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Development of Models and Methods for Automated Control of Heat Supply System with Optimization of Technical Means Structure

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Abstract

Analysis of the controlled object, as well as methods and models applied for controlling the heat supply process in a city and urban districts has been carried out. Simulation models of the controlled object functioning in the presence of alternative energy flows with different costs have been developed. The criteria and objective function for optimizing the city's heat supply process have been synthesized and substantiated. The task of optimizing the process of heat supply in urban districts has been solved based on the transition from the structural optimization of the controlled object to managing the price structure for the energy flows offered to the consumer. The computer-integrated control systems have been implemented for the proposed facilities and their effectiveness has been defined.

Keywords: computer-integrated control system; variable structure; optimal control; simulation; technical and economic indicators; actuarial mathematics.

1. Introduction

Modern computer-integrated control systems for heat supply systems make it possible to connect technological units of heat supply from those that work in the system with minimal current costs of financial resources when changing the environment of their use with the absence or minimization of operator intervention during operation. Today, the level of development of the theory of adaptive systems and control methods, as well as the theory of optimal control allow solving the task of managing the structure of interchangeable equipment of the heat supply system, which will ensure the search for minimum resource consumption. At the same time, it is understood a priori that each unit of equipment, which is controlled on the basis of certain parameters, works in the optimal mode. The purpose of automated control system is to maintain the minimum costs of financial resources in the heat supply system under the conditions of the existence of alternative energy resources (flows), which differ in different costs that change over time.

There are advantages and disadvantages of various heat supply systems with corresponding technical and economic indicators of efficiency. Based on the analysis of control methods for systems with variable structure [1], [2], [3] it has been shown that the cost of thermal energy from various sources that form the urban heat supply system varies widely not only depending on the amount of energy resource already consumed, but also when using multi-zone electricity tariffs, as well as during the day. The presence of several alternative heat supply sources for the end consumer potentially allows solving the problem of optimizing the heat supply process in order to minimize the financial costs [4].

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An analysis of the literature showed that initially the management of the structure of complex technical systems meant the management of the structure of the regulator in order to optimize its current settings. For the study of dynamic systems in the aviation industry, the theory of coordinate-parametric control was developed, which provided for the possibility of changing the mathematical model of the control object at any time. But in the field of thermal power engineering, the structural optimization of the control object has not been systematically studied and is considered at the level of individual works devoted to solving individual or applied problems [5], [6].

Currently, models and methods for managing the heat supply system of a city or its regions are known, but they are not capable of carrying out control at minimal economic costs in the presence of alternative energy flows with different costs [7].

2. Goal and tasks of research work

The goal of the article is to improve methods and models of automated control of a heat supply system to increase economic efficiency through targeted changes in the structure of the controlled object. This goal is achieved by solving the following tasks:

- Synthesis, substantiation of criteria and objective function, optimization of the city's heat supply process;
- Solving the problem of optimizing the process of heat supply to urban districts through the transition from structural optimization of the controlled object to managing the price structure offered to the consumer of energy flows.

3. Synthesis and substantiation of criteria for the objective function of heat supply process optimization

There is a distributed heat supply system for an urban area (Fig.1). The system consists of many thermal energy consumers located in the territory of this district. Each consumer potentially has a flow of thermal energy from more than one source. Sources connected to the consumer can work simultaneously. The fact of connecting the *i*-th source to the *j*-th consumer is determined by the presence of a connection $w_{ij} = 1$ (Fig.1). When a source is turned off, the corresponding link becomes 0.

For consumer *j*, each source *i* is characterized by the cost of the thermal energy generated. The cost is determined by the following factors: efficiency of conversion of primary energy resources into thermal energy, efficiency of delivery of thermal energy to the final consumer and its return to the source, reliability of source equipment and cost of consumed primary energy resources. A large number of influential factors form a variety of quality criteria. Quality criteria for the *j*-th consumer underlie local objective functions.

Structural optimization of the local heat supply system for the consumer will pursue the purpose of minimizing the objective function. Then the optimization problem can be formulated as follows: at each moment in time τ , select the following functions $w_{ij}(\tau)$:

$$f_j(w_{ij}(\tau)) \to \min \text{, at } K_{jk}(\tau) \le K_{jk\max}. \tag{1}$$

The condition $K_{jk}(\tau) \le K_{jk\max}$ means that it is impossible to endlessly improve some criteria at the expense of worsening others. Each criterion has a very acceptable value.

Therefore, each equipment switching plan can be determined using the objective function [1], [3]:

$$J(x;\tau) = \sqrt{\left(w_r R_n(x;\tau)\right)^2 + \left(w_q Q_n(x;\tau)\right)^2 + \left(w_s S_n(x;\tau)\right)^2 + \left(w_e E_n(x;\tau)\right)^2}, \tag{2}$$

where w_r, w_q, w_s, w_e are weighting coefficients determined by the expert method; $R_n(x;\tau)$ is the normalized value of system reliability; $Q_n(x;\tau)$ is the normalized value of management quality; $S_n(x;\tau)$ is the normalized value of the cost indicator of consumed resources; $E_n(x;\tau)$ is the standard value of installation efficiency; τ is the time.

