Decision support for optimal location of local heat source for small district heating system on the example of biogas plant

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Abstract. Developing a new district heating system requires making decisions affecting entire range of following activities and wellness of the system. The article presents methodics of choosing optimal location and crucial customers with three approaches to optimisation process, discuss obtained results and obstacles. Further improvements and potential applications are named.

1 Introduction

Establishing a new, local district heating (DH) network is a complex and long-lasting project, including cooperation and communication with both local community and individual potential heat receivers. Presented article describes an algorithm useful in the first stages of designing a DH network. The algorithm may support decision making and developing conceptual network's framework. Although the tool was primary developed to help owners of the biogas plants to increase waste heat utilisation, it is also fully applicable for any other DH heat source.

2 Algorithm description

2.1 Input data

As the algorithm is performed with Solver in Microsoft Excel, the input data must have been "translated" into a matrix of digits so that the problem might be given, "understood" by this extension and solved. First steps were performed out of Excel software, based on available terrain maps. Each building was marked and superimposed with regular, square network, what allowed to assign proper number of buildings for each square. Here, for a simplicity it has been assumed that all consumers exhibit the same level of power/heat

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demand, meaning that a digit "1" in given square corresponds to a heat demand equal to 43 GJ. Square with greater numbers have accordingly greater heat demand (see Fig. 2.).

If known was an exact annual energy demand, value of each square might be a sum of thermal energy amount required for households within certain cell. In this process useful is GIS software, which, beside fast and precise computing, allows for creating informative maps with customised layout (see Fig.1.) as well as tables significantly expediting creating the input matrix for the algorithm.
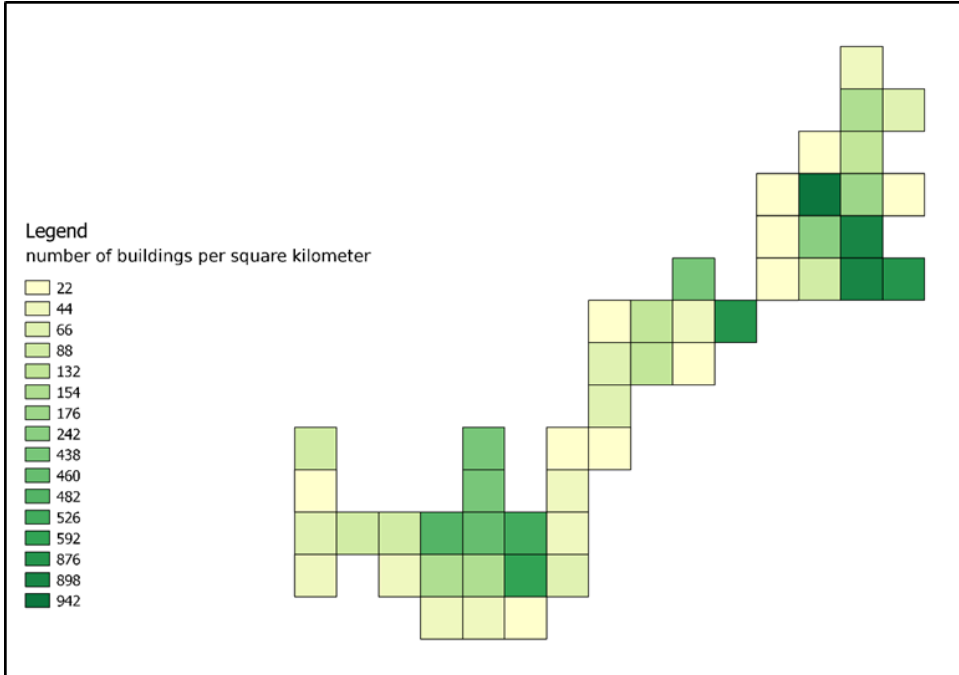
Fig. 1. A simplified map visualizing the heat demand/number of households over considered area.

2.2 Biogas plant location

In order to find the optimal location for the biogas power plant and to select heat receivers which should be connected a mixed integer nonlinear mathematical model has been introduces. The problem of finding the optimal location for a biogas plant is definitely a multi objective problem. Here we introduce three simple but meaningful objective functions. Literature commonly make of two units: GJ*km and GJ/km (called linear heat density) [1–3] alternative way of expressing energy rated to a relevant parameter is GJ/km^2 [3], nevertheless this approach is not useful in present consideration.

