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Operating Modes Optimization for the Boiler Units of Industrial Steam Plants

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Abstract: The free market forces energy-intensive industrial enterprises to continuously compete. A possible competitive advantage for such enterprises is reducing the finished products cost. This may be achieved by reducing the share of energy in this cost, including by rationalizing the use of energy resources. This study develops a system for the automated analysis and calculation of feasible boiler unit loads, defined according to the criterion of the minimum cost of live steam in a separate steam plant pipeline. The calculations consider the balance limit on the steam, the boiler unit's wear and tear, performance specifications, and economic indicators of fuel consumption in the calculation. The software also defines the optimal fuel mix composition when forecasting the operating modes of the power plant boiler units in real-time mode. The calculation algorithm is based on the dynamic programming technique combined with the sequential equivalenting method, which ensures the convergence of calculations. When a steam plant model is developed, much attention is paid to the thermal scheme and technical and economic specifications of boiler units. In the system, the boiler models are set as a table containing the ratio between the boiler unit's steam capacity and energy consumption while considering the cost of a ton of live steam with the specified parameters. The key economic effect of implementing the system is determined by reducing the fuel cost due to its rational redistribution between the power plant boiler units. Implementing the system allows the reduction of energy costs by 1.4%.

Keywords: secondary energy resources; dynamic programming technique; energy saving; energy carrier; technical and economic model

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1. Introduction

Solving energy-saving issues is the key point in reducing the share of energy in the cost of finished products of energy-intensive industrial enterprises.

Industrial enterprises use a number of measures to rationalize power consumption:

- implementing technologies for optimal power equipment control to reduce the consumption of electricity and other energy;
- designing and/or reconstructing power grids to reduce power losses and outages. The first allows for reducing the power cost, the second reduces the economic damage caused by a power outage;
- implementing IT solutions for routine monitoring, control, and analysis of the parameters of objects for current management, regulation, search for rational modes, as well as forecasting their possible operation modes, etc.

Energy-intensive enterprises, as a rule, have an internal generating base. These are mainly local steam plants operating on various fuels: crude oil, coal, natural gas, and, in some remote regions, fuel oil. Secondary energy carriers (coke oven and blast-furnace gases, in some cases, converter gas) are also used. This use allows improving the environmental situation in the location and reducing the live steam and electricity costs. For consumers with internal energy sources and a significant consumption, implementing energy-saving measures requires 3–4 times less investment compared to the cost of a corresponding increase in power generation, including the production of fuel and energy resources.

Improving the efficiency of the industrial steam plant operating modes has been studied and developed extensively to refine the power plant process at all its stages.

Improving the efficiency of energy resources use at industrial enterprises is among the most important problems. Building energy-saving heat engineering systems at industrial enterprises can be based on modern scientific achievements, but this approach requires large investments. Therefore, currently, the most relevant means is to revamp existing heat engineering systems for the wide use of internal energy resources.

Batukhtin A.G. and Makkaveev V.V. [1] describe an approach aimed at reducing the thermal energy cost through the use of optimization models for the heat supply system operation. It is based on a mathematical model of the 'heat supply source—heat network—heat consumers' scheme using systems of nonlinear algebraic equations composed on the assumption of continuity and conservation of energy. The technique considered herein allows for significant improvement of combined heat and power plants (CHPPs).

Baibakova S.A. applies optimization techniques to distribute the CHPP's heat and fuel between the heat and power generation. The paper proposes a method to calculate the current heat and fuel savings for a specific CHPP when using and changing its heat extraction parameters. A simplified way of distributing heat and fuel based on the proposed technique has been considered, an example of calculation using the considered method is provided, and the results of calculations by various methods have been compared [2].

To improve the efficiency of boiler units from the environmental standpoint, the authors of [3] use the technique for separating nodes and branches in the boiler based on the theory of signal flow graphs to determine the optimal proportional distribution of air in it.

Improving the efficiency of the boiler unit's auxiliary equipment has been considered separately. Ref. [4] provides an integrated approach to optimizing the air heater blowing in the boiler of a coal-fired power plant. The key problem of the study is creating a system to monitor pollution and optimize the soot blowing of the air heater.

The issues of controlling boiler units are of interest. Ref. [5] proposes a new control technique, parametric control using proportional-integral-derivative controllers capable of controlling the calculated pressure, temperature, and fan speed values. This technique can be applied to a gasified boiler designed for space or water heating.

Koptsev L.A., Zuevsky V.V., and Sedelnikov S.V. published a paper on the opportunities for saving energy in OJSC Magnitogorsk Iron and Steel Works (MMK), Russian Federation [6]. The enterprise has to save energy under constantly changing conditions, determined by fluctuations in production volumes caused by the sales market conditions and changes in the composition of production facilities and the assortment of products. Thereat, to analyze the energy saving results and find ways to optimize the enterprise's energy balance and energy content, OJSC MMK uses the technique of end-to-end energy analysis. It is developed based on the International Iron and Steel Institute's recommendations and serves as a tool for the integral comparison of the efficient use of energy resources. The technique is based on the concept of net power consumption, which is defined as the difference between the calorific value of purchased energy resources and raw materials on the one hand and sold energy resources on the other.

