1^2+2,38X_3^2 \quad (14)$$

Deterministic models are characterized by mutually unambiguous compatibility between the external interaction and the reaction to this impact. It was taken into account when testing the adequacy of models. Only one experiment was performed at each point of the plan. Then, in the absence of repetition and variance of measurement inaccuracies, the adequacy of the obtained equation according to (Durakovic, 2017) can be assessed by comparing the variances of the mean S^2_y and the residual variance S^2_r calculated according to the formulas:

$$S^2_y = \Sigma(Y_i - \bar{Y})^2/(N-1), \tag{15}$$

$$S^2_r = \Sigma(\hat{Y}_i - Y_i)^2/(N-N_b), \tag{16}$$

where:
N – number of calculations,
N_b – number of coefficients in the regression equation.

The Fischer criterion was applied for testing, which shows the reduction in spread with respect to the regression equation compared to the average spread (Durakovic, 2017):

$$F= S^2_y(f_1)/ S^2_r(f_2), \tag{17}$$

where:
f_1, f_2 – the number of degrees of freedom,
f_1 = (N-1)=26-1=25; f_2 = (N-N_b)=26-21=5.

The regression equation describes the results of calculations adequately if the value of F is much greater than the tabular value F_t at the level of significance p and degrees of freedom f_1 and f_2.

As it results from calculations, for the developed model (12): F_I=285283, 8738/0,0389=7333801,383; for the model (13): F_{II}=292547,6643/0,2611=1 120442,989; and for the model (14): F_{III}=473794,3215/0,0667 = 7106914,824. The tabular value $F_t = F_{0,05;\,25;5}$ = 4,525 (Durakovic, 2017). Thus, F_I, F_{II}, F_{III} values significantly exceed F_t, which means that the models are adequate. Their high quality also confirms the coefficient of determination at the level of R^2 = 0.9998-0.9999.

The significance of coefficients in equations (12) – (14) was also checked. Testing was performed using the t-criterion. Because at each point of the plan we have one result without repeats, the approach described in (Durakovic, 2017) was used, according to which for each coefficient was calculated $t_j = |b_j| / S_{bj}$, where b_j – values of coefficients of the regression equation; S_{bj} – standard deviation of the *j*-th coefficient. To determine S_{bj}, the residual variance S_r^2 was used based on the sum of squared deviations $(\hat{Y}_i - Y_i)^2$. The values were compared with the critical value of $t_{0,05;5}$=2,02 (Durakovic, 2017). If $t_j < t_{0,05;5}$, the coefficient was considered irrelevant. After the removal of nine irrelevant factors, the final form of equations (12) – (14) with *k*+1=12 coefficients were adopted. After testing and analyzing the results, the models were considered useful for further analysis.

Analysis of the studied dependence based on a mathematical model

The analysis of the impact of the considered factors on the annual demand for usable energy for heating and ventilation of the selected building was made on mathematical models (12) – (14). In order to ensure better clarity, the discussion of results will be made on natural variables. As the minimum U_i values were adopted as the lower levels of factors (which will be in force in Poland from 1 December 2020), the interpretation had to be performed "backwards" of time.

Analyzing the developed models, it was found that in the centre of multi-factorial space G_p, which is characterized by U_i values, corresponding to the current requirements for thermal protection of partitions in Poland (from 1/01/2017), namely: U_1=0.23 W/(m²K); U_2=0.18 W/(m²K); U_3=1.10 W/(m²K); U_4=1.30 W/(m²K) and U_5=1.50 W/(m²K), the building's energy demand for selected groups of climatic conditions is: for Szczecin (1st group) $Q_{I,H,nd}$ =7558.15; for Lodz (II group) $Q_{II,H,nd}$ =8343.84 and for Zakopane (III group) $Q_{II,H,nd}$ =8343.84 kWh/year.

As confirmed by the results of the calculations, the energy demand of the same building varies considerably depending on the location, namely, compared to Szczecin, it increases by 10.4% for Lodz and by 32.6% for Zakopane. This is caused by changes in various climate indicators, which determine heat losses and gains in the thermal balance of the building (table 2). However, the magnitude of these fluctuations, even when the locations were accidentally selected by the authors, surprises and convinced about the desirability of returning to the approach specifying the different thermal protection requirements for heated buildings in Poland (primarily regarding the thermal transmittance coefficient values), considering the climatic conditions of the location of the building.