First of all, it was decided to express all components of the objective function through a single monetary unit of measurement. This allowed us to move on to a single-criteria optimization problem.

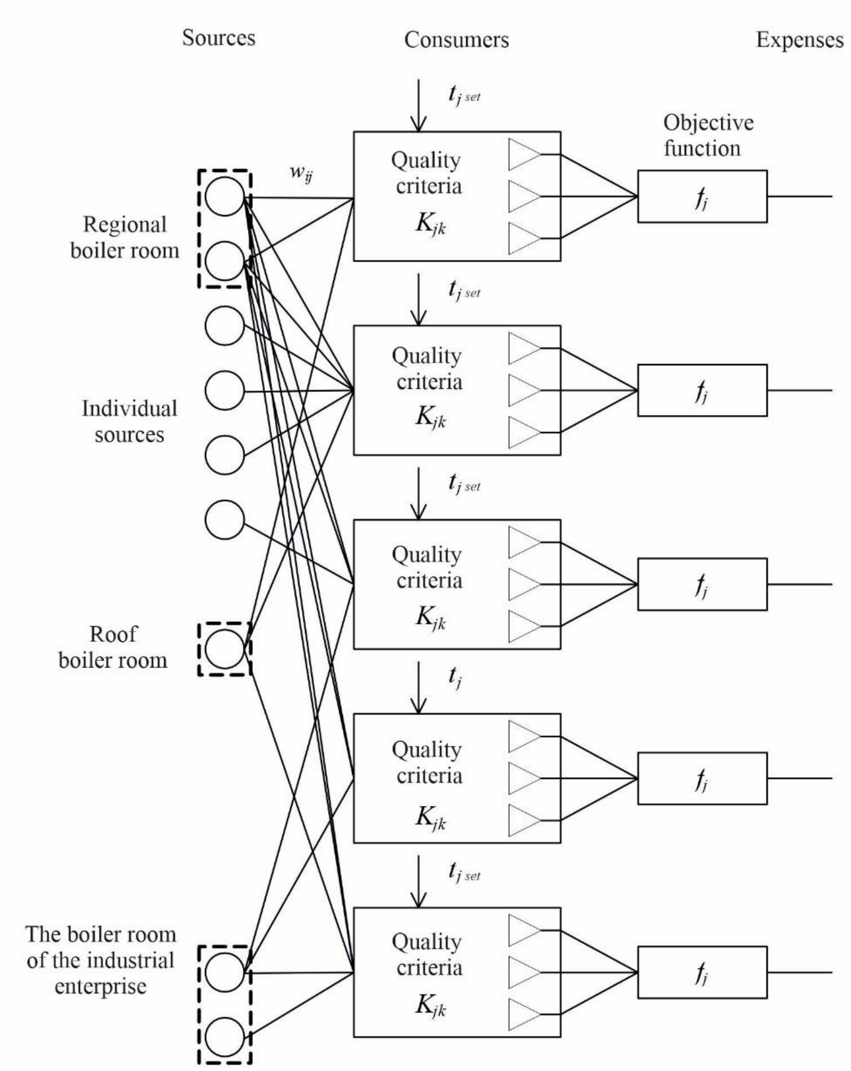

Fig.1. Example of the distributed heat supply system structure.

Based on an analysis of the results of a previous study, it was proposed to consider equipment efficiency as the sum of the theoretical efficiency and the value $\Delta\eta$:

$$\eta^* = \eta(\tau) + \Delta\eta(\tau). \tag{3}$$

The value η^* is determined based on the results of the actual launch of the heat supply system with the connection of the source in question. The value $\Delta\eta(\tau)$ will be adjusted with each subsequent connection. Obviously, the value $\Delta\eta(\tau)$ is influenced by the facts of maintenance, repairs, long inter-seasonal downtime, as well as various accidents in the transport system. The probabilistic nature of the events under consideration determines the need for a one-time connection of each source of thermal energy before the start of operation in order to determine the actual value of the quantity $\Delta\eta(\tau)$ [8].

The main condition for solving the problem of process optimization is the availability of individual metering devices for each consumer. Knowing the total power of heat losses of consumers N_Σ^{cons} and the current total power of the source N_Σ^{sour}, the actual efficiency is determined as:

$$\eta^* = \frac{N_\Sigma^{cons}}{N_\Sigma^{sour}}. \tag{4}$$

It should be noted that the power of the source N_{Σ}^{cons} is the sum of the powers of all components of the thermal energy generation process.