Lebedev V.M. and Prikhodko S.V. consider the issues of creating a low-capacity CHPP as an element of the cogeneration system. The paper concludes that the payback period for the reconstruction of low-capacity CHPP boiler houses is 3–4 years, and some enterprises can not only meet their internal demand for electricity, but also supply it to the external grid to consumers [7].

Optimizing the power plant operating modes requires its digital model to be built. Refs. [8,9] describe steam plant models similar to the factory CHPP using a combined process. The developed models allow for defining the boiler unit and turbogenerator loads while considering the power plant's internal needs and heat transfer [8], as well as the probable load nature under the conditions of industrial power generation systems [9].

The problems of optimal power distribution between the major power plant equipment are solved [10], considering the generation of reactive power [11]. For modern power supply systems based on renewable sources, the problem of defining the optimal battery system capacity [12] and building smart microgrid models to optimize their operating modes [13] is urgent.

Along with the aforementioned problems, the issues of the optimal management and development strategy are being solved for power systems with generation through various approaches. Ref. [14] provides a technique for defining the optimal battery power plant modes under the conditions of a power supply system, considering the control actions of dispatchers. The issues of improving the reliability of the autonomous power supply system operating modes are considered [15]. Approaches have been developed to control the generation of active and reactive power by generators operating within autonomous power generation systems [16]. Ref. [17] provides the optimal decision framework for simulating various power plants, which is an important step in developing IT solutions.

Currently, great attention is paid to the issues of improving the efficiency of the boiler unit operating modes. The issues of supercritical pressure boiler operating modes have been considered [18]. The boiler operating modes and the impact of secondary energy resources on the residual boiler life are considered in [19]. Particular attention is paid to the search for the optimal energy carrier parameters for generating electric power [20].

To solve the set problems, specialized mathematical tools should be used, considering the specifics of mathematical models of various units. Currently, the genetic algorithm [21,22] is widespread, which is used to solve problems in energy and other industries [23].

The considered scientific studies should be accounted for to improve the efficiency of both individual elements of boiler units and the entire power plant.

The literature review shows that, currently, there are a lot of approaches to improve the efficiency of operating modes of various electrical units. Various technologies and systems are being implemented at industrial power plants to improve their operating modes. However, one can find integrated solutions to optimizing the operating modes of industrial generating plants.

This study develops an integrated approach used to define the optimal load of industrial steam plant boiler units. This approach and its software implementation allow for both forecasting and controlling boiler units while considering the rational use of the fuel. The developed system is intended to plan the dispatching control departments of the enterprise's energy economy and the boiler sections of industrial steam plants as a workplace for a boiler unit operator.

The study comprises the following sections: Section 2 considers the approach to developing an optimization algorithm using dynamic programming; the issues of building a boiler unit model for solving the set optimization problem. Section 3 describes the computer-aided engineering (CAE) system structure and its additional capabilities in real-time operation; a refined calculation of the rational fuel mix composition. Section 4 provides the results of implementing the CAE system at an operating steam plant using a mix of natural, coke oven, and blast-furnace gases as fuel, specifies possible system application areas, gives recommendations to improve the efficiency of the power plant operating modes, and assesses the economic effect of implementing the study results. The conclusion describes the main fields to implement the results.

2. Algorithm for Optimizing the Operation of Boilers of an Industrial Seam Plant

Industrial steam plants usually feature very complex-to-determine feasible operating modes of the major power equipment. They are determined by non-block thermal circuits, the possibility of using secondary energy resources, equipment wear and tear, diversity of equipment, and the need to consider heat and production extractions.

A way to optimize the industrial power plant operating modes is to determine the cost-effective boiler loads.

The developed algorithm is based on the dynamic programming technique, which allows for setting the source data for the calculation in tabular form; the objective function can have discontinuity and inflection points; limitations can be given in the form of equalities and inequalities. However, the use of the dynamic programming technique is always associated with the processing and storing of large data. However, the development of high-performance computing systems makes this problem less relevant. To speed up the calculation, this technique is used in combination with sequential equivalentization, which ensures saving only optimal solutions while irrational ones are excluded, and computation time is reduced (for more details on the approach developed, see [24,25]).

The optimization problem is to find the optimal steam plant boiler load according to the criterion of minimum costs for live steam, required to generate required active power, considering the load of heat and production extractions from the steam pipeline. To find the optimal solution, the limitations on the minimum and maximum allowable steam capacity of the boiler should also be met, as determined by the boiler's performance chart:

$$\begin{cases} D_{i\ \min} \le D_i \le D_{i\ \max}, \\ \sum\limits_{i=1}^{n} D_i = \sum\limits_{i=1}^{n} D_{i\ TG} + D_{ex} + D_{i.n.}. \end{cases} \tag{1}$$

where D_i is the steam consumption of the i-th boiler unit; $D_{i\ \min}$, $D_{i\ \max}$ are the boiler's minimum and maximum steam capacity, corresponding to its performance chart, t/h; D_{iTG} is the steam consumption of the i-th turbogenerator, m^3; D_{ex} is the power plant heat load, considering the heat loss during transmission, t/h; $D_{i.n.}$ is the steam volume used for the power plant's internal needs, t/h.

