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OBJECTIVE FUNCTION FOR MUNICIPAL HEAT SUPPLY SYSTEMS' STRUCTURAL OPTIMIZATION

Introduction. The modern market of heat supply and hot water supply (HWS) offers a wide range of various thermal energy sources: from low-power individual fan heaters, intended for rooms heating, to large TPPs and boiler facilities purposed to provide the heat and HWS to several hundred houses.

Such variety allows the end user to select between flexible variances of satisfying his needs in heat and hot water. At the apartment level the consumer can install a boiler for hot water and choose between the oil-, fan-heater or even a heat-pump system. At the house/building level the residents can install a rooftop or modular boiler plant. At the level of city district the municipal services can build a TPP arranging a central heating system or choose other ways.

As a result, each consumer, while individually solving the heat supply problem, faces the problem of process optimization. What will be better? Should he install the autonomous gas boiler, the electric boiler or shall he use the central heating system hot water? As a rule, the priorities' sequence is following: central heating, AGB, electric boiler, etc. Ideally, that distribution makes sense, but let we consider the following conditions limiting the selection options:

— the consumer has already spent a certain limit of gas and now shall be switched to a more expensive tariff;

— a multitariff electric power counter installed allows an economy as at night the consumer is switched to 40% of the nominal tariff;

— the given city district central heating system is in a deplorable state, the main pipeline leaking and its thermal insulation being wore out;

— there is an opportunity to use thermal pumps for heating both at the level of certain apartments, and at the houses group level; thus, the more powerful is that equipment, the higher is used compressors' efficiency.

Under such circumstances the optimum choice problem solution as to the heat source selection under existing conditions is less evident requiring a more serious approach. And when considering the best solution in city scale, taking into account numerous thermal power units, boiler facilities, thermal pumps feeding heat from solar collectors, geothermal sources, subsoil and sewage water, various mobile modular boiler units installed at certain houses, etc., it is obvious that the choice of the optimal for present conditions heat sources' structure will allow not only to optimize costs of municipal heat supply, but also to reveal timely the functioning thermal energy sources' deterioration.

Literature review. Nowadays the methods of variable-structure objects management are actively progressing concurrently to that objects become more complex. Solutions, representing a separate private cottage heat supply give an example of such object management realization on the basis of criteria as: heat supply quality, equipment reliability and spent resources costs, are exposed at [1,2]. The publication [3] does consider the issues of heat alternative sources' integration into municipal heat supply networks and expected potential of such systems' optimum management. To be noted is that numerous works are devoted to the problem of increasing the efficiency of end user heat supply process at the account of alternative individual sources of thermal energy [4] engaging.

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In general, the global aim of all researches is the same: to elaborate such an optimal scheme when at each time-point the cheapest thermal energy source would be used. For this purpose it is necessary to have a set of alternative heat sources operated at various physical principles and using different energy resources.

Aim of the Research. The comprehensive solution of heat supply costs' optimization problem is possible in that case when the given source's thermal energy current cost formation algorithm includes whole complex of its generation costs, namely: capital expenditure for the source installation and adjustment, costs of its service maintenance and operation. Therefore, the present research purpose relates to synthesizing a complex criterion uniting all factors that define prime costs of thermal energy generated by a separate source.

Main Body. The reference [2] does suggest a variance of complex criterion synthesized on the goal-programming method basis. According to the proposed concept, each plan x of equipment switching shall be estimated using the criterion function:

$$J(x;\tau)=\sqrt{w_r R_n^2(x;\tau)+w_q Q_n^2(x;\tau)+w_s S_n^2(x;\tau)+w_e E_n^2(x;\tau)},\ \sum_k w_k=1\,, \tag{1}$$

where w_r, w_q, w_s, w_e — weight coefficient found by Delphi technique;

$R_n(x;\tau)$ — normalized system reliability rated value;

$Q_n(x;\tau)$ — normalized management quality rated value;

$S_n(x;\tau)$ — normalized spent resources cost parameter rated value;

$E_n(x;\tau)$ — normalized equipment efficiency rated value;

τ — time.

The features that could be assessed as the criterion function's (1) imperfections are following:

— multicriteria optimization technique applied, this function became rather personal judgment of optimality depending on the particular person making the decision;

— the function doesn't consider all complex of capital expenditures for installation, adjustment, service and operation;

— initially every criterion function's components have their proper units of measure, and even some unification implemented, their adequate comparison is difficult to implement;

— the criterion function is used to form the plan of equipment x switching that is a resource-intensive computing task requiring to simulate a complicated multiple-factor model of environment.