The influence of individual factors was then estimated. According to the developed models, it turned out that for each of the selected locations when the factors U_i changed from the lower to the upper level (table 3), the value of

$Q_{H,nd}$ increases equally: from the factor U_1 by about 11.1%; from factor U_2 by about 7.4%; from factor U_3 by about 10.4%; from factor U_4 by 2.4% and from the U_5 factor by 1.8%. The same percentage effects of factors were obtained in relation to individual models. The effects of factors for the relevant models and climatic conditions, after conversion into physical units, are presented in table 5.

The changes of the required values of the thermal transmittance coefficient of building partitions give diversified effects on the demand for usable energy of a selected building in various climatic conditions. Regarding the climatic conditions of Szczecin, these effects for each factor increase by 6.7% for Lodz and 29.0% for Zakopane (table 5).

Table 5. The influence of changes in the values of factors $X_1(U_1)$, $X_2(U_2)$, $X_3(U_3)$, $X_4(U_4)$, $X_5(U_5)$ from the lower to the upper level, in different climatic conditions

Group of climatic conditions	$\Delta Q_{H,nd}$ effects of changes in the values of selected factors, kWh/year					$\Sigma\Delta Q_{H,nd}$ kWh/year
	$X_1(U_1)$	$X_2(U_2)$	$X_3(U_3)$	$X_4(U_4)$	$X_5(U_5)$	
Effects, %	11.1	7.4	10.4	2.4	1.8	33.1
I	806.00	549.76	762.22	181.56	137.78	2437.32
II	860.76	586.76	811.44	193.12	146.88	2598.96
III	1040.22	709.22	980.32	233.00	177.78	3140.54

Source: author's work.

The total effect from the change from the lower to the upper level of all factors causes a significant increase $Q_{H,nd}$ for the considered building: for I group of climatic conditions from 6350.80 to 8788.12 kWh/year, i.e. an increase of 2437.32 kWh/year (+ 38.4%); for II group from 7055.56 to 9654.52 kWh/year, i.e. an increase of 2598.96 kWh/year (+ 36.8%) and for III group from 8464.52 to 11605.06 kWh/year, i.e. an increase of 3140.54 kWh/year (+ 37.1%). With reference to the I group of climatic conditions, the total effect was 6.6% in the second group and 28.8% in the third group.

The presented results show that currently the approach to approval of nationwide required values of thermal transmittance coefficient, placing all buildings in identical operating conditions is not right and does not allow forecasting the real effects of reducing the demand for utility energy of buildings after toughening requirements throughout the country.

Changes in the required U_i values in force from January 1, 2017, compared to the previous period (from January 1, 2014) (table 1) resulted in a decrease $Q_{H,nd}$ of the analyzed building in the group no I of climatic conditions from 8558.12 to 7558.15 kWh/year (- 999,97 kWh/year); in the group *no. II* from 9409.21 to 8343.84 kWh/year (- 1065.37 kWh/year); and in the group *no. III* from 11308.31 to 10020.03 kWh/year (- 1288,28 kWh/year).

Further tightening of the U_i to the values to be applied in Poland from 31.12.2020 in relation to the value from the current period will also bring a reduction in $Q_{H,nd}$ of this building: in I group of climatic conditions from 7558.15 to 6350.80 kWh/year (- 1207.35 kWh/year); in the second group from 8343.84 to 7055.56 kWh/year (- 1288,28 kWh/year) and in the third group from 10020.03 to 8464.52 kWh/year (- 1555.51 kWh/year).

The described nature of the factor influence complements the knowledge about energy and economic effects in the heated building from changes in thermal transmittance coefficient $U_{\max}$ of external partitions in various climatic conditions.

