Using the directed search method to select the degree of centralization of heat supply schemes in order to ensure the environmental sustainability of a settlement

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Abstract. An algorithm is proposed for the formalized choice of the degree of centralization of the heat supply scheme in order to ensure the environmental sustainability of the settlement. The algorithm is based on a directed search for combinations of centralization and decentralization of the scheme, with the construction of networks of optimal topology for each of the compared options. The calculation begins with a variant of a decentralized heat supply scheme (maximum number of sources), followed by a reduction in heat supply sources by one at each iteration, up to full centralization to achieve ecological balance in the settlement. Taking into account the directed search proposed in the algorithm and excluding non-optimal combinations at each iteration, the number of calculations is significantly reduced compared to a simple enumeration of options. In addition to practical application, the algorithm allows you to study the "heat load density" indicator, which affects the decision on the degree of centralization of the heat supply scheme, and at the same time take into account the uneven distribution of consumers on the ground, their number, the heterogeneity of heat loads and achieving a balance in the environment.

1. Introduction
The task of choosing a heat supply scheme for a settlement is to determine the number, unit heat capacity and mutual arrangement of heat sources, with the construction of engineering networks that are optimal in terms of configuration and diameters (first of all, heat and gas).

The problem of choosing the optimal capacity of district boiler houses was solved on the basis of determining the economically permissible range of heat transport under the assumption of a uniform distribution of heat load across the city, or by comparing a number of arbitrarily assigned options for the degree of heat supply centralization [1].

The most general formulation of the problem of optimizing the parameters of the heat supply system: the problem of choosing the composition, configuration and parameters of heat supply systems (hereinafter - TSS) is reflected in the monograph [2], in works [3-4]. The solution to the problem of joint optimization of parameters and configuration of heating networks and heat supply sources is envisaged. The methods given in [2-4] were preceded by the development of the theory of hydraulic circuits [5].

Based on the results of studies and the solution of circuit-structural problems for real objects [2], it was concluded that the most efficient and practically effective tree structure optimization method
should be recognized as the method of directed enumeration of trees of the original redundant circuit. On the basis of works [2; 5], the problems of constructing heat supply schemes for the largest cities of our country have been solved.

The most important purpose of the "heat load density" indicator is that its value can be associated with the choice of competing heat supply schemes - centralized and decentralized. Sources [6-7] give different limit values of the heat load density, above which the centralized scheme becomes more efficient than the decentralized one. The numerical indicators of the heat load density given in [6] are reflected in the 1998 regulatory document [8].

The current codes of practice for the design of heat supply systems [9-10] do not contain specific numerical indicators that would allow a conclusion on the choice of a heat supply scheme depending on the parameters characterizing the building area.

Thus:

- Existing optimization methods allow solving the complex problem of choosing the optimal structure of a heating system with branched heating networks [10]. In this case, the researcher must first build a redundant design scheme, which is a design scheme of the system as a set of acceptable configuration options for the heating network and the location of heat sources, taking into account the restrictions associated with natural and artificial obstacles on the ground and sites selected for the placement of sources. The problem is solved using complex algorithms using dynamic programming and discrete optimization methods, taking into account the multifactor nature of the problem and a large number of restrictions;
- Studies of the choice of a circuit design of a heat supply system depending on the type and characteristics of the heat load function in the area, except for its uniform distribution in the area, has not been carried out;
- The current sets of rules for design are limited by the requirement to perform technical and economic calculations.

2. Materials and methods

In the formulation of the problem of choosing heat supply schemes for small settlements with the subsequent development of practical recommendations, first of all, it is of interest to study the indicator "heat load density" (hereinafter - STP).

The term "heat load density" itself requires a more detailed description in conjunction with the following indicators: the distance between consumers; geometric uneven distribution of consumers on the ground; uneven distribution of heat load on the ground.

As an example illustrating the ambiguity of the concept of "heat load density", we will give numerical indicators: heat load density 1.0 Gcal / h / ha, can characterize as the placement of 4 consumers on an area of 9.0 ha with a heat load of 2.25 Gcal / hour each (roughly corresponds to the heat load of a 17-storey residential building of 6 sections of the standard series HMS-1 or P-44, the distance between load centers is 300 m), as well as the placement of 36 consumers on the same area, each with a heat load of 0.25 Gcal / hour (individual or small apartment building, the distance between the load centers is 60 m).