2.2.1 Minimizing the total length of the hot water pipes:

The following equation (1) describes objective function for this criterion, id est check for each consumer *j* and choose *m* receivers, which may be connected with minimal length of pipeline.

$$\min Z^{I} = \sum_{i=1}^{m} x_i d_{i,j} \ \vee j \tag{1}$$

where: x_i – is a binary variable (0,1) which value is estimated based on Eq. 2, $d_{i,j}$ – is a distance between heat source i and the heat consumer j.

The x_i parameter is determined as 0, when in location i has no heat source within or 1, when there is a heat source in the location i (equation (2).

$$x_i = \begin{cases} 1 \ if \ heat \ source \ has \ been \ located \ in \ location \ i \\ \qquad\qquad 0 \ otherwise \end{cases} \tag{2}$$

2.2.2 Minimizing the heat transferred over given distance [GJkm] pipes:

The equation (3) objective is to pick heat receivers, which are supposed to be connected to the pipeline. Each combination of set of connected receivers and heat source's location should be checked, what is extremally long-lasting.

$$\min Z^{II} = \sum_{i=1}^{m} \sum_{j=1}^{n} y_j c_j x_i d_{i,j} \tag{3}$$

where: c_j – is a heat demand from consumer j, y_j – is a binary variable calculated based on equation (4).

The following equation determines, that y_j variable is 1 when the heat receiver is connected to the network and equals 0, when building is not considered as prospective in the combination.

$$y_j = \begin{cases} 1 \ if \ consumer \ j \ has \ been \ connected \ to \ the \ biogas \ plant \\ \qquad\qquad 0 \ otherwise \end{cases} \tag{4}$$

2.2.3 Maximizing the heat transferred per unit of distance [GJ/km] pipes:

$$\max Z^{III} = \frac{\sum_{j=1}^{n} y_i c_j}{\sum_{i=1}^{m} x_i d_{i,j}} \ \vee j \tag{5}$$

2.2.4 Constraints

Naturally, objective functions are subject to the following constraints:

$$\sum_{i=1}^{m} x_i = 1 \tag{6}$$

which constitutes that only one location for heat source is allowed, and

$$\sum_{j=1}^{n} y_j c_j = P \tag{7}$$

providing that total required energy amount does not exceed capability of heat source, where: P – is the maximal volume of heat delivered by given biogas plant [GJ].

Constrains given above have been implemented in our example. Also additional constrains might be applied, for example:

$$\sum_{i=1}^{m} \sum_{j=1}^{n} d_{i,j} \leq D \tag{8}$$

where: D – is the given maximal length of hot water pipes.

It is important to bear in mind that such "facility location" problem is very specific. Meaning that connecting additional heat receiver will always lead to an increase in overall objective function. Therefore it was necessary to introduce an additional constraint which

will ensure that the algorithm will always connect some number of buildings. This constraint is given in Eq. 9, where N is the minimal number of connected heat receivers.

$$\sum_{j=1}^{n} y_j > N \qquad (9)$$

2.2.5 Algorithm operation

For selecting the optimal location of a local heat source, the *brute-force* method may be applied – in case of this research we have used an add-in to the MS Office Excel in form of Solver with its inbuilt Evolutionary and GRG methods for solving the nonlinear problems. Therefore not always the optimal configuration has been found for given objective function (as shown in Tab. 1). The step by step procedure of finding the optimal location of the heat source as well as selecting the subset of heat receivers which will be connected to the hot water heat pipe is as follows:

1. Determine the potential locations where the heat source can be located – a potential location in case of investigated model is a site free from heat receivers. Please bear in mind that an additional constraint may be introduced that ensures that the heat source is not closer to the next heat receiver than a given distance.
2. Select one of the location and create a distance matrix between heat source and each of the heat consumers.
3. Select a subset of heat consumers in case of which all constraints are satisfied and objective function reaches its minimum. Memorize the configuration and the results.
4. Go back to the second step and select another location. Repeat procedure from point 3. If all potential locations have been investigated choose that one for which the objective function is optimal.
5. Display resulting configuration and resulting objective function.

