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Evaluation of Linear Economic Characteristics of Machines for Optimal Operation of Heat Sources †

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Abstract: Optimization problems of heat source operation are solved by linear (LP) or nonlinear (NLP) programming. The optimization methods can be compared based on the complexity of the computational program setup, the time required to input and update data, and the computational time for optimal shifting and loading of installed power machinery. LP methods are preferred (e.g., simplex method, method characteristics), but the Lagrange multipliers NPL method is sometimes applied. In this paper, the method of proportional increments (LP, NLP) [1,2] is applied to compare the optimal loading of the power machinery installed in the thermal power plant using linear and quadratic economic characteristics.

Keywords: heat sources optimization; cogeneration units; linear and non-linear methods

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1. Introduction

Efficient energy transformation, reduction of emissions as well as improvement of economic indicators of systems of centralized heat supply SCHS are the main objectives of heat source operation optimization. Heat optimization directly translates into economic efficiency. Industries that rely heavily on heat processes, such as manufacturing, agriculture, and energy production, can experience significant cost savings by optimizing their heat-related operations. Improved energy efficiency means lower utility bills and reduced operational expenses. These savings can be reinvested in research, development, and innovation, fostering economic growth and competitiveness. It is far more important how the cogeneration units are operated than whether they represent the latest technology progress or not. Therefore, for the management of cogeneration units it is a key issue to find optimal operating conditions bringing in the largest income [3]. In Slovakia, as well as across the entire European Union (EU), there is a significant potential for a major increase in the efficiency of existing power plants and heat exchanger stations. This potential arises from various factors such as aging power infrastructure, advancements in technology combined heat and power (CHP), systems and environmental concerns [4]. Utilizing this potential can have substantial economic, environmental, and energy security benefits.

This paper deals with the optimal leading and shifting of heat sources. The result of the optimization is the optimal loading course—how the energy machines and equipment should be loaded—and the optimal shifting—which of the energy machines and equipment installed in the heat sources should be in operation [1].

2. Formulation of the Optimization Problem

The input components for the optimization of the heat source operation are [1]:

- simplified thermal diagram of the heat source,

- the energy and economic characteristics of the energy machines and equipment installed,
- definition of the objective function—optimization criterion,
- the choice of the method of dividing the fuel costs for heat and electricity in combined electricity and heat production (CHP).

The output of the optimization problem is the optimal shifting and loading of the power machines and equipment in the heating plant. A simplified thermal schematic of the plant is shown in Figure 1. In the heating plant, steam is produced in the boiler B4 (control range 30.0 ÷ 105.0 MW), then expanded in the back-pressure turbine T (electrical output 5.0 ÷ 25.0 MW) and in the heat exchanger HE (thermal output 19.8 ÷ 78.1 MW) the emission steam is condensed. Three hot water boilers B1 (3.0 ÷ 15.0 MW), B2 and B3 (17.0 ÷ 45.0 MW) and two cogeneration units CU1, CU2 (thermal output 2.7 ÷ 4.2 MW, electrical output 1.55 ÷ 3.1 MW) are also installed in the heating plant.

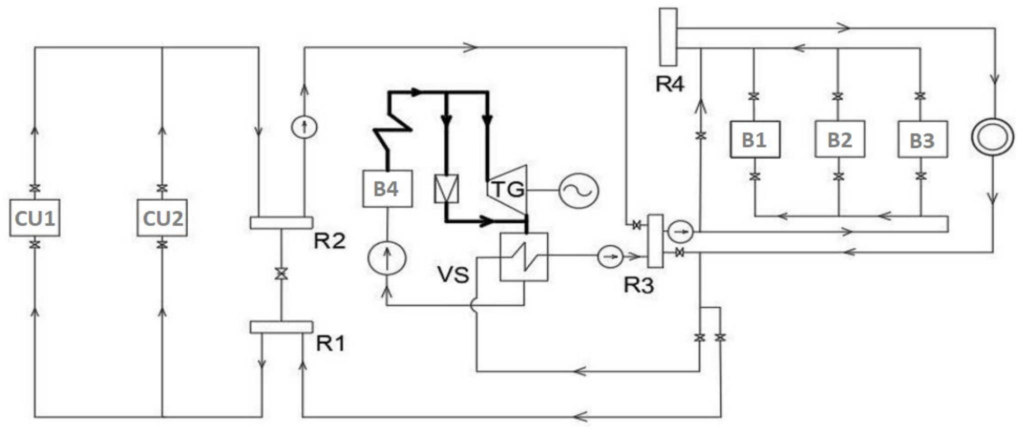

Figure 1. Simplified thermal diagram of the heating plant.

