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Optimization of Thermal Insulation and Regression Analysis of Fuel Consumption

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Abstract

In this paper analyses of the current state of the thermal insulation of walls without styrofoam and existing windows of Alipasino polje buildings in Sarajevo, Bosnia and Herzegovina, which is powered boiler K-5 through its substations, and current fuel consumption is performed. Research results lead to the conclusion that it is worth to consider insulation of buildings, i.e., simulation of adding styrofoam and new windows on the existing structure in order to reduce heat losses and thus reduce fuel consumption and gas emissions. Savings obtained by this simulation are over 30%. Surface area of buildings subject to the installation of the insulation is obtained on the basis of projects from the district heating system Toplane Sarajevo. Styrofoam thickness is determined by optimizing reduction of the payback period. Prediction of fuel consumption was evaluated for the existing and projected future depending on outside temperature.

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Keywords: optimization; energy efficiency; insulation; correlation; regression analysis; forecasting; return on investment

1. Introduction

Space heating and cooling ensure thermal comfort in buildings by maintaining the indoor temperature at a desired, uniform level and providing proper admission of fresh air. For the determination of the model parameters, also called coefficients, most authors adopt a statistical method "regression analysis", based on measured data.

The ambient (outdoor) temperature is the most dominating parameter for load simulations [1]. Beside the ambient temperature, heat demand depends on other parameters.

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Amplitude of the influences corresponds to the following share rate in total load for the mentioned influences [2]:

a. Ambient temperature: 83%,
b. Cold-water temperature: 8,8%,
c. Solar radiation: 7,7%,
d. Wind: 0,2%,
e. Humidity: < 0,1%.

The term "heat demand" relates to term "heat consumption". It expresses heat energy that is supplied to the customer in a specific time interval (generally a day or a year) [3]. The course of heat demand and heat consumption can be demonstrated by means of the heat demand diagrams. The most important one is the Daily Diagram of Heat Demand (DDHD) that demonstrates the course of requisite heat output during the day as shown in Fig. 1. These heat demand diagrams are of essential importance for technical and economic considerations. Therefore forecast of these diagrams is significant for short-term and long-term planning of heat production [4].

One of the major energy consumers is the building sector and thus requires the most of the energy research to analyse different energy options from various aspects [5]. In this research the environmental impact indices, renewable energy indices, and the renewable exergy indices are estimated for every energy option. This research shows that the hybrid systems are superior and having top indices without considering economic factors.

More exchange of information is required between interfaces in the energy system [6]. In this paper it is pointed out that one interface where lack of information exists is the interface in district heating substations, between the distribution network and the customer building heating systems. In order to reduce future customer and heat supplier costs, a smart functions identifying errors and deviations in substations should be derived as well as defining normal and abnormal heat load patterns in substations with the aim to provide information about substations for creating future applications in smart heat grids.

Heat load variations in district heating systems are both seasonal and daily and cause increased costs [7]. While seasonal heat load variations are well analysed, there is lack of analyses of daily heat load variations. It is concluded that daily heat load variations is small compared to seasonal heat load variation. Method developed in this paper defines three parameters: annual relative daily variation, relative daily variation and relative hourly variation. The method is applied on 20 Swedish district heating systems.

When it comes to daily operation of a district heating system, the structure of the problem is somewhat different. In this case, the task is to satisfy the consumers of heat demand in the cheapest possible way through the optimum use of the different head production units, and heat stores if available, where environmental issues may also be considered. This problem is highly dynamic, and operational optimization requires methods that are quite different from those used for the process documentation of the process in the form of on-line measurements, as well as an appropriate mathematical description and understanding of the different sub-processes [8].

In order to improve the operation of district-heating systems, it is necessary for the energy companies to have reliable computerized optimization routines implemented in their organizations [9].

The aim of this study is to develop reliable optimization model regarding building thermal insulation and fuel consumption, cost planning as well as to underscore the importance of energy consumption in energy efficiency of buildings by improving the thermal insulation of buildings, while respecting existing regulations and standards.

2. Problem description

Buildings in Alipasino polje in Sarajevo, Bosnia and Herzegovina, were built in late seventies of the last century without facade insulation. Current consumption of thermal energy in Bosnia and Herzegovina, in housing stock is, on average, 150 kWh/m^2 of living space [10], while the European standards and norms is 50 kWh/m^2 [11] what is three times less than the amount of energy that is currently consumed.

