GIS-based cost distribution analysis of new consumer connections to an urban power grid

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In this paper, we propose a method of cost distribution analysis of new consumer connections to a city power grid by accounting for spatial restrictions and characteristics of existing networks. In practice, the calculation of connection costs for each new consumer includes the network design and financial expenditure. We suggest that connection costs should be calculated for the whole city based on the normative parameters at the stage when the object location is selected by investors and when power grid development is planned by power companies. The proposed method enables the modeling of new power line connection routes from every parcel of city land to possible points of connection to the operating networks based on the raster design of the area. The optimal path is chosen by one criterion consisting of two components: the costs of both laying new power lines and providing sufficient power reserve in the chosen network connection point. Realized as a computer program, the method has been used to calculate the costs of connections to low-voltage power lines.

Keywords: GIS; least-cost path analysis; grid-connections; urban power grid

1. Introduction

When choosing the location of new buildings in cities and towns, investors must account for numerous territorial factors. An important criterion that is of similar interest to investors and that must be assessed when choosing the placement of real estate is the costs of connecting consumers to utilities, such as to power, water supply, gas, and so on. This expenditure and its share in the total project cost can be significant in a number of countries. However, this expenditure can only be determined by design engineering for every location option accounting for new consumers’ needs and network configurations. This is a long-term and costly procedure that cannot be performed at the stage of location selection. That is why such expenditure is now estimated by average parameters or by very simplified techniques, which raises the risks of incorrect expenditure estimation at the stage of optimum object location selection.

It is possible to reduce the risks of incorrect estimation of network connection expenditure by conducting express-analysis of cost distribution of consumer connections to various utilities within a certain area based on power consumption specific values and specific conditions of network reconfiguration in connection points. The results of such analysis can be presented as thematic maps. The values of thematic cost variables on such maps can represent partial criteria in a multi-criterion location problem. An overall view of the cost distribution of consumer connections to various utilities within a certain area can also be of interest to the public, utility companies, and local authorities. It is difficult, however, to obtain current city maps that show the cost distribution of connecting objects of varying capacities to utilities while accounting for specific territorial factors. Such predictions are difficult to make on account of the unknown network routes when building new power grid sections.

Geographical information systems (GIS) are widely used to solve such problems. Applying GIS for decision-making support has been studied in many works starting from Carver’s research ([1]). A review of these works is given in ([2]). In recent years, such systems have had varying applications in which alternatives and analysis results are represented as thematic maps ([3]). These methods are described in the works of Refs. ([4–8]). An important research direction connected with selecting land parcels for new objects within cities is GIS-based land price prediction. Land price assessment is a complex procedure including social, economic, urban planning, construction, environmental, and other aspects. The problems of land choice and forecast by GIS tools have been studied in Refs. ([9–11]). However, they do not present a detailed analysis of utility connection cost. Such predictions are difficult to make on account of the unknown network routes when building new power grid sections. In papers analyzing the development of distribution power lines and locations of new objects, such as power substations, the cost of laying new power lines is typically calculated by the Euclidean distance between the network nodes ([12–14]), with the distance obtained by the formula:

\[ r = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}, \]  

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where \((x_1, y_1)\) and \((x_2, y_2)\) are the coordinates of the object location points. Such approach can be used in sparsely populated territories with no obstacles for laying new power lines. However, presence of other objects can significantly impact the analysis results in towns and cities where the possibilities of laying new network routes are often limited. In this paper, we propose a method of solving the above problems by using GIS spatial analysis tools. We investigate situations in which distances have to be calculated by a more complicated technique. This method considers the structure of the network itself and new network paths between certain network elements and objects to be located.

Modern GIS widely employs different methods of finding possible paths on maps. The theory of algorithms used in path finding is typically referred to as the all-pairs shortest path problem (APSSP) and the single source shortest path problem (SSSPP). The APSSP can be reduced to that of searching for the shortest path between two nodes of a graph; it involves finding a circuit that extends from the start node to the goal node with the minimum cost of flow passage of a given value in this network. The single source shortest path algorithms find the minimum cost paths from the start node to every vertex in the graph. It is possible to use regular graphs, formed by superimposing a rectangular grid on the area, as well as irregular graphs, such as road network graphs. The general problem definition is given in Ref. (15).

Algorithms that find the shortest paths on regular graphs formed by raster map models can be used in this case to solve the problem. The cost of passing graph arcs and limitations are set by weight coefficients determined by raster cell semantics in this case. Many existing algorithms solve this problem; they are conventionally divided into two groups. One group is based on heuristics and originates from the renowned algorithm A* (16). Currently, several types of this algorithm, including improved variants, exist that make it considerably more efficient (17) and address participant peculiarities (18). The other group of algorithms implements the breadth-first search strategy. The most renowned representative of this group is Dijkstra's algorithm (19). The algorithm is effective on both regular and irregular power grid models. It guarantees the finding of an optimal solution; however, it is slower than heuristic algorithms.

