An Approach for Efficient Heat Source Selection in Long-Term Expansion Planning of Urban District Heating Systems

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Abstract. This study proposes an approach to selecting efficient heat sources in the context of long-term expansion planning for urban district heating systems. The approach includes two stages: synthesis and optimization. During the synthesis stage, potential heat source structures are generated using graph grammars. In the optimization stage, the most effective combination of heat source equipment is selected based on minimum construction costs, heat network costs, and pollutant emissions fees. Iterative linking of these two stages provides a coherent solution for determining the structure and parameters of heat sources, for streamlining the process of performing computational studies. The proposed approach is a comprehensive and cost-effective method for selecting heat source structures for urban district heating systems.

1 Introduction

The structure of heat sources (HS) is defined as the number, location, capacity, type, and mix of HS equipment. The choice of an efficient HS structure along with determination of a rational configuration of the heat network (HN) is an integral part of problems related to layout topology and structure for long-term expansion planning of district heating systems (DHS) (as a rule, it is the level of regional and municipal district heating layouts designed for 5 to 25 years ahead).

The choice of an efficient HS structure is aimed at minimizing costs, subject to achieving the required technical, economic, and environmental performance resulting from its implementation, by changing the values of design variables. The representation of the solution space of these variables affects the capabilities and performance of optimization methods, because the space is a complex dynamic set, the processing of which for most optimization methods can prove an overwhelming task.

State-of-the-art approaches to generating and optimizing such spaces of variables can be divided into two groups. The first group is based on the generation of superstructures (redundant layouts), whereas the second group is that of non-structural approaches.

In a superstructure, the solution space has a fixed number of variables, which means that all alternatives are hardcoded, thus creating a static structure of the set of variable values

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[1-8]. This allows for a systematic search for an optimum using well-established optimization methods. As a rule, superstructures lend themselves to stating optimization problems in the language of mathematical programming (using equations and logical conditions).

Non-structural optimization methods use a solution space in which new variables can appear or disappear, creating a dynamic set of variable values. Such a solution space makes it possible to discover unexpected new alternatives that have not been predefined. In general, non-structural approaches [9-14] reduce the number of integer variables by ruling them out when representing HS types. This greatly accelerates the speed of generating new alternatives. However, in this case the strict lower bounds of the optimization problem are lost, the presence of which allows one to avoid redundant enumeration of available options. In problems for which these lower bounds are not important or are of less importance, non-structural approaches may be a suitable method for heuristic search [15].

Previously, the authors [16] proposed and formalized the problem of determining the optimal mix of HS equipment for the tasks of DHS expansion planning. It uses such a technique to represent the solution space in the form of a redundant designed layout (superstructure). However, the practical implementation of the technique based on P-graphs [17], revealed the issues related to the difficulties of generating and analyzing large HS designed layouts in the P-Graph Studio software. Other workers reported [18] the low speed of the analysis of such layouts implemented by them with the use of freely available linear programming solvers.

To address the above issues, a non-structural two-stage (hybrid) approach was proposed [1, 18], where one of the stages serves as a special-type superstructure over the optimization model and relies on evolutionary algorithms to solve the problem of structure synthesis.

2 Technique for choosing an efficient structure of heat sources

As suggested above, the investigated problem can be represented as two stages [18] with Stage 1 related to synthesis (1), and Stage 2 related to design (2):

$$\min_{\psi} S(\psi)\text{, where } \psi \in \Psi, \tag{1}$$

$$\text{if} \min_{V_z^m, Q_z, W^{eps}, F_{z,k}} S^{\psi}(V_z^m, Q_z, W^{eps}, F_{z,k}) \tag{2}$$

where S - the present value of DHS costs of the settlement; ψ - mutation of the evolving DHS structure; Ψ - set of all possible DHS structures; S^{ψ} - the present value of DHS costs in the case when the structure ψ is implemented; V_z^m - Boolean variable determining whether an equipment mix m for the z-th HS as defined by certain technical and economic parameters will be implemented; z - heat generation by the Q_z -th HS; W^{eps} - amount of power system electricity sold/purchased; F_{zk} - gross emissions of the harmful substance $k \in K$ from the z -th HS.

Stage 1 solves the problem of synthesis of HS structures as part of the DHS by evolutionary algorithms (1). Stage 2 optimizes HS structures (2) with such optimization serving as a local refinement (Fig. 1). That is to say that for each alternative of HS structures, Stage 2 solves the problem of determining the optimal mix of HS equipment and the key parameters of the DHS that minimize the cost of implementing this alternative.