The dependent limitations should also be considered:

$$\begin{cases} P_{bar\ i\ \min} \le P_{bar\ i} \le P_{bar\ i\ \max}, \\ T_{fw\ i\ \min} \le T_{fw\ i} \le T_{fw\ i\ \max}. \end{cases} \tag{2}$$

where $P_{bar\ i\ \min}$, $P_{bari\ \max}$ are minimum and maximum steam pressure in the drum, kgf/cm^2; $T_{fwi\ \min}$, $T_{fwi\ \max}$ are minimum and maximum feed water temperature, °C.

The objective function has the following form:

$$Z_n = \sum_{j=1}^{n} \left(\sum_{k=1}^{m} \left(C_{k,j}(y_j) + C_{ex\ k,\ j}(y_j) \right) \right) \to \min, \tag{3}$$

where y_j is the optimal control at the j-th step; $C_{k,j}(y_j)$ is the cost of the primary energy carrier used to generate steam, required for power generation with a total load of sources P_G; P_G is the total power of turbogenerators receiving steam from a single steam pipeline; $C_{exk,j}(y_j)$ is the cost of steam consumption through extractions (industrial and/or heat); n is the number of the power plant boilers connected to a single steam pipeline; m is the total number of different primary energy carriers used at the power plant.

The developed algorithm uses source data for calculation in tabular form.

To find optimal boiler unit loads, an approach to building feasibility models of boiler units has been developed. These models represent the dependence of the boiler's steam capacity on the unit cost of live steam and the fuel mix composition ratio.

Boiler models are built based on performance charts that allow defining the minimum and maximum values of the boiler's steam capacity and the corresponding possible energy carrier consumption. A fragment of the performance chart of a TP-7 boiler operating on a mix of natural, blast-furnace, and coke oven gases, with a rated steam capacity of 150 t/h, an operating pressure of 34 kgf/cm^2, and a superheated steam temperature of 420 °C, is given in Table 1.

Table 1. Fragment of the Boiler Unit Performance Chart.

No	Parameter		Unit of Measure	Boiler Steam Capacity, t/h											
				75–100					...	120–150					
1	Drum pressure		kgf/cm^2	33–34											
2	Superheated steam pressure		kgf/cm^2	30–31											
3	Superheated steam temperature		°C	400–420											
4	Feed water temperature		°C	100–105											
5	Gauge gas consumption	natural B_{NG}	MCM/h	2.1	3.9	2.4	2.4	1.5	...	0	2	7.5	5.5	6.1	7.9
6		coke oven B_{CO}	MCM/h	5	6.5	7	0	13.5	...	13	12.5	9	8	8.5	8.5
7		blast furnace B_{BF}	MCM/h	8	11	10	64	20	...	40	32	0	9	10	5
8	Gauge gas pressure	natural	kgf/cm^2	0.62	0.62	0.61	0.62	0.63	...	0	0.6	0.61	0.62	0.61	0.63
9		coke oven	kgf/cm^2	0.06	0.06	0.07	0	0.08	...	0.06	0.06	0.07	0.07	0.06	0.08
10		blast furnace	kgf/cm^2	0.09	0.11	0.13	0.14	0.14	...	0.13	0.13	0	0.12	0.12	0.12
11	Air pressure upstream BAH		kgf/cm^2	85	90	95	173	190	...	184	185	263	249	252	278
12	Air pressure downstream BAH		kgf/cm^2	59	64	67	119	138	...	130	131	197	185	185	209
...															
24	Flue gas temperature		°C	133	135	136	170	171	...	158	162	156	165	166	168
25	Specific fuel consumption		kg o.e./Gcal	156	156	156	165	160	...	160	159	160	158	162	160

The general boiler model is given in Table 2. Data were taken from the previous paper of the authors [26]. The steam capacity D_i is defined based on the boiler's performance chart while D_{i1} and D_{ij} are always the minimum and maximum values, respectively. In the feasibility model, the i-th energy carrier consumption is also taken from the boiler's performance chart. The specifics of the steam plant boiler operating modes under the conditions of an industrial enterprise are here defined. The metallurgical process is accompanied by the generation of secondary gases, e.g., blast furnace and coke oven ones. Secondary energy carriers are generated under the conditions of an energy-intensive enterprise in very large volumes.

Table 2. General View of the Boiler Unit Feasibility Model.

D_i, t/h	D_{i1}			D_{i2}			...	D_{ij}		
B_i, m^3/h	B_{i1}	...	B_{ij}	B_{i1}	...	B_{ij}	...	B_{i1}	...	B_{ij}
B_{i+1}, m^3/h	$B_{(i+1)1}$	...	$B_{(i+1)j}$	$B_{(i+1)1}$	...	$B_{(i+1)j}$	...	$B_{(i+1)1}$	...	$B_{(i+1)j}$
...	...	...	...	...	...	...	...	...	...	...
B_{i+n}, m^3/h	$B_{(i+n)1}$	...	$B_{(i+n)j}$	$B_{(i+n)1}$	...	$B_{(i+n)j}$	...	$B_{(i+n)1}$	...	$B_{(i+n)j}$
S_i, \$/t	S_{i1}	...	S_{ij}	S_{i1}	...	S_{ij}	...	S_{i1}	...	S_{ij}

Burning such gases in a flare deteriorates the local environment, and they have been used as fuel at industrial steam plants for quite a long time. As a rule, a mix of blast-furnace and natural or blast-furnace, coke oven, and natural gases is used. This solution solves the problems of improving both the environment and efficiency of industrial power plants through the use of 'own fuel'.