3. Results

The applicability of the proposed models has been tested for an exemplary commune (see Fig. 2. for its layout) which consist of 146 buildings. The colourful squares represent areas where buildings (heat consumers) are located, whereas blank squares are free zones where a biogas plant might be located. The red square represents area, where heat source should be optimally placed. As it was mentioned above, presented is simplified model, with buildings of the same heat demand, meaning that a digit in given square corresponds to a heat demand equal to 43 GJ multiplied by square's value. The maximal volume of heat which can be delivered by the considered biogas plant amounts to 4300 GJ. Here it is important to underline that we refer only to the heat – meaning the energy, not the biogas heating plant momentary power output. It is an important issue which should be addressed in future works, because heat demand is not constant and exhibit significant variations even during the heating (autumn – spring) period. Apart from the above, the minimal number of connected households should be not smaller than N = 50. Additionally it is important to add that each square represents an area equal to 10 000 m^2.

Hereunder, on Fig. 3–5 are presenting optimal configuration for three investigated objective functions Eq. 1, 3 and 5. In further analysis we will refer to them as cases A, B and C, where in A the objective function was minimize the total length of the hot water pipes, in B the objective was to minimize the value of "GJkm" parameter and in C the objective was the find the configuration which will result in the maximal value of "GJ/km" parameter. Results are summarized in Table 1.
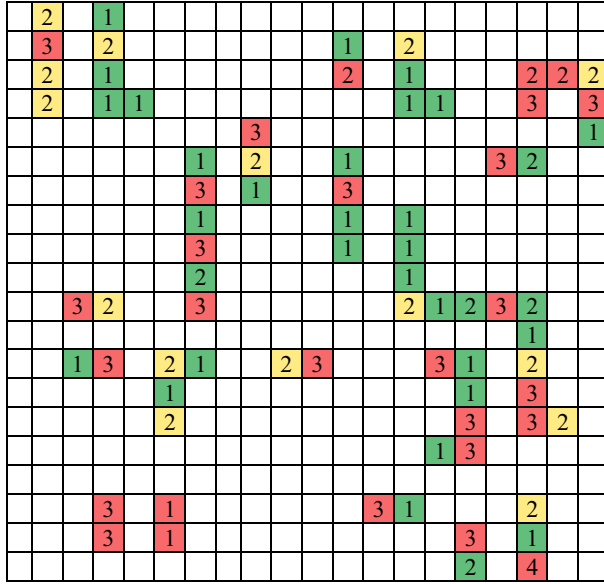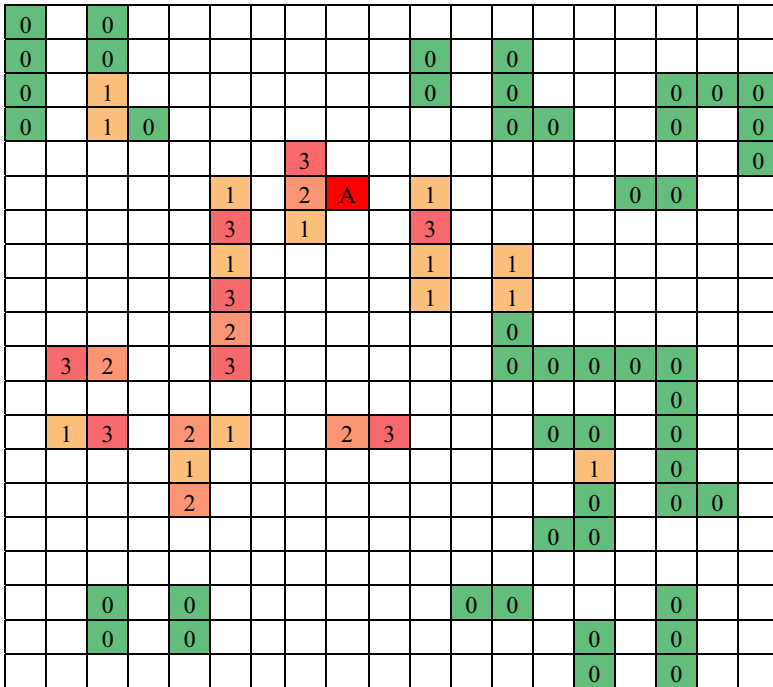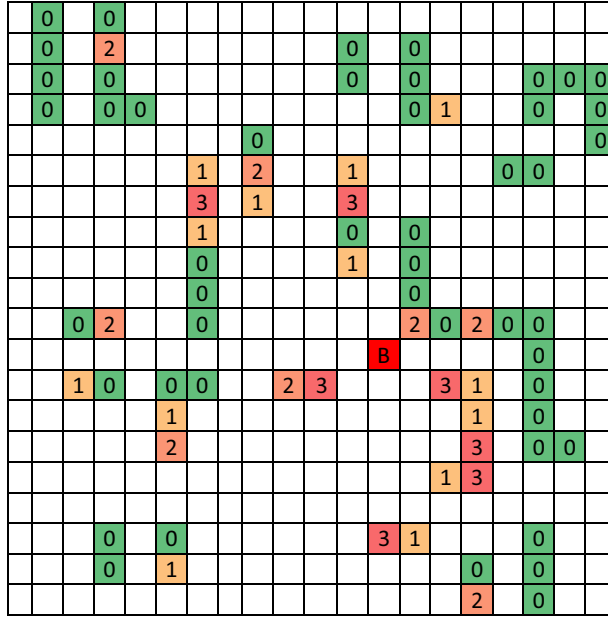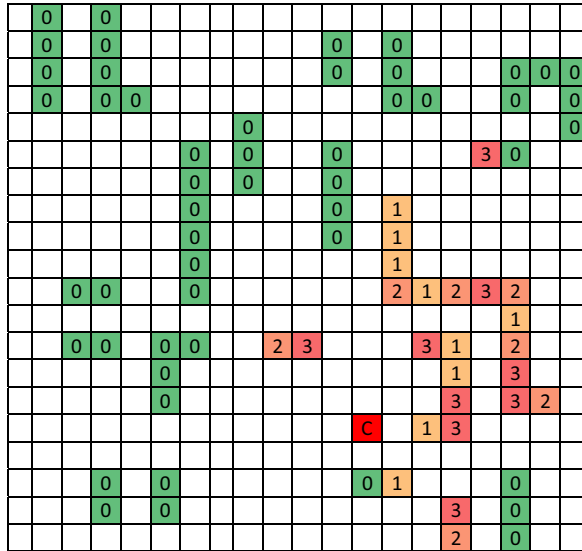
Fig. 2. Village layout.