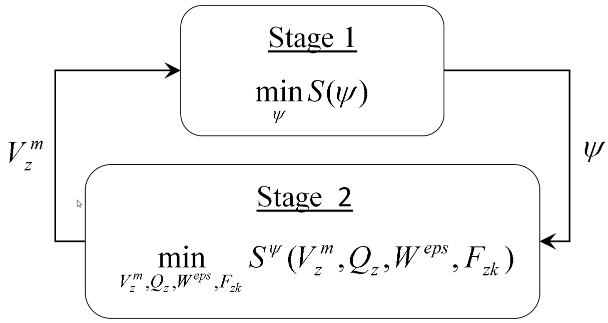

Fig. 1. Two-stage optimization technique.

The mathematical statement of the problem of determining the optimal HS structure is to find the minimum of the objective function, which is the sum of the present values of costs of HSs and heat networks, as well as the cost of sale/purchase of electricity from the system, and emission fees, as expressed in rubles:

$$S^{\psi} = \sum_{z}^{Z} (s_z \cdot Q_z) \cdot V_m^z + S_{net} + \sum_{k \in K} S_k \cdot F_{zk} - S_{out}^{eps} \cdot W_{out}^{eps} + S_{in}^{eps} \cdot W_{in}^{eps} \Rightarrow \min, \quad (3)$$

where s_z - the present value of specific costs of the z -th HS, which are defined as the ratio of discounted capital expenses and annual operating costs to the amount of heat generation by the z -th HS; S_{net} - HS costs; S_k - the penalty for exceeding the emissions limit for the k -th substance; S_{in}^{eps} - the tariff for purchasing electricity from the power system; S_{out}^{eps} - the tariff for selling electricity to the power system; W_{in}^{eps} - the amount of electricity purchased from the power system; W_{out}^{eps} - the amount of electricity sold to the power system.

The objective function (4) is specified together with a number of constraints on meeting heat and electricity balances, the amounts of fuel burned, the conditions of competition between alternatives, and compliance with pollution limits induced by regulators, as detailed in [16].

3 Technique for synthesizing heat source structures based on evolutionary algorithms

Our approach to the synthesis of HS structures based on evolutionary algorithms can be represented as a cycle of Steps 1 to 7 (Fig. 2), which includes the action of a genetic algorithm in its conventional sense [19].

At Step 1 (Fig. 2) the starting population is created, with such population consisting of individuals, each of which is a separate HS structure. Its fitness is then evaluated (Step 2, Fig. 2), that is, the optimal equipment mix is selected with the aid of the source structure optimization model for each individual and its costs are estimated (see description of Step 2 below). Then we come down to condition 3 (Fig. 2), the termination condition can be a comparison of the cost difference between the new population and the preceding population with some given constant cost value.

If the condition fails to be met, selection is performed within the population (Step 4, Fig. 2). Next, the best individual (structure) is mutated (Step 5, Fig. 2). For the new population (Step 6, Fig. 2), fitness is re-evaluated, and the process is reiterated in order to obtain a family of alternatives and select the best one (Step 7, Fig. 2). Let us detail the operators of the genetic algorithm:

– Fitness evaluation involves calculating the values of the fitness function for any HS structure, which is in our case finding the minimum of function (4);

– Selection is choosing individuals from a population for reproduction purposes, that is, the selection of the fittest individuals;

– Mutation changes the fittest individual (structure). The mutation operator consists of two parts, application of graph grammar rules and post-processing. The rules of graph grammar generate a new individual, the rules are applied randomly. Next, post-processing fills in the missing connections in the individual by input and output parameters (e.g., input parameters: type, amount, and transport of fuel; output parameters: amount of consumed heat and electricity, pollutant emissions).

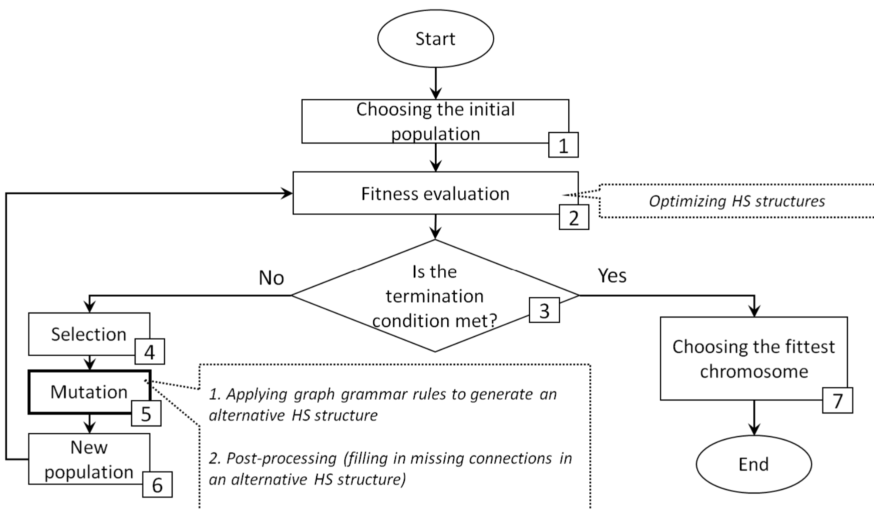

Fig. 2. Action of a genetic algorithm for synthesizing HS structures.