By measurements on the boilers, the energy characteristic of the boiler B_i can be determined, i.e., the dependence of the boiler efficiency η_{Bi} on its heat output P_{Bi}. The points η_{Bi} (P_{Bi}) are translated as 2nd degree regression polynomials described by the equation.

$$\eta_{Bi} = \alpha_{2i}P_{Bi}^2 + \alpha_{1i}P_{Bi}^2 + \alpha_{0i} \tag{1}$$

Boiler input in fuel $P_{fuel\ i}$ is:

$$P_{fuel\ i} = \frac{P_{Bi}}{\eta_{Bi}} \tag{2}$$

The energy characteristic of the boiler B_i in another form is obtained by translating the regression line through the points $P_{fuel\ i}$ (P_{Bi})

$$\mathrm{P}_{pal\ i} = b_{1i}P_{Bi} + b_{0i} \tag{3}$$

For the economic characterization of the boiler B_i it is necessary to calculate the fuel cost flow $n_{fuel\ i}$ (€.s^{-1}), which depends on the price $c_{fuel\ i}$, the flow rate $\dot{m}_{fuel\ i}$ and the calorific value $Q_{n\ i}$ of the fuel (natural gas), and the power input in the fuel $P_{fuel\ i}$

$$\mathrm{n}_{fuel\ i} = c_{fuel\ i}\,\dot{m}_{fuel} = c_{fuel\ i}\frac{P_{fuel\ i}}{Q_{n\ i}} \tag{4}$$

After adjusting these relations, the linear and quadratic economic characteristics of the boiler are B_i will be:

$$\mathrm{n}_{fuel\ i} = \frac{C_{fuel\ i}}{Q_{n\ i}}\ (b_{1i}P_{Bi} + b_{0i}) = c_{1i}P_{Bi} + c_{0i} \tag{5}$$

$$\mathrm{n}_{fuel\ i} = d_{2i}P_{Bi}^{2} + d_{1i}P_{Bi} + d_{0i} \tag{6}$$

Figure 2 shows the energy characteristic of the boiler B4 (Equation (1)), the Figure 3 shows its linear and quadratic economic characteristics (Equations (5) and (6)).

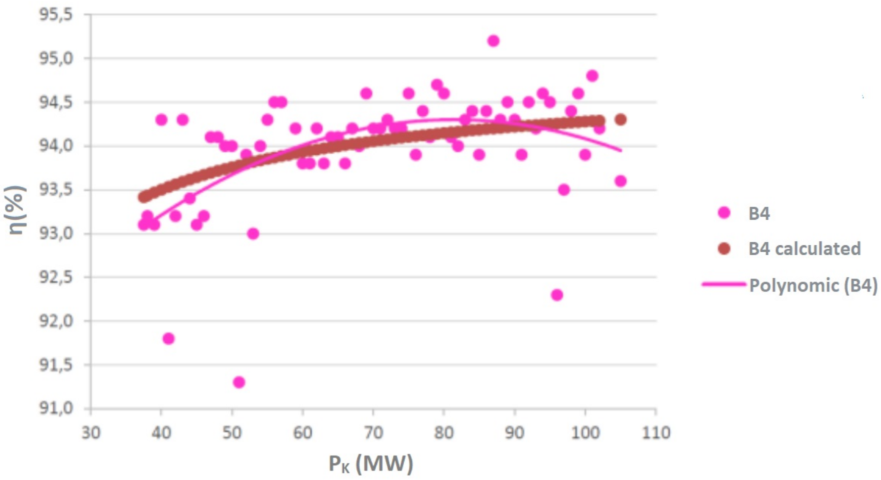

Figure 2. Energy characteristics of boiler B4 according to Equation (1).