However, as noted earlier, the generation of secondary gases depends primarily on the process, and their parameters (pressure, temperature) are continuously changing in the gas pipeline. This requires maintaining the calorific value of the mix with natural gas. This issue is further considered in more detail.

When using a mix of natural and secondary gases as fuel, the boiler's performance chart provides the ratios of gases in the mix, $B_{(i+1)j}$, obtained in the boiler tests during the overhaul.

For each boiler steam capacity, the unit cost of live steam, S_i, is calculated based on the given gas ratios in the mix:

$$S_i = \frac{\left(\sum_{k=1}^{n} C_k \cdot B_k\right) \cdot 1.05}{D_i}, \quad (4)$$

where C_k is the cost of the k-th energy resource, $\$/m^3$; B_k is the consumption of the kth energy resource, MCM/h; D_i is the boiler steam capacity, t/h; 1.05 is the factor considering conditionally fixed costs: wage fund, steam loss.

Table 3 and Figure 1 show an example of a feasibility model of a TP-7 boiler, built using the performance chart in Table 1.

Table 3. Feasibility Model of a TP-7 Boiler Unit.

D_0, t/h	75	100	130	150
S, \$/t	3.304	3.941	4.203	3.701
B_{NG}, $\cdot 10^3$ m^3/h	2.1	8	2	7.9
B_{BF}, $\cdot 10^3$ m^3/h	8	0	32	5
D_0, t/h	5	2.5	12.5	8.5

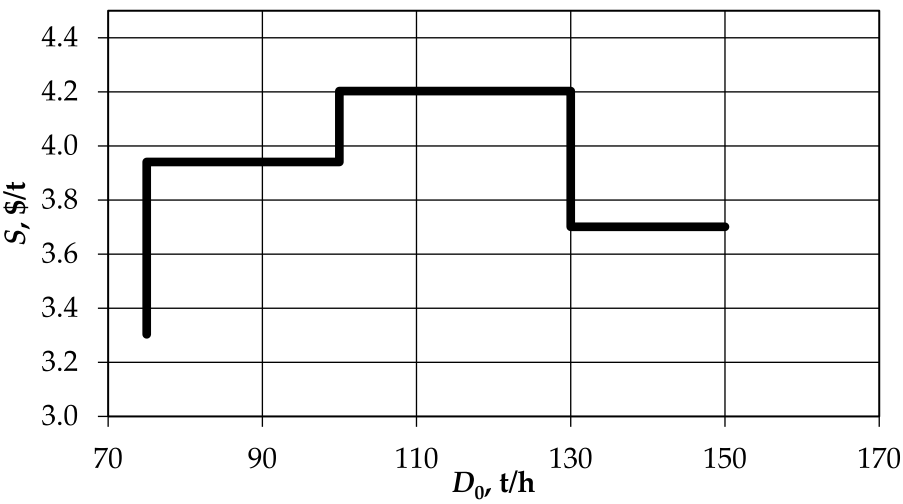

Figure 1. Example of a Feasibility Model of a TP-7 Boiler Unit.

The boiler unit feasibility models developed are a universal tool to find the optimal steam capacity distribution between the power plant units operating on a common steam pipeline. The models consider the boiler's specifications, permissible modes, and economic indicators, and estimate the efficiency of a particular mode for a given equipment.

In addition, as noted earlier, the boiler unit models in tabular form are specially adapted to solve the optimization problem of finding feasible steam capacities of boiler units using the dynamic programming technique.

The equivalent characteristic of the boiler unit is determined on the forward path of the calculation (Figure 2) [24]. At each stage of equivalentization, intermediate equivalent characteristics of boiler units are defined, comprising steam capacity, allowable energy costs, and average steam cost for two equivalented boilers. The transformation is performed for m boilers (having feasibility models shown in Table 2) operating on a common steam pipeline while each boiler can be characterized by an individual feasibility model considering the n number of fuels used.