The crossover operator does not apply in this formulation, since dividing an individual and connecting its parts to parts of another individual is impossible for the HS structure.

Fitness evaluation is the task of Stage 2 (Fig. 1), at this stage we use the model developed previously by the authors to determine the optimal HS structures in the DHS, which is based on generating and optimizing redundant layouts [16].

4 Application of graph grammars and post-processing to generate heat source structures

The first step of the mutation operator is to use graph grammars (Fig. 2, item 5). The theory of sequential graph grammars is a generalization of Chomsky's theory of formal grammars [20].

The theory of sequential graph grammars considers graphs instead of sequences of symbols proposed in [21]. The graph grammar rule describes the replacement of a subgraph in a graph by a set of terminal and non-terminal symbols. The set of terminal symbols consists of definite valid characters, and the set of non-terminal characters consists of abstract indefinite characters. The transformation from the initial sequence to the subsequent sequence follows certain rules.

To define a rule, it is not enough to specify two graphs as it is additionally required to describe the transformation of the inclusion of the replaced graph into the remaining graph [20].

As applied to the task of generating alternative HS structures, a hierarchically structured graph, the so-called Energy Conversion Hierarchy (ECH) [18], is generated, which allows one, following certain general rules, to change the type of HS equipment in the DHS being designed. ECH can be represented as three interrelated levels: the meta level, the function level, and the technology level (Fig. 3).

Mutation rules, or graph transformation rules (Fig. 2, item 5) are derived based on the properties and features of the hierarchy of energy technologies. The rules guide the enumeration process so as to avoid unacceptable configurations in structures.

They are formulated so as to tailor a specific problem being solved, e.g. [18]:

1. Remove one component with all its connections (a component means a HS of a certain type and capacity).
2. Remove one component and insert another similar component.
3. Remove one component and insert two other similar components connected in parallel.
4. Remove one component and insert two other similar components connected in series.
5. Remove one component and insert another component with extended functions.

In Rule 5, extended functions mean enhanced functional properties of a component (e.g., removing a heat source and inserting a source that generates heat and electricity).

The post-processing step in the mutation operator (Fig. 2, item 5) is the filling in of missing connections in the graph transformation. As a rule, these are links to primary energy resources (fuel, electricity, wind, etc.) and outputs (heat, electricity, gross emissions). Post-processing starts with removing all components present in the process flow diagram that do not perform their primary function, and then we check if there are unconnected components. If that is the case, the post-processing step checks how to establish allowable connections for each of these components. To this end, we first establish a connection with any of the components already existing within the current process flow diagram. If that is not possible, a new component is inserted to close the open connections. Post-processing continues until an acceptable alternative is generated.

5 A basic example of the synthesis of alternative heat source structures

The ECH in Fig. 3 is based on the general hierarchy of energy technologies. The hierarchy of energy technologies is presented in the form of a hierarchical database, which is populated based on reference data, equipment catalogs, and specifications of real-life projects.

Energy technologies in the database are divided into three levels and presented as a hierarchical structure: Level 1: technology type, Level 2: plant type, and Level 3: process flow diagram type (for example: gas, gas turbine, open-cycle single-shaft gas turbine with regeneration).

By way of example, we consider three options for alternative sources of heat and electricity: gas-fired GT-based CCHP, an Organic Rankine Cycle (ORC) / gasifier unit fired by wood chips, and a coal-fired boiler plant. Moreover, the options are equal by design in terms of their energy effect, and in the case of boiler plants we provide for the supply of electricity from an outside electric power system (EPS). Fig. 3 presents the proposed options in the form of the ECH.

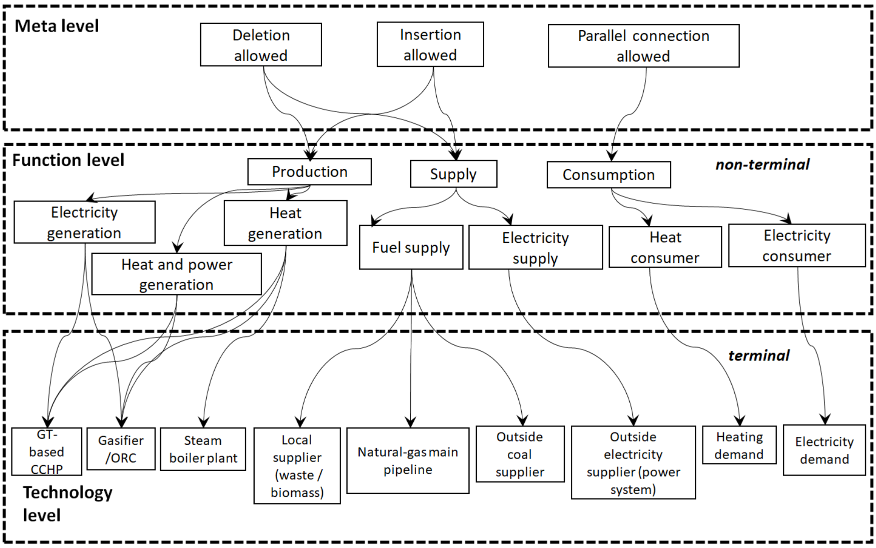

Fig. 3. An ECH example.