It was assumed that the heat supply system has the following characteristics:

T is the system resource, s;

$\Delta\tau$ is the modeling interval or interval at which the operation of the system is assessed, s;

C_e is the cost of equipment, UAH;

C_{ia} is the cost of installation and adjustment, UAH;

C_s is the cost of maintaining the system for a period of time T, UAH;

C^* is the other expenses for the reporting period T_{rp}, UAH;

G_c^i is the amount of already consumed i-th resource for the reporting period T_{rp} (month), depending on the type of source, can be measured in kg, m^3, kWh;

$C_r^i(\tau, G_c^i)$ is the current price of the of the i-th resource, which depends both on the time of day and on the amount of energy resource already consumed, depending on the type of source, can be measured in UAH /kg, UAH /J, UAH / kWh, UAH/m^3;

G_r^i is the current consumption of the i-th resource for the reporting period T_{rp} (month);

N_c is the number of connected consumers;

N_{Σ}^{cons} is the total heat loss capacity of consumers, W;

N_{Σ}^{sour} is the total power of heat-generating equipment.

The cost component $S(\tau)$ of the objective function is calculated using the expression:

$$S(\tau) = \frac{(C_e + C_{ia} + C_s)\Delta\tau}{N_c T} + \frac{C^*\Delta\tau}{N_c T_{rp}} + C_r^i(\tau, G_c^i)\frac{3600000}{R_i \eta_i^*} + \Delta S, \tag{5}$$

where R_i is the specific energy intensity of the i-th energy resource, for fuel it is the specific heat of combustion, for electricians $R_i = 1$; ΔS is the cost of additional costs of resources to ensure the process and compensate for losses, UAH.

$$\Delta S = \frac{\sum_j C_r^j(\tau, G_c^j) G_r^j \Delta\tau}{N_c}. \tag{6}$$

The first term in (5) takes into account capital costs for the purchase, installation, adjustment and operation of equipment in terms of one consumer for time $\Delta\tau$. The second term allows you to take into account all other costs of operating the equipment. The third term takes into account the cost of fuel required to produce 1 kWh of energy. And finally, the last term takes into account the cost of related resources.

The value of ΔS can be determined only by actually turning on the source of thermal energy. It will also be influenced by maintenance, repairs and long-term equipment downtime. Thus, as in the case of efficiency, for the value of ΔS during operation, statistics on the current value must be accumulated and constantly updated [6], [9].

Further analysis showed that in order to express reliability characteristics in monetary terms, it is advisable to use the methods of actuarial mathematics used in the insurance business to calculate tariff rates for mass risk types of insurance.

The initial data for calculation are as follows:

$\bar{S}_n$ is the average sum insured under one contract;

$\bar{Q}$ is the average deviation under one insurance contract;

N is the total number of contracts concluded for a certain period of time in the past;

M is the number of insurance cases in N contracts;

p is the possibility of an insurance event under one contract;

n is the number of insurance contracts related to the time period for which insurance is provided.

The value of p is defined as:

$$p = \frac{M}{N}. \tag{7}$$

The calculation of the reliability component $R(\tau)$ can be carried out for a certain period ΔT equal to a month, quarter, year, and thus take into account changes in reliability in the system due to accidents and repair activities.

In this case, the reliability component taking into account (8) – (10) is determined by the expression:

$$R(\tau) = \left((1 - P(\tau))0.7 \left(1 + 1.2\alpha(\gamma) \sqrt{\frac{P(\tau)}{n(1 - P(\tau))}} \right) \right) \frac{(C_e + C_{ia})\Delta\tau}{\Delta T}. \tag{8}$$

The possibility of failure-free operation of equipment is proposed to be calculated according to the methodology outlined in [2], [8], according to which the reliability of equipment is determined by two types of failures: random and wear-out, and depends on the state of the environment and the relative power at which the equipment operates.

Thus, the objective function for solving the local optimization problem takes the below form:

$$f_j\left(w_{ij}(\tau)\right) = S(\tau) + R(\tau) \to \min. \tag{9}$$

All components are expressed in monetary units, therefore, the search for the optimal solution comes down to choosing the cheapest source of thermal energy at each moment of time (see Fig.1). If it is not enough to ensure the set temperature, the next source with the minimum cost of generated energy is selected from those remaining.

Further research revealed two shortcomings of the proposed method of calculating the cost of thermal energy. The first was that the amount of resource consumption in can be determined only when the source is turned on. If the source is turned off, it is necessary to roughly estimate what the cost of the heat energy generated by it will be.

In general, the global optimization task can be formulated as follows: in the conditions of limited available energy flows, it is necessary to provide such a structure of energy consumption that will ensure the process of heating the city during the maximum possible time.

The price of energy resources is the only available lever for managing heat consumption on a city scale. An increase or decrease in the price of gas and electricity will lead to a change in the cost of heat energy and, in turn, to a change in the structure of each consumer's local heat supply systems.