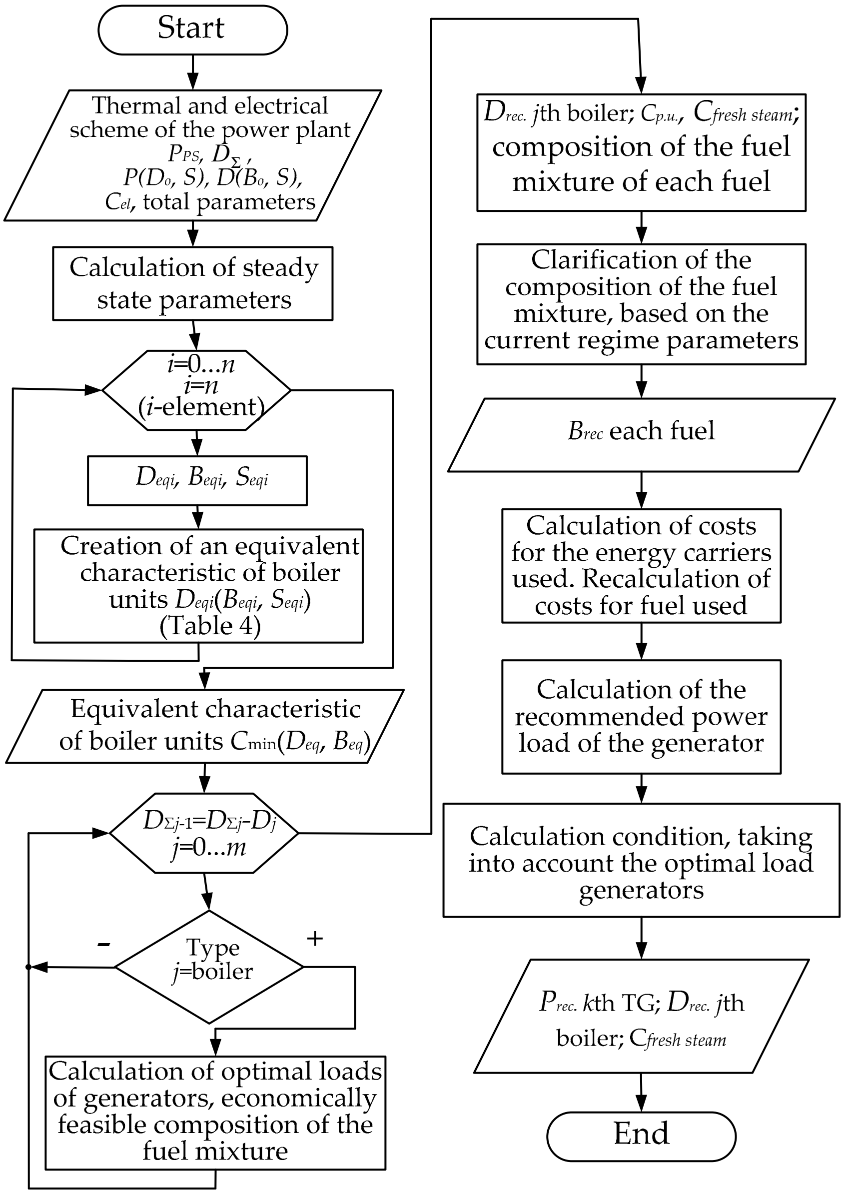

Figure 2. Flowchart for Optimizing the Operation of Boilers of an Industrial Enterprise's Internal Power Plants.

Upon defining the equivalent feasibility model, based on the required total steam capacity of the power plant D_{PP} for a given steam pipeline, the optimal boiler unit loads, and the corresponding power consumption are determined by the model. For example, if $D_{PP} = D_{eq(i+(i+m))2}$ (Table 4), then the optimal load of each i-th boiler corresponds to the third column. An equivalent model was developed in the paper of the authors [26] and adapted for this research.

Table 4. Equivalent Boiler Unit Characteristics on the Forward Path of Solving the Dynamic Programming Problem.

$D_{eq(i+(i+m))}$, t/h	$D_{eq(i+(i+m))1}$	$D_{eq(i+(i+m))2}$	...	$D_{eq(i+(i+m))j}$
$B_{eq(i+(i+m))}$, m^3/h	$B_{eq(i+(i+m))1}$	$B_{eq(i+(i+m))2}$	...	$B_{eq(i+(i+m))j}$
$S_{eq(i+(i+m))}$, $/t	$S_{eq(i+(i+m))1}$	$S_{eq(i+(i+m))2}$	...	$S_{eq(i+(i+m))j}$
D_i, t/h	D_{i1}	D_{i2}	...	D_{ij}
B_i, m^3/h	B_{i1}	B_{i2}	...	B_{ij}
B_{i+n}, m^3/h	$B_{(i+n)1}$	$B_{(i+n)2}$	...	$B_{(i+n)j}$
S_i, $/t	S_{i1}	S_{i2}	...	S_{iJ}
D_{i+1}, t/h	$D_{(i+1)1}$	$D_{(i+1)2}$	...	$D_{(i+1)j}$
B_{i+1}, m^3/h	$B_{(i+1)1}$	$B_{(i+1)2}$	...	$B_{(i+1)j}$
$B_{(i+1)+n}$, m^3/h	$B_{((i+1)+n)1}$	$B_{((i+1)+n)2}$	...	$B_{((i+1)+n)j}$
S_{i+1}, $/t	$S_{(i+1)1}$	$S_{(i+1)2}$	...	$S_{(i+1)j}$
...	...	....	...	...
D_{i+m}, t/h	$D_{(i+m)1}$	$D_{(i+m)2}$	...	$D_{(i+m)j}$
B_{i+m}, m^3/h	$B_{(i+m)1}$	$B_{(i+m)2}$	...	$B_{(i+m)j}$
$B_{(i+m)+n}$, m^3/h	$B_{((i+m)+n)1}$	$B_{((i+m)+n)2}$	...	$B_{((i+m)+n)j}$
S_{i+m}, $/t	$S_{(i+m)1}$	$S_{(i+m)2}$	...	$S_{(i+m)j}$

Since the cost value is preserved in the calculations, the algorithm allows calculating the steam and power generation costs under the conditions of an industrial power plant. Section 4 considers this issue in more detail.

Figure 2 shows the general optimization algorithm.

The developed approach is also adapted to solve the problems of intra-station optimization of CHPP basic equipment operating modes under normal [27] and repair conditions [28]. Ref. [29] provides a comparative analysis of optimization techniques for solving problems of improving the efficiency of operating modes of industrial generation systems.