Despite all shortcomings, in the absence of alternatives the heat supply system management using criterion function (1) really allows to support a certain balance between the efficiency of resources-to-thermal energy transformation, equipment reliability, quality of required temperature ensuring and the value of expenditure for resources involved. Thus the criterion function's some component priority is defined by weight coefficient.

The suggested solution is seeking to improve the criterion function (1) representing all its components through an uniform unit of measure. It allows the passage to a monocriterial optimization problem. Another key feature of this research relates, having refused to seek the forecast and equipment switching plan formation problem solution, to searching for the optimum decision for each time instance.

All criterion function components can be expressed through monetary units of measurement, the money representing an universal equivalent of goods' and services' cost.

In quality of initial data it is supposed that the generalized heat supply system has the following characteristics:

T — system resource, s;

$\Delta\tau$ — simulation interval either an interval within which the system operation is assessed, s;

C_e — equipment value;

C_{ia} — installation and adjustment value;

C_s — system servicing value for a time period T ;

G_c^i — quantity of i th energy resource consumed during the reported period (month);

$C_r^i(\tau, G_c^i)$ — current price of i th energy resource depending on day time as well as on the previously consumed energy resource quantity;

G_r^i — current expenditure of i th energy resource during the reported period (month);

N_c — number of consumers connected.

Calculation of the criterion function's cost-related component $S(\tau)$

$$S(\tau) = \frac{(C_e + C_{ia} + C_s)\Delta\tau}{N_c T} + \sum_i C_r^i(\tau, G_c^i) G_r^i(\tau)\Delta\tau . \qquad (2)$$

Depending on the given heat source type, the value $C_r^i(\tau)$ can be represented as UAH/kg, UAH/J, UAH/kWh, UAH/m^3. The summation symbol at (2) does signify that some heat sources while operated are using the electrical power (e.g. for pumps function).

Further simulative modeling revealed that the $G_r^i(\tau)$ value does indirectly represent the energy resource – into thermal energy transformation efficiency. As a rule, all heat sources structurally are designed in a manner maintaining the required temperature at the heating element's output (should it be the furnace either thermoelectric heater). The consumed quantities and heat carrier temperature at the system being known, we can calculate theoretically the required thermal energy quantity, needed for heat carrier heating. Meanwhile the thermal processes' shortcomings as well as various thermal an physical heat carrier's losses result is actually greater energy amount required for heat carrier heating. The $G_r^i(\tau)$ value represents the actual energy resource expenditure immediately determining the changes of thermal energy cost when that energy production efficiency changed.

To represent the reliability characteristic in money units equivalent, it is suggested to us the actuary mathematics' methods applied at insuring to calculate the tariffs for high risk insurances [5].

The initial data:

$\overline{S}_n$ — average insurance coverage of one agreement;

$\overline{Q}$ — average indemnification per one agreement;

N — total number of agreements concluded during some preceding period;

M — insured occurrences number at N agreements;

p — probability of one agreement insured occurrence arising;

n — quantity of insurance agreements proportioned to the time period for which the insurance coverage is provided.

The probability of one agreement insured occurrence arising:

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

In the absence of p , $\overline{S}_n$, $\overline{Q}$ values' statistics, they can be assessed by Delphi method or substituted with analogous parameters. So, the insured occurrence probability p we can replace with a value reciprocal to the heat energy source' reliability $p = 1 - P(\tau)$. The average insurance coverage per on agreement $\overline{S}_n$ can be approximated as equal to capital costs for purchase, installation and adjustment divided to the consumers number:

$$\overline{S}_n = \frac{C_e + C_{ia}}{n} .$$

Essential to note is the insurance agreements number doesn't always enter in direct correlation to the connected consumers numbers N_c . Case of district boiler facility, such approximation is wellreasoned as, when equipment failure to compensation should be paid to every subscriber; and case of individual heat sources, advised is to estimate some limited totality of subscribers, e.g. a living house.

The sought reliability index represented in money equivalent can be found on the net-premium basis T_n.

$$T_n = T_0 + T_p, \qquad (3)$$

where T_0 — net-premium main part;

T_p — risk loading.

$$T_0 = p\frac{\bar{Q}}{\bar{\bar{S}}_n} = \left(1 - P(\tau)\right)\frac{\bar{Q}}{\bar{\bar{S}}_n}, \qquad (4)$$

$$T_p = 1{,}2T_0\alpha(\gamma)\sqrt{\frac{1-p}{np}} = 1{,}2T_0\alpha(\gamma)\sqrt{\frac{P(\tau)}{n(1-P(\tau))}}, \qquad (5)$$

where $\alpha(\gamma)$ — coefficient depending onto safety guarantees γ (to be selected from reference tables).

The resulting from (3) net-premium value represents a share of relative insurance sum. In quality of such relative insurance advisable is to admit the summary capital costs for installing and adjusting the thermal energy source.