4. Definition of the decisive rule for changing the price structure of energy flows

The main difficulty in the global optimization problem under consideration is that the heat supply process is controlled only on the basis of indirect influences and measurements, and is also characterized by significant inertia. Changing the price of a particular energy flow can have an effect in an hour or even a day. Therefore, the main requirement for solving a global optimization problem is that the period of control signals must be large enough to be able to evaluate the effect of their influence [9].

The global optimization task was formulated as follows: in the conditions of limited available energy flows, it is necessary to provide a structure of energy consumption that will ensure the process of heating the city for the maximum possible time.

The only available argument for managing the process of heat consumption on a city scale is the price of energy resources. An increase or decrease in the price of gas and electricity will lead to a change in the cost of heat energy and, in turn, to a change in the structure of each consumer's local heat supply systems.

A uniform increase in prices for all energy resources in general will lead to an increase in the price of thermal energy and, as a result, to a potential decrease in the set temperature for a number of consumers. This will allow reducing the consumption of energy resources due to the forced reduction in the quality of heat supply by consumers.

On the other hand, changing the ratio of prices for gas and electricity will allow changing the structure of energy consumption while preserving the total budget revenues.

The main criterion for solving the global optimization task should be the operation time τ_{func} of urban heat supply systems with the current consumption of energy resources G_i and their available limit M_i

$$\tau_{func} = f(G_1, G_2, ..., M_1, M_2, ...). \tag{10}$$

It is obvious that at $M_i = const$ the function $\tau_{func} = f(G_1, G_2, ..., M_1, M_2, ...)$ does not have an optimum and increases linearly with decrease in costs, and after using the available amount of energy resources, the system degrades.

If it is assumed that the available amount of energy resources is constantly updated with a certain period, then global optimization will be achieved when the condition is met:

$$M_i^{rem} - G_i(t_t - t) - M_i^{ur} \le \delta_i, \tag{11}$$

where M_i^{rem} is the remainder of the *i*-th energy resource; M_i^{ur} is the untouched reserve of the *i*-th energy resource; δ_i is the permissible error in determining the quantity of the *i*-th energy resource.

At the same time, it should be noted that the value $G_i = f(C_r^i)$ is probable and cannot be accurately determined.

Thus, global optimization consists in maintaining a balance between the remaining resources M_i^{rem} and the speed of their consumption G_i by influencing the prices of energy resources C_r^i.

The local task of optimization consists in choosing at each moment of time τ such connections $w_{ij}(\tau)$ between sources and consumers, that is, in organizing such a structure of the heat supply system, which will provide, which will provide the minimum objective function $f_j()$ for each consumer:

$$f_j(w_{ij}(\tau)) \to \min, \text{ when } K_{jk}(\tau) \le K_{jk\max}. \tag{12}$$

Global optimization (11) can be achieved by maintaining a balance between the remaining amount of resources M_i^{rem} and the speed of their consumption G_i.

Despite the simplicity of the given expressions, in practice their implementation for a control system may require the synthesis of a rather complex system of rules and conditions [10].

Preliminary modeling showed that two approaches are generally possible for local optimization. Conventionally, they are determined by the following two rules:

- at each moment of time, the consumer can be supplied with heat only from one source of thermal energy;
- at any given time, heat supply to the consumer can only be provided from multiple sources of thermal energy.

The first option in practice requires that each alternative source can fully provide the consumer with heat. The second approach does not have such a limitation and is more universal. On the other hand, the second approach requires introducing certain restrictions into the control algorithm. So, for example, if a source with a lower cost of thermal energy does not operate at full capacity, there is no point in connecting another one in parallel.

In general, the heat supply system control algorithm for solving the local optimization problem is presented in Fig.2. It should be noted that if there is a shortage of any one resource, the system proposed in this work can increase the cost of this resource and, as part of solving the local optimization problem, redistribute the use of available resources automatically. In this case, consumer intervention is not required, and changes in the price structure have a direct impact on the rate of consumption of the resource in question.

In the case where the shortage extends to all resources, there are two possible solutions to the global optimization problem. The first implies the ability of the control system to directly change the set temperature in consumer premises. The emergence of a shortage of all resources will lead to an automatic decrease in the maintained temperature, that is, to a decrease in the quality of providing the given temperature to consumers, which will directly lead to a decrease in the rate of resource consumption by reducing heat losses. In addition, all consumers will be in equal conditions [7], [8].

Formalization of a method for managing the structure of a heat supply system under conditions of resource limitations. The essence of the management method is as follows.

1) The consumer's current need for thermal energy N_{req} is assessed, taking into account heating and hot water supply. Since many sources of thermal energy can fully provide any individual consumer with heat and hot water, for an assessment N_{req} it is enough to determine the amount of heat emitted by heating radiators, as well as the current consumption of hot water. For rooftop boiler houses and centralized heating systems, the total required power is determined taking into account all connected subscribers.