3. CAE for Optimizing Industrial Steam Plant Boiler Units

The developed approach is implemented in the original software product [30]. The software allows planning the optimal boiler unit modes depending on the season, based on the source data and the thermal scheme of the industrial power plant: each boiler unit's load and the corresponding fuel mix composition are calculated. Figure 3 shows the block diagram of the developed software product.

As already noted, this software product allows for defining optimal power plant operating modes to plan and calculate their forecasted economic and technical indicators. To use this algorithm under the conditions of an operating facility, the software product was refined to an automated system for defining feasible operating modes for a boiler unit, considering the current actual volume of secondary energy carriers. Figure 4 shows an explanatory diagram of an automated engineering system.

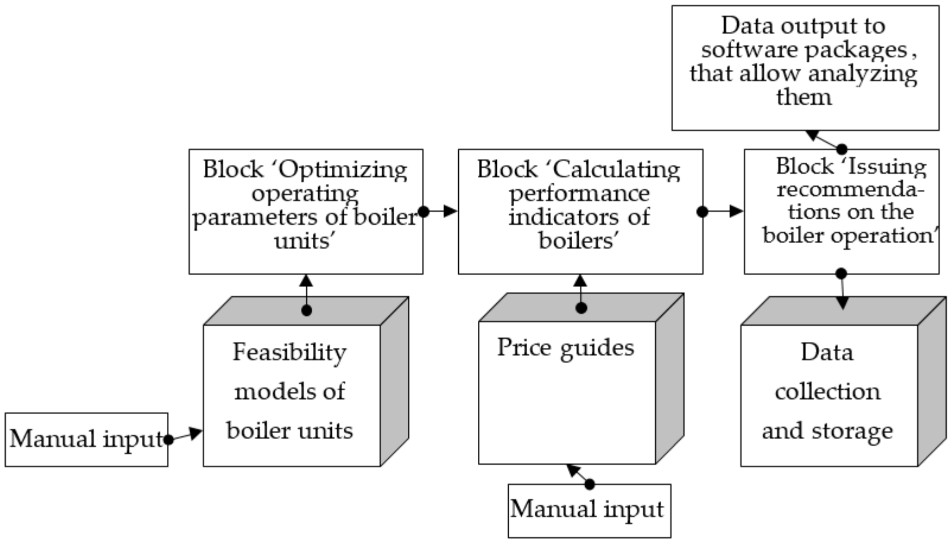

Figure 3. Explanatory Diagram. Software Product for Optimizing the Operating Modes of Industrial Power Plants Boiler Units.

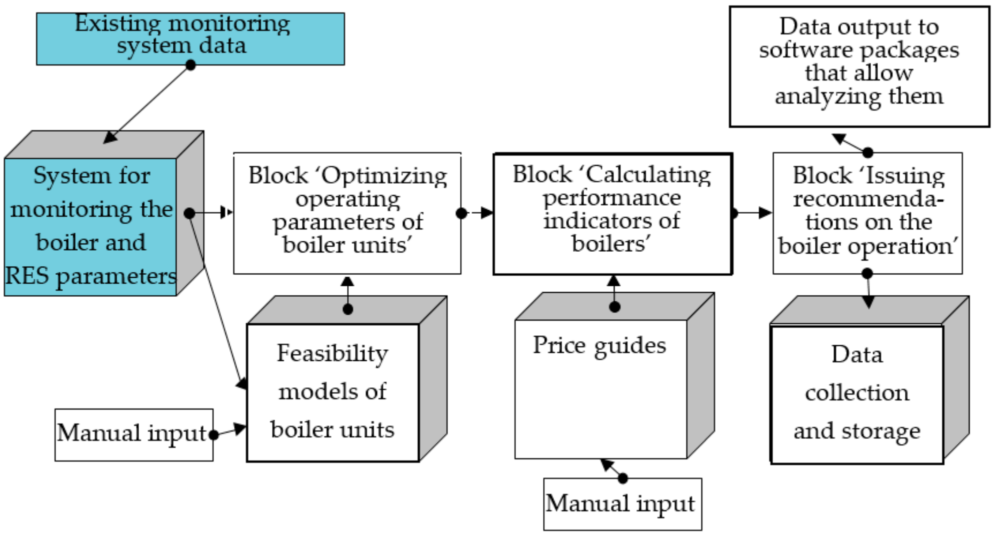

Figure 4. Explanatory Diagram. CAE for Optimizing the Operating Modes of Industrial Power Plants Boiler Units.

This system comprises the block 'System for monitoring the boiler and RES parameters'. This system allows defining the actual parameters of secondary energy resources, such as pressure and temperature, which ensures correcting the search for the optimal boiler operating mode according to the actual possible internal fuel consumption in the gas pipeline.

The developed system considers the boiler parameters required to define the natural gas volume to obtain a given steam capacity.

A calculation algorithm has also been introduced into the 'Feasibility models of boiler units' block, which refines the fuel mix composition based on the actual parameters of secondary energy resources.

To define the optimal composition of individual fuel mix elements, the specific fuel consumption for the generation of process steam should be calculated:

$$b_n = \frac{1 \cdot 10^3 \cdot \left[\left(h'' - h_{fw} \right) + P/100 \cdot \left(h' - h_{fw} \right) \right]}{Q_l^P \cdot 10^3 \cdot \eta}, \tag{5}$$

where Q_l^P is the lower calorific value, kJ/m^3; η is the Gross efficiency of the boiler, %; P is the blowdown percentage, %; h'', h', and h_{fw} are enthalpies of superheated steam, blowdown, and feed water kJ/m^3.