An algorithm for constructing a heat supply scheme has been developed, which makes it possible to take into account the above factors. The generation of a scheme is envisaged, which can be considered the most optimal for the corresponding geometric placement of heat consumers on the ground.

When setting the problem in the form of a simple enumeration of possible options when generating a heat supply scheme for N consumers, it would be necessary to perform calculations for 2N options for possible schemes. The proposed algorithm provides for a directed search with the elimination of non-optimal combinations in the calculation process.

The statement of the problem provides for a directed search, starting from the state corresponding to the decentralization of the scheme (heat supply from autonomous sources - roof, built-in, attached boiler houses), and ending with centralization (heat supply from a single source).
As an objective function, when searching for the optimal option, the total discounted costs for the system for the billing period are provided [12].

Initial data for the calculation: location of consumers on the ground (coordinates) and information on heat loads.

Technical and economic indicators that affect the target function, but depend on local conditions, are taken as data for the region under consideration. Among them: the cost of thermal mechanical equipment (in the software implementation of the algorithm, the cost of modular boiler houses is used); the cost of building engineering networks; the cost of fuel, electricity, water; estimated service life; discount rate.

The search for a solution starts from the state of the system, which corresponds to the decentralized scheme (number of sources = N). The main costs of the system are characterized by the cost of building and operating individual boiler houses and gas networks. The costs of connecting to water supply, sewerage, power supply and communication networks are not taken into account by the proposed algorithm. The complexity of the algorithm is possible taking into account the listed networks.

At the next iterations, a directed construction of heat supply schemes takes place, which can be generated for the case under consideration. For the first step, the sequence of consideration of possible states of the heat supply system, each of which is characterized by its own value of the objective function, can be represented in the form of a matrix. Let's call it the matrix of system states (hereinafter - MSS):

\[
\begin{array}{cccccc}
1-2 & 1-3 & 1-4 & \ldots & 1-N \\
2-1 & 2-3 & 2-4 & \ldots & 2-N \\
3-1 & 3-2 & 3-4 & \ldots & 3-N \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
(N-1)-1 & (N-1)-2 & (N-1)-3 & \ldots & (N-1)-N \\
\end{array}
\] (1)

Cell "1-2" assumes the construction of a heat supply scheme, in which heat is supplied from one source to consumers No. 1 and No. 2, and the method of heat supply to other consumers - No. 3, 4 ... N - is decentralized.

The search for a solution is performed by iteration. The number of iterations is equal to the number of consumers. At each iteration, the number of consumers supplied from individual sources is reduced by one. Each iteration (It) provides for the construction (N-It) of heat supply schemes. The result of calculations of each iteration is information - which of the consumer associations provides the greatest reduction in estimated costs. The calculation results of each iteration are the initial data for the subsequent ones.

Key features of the proposed algorithm:

- Enumeration of options is performed for cases corresponding to the states of the system above the main diagonal;
- At each iteration, the size of the matrix is reduced by one column and one row;
- Directed enumeration of options eliminates non-optimal combinations, reduces the number of computations and allows a strictly formalized determination of the state of the system corresponding to the minimum value of the objective function.

Let us illustrate the operation of the algorithm with a simple example for 4 conditional consumers. MSS looks like:
Let's comment on the information provided in the MSS:

- Based on the results of enumerating options for heat supply schemes at Iteration No. 1, the optimal state of the system corresponds to the scheme “Heat supply to consumers No. 1 and No. 2 from a common source, to consumers No. 3 and No. 4 - decentralized”;
- Based on the results of enumerating options for heat supply schemes at Iteration No. 2 (initial data for Iteration No. 2 - the results of Iteration No. 1), the optimal state of the system corresponds to the scheme "Heat supply to consumers No. 1, No. 2, No. 3 from a common source, consumer No. 4 is decentralized";
- At Iteration No. 3, it remains to compare two options - complete centralization or the optimal state of the system at Iteration No. 2.