That is why the current heating system, even if reaching the goal of heating the households cannot be treated as energy efficient system. To reach the European standard of energy consumption it is necessary to consider installing adequate insulation on walls on these buildings as well as installing new windows.

This approach will lead to better energy efficiency and gas reduction while satisfying household living conditions.

3. Research methodology

Heat transfer coefficient of the current state of construction and new simulated structure of walls on the buildings is determined. On the basis of determined heat transfer coefficient thermal losses are calculated, and thus the energy savings after installing insulating material on the walls of the building are calculated. Insulating material in this simulation that is considered is styrofoam, and the thickness of styrofoam is determined by optimizing return on investment. Apart from styrofoam new windows are considered to be installed. After getting the values of the savings in this simulation return on investment is calculated as well as prediction of fuel consumption.

The structure of the wall claddings of buildings in Alipasino polje is as follows:

a. Reinforced concrete blocks 25 cm thick.
b. Perlite coating 5 cm thick.
c. Mortar, inner and outer 2 cm thick.

The total heat loss is divided into two segments:

a. Heat losses due to the transmission.
b. Heat losses due to the ventilation.

70% of the total heat loss comes from transmission losses, while 30% comes from ventilation losses [12]. Calculating of the total heat loss is described by equation (1):

$$Q = Q_t + Q_v \ [W] \tag{1}$$

where:

- Q_t = transmission losses.
- Q_v = ventilation losses.

Transmission losses are divided into losses through walls (Q_1) and losses through windows (Q_2) as shown by equation (2).

$$Q_t = Q_1 + Q_2 = U_1 \cdot A_1 \cdot \Delta t + U_2 \cdot A_2 \cdot \Delta t \ [W] \tag{2}$$

where:

- U_1, U_2 = coefficients of heat transfer through walls and windows respectively in W/m^2K.
- A_1, A_2= area of walls and windows respectively in m^2.
- Δt = difference between inside and outside temperature.

Targeted household inside temperature is 20 $°C$, while outside temperature in this simulation is -18 $°C$. This assumption leads to Δt value of 38 $°C$.

In order to calculate transmission losses it is necessary to calculate the heat transfer coefficient. Heat transfer coefficient U is calculated by equation (3).

$$U = \frac{1}{\frac{1}{\alpha_u} + \sum_{i=1}^{n} \frac{\delta_i}{\lambda_i} + \frac{1}{\alpha_s}} \left[\frac{W}{m^2K}\right] \tag{3}$$

where:

- α_u = heat transfer coefficient due to convection and radiation exchange on inside surface ($\alpha_u = 8\ W/m^2K$).
- λ_i = thermal conductivity of each layers of material of the wall (W/mK).
- δ_i = thickness of each layers of material of the wall (m).
- α_s = heat transfer coefficient due to convection and radiation exchange on outside surface ($\alpha_s = 23\ W/m^2K$).
- n = number of layers of materials of the wall.

On basis of EN 673 standards and thickness of each material, the values of coefficients for calculating heat transfer coefficient are determined. Value of those coefficients is shown in Table 1.

Table 1. Coefficients on the basis of EN673 standards.

Material	$\lambda_i\ [W/mK]$	$\delta_i\ [m]$
Inner lime mortar	0,81	0,02
Reinforced concrete blocks	2,33	0,25
Perlite coating	0,05	0,05
Outer cement mortar	0,81	0,02
Styrofoam	0,041	thickness of styrofoam (determined by optimizing return on investment)

Using equation (3), heat transfer coefficient of walls is calculated as shown by equation (4).

$$U_1 = \frac{1}{\frac{1}{8}+\frac{0{,}02}{0{,}81}+\frac{0{,}25}{2{,}33}+\frac{0{,}05}{0{,}05}+\frac{0{,}02}{1{,}40}+\frac{1}{23}} = 0{,}761\ W/m^2K \tag{4}$$

Heat transfer coefficient value through existing windows on the buildings is determined on the basis of EN 673 standards.

$$U_2 = 3{,}10\ W/m^2K \tag{5}$$

Surface area of the walls and windows of the buildings subject to the insulation installation is shown in Table 2.

Table 2. Coefficients on the basis of EN673 standards.

Surface for warmth	Surface of walls (70%)	Surface of windows (30 %)	Heat losses Q
316.709 m^2	221.696 m^2	95.012 m^2	30.507 kW

Heat losses for the first series of the buildings are depicted in Fig. 1 [13].