2) For each source of thermal energy, the thermal efficiency of the heat supply process is assessed and the required power of the source is determined. Since it is impossible to determine the thermal efficiency of a process without connecting the source to the consumer, this assessment is made based on simulation data. In this case, the values of thermal and physical losses in heating networks are modeled either as of the time of the last start of the system or, in the absence of the necessary data, according to the regulatory values of regulatory documentation.

3) For the required power of the source and its efficiency value, the consumption of primary energy resources necessary to ensure the heat supply process is determined.

4) The values of thermal and physical losses obtained either by direct measurement or on the basis of simulation modeling are analyzed. The additional amount of thermal energy and primary resources needed to compensate for thermal and physical losses is determined. The resulting costs are expressed in monetary equivalents.

5) The current state of equipment reliability is determined at an accepted frequency (month, quarter, year, etc.). The amount of insurance contributions for the current period is calculated. This value is the monetary equivalent of reliability.

6) For each source, an analysis of capital and associated costs is carried out, independent of the power of the source. This includes depreciation of equipment, wages, deductions for various loans, etc. At the same time, depreciation expenses include depreciation of all sources, regardless of whether they are included or not.

7) For each source, the sum of all basic and additional costs is normalized by the number of subscribers and the cost of thermal energy is determined for one user.

8) For each consumer, a list of alternative sources from which heat and hot water can be supplied is compiled and sorted by increasing price.

9) The next source in the list in ascending order of price is connected. If one or more sources are already connected to the consumer, and the air temperature in the premises is below the set one by a certain amount δ_t, or there is not enough thermal energy for hot water supply, the next source in the list is connected. If there is an excess of thermal energy and several sources are connected, then the source with the highest of cost. At the same time, the connection of the second and further sources can take place only if the previous source reaches the maximum thermal power. If necessary, based on the results of turning on the source, the value of thermal and physical losses, costs for their compensation and the thermal efficiency of the process are adjusted, which will allow to clarify the cost of thermal energy in subsequent iterations.

10) With the accepted periodicity (1 day) values of deficits of energy resources are analyzed. With the appearance of a potential negative balance of the amount of energy resource at the end of the reporting period (month, quarter, year, etc.), the price of the corresponding resource increases. When a potentially positive energy resource

balance appears, its price decreases. If it is possible to directly control the set temperature of the consumer, the formation of a negative balance also leads to a decrease in the given temperature. Similarly, a positive balance leads to a return to the nominal value of the air temperature in the consumers' premises.