According to the actual techniques of tariffs calculation the lower limit of relation between $\bar{Q}$ and $\bar{S}_n$ at (4) shall be within scale from 0,3 (medical insurances) up to 0,7 (liability insuring) [5]. In our case these values' relation can symbolize some heat supply quality criterion. When the final consumer suffers from thermal energy deficiency, he is forced to bear some additional costs (e.g. to purchase alternative thermal power sources). Such expenses must be repaid by the principal heat supplier. At that the $\bar{Q}$ and, consecutively, the relations $\bar{Q}/\bar{S}_n$ do increase. Under circumstances of qualitative heat supply the $\bar{Q}$, time elapsing, decreases.

Further we suppose to investigate the possibility of using the ratio $\bar{Q}/\bar{S}_n$ to assess the process heating quality. In this paper, it was assumed to be 0,7.

The calculation of reliability component $R(\tau)$ can be carried out for some ΔT, a period equal to the month, quarter, year and thus take into account changes in the system reliability when an accident occurred.

In general, the reliability component, taking into account (3)…(5) is:

$$R(\tau) = \left((1 - P(\tau))0{,}7\left(1 + 1{,}2\alpha(\gamma)\sqrt{\frac{P(\tau)}{n(1-P(\tau))}}\right)\right)\frac{(C_e + C_{ia})\Delta\tau}{\Delta T}.$$

Proposed is to calculate the equipment failure-free operation probability $P(\tau)$ by the method described in [2] when the equipment reliability is determined by two kinds of failures: random and wear-dependent, and depends on the environment condition and the relative power of equipment operation.

Further analysis revealed that this objective function can exclude the quality component.

When several alternative heat sources, the required temperature can be maintained always, controlling the amount of sources engaged. If heated premises' overheating occurs, (for example, in the case of central heating system) the point temperature is maintained by venting excess heat to the environment via a ventilation system. In this case, the consumer pays the entire cost of recoverable thermal energy, and, consequently, the unit cost per heat unit may exceed the cost of heat from alternative sources, that should lead to a change in the heating system structure.

Thus, the modified form of the objective function (1) is:

$$J(\tau) = S(\tau) + R(\tau). \qquad (6)$$

All components are expressed in monetary units, and hence the optimal solution search refers to choosing at every moment the cheapest source of thermal energy. If it is not sufficient to ensure a required temperature, we proceed to further selection of the next source with minimal cost of power generation.

Results. We consider a generalized district of the Odessa city consisting of 200 houses 72 apartments at each. Heat losses per one house at -18 °C are reaching 200 kW, that results in average heat loss per one apartment about 2,8 kW. Let the district is heated with one boiler facility. As an alternative, we assume that each apartment is equipped with a gas boiler, electric boiler and heat pump at that the boiler covers only the HWS need. Also we assume that the house has a rooftop boiler. The energy tariffs are given in Table. 1...3. Tariffs rates are as of 02/01/2014.

Table 1

Natural gas consumption tariffs

	When annual gas consumption below 2500 m^3	When annual gas consumption below 6000 m^3	When annual gas consumption below 12000 m^3	When annual gas consumption exceeds 12000 m^3
Price per 1 m^3, UAH	0,725	1,098	2,248	2,686

Table 2

Electrical power consumption tariffs

	When monthly consumption below 150 kWt·h	When monthly consumption below 800 kWt·h	When monthly consumption exceeds 800 kWt·h
Price per 1 kWt·h, UAH	0,2802	0,3648	0,9576

Table 3

Tariff coefficients for electrical power differentiated 24-hours round

Tariff zone	limits	coefficient
Pique	from 08-00 to 11-00 from 20-00 to 22-00	1,5
Semipique	from 07-00 to 08-00 from 11-00 to 20-00 from 22-00 to 23-00	1,0
Night	from 23-00 ro 07-00	0,4

The fresh water supply tariff in Odessa city makes 2,736 UAH/m^3.

Let the thermal power sources' characteristics are following:

Table 4

Thermal power sources' principal characteristics

Thermal energy source	Resource, years	Summary capital expenditures, UAH	Reliability	Efficiency
District boiler facility	25	13000000	0,999	0,98
Rooftop boiler facility	25	400000	0,999	0,96
Gas boiler	15	10000	0,999	0,75
Electrical boiler	10	3000	0,999	0,95
Heat pump	10	6000	0,999	*

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* the heat pump thermal expansion coefficient depends onto the ambient environment' temperature

We assume that the simulation interval $\Delta\tau$ is 120 seconds. At that the central heating, hot and cold water in Odessa are supplied at fixed value 365,58 UAH/Gcal, 20,186 UAH/m^3 and 2,736 UAH/m^3, respectively.