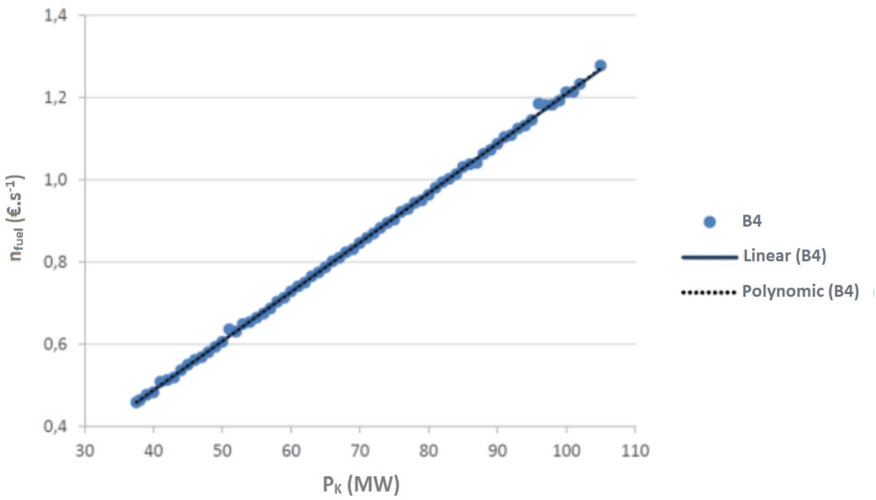

Figure 3. Linear and quadratic economic characteristics of boiler B4 according to Equations (5) and (6).

For CHP (CU or combination of boiler B4, T and HE) for the chosen method m of fuel cost splitting for heat and electricity, the fuel cost flow $\mathrm{n}_{\mathrm{fuel\ i}}$ is defined as the sum of the fuel cost flows for heat $\mathrm{n}_{\mathrm{fuel\ q\ i,m}}$ and for electricity $\mathrm{n}_{\mathrm{fuel\ e\ i,m}}$

$$\mathrm{n}_{fuel\ i} = \mathrm{n}_{fuel\ q\ i,m} + \mathrm{n}_{fuel\ e\ i,m} \tag{7}$$

By introducing fuel fractions for the production of heat $\beta_{\mathrm{q\ i,m}}$ and electricity $\beta_{\mathrm{e\ i,m}}$, the fuel cost stream is reduced to $\mathrm{n}_{\mathrm{fuel\ i}}$

$$\mathrm{n}_{fuel\ i} = \beta_{q\ i,m}\, n_{fuel\ i} + \beta_{e\ i,m}\, n_{fuel\ i} \tag{8}$$

where:

$$\beta_{q\,i,m} + \beta_{e\,i,m} = 1 \tag{9}$$

After adjustments, the linear and quadratic economic characteristics of the device are B_i

$$n_{fuel\,q\,i,m} = c_{1i,m} P_{Bi} + c_{0i,m} \tag{10}$$

$$n_{fuel\,q\,i,m} = d_{2i,m} P_{Bi}^2 + d_{1i} P_{Bi} + d_{0i} \tag{11}$$

To optimize the operation of the heating plant, a daily load diagram (DLD) was selected to determine the heat demand of the SCHS at the threshold of the heating plant at hourly intervals Δτ = 1 h during time τ < 0 h, 24 h> of the heating period with an average daily outdoor air temperature of −7.7 °C. The daily heat supply to the SCHS at the threshold of the heating plant was 1 707 MWh, with heat outputs ranging from 53.4 ÷ 84.8 MW. The basic requirement of the optimization calculation is to cover the heat demand of the $P_{HS,\tau}$ SCHS at the source threshold at time τ by the operated power machines and equipment.

$$P_{HS,\tau} = \sum_{j=1}^{n} j_{Bi} P_{Bi} \tag{12}$$

For the operating state of the energy machine and equipment B_i, $j_{Bi} = 0$ if the equipment is shut down and $j_{Ki} = 1$ if the equipment is in operation. Solving the optimization problems with the m method of fuel cost sharing, the following was chosen as minimum daily fuel cost criterion for heat $N_{fuel\,q,m}$ (€.day^{-1})

$$N_{fuel\,q,m} \xrightarrow{def} min \tag{13}$$

Based on this criterion, the boilers, CHP, HE, T installed in the heating plant are sorted and loaded during the day. The economic and energy intensity of the production as well as the ecological impact are considered.