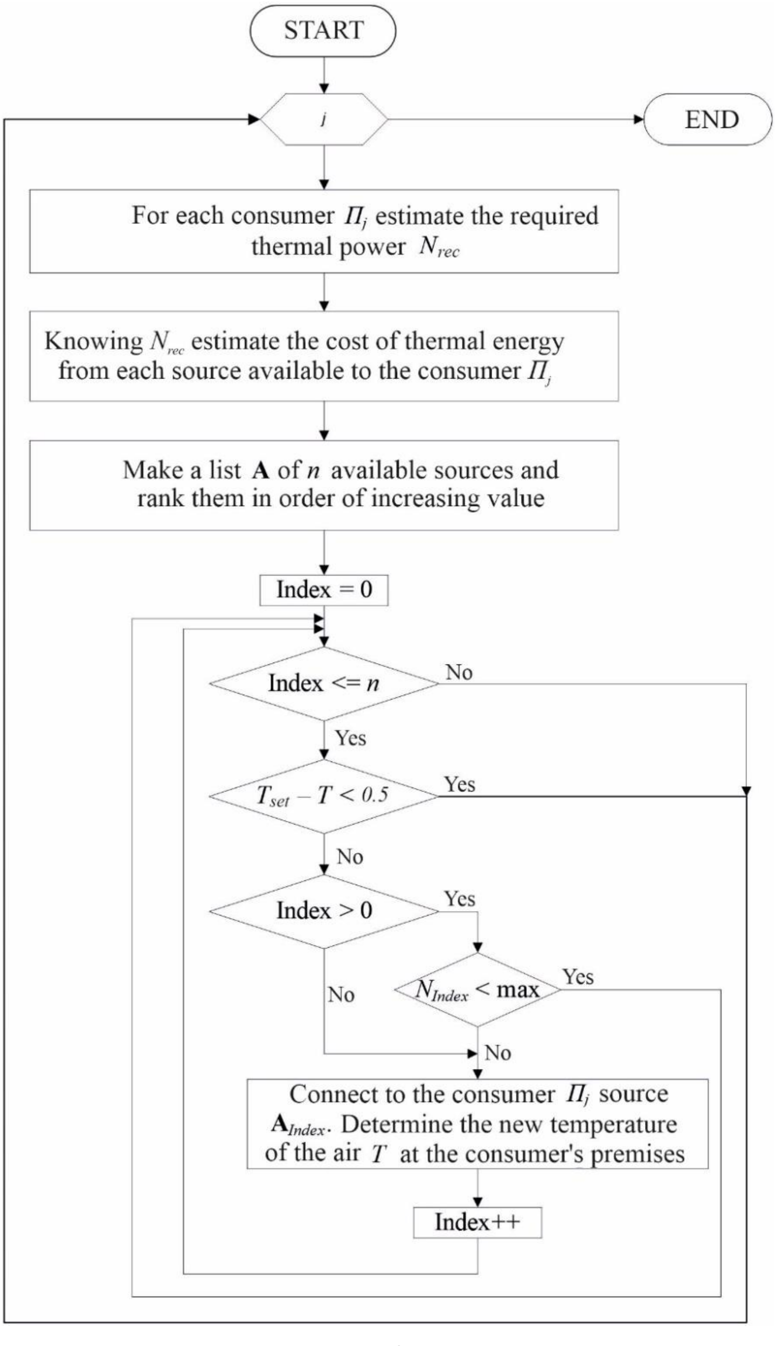

Fig.2. Generalized control algorithm for the local optimization problem.

Fig.3 presents a generalized structural diagram of the city’s heat supply management system [8], [9], [10].

Option 1. When solving a local optimization problem (Fig.2), one control cycle consists of the following. The price analysis unit receives information from source and consumer accounting devices, as well as model data of the control object. Lists of heat energy sources formed for each consumer, ranked in order of increasing price, are transferred to the structure control unit, which directly switches the selected sources and forms the current structure of the heat supply system. Values of set air temperatures and exact consumption of hot water from consumers enter the unit of analysis of the required power N_{rec}.

After analyzing the current needs of each consumer for thermal energy, the required power of all connected sources at a given time is determined and, through the appropriate control unit N_{rec} controlling the impact of those supplied to specific sources.

Sources operating at the moment of time require a certain amount of gas and electricity, which is recorded in the corresponding source metering devices. The amount of energy resources consumed at the present time, as well as already consumed, affect the cost of thermal energy of the next management cycle. This completes one cycle of management.

Consider the solution of the problem of global optimization.

Option 2. Data on the available amount of energy resources are sent to the analysis block of their balances, in which the amount of the deficit is determined. If there is a shortage of only one of the energy resources, it enters the tariff management unit and, depending on that, the positive or negative value of the corresponding energy resource decreases or increases, which leads to a redistribution of energy consumption. In the latter, the management cycle is the same as for local optimization.

Option 3. In the case when it is possible to directly control the value of the set temperature at each consumer, the required temperature value is determined in the residual analysis unit and through the control unit T_{set}, the influence controllers are transferred to consumers. Further, the control cycle is the same as for local optimization.