Table 5 does expose the calculations results as to the minimum and maximum cost of heating and hot water using the expression (6) for different heat energy sources. To simply the comparison, the heating system results are expressed in UAH/Gcal, and the hot water in the UAH/m^3.

Table 5

Results of calculating the minimum and maximum cost of heating and hot water for different energy sources

Source	$J_{\min}$, UAH/Gcal	$J_{\max}$, UAH/Gcal
Heating		
Gas boiler	34,0	36,6
Thermal pump (electrical energy standard tariff)	325,5	1041
Thermal pump (electrical energy 3-zones tariff)	177,3	1547
Rooftop boiler unit	85,5	87,6
District boiler facility	365	365
Hot-Water Supply		
Gas boiler	9,3	25,0
Thermal pump (electrical energy standard tariff)	11,6	54,0
Thermal pump (electrical energy 3-zones tariff)	7,5	79,4
Electrical boiler (electrical energy standard tariff)	20,2	59,0
Electrical boiler (electrical energy 3-zones tariff)	11,7	88,3
Rooftop boiler unit	9,3	21,5
District boiler facility	20,2	20,2

Conclusions. The obtained results analysis leads to several important conclusions.

The proposed optimal management objective function takes into account as the thermal energy final cost integral components such factors as capital expenditure for required equipment purchase, installation, commissioning and maintenance, its equipment reliability and efficiency. At that this optimization problem is reduced to a monocriterial one. An optimal solution is taken by selecting at each time point the heat source or heat supply system structure that allow obtaining the final product (heat, hot water) at a minimal cost.

The heating system combining various alternative sources of heat (which consume different primary energy), potentially allows when threshold quantity of some energy source used (that defines transition to a more expensive tariff), switching to heat sources, that use another kind of energy source with cheaper current tariff.

A promising solution in this respect is to use a 3-zone electrical power tariffs allowing to accumulate at night the thermal energy generated by electric heat sources, especially heat pumps.

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АНОТАЦІЯ / АННОТАЦИЯ / ABSTRACT

С.В. Бабіч, В.О. Давидов. **Цільова функція структурної оптимізації міських систем теплопостачання**. Сучасні системи теплопостачання міських районів потенційно дозволяють знизити витрати на теплопостачання за рахунок використання різних альтернативних джерел теплової енергії. Наявність альтернативи дозволяє обирати те джерело, яке генерує дешевшу теплову енергію. При цьому виникає питання, як виразити в єдиних одиницях виміру такі різні характеристики джерел як капітальні витрати, надійність та ефективність. У роботі запропоновано цільову функцію, в якій всі чинники, що впливають на кінцеву вартість теплової енергії, виражені в грошових одиницях. Показано, що діапазони зміни собівартості різних джерел в залежності від впливу зовнішніх чинників значно змінюються. Застосування запропонованої цільової функції для управління структурою систем теплопостачання міських районів дозволить істотно знизити експлуатаційні витрати.

Ключові слова: система опалення, управління структурою, цільова функція.

С.В. Бабич, В.О. Давыдов. **Целевая функция структурной оптимизации городских систем теплоснабжения**. Современные системы теплоснабжения городских районов потенциально позволяют снизить затраты на теплоснабжение за счет использования различных альтернативных источников тепловой энергии. Наличие альтернативы позволяет выбирать тот источник, который генерирует более дешевую тепловую энергию. При этом возникает вопрос, как выразить в единых единицах измерения такие различные характеристики источников, как капитальные затраты, надежность и эффективность. В данной работе предлагается целевая функция, в которой все факторы, влияющие на конечную стоимость тепловой энергии, выражены в денежных единицах. Показано, что диапазоны изменения себестоимости различных источников в зависимости от воздействия внешних факторов значительно изменяются. Применение предложенной целевой функции для управления структурой систем теплоснабжения городских районов позволит существенно снизить эксплуатационные затраты.

Ключевые слова: система отопления, управление структурой, целевая функция.

S.V. Babich, V.O. Davydov. **Objective function for municipal heat supply systems' structural optimization**. Modern heat supply systems in urban areas have the potential to heat supply cost reduction when using various alternative thermal energy sources. Availability of possible alternatives allows to select the source that generates a cheaper heat. At that arises the question of expressing such different sources' characteristics as capital cost, reliability and efficiency in the consistent measurement units. This paper proposes an objective function representing all the factors affecting the thermal energy final cost in monetary units. It is shown that depending on external factors the range of prime cost for heat from various sources does vary considerably. Expected is that the proposed objective function application for managing the heat supply systems structure in urban areas will significantly reduce the operating costs.

Keywords: heat supply system, structure management, objective function.

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