The lower calorific value is determined by the chemical composition of the combustible substance. As Q_l^P grows, the specific fuel consumption decreases, i.e., the volume of gas required to generate 1 m^3 of steam decreases, and vice versa.

Natural gas consumption is defined as follows:

$$B_{NG} = b_n - \Sigma b_i, \tag{6}$$

where B_{NG} is the specific natural gas consumption for the generation of 1 m^3 of live steam, MCM; Σb_i is the total specific consumption of secondary gases for the generation of 1 m^3 of live steam, considering the actual values of their parameters, MCM.

With this approach, automated calculation allows for obtaining various possible gas ratios based on their current parameters.

Table 5 provides an example of calculating the CAE system for a TP-7 boiler in real-time mode at a given steam capacity of 135 t/h.

Table 5. Refining the Fuel Mix Composition for a TP-7 Boiler at a Given Steam Capacity of 135 t/h.

Fuel Mix Composition	**Gas Consumption in the Mix**
	MCM/h
Natural gas only	12
Natural gas + blast furnace gas (B_{NG}/B_{BF})	11/10.2 10/32.4 9/68.3 8/79.2 7/90.4 6/140.6 5/156.4
Natural, blast-furnace, and coke oven gases (B_{NG} /B_{BF}/B_{CO})	10/12.3/1 7/35.4/3 4.2/62.1/5 3.4/68.6/6 0/90.3/7.22 0/100.72/5.33 0/132.2/3.21

4. Practical Implementation of the Optimization CAE System Developed

The developed system, under the conditions of an industrial power plant, the thermal scheme of which is shown in Figure 5, was used to obtain the planned optimal distribution values of the boiler unit steam capacities and the corresponding fuel consumption has been obtained (Table 6). The examples of feasibility models of boiler units No. 1 and 3 are given in Tables 7 and 8.

Under the conditions of an operating electrical unit, considering the continuous change in the parameters of secondary energy resources, the developed system corrected the obtained values of power consumption for a given time interval with the actual total steam generation of 104 t/h. The results are given in Table 9.

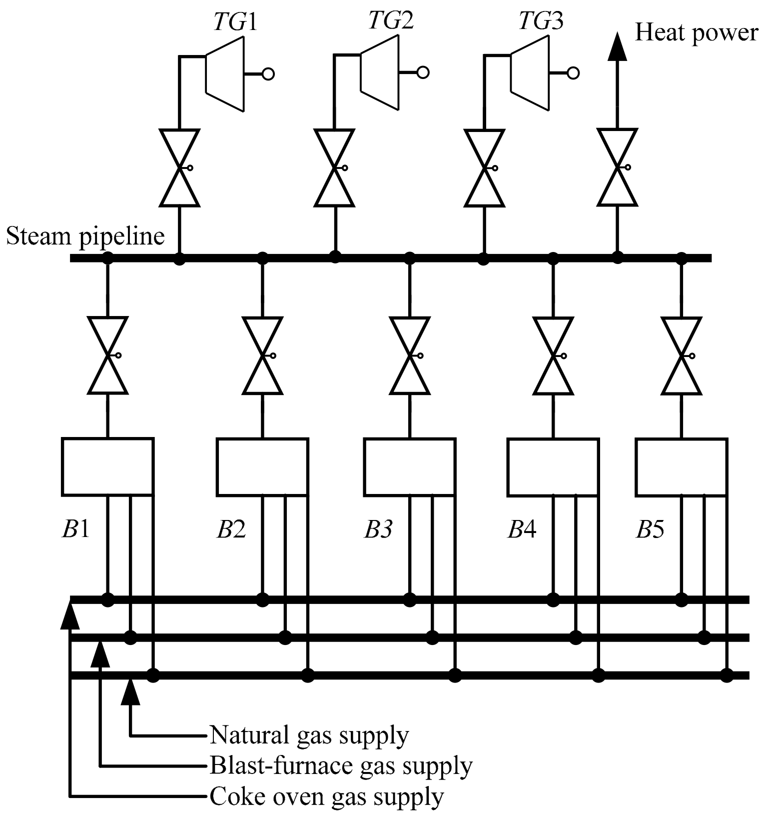

Figure 5. An Example of the Thermal Scheme of an Industrial Power Plant.

Table 6. Planned Optimal Boiler Units Operating Modes of the Studied Industrial Power Plant in the Winter Period.

Total Power Plant Output, t/h	**Parameter**	**Boiler Number**				
		1	**2**	**3**	**4**	**5**
90	D, t/h	75	90	90	205	200
	B_{NG}, MCM	2.8	6	0.5	6.4	7.2
	B_{BF}, MCM	50	50	48	120	80
	B_{CO}, MCM	9.5	12	8.1	21.4	20
93	D, t/h	75	90	90	210	201
	B_{NG}, MCM	2.8	6	0.5	6.4	8
	B_{BF}, MCM	50	50	48	120	90
	B_{CO}, MCM	9.5	12	8.1	21.4	23
94	D, t/h	75	90	90	210	203
	B_{NG}, MCM	2.8	6	0.5	6.4	8
	B_{BF}, MCM	50	50	48	120	90
	B_{CO}, MCM	9.5	12	8.1	21.4	23
...						
104	D, t/h	75	90	140	213	225
	B_{NG}, MCM	2.8	6	3.6	8	8
	B_{BF}, MCM	50	50	45	120	90
	B_{CO}, MCM	9.5	12	10	26.3	23

Table 7. Feasibility Model of Boiler No. 1.