At each iteration, when a new option is taken into consideration with its own number, power and mutual arrangement of heat supply sources, it is necessary to generate heat and gas networks with optimal routing and diameters corresponding to the location of heat supply sources.

To solve the problem of building networks, the following formulation is adopted: it is necessary to determine the groups of consumers who are supplied through common branches and consumers supplied through individual branches from the backbone network. The problem in this setting was formulated in 1950 in the works of Shifrinson B.L. [11].

In development of this formulation of the problem, an algorithm for directed enumeration of the network topology is implemented. The initial state of the system is characterized by a tree, when each consumer is supplied from the backbone through an individual branch. Those the number of connections to the backbone network is equal to the number of consumers. All other states are generated starting from the first one, with the subsequent directed unification of consumer groups (based on the results of comparing the value of the objective function for the generated options). The solution to the problem of finding the optimal network topology in this setting is presented in more detail in the publication [13-14].

3. Results

The practical use of the proposed algorithm will be illustrated by the example of choosing a heat supply scheme for eight consumers (each load is 1.5 Gcal / hour, location on the ground is reflected in the diagrams, distances are indicated in meters).

Estimated costs and construction costs for three representative options are shown below in the text. To perform the calculations, approximations were made for the cost of heat supply sources depending on the thermal power. The cost of heating and gas networks, depending on the diameter, is taken according to the collections of basic prices for construction (figure 1).
Centralization degree

Centralized scheme (source N-1)
Costs, million rubles / year: 31.126
Construction cost, million rubles: 80.338

Combination of centralized and decentralized scheme (sources N-1, N-2)
Costs, million rubles / year: 30.473
Construction cost, million rubles: 72.94

Decentralized scheme (sources N-1 ... N-8)
Costs, million rubles / year: 29.086
Construction cost, million rubles: 74.048

**Figure 1.** Feasibility study of schemes.

As can be seen from the results of the presented calculations, with comparable costs for the billing period, there is a significant difference in the cost of construction. This factor must be taken into account when choosing an option, because costs during the life cycle of the designed heat supply system may not always be a priority.

Using the proposed algorithm, calculations were performed with building densities typical for rural settlements and urban-type settlements, which made it possible to determine the qualitative type of change in the boundary heat load density depending on the area of the occupied territory and the nature of the location of consumers. The boundary density means the value below which the decentralization of the heat supply scheme becomes optimal. According to the results of calculations, the boundary density is parabolic and varies in the range of 0.4 ... 0.05 Gcal / h / ha with uniform distribution over an area of 4 ... 36 ha. The calculations also showed the presence of a zone in which the construction of schemes with different degrees of centralization is comparable in terms of costs [15-16].

4. Discussion

The main disadvantages of the proposed algorithm are the construction of an "ideal" heat supply scheme (without taking into account the local features) and a number of assumptions, including: placement of boiler houses in the center of consumers' heat loads; routing of heating networks along straight paths; lack of accounting for the location of points of connection to the networks of engineering and technical support in real conditions; the presence of restrictions on the dispersion of combustion products. The generation of real heat supply schemes requires the introduction of appropriate boundary conditions into the algorithm [17].

At the same time, the algorithm allows, by conducting a computational experiment, to identify the characteristic features of the indicator "heat load density", taking into account the above factors of unevenness, and also to consider such a term as "optimal radius of heat supply" in a new way. In light
of the proposed formulation of the solution to the problem of choosing a heat supply scheme, it can be seen that the optimal option is characterized by an appropriate degree of centralization and the radius of heat supply is not always dictating for decision making.

The proposed algorithm can be used to solve similar problems in other areas, for example: determining the degree of centralization of air supply systems of an industrial enterprise; making decisions on the number and capacity of transformer substations of electrical networks; placement of refrigeration centers, etc [18-21].

5. Conclusion
The results obtained provide practical recommendations for optimizing heat supply systems in settlements, indicate the effectiveness of using the "heat load density" indicator in the design of energy-saving heat supply systems and determine the directions for further research with a computational experiment for a more in-depth identification of factors affecting the choice of an optimal heat supply scheme.

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