An important GIS-based spatial analysis approach to pathfinding is the least-cost path analysis (LCPA). LCPA provides the identification of the best path from one point to another over a cost surface or raster. The least-cost path procedure is an efficient and therefore also a highly attractive method. It has been used to solve many real problems, such as finding the best traversal paths across off-road terrain (20–24), the alignment of roads (25), route planning in landslide-prone areas (26), power lines (27), pipelines (28), canals (29). The method has also been applied in public health (30,31), to name just a few examples. Besides, the method itself is still being studied and improved (32,33).

The peculiarity of the problem in the center of this paper is the large number of routes from multiple points, each having numerous potential nonequivalent goals (possible places of network connection). This fact makes it necessary to modify the known path finding algorithms in view of the problem peculiarity. The paper represents the results of modifying the known path finding algorithms A* and Dijkstra for their effective use in cost calculation of customers’ connections to the city utilities and an example of practical application of the method in thematic map plotting.

2. Problem formulation

The problem of designing consumer connections to utility networks in urban areas is typically solved on maps in local rectangular coordinate systems. The source data are the coordinates of the power input point (consumer), \(p = (x, y)\), and a set of allowable connection points, \(W = \{w_1, w_2, w_l = (x, y)\}\), to the network (a set of sources). The sources are depicted on the map as linear or point objects depending on the network type. In the case of a power grid, for example, connections can only be made at specific points: at substations for connecting to cable power transmission lines, or at towers to connect to overhead power lines. Connections to a pipeline system can be made by cutting into some sections of the existing pipe, where it is allowed by technological specifications. In this case, the source can additionally be shown on the map as a set of \(W\), which includes all points of the linear objects with the required parameters. Moreover, the map includes a set of areal spatial objects, \(E = \{e_\alpha\}\). These objects determine various limitations for laying new network lines when connecting consumers to sources, or insurmountable obstacles for new utility lines, such as building outlines, water bodies, and so on. The aim is to find a source, \(w_l \in W\), a new network path, \(l \in L\), and equipment, \(q_k \in Q\), that will minimize the connection costs, \(Z\). Figure 1 represents a fragment of a city map that shows several possible variants of connecting a new building located in point \(p_1\) to electric power sources \(w_1\) and \(w_2\) and to gas supply sources \(w_3\), \(w_4\), and \(w_5\). As the map shows, both connection points and new network routes can vary (\(l_2, l_3\)).

In general terms, the problem of choosing a utility network connection can be expressed as a problem of connection costs minimization:

\[
Z = z_0 + F(L \times W \times Q) \rightarrow \min,
\]

where \(z_0\) is a certain fixed part of the cost that does not depend on location, and \(L\), \(W\), and \(Q\) are the sets of admissible alternative routes of the new network section, connection points, and equipment.

Function \(F\) in Equation (2) cannot be represented algebraically. Consequently, problem (2) is typically solved in practice by empirical methods in which
The problems of forecasting and comparative evaluation of different variants of a consumer’s location can be solved without detailed engineering analysis by using standardized unit tariff rates. In country Russian Federation such rates are set and published by the government and antimonopoly state services. The regulatory documents of regional governments also contain formulae of calculating marginal standard costs of connection to different utilities. By analyzing these formulae, we have determined that the calculation of marginal costs of connection to any network type without addressing component $z_0$, independent of the object location, can be presented as the following simple expression:

$$z = c_1 l + c_2 N$$

(3)

where $c_1$ is the limit tariff rates of the costs of building a length unit of the new network (measured in currency units/length units); $l$ is the length of the network to be constructed; $c_2$ is the limit tariff rates covering the costs of building a new power capacity unit in connection points (measured in currency units/capacity units); and $N$ is the value of the lack of power reserve at the connection point. Coefficients $c_1$ and $c_2$ are stipulated by the documents that are approved annually by local authorities in order to limit the price of connection offered by monopolist companies.

Reserve lack $N$ is determined by the formula:

$$N = \begin{cases} 0, & N^Q \geq N^P \\ N^P - N^Q, & N^Q < N^P \end{cases}$$

(4)

where $N^Q$ is the value of power reserve available at the connection point, and $N^P$ is the value of power for the grid-connected customer.

As problem Equation (2) and costs calculation Formula (3) suggest, the choice of connection variant should be viewed as a two-criterion optimization problem. On the one hand, the aim is to choose the source, $w_i$, with a sufficient reserve of power, $N^Q$, to null $N$ by Equation (4). On the other hand, the new line length, $l_j$, should be minimized in accordance with the limitations (set $E$) of the given land parcel. It should be noted that sources with a minimal line length may have an insufficient power reserve, $N^Q$, which can lead to an increase in $N$. This means that it is sometimes more cost-effective to lay longer lines to a farther power source that has a sufficient power reserve, $N^Q$. It is evident that the results of solving such an optimization problem depend on the power of the grid-connected customer, $N^P$, because it affects the choice of the source, $w_i$, with a sufficient power reserve.