***D*, t/h**	**75**	**95**	**116**	**120**	**130**	**134**	**137**
B_{NG}, MCM	0	0	0	0	0	1.2	1.9
B_{BF}, MCM	11.5	29.7	49	50	58	43	45
B_{CO}, MCM	8.2	8.5	9.1	9	9.8	8	9.2
S, \$/t	0.666	0.666	0.686	0.658	0.679	0.980	1.278

Table 8. Feasibility Model of Boiler No. 3.

***D*, t/h**	**70**	**88**	**90**	**100**	**110**	**120**	**125**	**130**	**143**
B_{NG}, MCM	0	0.5	0	0.5	0.9	3	3.3	3.6	6.3
B_{BF}, MCM	37	48	50	58	59	46	49	45	39
B_{CO}, MCM	6.6	8.1	8.8	9.8	9.6	9.3	9.9	10	7.3
S, \$/t	0.830	1.124	0.866	1.142	1.222	1.943	2.030	2.055	2.721

Table 9. Optimal Boiler Units Operating Modes of the Studied Industrial Power Plant in the Winter Period, Considering the Actual Parameters of Secondary Energy Carriers.

Total Power Plant Output, t/h	**Parameter**	**Boiler Number**				
		1	**2**	**3**	**4**	**5**
104	D, t/h	75	90	140	213	225
	B_{NG}, MCM	2.3	5.2	2.8	7.9	7.5
	B_{BF}, MCM	63.5	62.1	48.6	130.1	95.4
	B_{CO}, MCM	9.8	14.4	11.3	25.3	23.4

The developed system provides for prompt decision-making on the feasible operating mode of industrial power plant boilers. Thereby, it allows saving on purchased energy carriers due to the rational use of secondary gases and their optimal ratio in the fuel mix being set for each power plant boiler unit.

The system also allows forecasting the optimal power plant operating modes when the major energy equipment is shut down for repair.

For the considered industrial power plant, the operating modes have been simulated, and the efficiency of the system implementation has been estimated. The results are given in Table 10.

Table 10. Estimate of the Efficiency of Implementing the Study Results.

Calculation Mode	$Z_{pp\ opt}$, 10^3 \$/h	ΣZ_{act}, 10^3 \$/h	ΣZ_{opt}, 10^3 \$/h	***E*, %**
Normal	14,456.34	34,182.72	34,155.57	0.08
Repair of TG-3 and TG-2	13,136.87	35,208.72	34,606.38	1.71
Repair of TG-3 and TG-1	13,425.33	34,016.93	33,947.80	0.20
Repair of TG-1 and TG-2	14,445.13	34,582.57	34,155.57	1.23
Repair of boiler K-1	14,456.19	34,183.27	34,167.58	0.05
Repair of boiler K-2	13,095.67	34,189.13	33,953.62	0.69
Repair of boiler K-3	13,501.90	35,483.14	34,925.33	1.57
Repair of TG-1 and K-1	14,160.24	34,328.50	34,298.87	0.09

The economic effect in normal and repair modes is calculated by the equation:

$$E = \frac{(\Sigma Z_{act} - \Sigma Z_{opt})}{\Sigma Z_{act}} \cdot 100\%, \tag{7}$$

where E is the economic effect, %; ΣZ_{act} and ΣZ_{opt} are total costs for receiving, transmitting, and generating power in the current mode and that after optimization, respectively, 10^3 \$/h.

5. Conclusions

The developed system for optimizing the industrial steam plant operating modes allows defining the best boiler unit loads. It considers the remaining unit life, the possible fuel mix composition, the allowable unit loads, the feed water temperature (which allows accounting for the seasonality of the power plant operation since local steam plants operate according to heat load pattern), and the drum steam pressure. The developed feasibility models are adapted to solve the optimization problem using the dynamic programming technique, and the specifications of real boiler units (performance charts).

The system allows changing the existing source data, such as a steam plant scheme, a boiler unit feasibility model, and energy carrier costs.

The system is used to both solve the problems of medium-term planning of normal, repair, and post-emergency power plant operating modes (planning of energy consumption and budgeting) and to determine rational boiler loads in real-time mode considering the current energy carrier parameters (considering continuous fluctuations in the pressure of blast furnace and coke oven gases in the pipeline).

Implementing the system reduces the fresh steam generation cost by reducing the cost of energy carriers used by 1.4%, which in monetary terms amounts to USD tens of millions a year. The effect of implementing the study results has been estimated based on the equipment wear and tear, its technical and economic indicators, the cost of energy resources, and their types used at the industrial power plant.

Given the aforementioned benefits of the proposed approach, assessing the efficiency of loading internal power plants under the conditions of their operation jointly with the power grid remains in question. The authors consider this topic relevant and promising for further research.

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Abbreviations

CHPP	Combined Heat and Power Plants
CAE	Computer-Aided Engineering
BAH	Boiler Air Heater
TG	Turbo Generator
OJSC MMK	OJSC Magnitogorsk Iron and Steel Works
RES	Secondary Energy Resources

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