To meet the criterion of minimum fuel cost $N_{fuel\,q,m}$ for the heat delivered during the day, the fuel cost flow for the heat $n_{fuel\,q,m\,\tau}$ must be minimum at each time τ

$$n_{fuel\,q,m\,\tau} \xrightarrow{def} min \tag{14}$$

where:

$$n_{fuel\,q,m\,\tau} = \sum_{i=1}^{n} j_{Bi}\, n_{fuel\,q\,i,m} \tag{15}$$

Using the trapezoidal method, the daily fuel cost of heat $N_{fuel\,q,m}$ is defined as:

$$N_{fuel\,q,m} = \sum_{i=1}^{24} \frac{n_{fuel\,q,m,\tau} + n_{fuel\,q,m\,\tau^{-1}}}{2} \Delta\tau \tag{16}$$

For the solution of the optimization problem, the method of proportional increments was chosen because according to this method, using the same algorithm, both linear and quadratic economic characteristics can be applied [1,2]. The aim is to verify the application of linear economic characteristics in comparison with quadratic economic characteristics in the optimization of the loading of power machinery and equipment installed in the thermal power plant. The optimization criterion also includes the method of dividing the fuel costs into electricity and heat. In the calculations of optimization of the heating plant operation, the energy, Kadrnok’s [5] and differential methods of division for these costs were applied. The results of optimization calculations are compared depending on the choice of the method of fuel cost division in CHP and the use of linear or quadratic economic characteristics [6].

3. Optimization of Power Plant Operation

For the selected DLD, 51 combinations of sequencing of energy machines and equipment installed in the CHP plant (43 variants boilers + CHP and 8 variants boilers only) are suitable, provided that these energy machines and equipment cannot be started up or shut down during the day.

The paper presents the results of the operation of the shifting variant in which the boilers B1, B4, the turbogenerator T, the substation HE and the cogeneration units CU1, CU2 are optimally loaded. From the point of view of the daily fuel cost of heat, this variant is the optimal shifting variant when applying the differential method of dividing the fuel cost of heat, 2nd in the order according to the Kadrnok's method and 16th according to the energy method.

For Kadrnok's and differential methods of dividing the fuel heat cost using both linear and quadratic economic characteristics (Figure 4), the optimal loadings of B1, CU1, CU2, HE and T are the same during the day. The range of thermal and electrical outputs of these optimally loaded energy machines and equipment is summarized in Table 1. The loading of boiler B1 is the same for both splitting methods. When the economic characteristics of linear CU1, CU2 are applied, they are operated at nominal power throughout the day. The thermal output of the HE supplements the output of the heating plant so that the heat demand of the centralized heat supply is covered. When quadratic economic characteristics are applied, HE is loaded first, then CU1 and CU2 supplement the heat output of the heating plant.

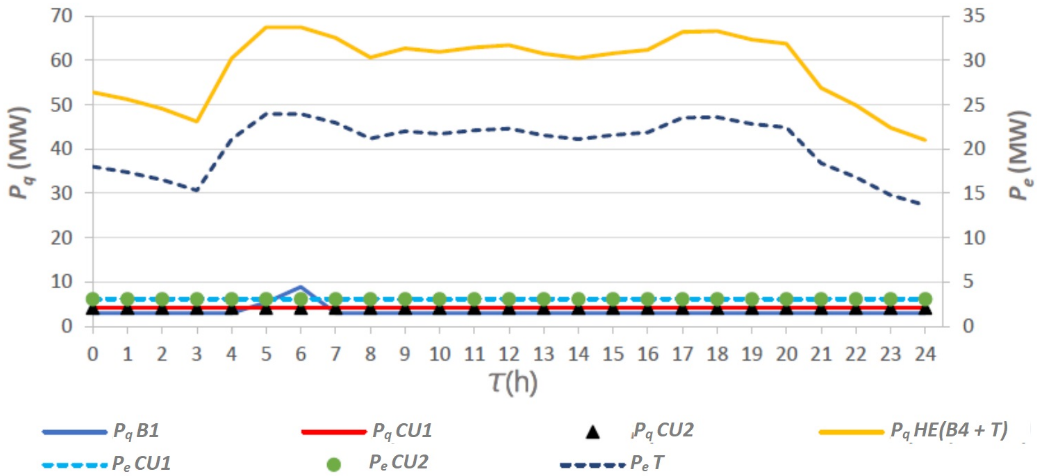

Figure 4. Optimal loading of B1, CU1, CU2, HE and T according to the Kadrnok's and differential method of division of fuel costs for heat using linear economic characteristics.