Annual financial savings caused by a change in the requirements for thermal protection of partitions

Then financial effects were calculated as related to the reduction of heating demand of the analyzed building after the tightening of the required thermal transmittance coefficient values (U_{Cmax}). According to the algorithms in (PL, 2015), the demand for final energy was determined on the basis of formula 18 and the cost of heating according to 19. Fixed charges were omitted due to the fact that their amount was not changed while the building's energy demand was reduced.

$$Q_{k,H} = Q_{H,nd}/\eta_{H,tot}, \quad (18)$$

where:
$Q_{H.nd}$ – annual heating energy demand, [kWh/year],
$\eta_{H.tot}$ – seasonal average total efficiency of the heating system [-],

$$K_H = Q_{k,H,nd} \cdot O_z, \quad (19)$$

where:
K_H – annual energy cost for heating [EUR],
O_z – unit price of energy [EUR/kWh].

The adopted average in Poland unit price of 1 kWh of thermal energy for natural gas and the average annual efficiency of the heating system are presented in table 6.

Table 8. The average seasonal efficiency of the heating system and unit price of 1 kWh of thermal energy for natural gas

Fuel type	The average seasonal efficiency					unit prices O_z
	energy conversion of energy source $\eta_{H.g}$	regulatory control $\eta_{H.e}$	energy distribution $\eta_{H.d}$	energy storage (eg., in tanks) $\eta_{H.s}$	total efficiency $\eta_{H.tot}=\eta_{H.g} \cdot \eta_{H.e} \cdot \eta_{H.d} \cdot \eta_{H.s}$	EUR/kWh
Natural gas	0.94	0.89	0.96	1.00	0.80	0.0687

Source: author's work based on PL, 2013.

Changes in the required U_i values in force from January 1, 2017, compared to the previous period (from January 1, 2014) (table 1) resulted in a decrease K_H for the analyzed building of 43 Euros in the first group of climatic conditions; 46 Euros in the second group and 55 Euros in the third group.

Further tightening of the U_i to the values to be applied in Poland from 31.12.2020 in relation to the value from the current period will also bring a reduction in K_H for this building. This was estimated at 52 Euros in the first group of climatic conditions, 55 Euros in the second group and 67 Euros in the third group.

Conclusions

1. Developed deterministic mathematical models allowed to calculate energy effects from changes in the $U_{i,max}$ of building partitions that meet Polish national regulations from January 1, 2014; January 1, 2017, and December 1, 2020. They also allowed estimating the financial benefits from a reduction in the usable energy demand of a selected residential building under the climatic conditions of three cities – Szczecin, Lodz and Zakopane.
2. The change in the required U-values of selected partitions from the level meeting the Polish national regulations from January 1, 2014, to the current one resulted in a reduction of the heating demand for a selected residential building by 999.97 kWh/year in Szczecin, by 1065.37 kWh/year in Lodz and by 1288.28 kWh/year in Zakopane. Financial benefits (in a house which uses natural gas as fuel in the heating system) in these locations amount to 43 Euros, 46 Euros and 55 Euros, respectively.
3. The change of the required U-values of selected partitions from the current level to the requirements from 31.12.2020 will cause a further

reduction in $Q_{H,nd}$ of the selected residential building by 1207.35 kWh/year in Szczecin, by 1288.32 kWh/year in Lodz and 1555.51 kWh/year in Zakopane. Financial benefits in these locations will amount to 52 Euros, 55 Euros and 67 Euros.

4. The most significant impact on reducing the usable energy demand $Q_{H,nd}$ of a selected residential building has thermal transmittance coefficient of walls (U_1) and windows (U_3), whose total share (after changing the requirements from currently in force to those that will apply from December 1, 2020) for each location is 64.3% of the total decrease from all analyzed factors.
5. It is reasonable to return to the approach determining the requirements for thermal protection of heated buildings in Poland, not the same for the whole country, but varied, taking into account the climatic conditions of the building erection.

Acknowledgements

The research was carried out under statute grant no. WZ/WBIIŚ/5/2019 and financed from the funds for the science of the Ministry of Science and Higher Education.

The contribution of the authors

Walery Jezierski – 50%
Beata Sadowska – 50%

Literature

Bogusławski, L.D., 1969. Techniko-ekonomiczeske rasczety pri projektirowanii narużnych ograzdżajuszczich zdanii. Izd. Vyszaszaja Szkoła, Moskwa.