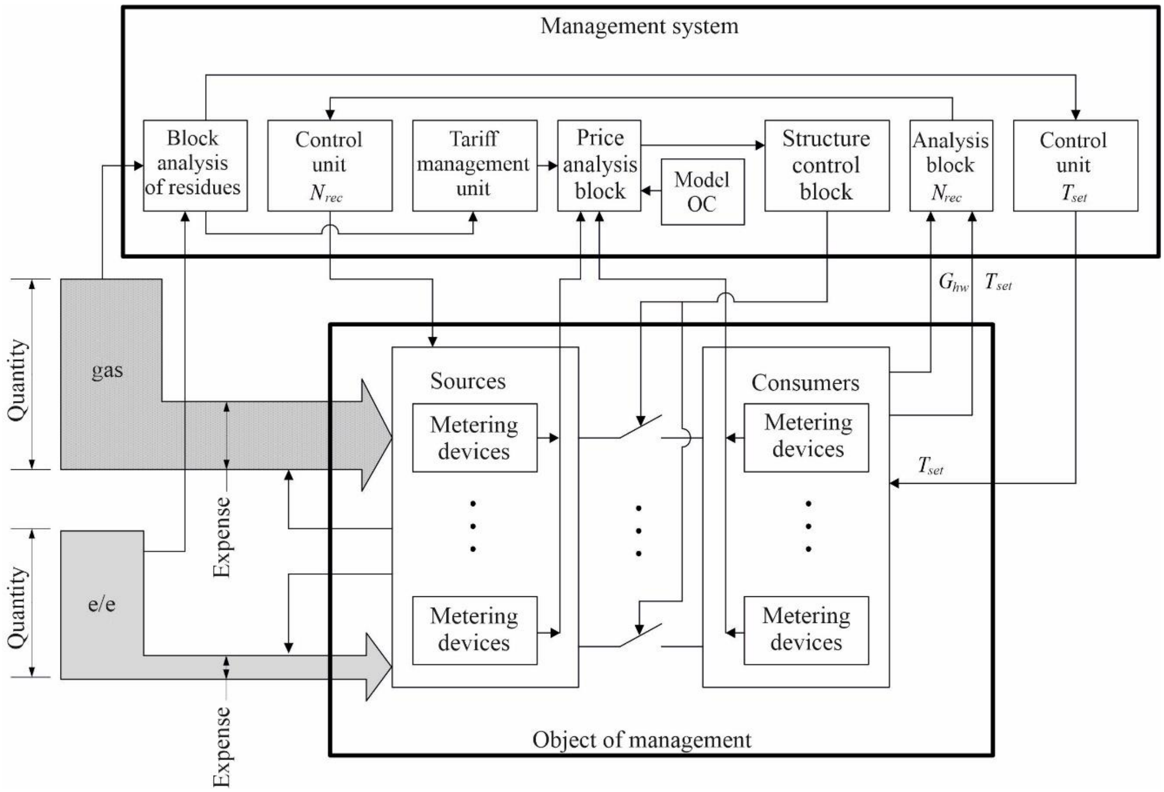

Fig.3. Structural diagram of the system of automated control of the city's heat supply.

Option 4. In the case when there is a shortage of all energy resources, and there is no possibility of controlling the set temperature, the main control cycle corresponds to option 2, with the difference that the redistribution of energy consumption is impossible without the intervention of consumers. In the absence of consumer reaction, the tariff management unit will increase the cost of energy resources to the maximum possible value, and only the reduction of T_{set} and G_{hw} values by consumers will lead to a decrease in the consumption of energy resources.

5. Results of computer-integrated control system modeling

During the simulation, the impact on the structure of the heat supply system by introducing various restrictions on resources was determined [11], [12]. The simulation step was taken to be 120 s. The modeling interval was

1 month. A series of experiments was carried out in which it was believed that heat supply to houses is carried out only from one source and there is no alternative.

It was believed that the levels of physical and thermal costs correspond to standard values. During the experiments, the monthly expenses of consumers and sources of thermal energy in the urban area under consideration were estimated. The simulation results are presented in Table 1.

Table 1. Results of simulation of heat supply from single sources.

	DH	DH with HPU	RH	IGB	IHPI	IHPI*
Consumer spending						
Main, UAH	6,482.0	5,126.7	4,950.4	2,663.4	1,771.9	2,631.4
Additional, UAH	602.8	899.8	846.5	146.6	195.5	200.2
Total, UAH	7,084.9	6,026.5	5,796.8	2,809.9	1,967.4	2,831.6
Source costs						
gas, UAH	6,465.0	0	4,953.9	2,763.1	0	
c/w, UAH	21.3	22.5	0	0	0	
e/e, UAH	302.8	5,015.2	557.1	135.7	1,855.5	2,754.1
Total, UAH	6,789.1	5,037.7	5,511.1	2,898.8	1,855.5	2,754.1
Profit, UAH	295.8	988.8	285.8	-88.9	111.8	77.5

In Table 1, the following designations are accepted: DH is district boiler house which functions on gas; DH with HPU is regional boiler house with heat pump unit; RH is gas rooftop boiler house; IGB is individual gas boilers; IHPI is individual heat pump installations. At the same time, two experiments were performed. In the first (IHPI column) it was considered that IHPI utilize the heat of waste water with an average temperature of 20 ºC. In the second (column IHPI*) it was assumed that heat is taken from cold water with a temperature of 5 ºC.

Consumer expenses in Table 1 are divided into main (multiplicative) and additional (additive). Analysis of the results showed that the most optimal source is IHPI. At the same time, the use of wastewater heat as a heat source for IHPI can significantly (30%) reduce the costs of solving the heat supply issue. It should also be noted that in summer the average temperature of wastewater can reach 28 ºC, which can also reduce the cost of hot water supply in the summer [8], [9], [10].

Separately, a simulation of heat supply from district boiler houses was carried out at a level of thermal and physical costs 10 times higher than the standard ones. At the same time, consumer expenses for DH amounted to UAH 10,616.3 thousand, and for DH with HPU – UAH 7,066.6 thousand. It should be noted that in reality these figures are significantly higher, since the wear and tear of heating networks today is such that costs are tens of times higher than the standard ones. In addition, the use of HPU can potentially reduce the temperature of the coolant and thereby reduce heat losses.

In the next group of experiments, all sources were interchangeable and could work in parallel. The simulation results are presented in Table. 2.

Table 2. Results of simulation of heat supply from many sources under various constraints.

Expenses	Without limits	Max. IHPI power reduced by 50%	Without IHPI	Without IGB
Consumer spending				
Main, UAH	2,122.7	2,202.3	2,522.7	3,581.5
Additional, UAH	196.9	206.1	288.2	771.1
Total, UAH	2,319.5	2,408.4	2,810.8	4,352.5
Source costs				
gas, UAH	1,130.0	815.0	2,461.7	1,673.3
c/w, UAH	0	5.1	7.9	14.5
e/e, UAH	1,422.2	1,768.1	763.9	1,878.6
Total, UAH	2,552.3	2,588.2	3,233.5	3,566.4
Profit, UAH	-232.7	-179.9	-422.6	786.1

The analysis of the obtained results showed that the optimal use of many alternative sources of thermal energy allows for a stable solution to the problem of heat supply with lower costs compared to the use of only one source.