At the technology level, which is the terminal level, the actual nodes of the graph are shown (Fig. 3). At the non-terminal function level, we have abstract nodes, and the meta level shows a set of applied rules that allows us to generate alternatives

Suppose the initial terminal graph/alternative consists of a coal-fired boiler plant, then at the output we obtain heat and electricity purchased from an outside power system (Fig. 4, item 1).

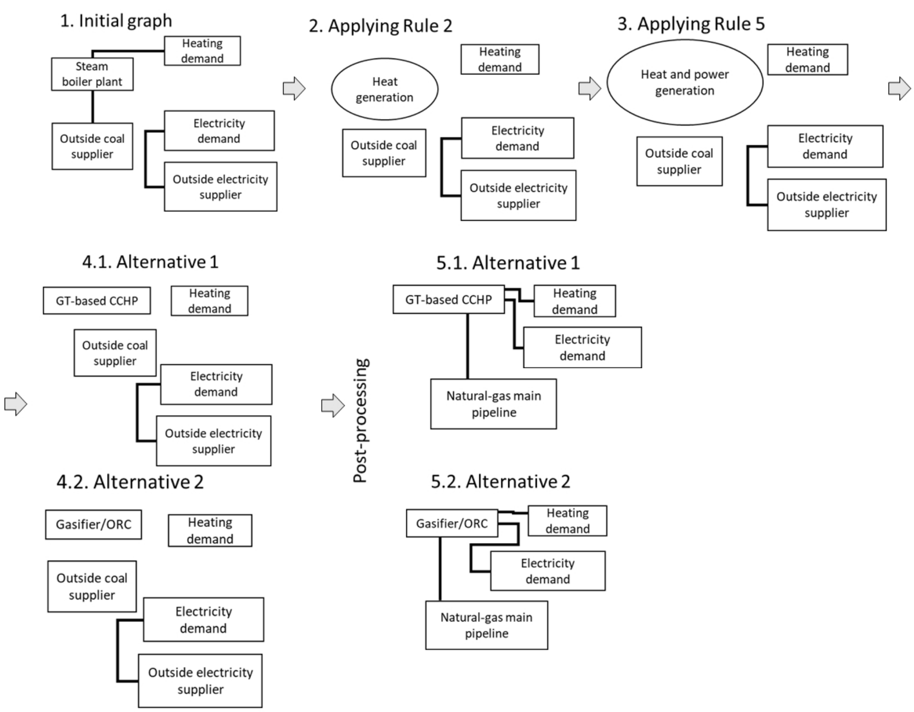

Fig. 4. Example of the synthesis of alternative HS structures.

Coal is delivered by an outside supplier. We change the terminal node to a non-terminal node by applying Mutation Rule 2 (Fig. 4, item 2). As a result of applying the following Mutation Rule 5, this node is replaced with another node with extended functions, i.e., heat and electric power generation (Fig. 4, item 3).

Next, we replace non-terminal symbols with terminal ones, and returning to the technological process level and replacing the non-terminal node with a terminal one we end up with a population of 2 individuals (Fig. 4, items 4.1, 4.2). These individuals undergo post-processing, making up for missing resource links and are fed into the fitness model for optimization (Fig. 4, items 5.1, 5.2).

The structural alternatives thus formed constitute a new population and undergo fitness evaluation (Fig. 2, item 2), that is when their optimization takes place.

6 Conclusion

We have presented an approach to synthesizing heat source structures using evolutionary algorithms, which can be used to efficiently select heat source types in the context of evolving district heating systems. Although evolutionary algorithms are commonly used to synthesize manufacturing processes, their application in the energy sector has been limited to individual combined heat and power plants (CHPPs). Our proposed approach extends the use of evolutionary algorithms to the level of district heating systems with multiple sources. To ensure the generation of feasible heat source structures, our approach uses graph grammar rules and post-processing techniques based on the energy conversion hierarchy. This approach helps prevent the appearance of unacceptable heat source structures during the mutation process of the parent structures.

Finally, we have incorporated a previously developed model to optimize heat source structures, which is designed to efficiently select the optimal mix of main equipment and estimate the associated costs. Our proposed approach can serve as a valuable tool for decision makers involved in long-term expansion planning of urban district heating systems.

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