D'Agostinoc, D. et al., 2019. Evaluation of the optimal thermal insulation thickness for an office building in different climates by means of the basic and modified "cost-optimal" methodology. Journal of Building Engineering, 24, DOI: 10.1016/j.jobe.2019.100743.

Durakovic, B., 2017. Design of Experiments Application, Concepts, Examples, State of the Art. Periodicals of Engineering and Natural Sciences, 5(3), 421-439, DOI: 10.21533/pen.v5i3.145.

ECOFYS, 2007. U-values for better energy performance of buildings – Report established by ECOFYS for EURIMA, https://www.eurima.org/reports/u-values-for-better-energy-performance-of-buildings/.

Górzyński, J., 1995. Audyting energetyczny obiektów przemysłowych. Fundacja Poszanowania Energii, Warszawa.

Gutenbaum, J., 2003. Mathematical modeling of systems. EXIT, Warsaw.

Jezierski, W., Sadowska, B., 2016. Optimal thickness of thermal insulation layer of external walls in current economic conditions. Inżynieria i Budownictwo, 72(8), 421-425.

Korzyński, M., 2006. Methodology of the experiment. Planning, implementation and statistical analysis of the results of technological experiments. WNT, Warsaw.

Laskowski, L., 2005. Ochrona cieplna i charakterystyka energetyczna budynku. Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa.

NECA, 2012. Energy-efficient houses, Good practice guide, prepared on the basis of the study of the National Energy Conservation Agency SA, https://www.nfosigw.gov.pl/oferta-finansowania/srodki-krajowe/programy-priorytetowe/doplaty-do--kredytow-na-domy-energooszczedne/podrecznik-dobrych-praktyk/.

Nyers. J. et al., 2015. Investment saving method for energy-economic optimization of external wall thermal insulation thickness. Energy and Buildings, 86, 268-274, https://doi.org/10.1016/j.enbuild.2014.10.023.

PL, 2008. Typical meteorological years and statistical climate data for Poland for energy calculations of buildings: <https://dane.gov.pl/dataset/797,typowe-lata-meteorologiczne-i-statystyczne-dane-klimatyczne-dla-obszaru-polski-do-obliczen-energetycznych-budynkow>.

Pogorzelski, J.A., 1998. Opłacalna grubość izolacji cieplnej przegród zewnętrznych. Materiały Budowlane, 1.

Pogorzelski, J.A., 1999. Standardization of thermal protection of buildings in EU countries and in Poland. Overview of the current situation, Building Research Institute, Quarterly, 4(112).

Regulation by the Minister of Infrastructure of 18 March 2015 on the methodology for determining the energy performance of a building or part of a building and building performance certificates (Journal of Laws of the Republic of Poland, item 376).

Regulation of the Minister of Transport, Construction and Maritime Economy of 5 July 2013 on the Technical Conditions that buildings and their location should satisfy (Journal of Laws of the Republic of Poland, item 926).

Robakiewicz, M., 1998. Optymalizacja grubości warstw izolacji termicznej przegród budowlanych, IV Ogólnopolska Konferencja Naukowo-Techniczna: Problemy projektowania, realizacji i eksploatacji budynków o niskim zapotrzebowaniu na energię – ENERGODOM'98, Kraków-Mogilany, 365-378.

Rudczyk-Malijewska, E., 1999. Optymalizacja izolacji cieplnej przegród budowlanych w aspekcie efektywności ekonomicznej, rozprawa doktorska, Wydział Budownictwa i Inżynierii Środowiska Politechniki Białostockiej, Białystok.

Sanecki, J., Skoczek, W., 1966. Ekonomika ogrzewania budynków. Arkady, Warszawa.

Stachniewicz, R., 2002. Efektywność termomodernizacji budynków w zabudowie miejskiej, rozprawa doktorska, Wydział Budownictwa i Inżynierii Środowiska Politechniki Białostockiej, Białystok.

Tzoulisa, T., Kontoleon, K.J., 2017. Thermal Behaviour of Concrete Walls Around all Cardinal Orientations and Optimal Thickness of Insulation from an Economic Point of View. Procedia Environmental Sciences, 38, 381-388, https://doi.org/10.1016/j.proenv.2017.03.119.