Table 1. The range of thermal and electrical outputs of optimally loaded B1, CU1, CU2, HE and T during of the day according to the Kadrnok's and the differential method of dividing the fuel cost of heat.

Economic characteristics	*Pq B1*	*Pq CU1*	*Pq CU2*	*Pq HE*	*Pe CU1*	*Pe CU2*	*Pe T*
				(MW)			
Linear	3.0 ÷ 8.9	4.2	4.2	42.0 ÷ 67.5	3.1	3.1	13.7 ÷ 24.0
Quadratic	3.0 ÷ 8.9	3.7 ÷ 4.2	3.7 ÷ 4.2	43.0 ÷ 67.5	2.7 ÷ 3.1	2.7 ÷ 3.1	14.1 ÷ 24.0

For the energy method of dividing the fuel cost of heat according to both linear and quadratic economic characteristics, the order of optimal loading is as follows: preferably

B4, T and HE are loaded, then B1 and CU1, CU2 are loaded at minimum power during the whole day.

Figure 5 shows the daily fuel cost of heat for the combination of B1, CU1, CU2, CU3, HE and T shifting according to the energy, Kadrnok's and differential partitioning methods using linear and quadratic economic characteristics. According to the energy method, the difference between the fuel cost $N_{fuel\ q}$ calculated using linear and quadratic characteristics is 71 €.day^{-1}, which is a 0.1% increase when using linear characteristics. According to Kadrnok's method, the difference is 176 €.day^{-1}, i.e., an increase of 0.3% compared to linear characteristics. Using the differential method, the difference is 27 €.day^{-1}, an increase in daily costs of 0.1% using linear characteristics.

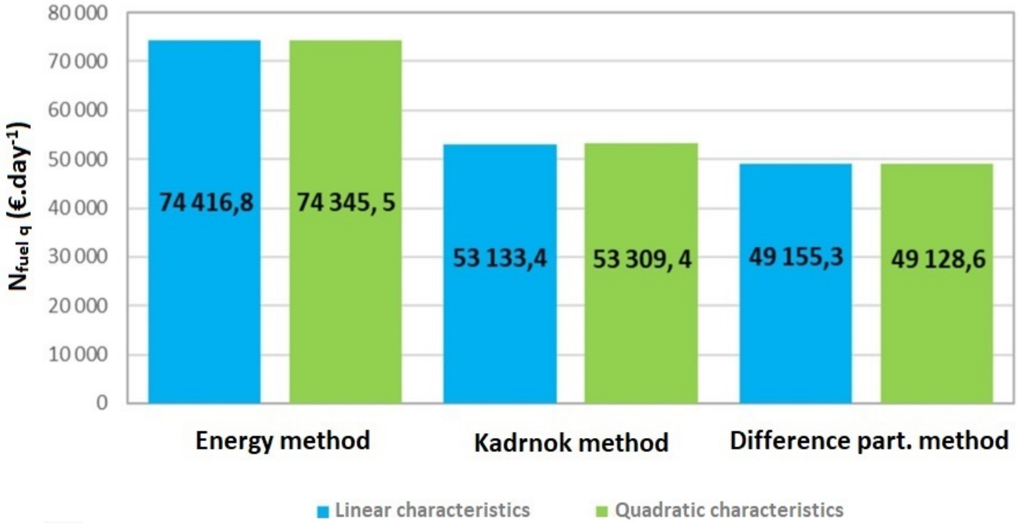

Figure 5. Combination of B1, CU1, CU1, CU2, HE and T—daily fuel cost of heat by energy, Kadrnok's and differential partitioning methods using linear and quadratic economic characteristics.

4. Conclusions

Using linear economic characteristics of power machinery and equipment, the daily fuel cost of heat is increased by 0.1% to 0.3% compared to the application of quadratic characteristics in the optimization calculations of the heating plant operation. These analyses show that it is possible to apply linear economic characteristics and linear programming methods for heat source operation optimization calculations.

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