Fig. 3. Heat source location (A) and number of selected heat consumers – for the minimal length of the hot water pipes objective function.

Fig. 4. Heat source location (B) and number of selected heat consumers for the minimal value of "GJkm" objective function.

Fig. 5. Heat source location (C) and number of selected heat consumers – for the maximal value of the "GJ/km" objective function.

Table 1. Results for the conducted optimization
(value in shadowed cell is the subject of the optimisation).

Case	Objective function		
	Minimal length of the hot water pipes [km]	Minimal value of "GJkm"	Maximal value of "GJ/km"
A	2.9	6235	741.37
B	3.64	7826	590.65
C	**2.01**	**4321.5**	**1069.65**

4. Discussion

One of the most obvious aspects of proposed method is why length of the pipeline is counted as a sum of distance between each heat receiver and thermogenic plant meanwhile buildings might be grouped in a single pipeline. Main reason of this approach is, that chosen receivers will certainly be the optimal set, as simulation conducts worst-case scenario. What is more, even grouped receiver require the pipeline of increased diameter, thus investment costs are increased per meter of such pipeline. It is worth to emphasize, that the algorithm does not provide proposition of the pipeline tracing, neither takes into consideration a shape of the parcels or existing buildings/pipelines.

The A case may seem to be surprising, as expected would be rather circular shape of network range, nevertheless the second constrain - required number of 50 connected dwellings - interferences typical behaviour of the algorithm. Actually, it tends to connect required number of heat receivers in as numerous groups as possible. Such an approach may be useful, if target was to connect maximal number of dwellings within strongly limited budget.

This and further results clearly show, that proposed solutions of this highly complex and multi-optional problem are not optimal, due to limited time of computation and, thus, incomplete collections of possible solutions, which number amounts to:

$$\frac{L!}{B!(L-B)!} \times N \tag{10}$$

where L is number of all buildings, B is number of buildings to be connected and N is number of available heat source positions.

In future considerations, authors will pursue to perform full brute force analysis. Of course, differences in obtained results (A, B, C) come from different applied objective functions. A case described in 2.2.2 subsection (B) tends to indicate as prospective groups of buildings, even if they are placed farther, whilst method from subsection 2.2.3 (C) tends to point location close to selected buildings. The C objective function provides high linear energy density, id est comparatively favourable investment return time, whilst the B objective function is supposed to minimise the share of energy that is lost over the pipeline, although it is disputable.

Although the algorithm was primarily developed to point the best position of the biogas plant, it is fully useful also in considerations of other heat sources, with properly stated constrains, even geothermal energy sources (with directional drilling wells).

References

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