The last group of experiments aimed to test a method for managing the process of heat supply to urban areas under resource constraints, by moving from the structural optimization of multiple heat-generating sources to managing the price structure of the energy flow offered to the consumer. It should be noted that it is not possible to completely automate the control process in this matter, since each consumer determines the value of the set temperature independently.

The essence of the method is that when there is a shortage of any energy resource, the system makes a decision to increase the price of this resource relative to the market value. The consequence of solving a local optimization problem should be a redistribution of used resources. The price change process continues until condition (1) is met. If there is an excess of energy resources, the system gradually reduces its price to the market value. If a price increase does not lead to a decrease in the consumption of a given resource, this means that it is impossible to resolve the issue automatically. In this case, the price will increase until consumers decide to reduce the quality of heat supply, that is, they lower the set temperatures.

In the last group of experiments, the price of electricity and gas was changed by multiplying the corresponding tariffs by a scale factor x. Figure 4 shows the dependence of the consumed amount of electricity E on the multiplier x. Figure 5 shows a similar dependence of the consumed volume of gas.

Analysis of the results obtained indicates the potential opportunity to control the consumption of energy resources by influencing their price [8], [9], [10].

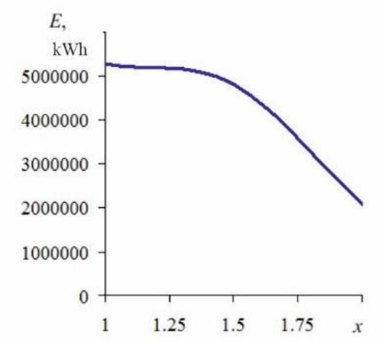

Fig.4. Dependence of consumed amount of electricity on multiplier x.

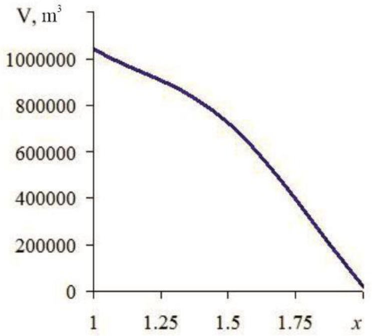

Fig.5. Dependence of consumed gas volume on multiplier x.

As a result of the work carried out, a method was proposed for managing the process of heat supply to urban areas in conditions of resource restrictions through the transition from the structural optimization of many heat-generating sources to managing the price structure of the energy flow offered to the consumer, which allows achieving rational use of energy resources.

Thus, the results of the conducted research allow us to draw a conclusion about the possibility of optimizing financial costs for heat supply in urban areas by managing the structure of the city's heat supply system, provided there are alternative sources of heat energy.

6. Conclusion

To solve the control problem, an objective function of the optimization problem is proposed for a heat supply system with a changing structure of the control object. The objective function combines the efficiency of the equipment used, its reliability and the cost of resources. The objective function differs from the known ones in that the reliability criterion is calculated on the basis of actuarial mathematics methods, which made it possible to reduce the optimization problem to one argument (flow) and find its value in real-time control under any restrictions and disturbances.

To control the structure of the heat supply system under conditions of resource limitations and disturbances, a method has been developed, which consists in the fact that the solution of the problem of heat supply control at each step of the simulation is provided by a set of heat energy sources, which in turn provide the minimum value of the objective function, which made it possible to obtain the highest efficiency

A method for managing the process of heat supply to urban areas under conditions of resource constraints is considered and proposed through the transition from the structural optimization of multiple heat-generating sources to the management of the price structure of the energy flow offered to the consumer, which made it possible to achieve the rational use of energy resources in the system.

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Розробка моделей і методів автоматизованого керування системою теплопостачання з оптимізацією структури технічних засобів

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Анотація

Проведено аналіз об’єкта керування, а також методів і моделей, що використовуються при керуванні процесом теплопостачання міста і міських районів. Розроблено імітаційні моделі об'єкта керування, що функціонує в умовах наявності альтернативних енергетичних потоків, які відрізняються різною вартістю. Синтезовано й обґрунтовано критерії і цільову функцію оптимізації процесу теплопостачання міста. Розв’язано завдання оптимізації процесу теплопостачання міських районів за рахунок переходу від структурної оптимізації об’єкта керування до керування структурою ціни запропонованих споживачу енергетичних потоків. Проведено впровадження і визначено ефективність комп'ютерно-інтегрованих систем керування для запропонованих об’єктів.

Ключові слова: комп'ютерно-інтегрована система керування; змінна структура; оптимальне керування; моделювання; техніко-економічні показники; актуарна математика.