The choice of equipment for such a problem statement determines the values of parameters $c_1$ and $c_2$. For example, different $c_1$ values should be chosen to connect to the grid by laying overhead and cable power lines. These values can be found in regulatory documents. It is evident that it is not the coefficients’ values but their ratio that influences the results of solving this optimization problem. In fact, these parameters are weights of costs of different origins. Therefore, if no standard values exist, they can be determined based on previous design practices.

To substantiate the choice of a new object’s location, it is important to determine the function of the connection cost calculation of every utility type of $m$ and the required power capacity values for every network type, $P_m$:

$$z_m = f_m(x, y, P_m),$$

(5)

where $x$ and $y$ are the point coordinates on the map.

To make further analysis more convenient and clear, Equation (5) for every $N^P_m$ value should be shown in
GIS as thematic maps. After the function values are determined for a specific set of m and $N^p_m$ values, the optimum object locations can be found by the additive criterion of minimum total costs:

$$\sum_m z_m \rightarrow \text{min.}$$

Equation (5) cannot be algebraically represented. This can be explained by the fact that a small shift in a consumer’s location point, $p = (x, y)$, on the map can change the choice of nearest power source $w_j$ and path direction $l_j$. Therefore, $z_m$ can be calculated for any point of the area by an algorithm that enables the automatic selection of connection points and the prediction of paths of new supply networks by considering criterion (Equation (3)). In fact, this algorithm is intended to model designers’ work solutions to the multitasking problem of choosing the variant of the consumer connection to the grid.

3. Method of modeling consumer-to-grid connection
A method based on area raster layout algorithms is proposed for modeling the process of connecting a consumer, located in point $p = (x, y)$, to the network. In our evaluation, parcels of land plotted according to cadastral area division are used as evaluation objects. This corresponds to the real practice of a land parcel becoming an object of legal relations. It is assumed that the cost of the estate object utilities connection on a certain land parcel is determined for the object location set by the plot centroid. This is a typical approach for selecting points to calculate the distance to polygonal objects in GIS, which has been investigated in Ref. (4).

We assume that the most important factors in determining the length of utility lines to be constructed are buildings that should be skirted when laying cables and pipelines (Figure 1) and differences in route laying costs on territories with differing surface types. These factors can be represented by the cell weight in the area raster model formed in GIS. The problem of calculating the length of a new utility line section can then be reduced to the problem of finding a route with the minimum total weight on a graph, which is represented as an undirected uniform-cost grid map, as in Ref. (17). Each node has eight neighbors and is either traversable or not. Each straight (i.e., horizontal or vertical) move, from a traversable node to one of its neighbors, has a cost of 1; diagonal moves cost $\sqrt{2}$. Moves involving non-traversable nodes are disallowed. Figure 2 presents a graph fragment for the route choice for nine raster cells. The dark color is used for raster cells containing insurmountable obstacles. Routes cannot be made inside them.

Figure 3 shows an example situation in which a cable power line must connect a building to an electrical substation (Figure 3(a)) in city Ivanovo (Russian Federation) and the result of modeling the optimal path by the layout of algorithm A* (Figure 3(b)). The insurmountable obstacles are represented by buildings with buffer zones plotted with a 1-m indent from their outlines. The raster model has a 2-m interval on the area. The models were plotted by geoprocessing tools ArcGIS, with the route layout algorithms realized in the programming language Python and added to these tools.

A comparison of the different layout algorithms based on real maps of city Ivanovo area development and the electric power grid showed that their layout quality (the path length) was practically the same, while the operation speed was much higher for the group A* algorithms, especially the jump point search. This can be explained by heuristics that determine the direction to the target point. However, these algorithms can only be used for one goal node. For example, it is reasonable to use them for determining places to connect to point sources, such as power grid substations. In this case, a zoning map could only be plotted after making several layouts for each parcel of land to find the optimal connection variant by the complex criterion (Equation (3)).

A land parcel centroid was taken as a consumer’s location point $p_i$, $i \in \{1, \ldots, I\}$. Then, based on the straight distance $r$ (Equation (1)) from the consumer, the nearest $K$ candidates, $w_j$, were selected among connection points $W$, as shown in Figure 4. To generate a set of candidate points at the connection point, the authors assumed $K = 6$. The results of practical calculations confirmed that this number was sufficient for electric power lines.