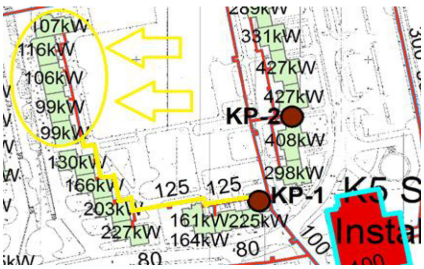

Fig. 1. First series of buildings on Alipasino polje.

Costs of installing styrofoam and new windows on buildings used in this research (based on local prices) are:

a. Price of styrofoam 1 cm thick is 0,40 € + 11,90 € for other materials and works apart from styrofoam.
b. Price of new windows is 114,70 € per m^2.

Selection of the thickness for styrofoam is done by minimizing return on investment. Discount due to the quantity of styrofoam is assumed to be 15%, while discount due to the quantity of new windows is 10%.

4. Mathematical model and results

It is necessary to construct a model to obtain the results by minimizing return on investment. Selection of thickness for styrofoam is done by optimization technique using Solver Add-in. Results of the optimization process include the investment and savings of the gas calculation.

4.1. Optimization

For the defined problem, model developed in this paper should calculate the thickness of styrofoam by minimizing payback time. Investment is described by the equation (6).

$$Investment = [(p_s \cdot d + p_{om}) \cdot A_1] \cdot (1 - d_1) + (p_2 \cdot A_2) \cdot (1 - d_2) \quad (6)$$

where:
- d = thickness of styrofoam.
- p_s = price of styrofoam.
- p_{om} = price of other materials and works when installing styrofoam on walls of buildings.
- p_p = price for new windows.
- d_1 = discount due to the quantity of styrofoam.
- d_2 = discount due to the quantity of windows.

Calculation of the heat transfer coefficient is done applying equation (3) based on thickness of styrofoam. Heat losses Qt are calculated applying equation (2), which depends on the heat transfer coefficient.
On the basis of current and new projected heat losses, savings can be determined using the equation (7).

$$Savings = 1 - \left(\frac{Qtnew + Qv}{Q}\right) \quad (7)$$

where:
- Q_{tnew} = new transmission losses.
- Q_v = ventilation losses.
- Q = current total heat losses (determined by equation (1)).

Calculation of profit coming from the investment is observed as difference between current and new costs which is shown by equation (8).

$$Profit = (Current\ cost - New\ cost) \quad (8)$$

Standard cubic meter, m_s^3, represents standard gas volumes expressed at temperature of 15 °C and pressure of 1,013 bar. Current cost is determined on the basis of gas price (0,455 €) and gas consumption (8.059.271,40 Sm^3) as calculated by equation (9).

$$Current\ cost = 8.059.271{,}40 \cdot 0{,}455 = 3.707.968{,}50\ € \quad (9)$$

New cost is calculated as current cost minus savings obtained by installing insulation on the buildings. Calculation of return on investment (ROI) is shown by equation (10) [14].

$$ROI = \frac{ln\left[1-\left(\frac{c_i}{c_d}\right)\cdot\frac{(i-r)}{(1+r)}\right]}{ln\left[\frac{(1+r)}{(1+i)}\right]} \tag{10}$$

where:

- c_i = value of investment.
- c_d = value of profit from investment.
- i = interest rate.
- r = value of inflation.

Model optimization of the thickness of the styrofoam includes equations (3), (4), (6), (7), (8), (9) and (10). This calculation is done using Solver Add-in. “Objective Cell” in Solver window is defined as return on investment. This optimization is done by changing variable cell of thickness of styrofoam. Constraints in the optimization model are added in the field “Subject to the Constraints”. After that Solver is ready to perform optimization.

Table 3. Return on investment.

d	Investment	U	Qt
18 cm	13.430.550,66 €	0,175 W/m^{2}K	6.170,39 kW
Savings	Profit	Return on investment	
0.3747	1.374.014,65 €	9,00 years	

For the case of the minimization of the return on investment, the model solution is to use styrofoam 18 cm thick, and the obtained payback period is 9 years. Other values are shown in Table 3.

4.2. Regression and correlation analysis

Regression analysis is a statistical technique used to determine the relationship between a dependent variable and one or more independent variables. More specifically, simple regression analysis helps to understand how the typical value of the dependent variable changes when the independent variable is varied.

Correlation and regression analysis are related in the sense that both deal with relationship among variables. The correlation coefficient is a measure of linear association between two variables and no casual effect is implied. Values of the correlation coefficient r are always between -1 and +1. A correlation coefficient of -1 and 1 indicates that two variables are perfectly related in a negative and positive linear sense, respectively [15]. Heat power demand for a heating system during the heating season mainly depends on outside temperature, so there is a causative relationship between these two variables.

Data about the gas consumption and outside temperature are provided by local district heating company Toplane. Based on this data correlation matrix was derived with calculation of the value of coefficient of correlation $r = -0{,}9557$. Also the same set of data is used to derive the scatter plot as shown in Fig. 2.

The scatter plot clearly shows strong linear relationship between dependent variable gas consumption and independent variable outside temperature, as proved by the value of the correlation coefficient, which means that the more outside temperature drops down the more increase of gas consumption (and vice versa). Scatter plot is used to draw linear trend line. The trend line has negative slope and positive intercept indicating negative relationship between two variables. Equation of the trend line and associated coefficient of determination, R^2, is shown in Fig. 3.

Due to the fact that in simple regression with one independent variable, coefficient of determination, R^2, equals r^2, and one can obtain the value of the coefficient of determination which is $R^2 = 91{,}34$ %. The meaning of R^2 is that 91,34% variability of gas consumption is explained by variability of outside temperature.

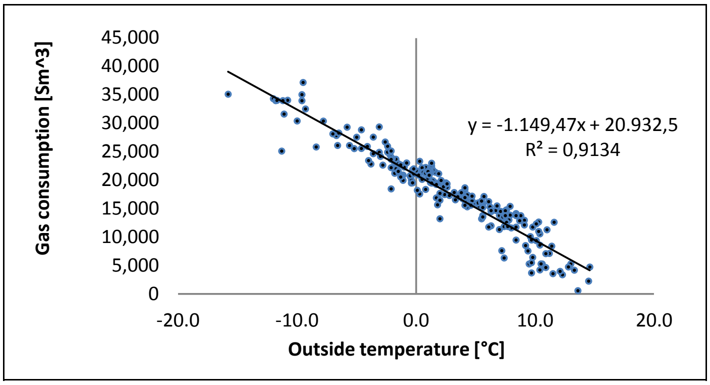

Fig. 2. Gas consumption vs. outside temperature.

Regression analysis is performed as well in order to predict the gas consumption of new simulated state. Level of significance α or the probability of Type I Error (rejecting H_0 when it is true) used in this research is 0,05.

Part of the regression output is given in Table 4. including the values of regression coefficients, standard error, t-stat and p-value.

Table 4. Regression output.

	Coefficients	Standard error	t-stat	p-value
Intercept	20.932,50	164,74	127,07	0,00
Outside temper.	-1.149,47	24,84	-46,27	0,00

Based on data given in Table 4. the regression equation is given by equation (11), and is same as the equation of the trendline as shown in Fig. 3.

$$y = 20.932{,}50 - 1.149{,}47 \cdot x \tag{11}$$

Dependent variable is gas consumption (y), and the independent variable is outside temperature (x). Coefficinet of the independent varibale represents the slope of the sample regression line (b_1). Standard error represents standard deviation of the slope of the regression line (s_{b_1}).

The conclusion about the slope of the regression line is done by formal two tail hypothesis test. Hypothesised slope is denoted as β_1. The null and the research hypothesis are defined as follows:

- $H_0: \beta_1 = 0$
- $H_1: \beta_1 \neq 0$

Test statistic for the formal hypothesis testing is defined by the following equation:

$$t_{stat} = \frac{b_1 - \beta_1}{s_{b_1}} \tag{12}$$

Calculated value for t_{stat} is -46,27, which means that this value falls into rejection region. Also, p-value for this test is 0,00. The conclusion of the formal hypothesis testing is to reject the null hypothesis and that there is sufficient evidence that outside temperature affects gas consumption.

From the results of the regression analysis, confidence interval of the slope of the regression line with lower and upper limts are calculted as shown in Table 5.

Table 5. Confidence interval.

	Lower 95%	Upper 95%
Intercept	20.932,50	21.257,32
Outside temperature	-1.149,47	-1.100,49

The confidence interval for the slope for 95% level of confidence is from -1.149,47 to -1.100,49, as it is shown in Table 5.

Residual of an observed value is the difference between the observed value and the estimated function value. The differences in values of the dependent variable y and regression values are residual deviations.

Two important assumptions of linear regression, when it comes to residuals, are:

- Residuals in the model are normally distributed – the values of the residuals are centered around zero.
- Residuals in the model have a constant variance for the full range of independent variables.

To verify these two assumptions it a histogram of residuals is plotted as shown in Fig. 3. From the histogram one can conclude that the first assumption is satisfied.

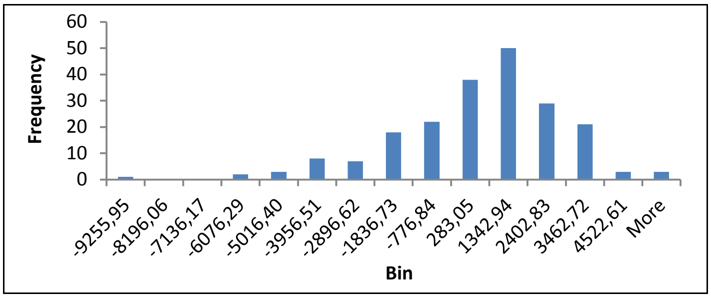

Fig. 3. Histogram of residuals.

The second assumption is checked by drawing scatter plot of standardized residulas vs. predicted gas consumption (Fig. 4). The scatter plot depicted in Fig. 4. indicates that the second assumption is satisfied as well.

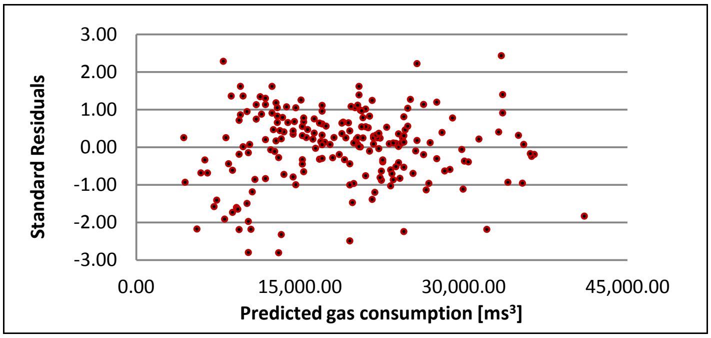

Fig. 4. Standardized residuals vs. predicted gas consumption [ms^3].

Calculted mean value of the standardized residuals in this research equals zero. All points of standardized residuals are between three standard deviations from the mean value with constant variance for the full range of independent variable.

Based on regression analysis it can be confirmed that there are clear evidences of casual effect between gas consumption and outside temperature.

Prediction of the gas consumption can be made based on regression line.

5. Conclusion

This research is focused on investing in insulation of buildings to increase energy efficiency. Investments in insulation of buildings can be considered as suitable approach and the right way to increase energy efficiency whether it is an older building or recently constructed building. By analyzing the current state of insulation of buildings and simulation done in this research (after installing styrofoam on the facade and replacing the old with the new windows) it can be concluded that the investment in the insulation of buildings is profitable investment. Model developed in this paper shows that when the return on investment is minimized styrofoam 18 cm thick is selected, and the obtained payback period is 9 years. Looking at the long term, after the return on investment period, significant savings will take place especially having in mind that the price of gas is constantly increasing.

Besides insulation of buildings, efficiency of the process of distribution of thermal energy could be improved if the system includes prediction of the outside temperature. This would eliminate the delay of delivery of thermal energy when there is no need for it. Also, the case of maintaining a temperature of water in the pipes during nights when heating is not supposed to work, to save fuel when starting the boiler next morning, to avoid increase in gas consumption to reach required water temperature. After examination of such case, it is possible to reach a conclusion whether it is worth to keep boilers at a lower frequency operation during nights in order to achieve greater energy efficiency. Another aspect of energy efficiency is through the analysis of possible reconstruction of boilers and pipelines. Analyzing this aspect, a concrete conclusion can be expressed in order to increase energy efficiency.

The results of this research could be of benefit to local district heating company regarding the cost of heat energy production and protection of environment regarding CO_2 emission. Model developed in this paper should be applied to all buildings connected to Sarajevo district heating system with the aim to reduce thermal energy consumption. Future research could consider analysis of impact of other influential factors such as wind, humidity, solar radiation, cold-water temperature etc. and possible inclusion in the model.

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