In the comparison, a raster model was used to find a route, and the variant with minimum costs was selected by Formula (3). This variant was taken as the standard cost of the technological connection to the grid on the given parcel of land, which is reflected on the map. Table 1 shows the results of calculating the direct
distance, shortest path, and connection cost for this situation in Figure 4. As shown in the table, the best option in this case was connecting to point \( w_2 \). Figure 5 shows the algorithm scheme (as an activity diagram UML) that is implemented in a GIS to build thematic maps of the cost distribution of new consumers’ connections to a power grid.

Experiments conducted based on the same city example demonstrated that the algorithms in the breadth-first search technique group were much slower than A*. The results showed that the path search for two points by the Dijkstra algorithm took 50 times more time than the algorithm A* search. However, the algorithms of the first group can be used to find paths to a set of goal nodes; therefore, testing by the second component of criterion (Equation (3)) in this case could be incorporated in the main algorithm cycle. The Dijkstra algorithm offers obvious advantages for searching variants of a connection to linear objects (e.g. pipeline junctions). In this case, each raster cell belonging to the pipeline layout was considered a potential connection point \( w_j \). The goal node number greatly increased, which means the directed search algorithm, as part of the inner cycle of the general algorithm (Figure 5), should have been launched many times. Therefore, in this case, it was more efficient to use the algorithm for choosing the least expensive variant of consumers’ connections to utilities based on Dijkstra’s algorithm. A simplified scheme of plotting a thematic
The algorithm in Figure 6 finds the shortest paths for every point of object $p_i, i \in \{1, \ldots, I\}$ possible location, simultaneously choosing the final point of route $w_j$ corresponding to the minimum total connection cost by criterion (Equation (3)). Initially, the value of the minimum connection cost for point $\text{min}_z$ is taken as the known big number $\text{max}$. Further, the algorithm makes the breadth-first search and reduces this cost while passing sources $w_j$. The search continues until it finds a power source with a sufficient reserve $\text{Nw}_j$ exceeding the required connection power $N$. In this case further search is meaningless as all other variants will have longer paths with no possibility to reduce the second summand of criteria function (Equation (3)). If no routes can be plotted, the cost remains equal to its initial value. It means that the raster model neighborhood $p_i$ should be corrected.

4. Practical application of method

The experiments conducted for this evaluation were based on the spatial data of city Ivanovo and its power companies. Figure 7 shows the results of plotting a zoning model on a map of the city according to the cost of connecting 150 kW maximum-contracted capacity low-voltage consumers to the power grid. In the experiment, possible location sites were represented by land parcels constructed around existing buildings. For the sources, 6/10 kW (950 units) substations were chosen; the raster model interval was equal to 2 m; and 9800 land parcels were analyzed. The raster model considered only insurmountable obstacles formed by overlaying the raster on the buffer zones created around the building with a 1-m indent.

Figure 8 shows the distribution of the number of connection points selected by the algorithm according to their remoteness from consumers at a straight distance. As the analysis revealed, the probability of connecting a consumer to a source, which is further away according to a straight distance, decreases by a law similar to exponential dependence. It is evident that an increase in $K$ will cause the suggested algorithm to seek sources that are even further away at a straight distance. However, such situations are not worth considering because, in the process of engineering design, new variants of connections to closer sources are most likely to be found by parameters not included in the model.

It should be reiterated that the aim of modeling in this approach does not involve finding a specific technical solution and precise connection point; rather, it focuses on forecasting the connection costs. Real paths and connection points in engineering design are likely to be different but the calculated standard costs will be closer to the real value than those in other methods. The accuracy is enhanced by accounting for the value of the expected path lengthening on the respective section of the territory with real obstacles that are to be avoided by these paths. The distribution of the obtained values of path lengthening is represented in Figure 9. As the figure shows, on average, paths plotted based on the model are 30% longer than the Euclidean distances. Moreover, the lengthening instances are distributed within a wide range of values. This detail proves that the model actually accounts for path-lengthening factors, and the influence of this fact is quite significant.

As part of the evaluation, we performed a sampling comparative analysis of cost modeling results and open-source data on the actual costs of contracts of new object connections to utilities. In the studied cases, the analysis demonstrated that the deviation of predicted results from the real costs of the contracts did not exceed 10%. The average path length was 289 m and the average straight distance was 205 m; the differences in lengths of the laid paths and straight distances were equal on average to 30%. A zoning model on a map of the city (Figure 7) in this case has a different view than those calculated by the Euclidean distance and is more adequate.
The proposed program was implemented in ArcGIS 10.1. ArcGIS application development tools were used to realize specialized path search algorithms on the graphs.

5. Discussion and conclusions

In this paper, we proposed a method of cost distribution analysis of new consumer connections to a city power grid by accounting for spatial restrictions and characteristics of existing networks. The method shows how to get a parameter distribution pattern in GIS by simultaneously using aggregation, decomposition, path finding algorithms and rules of selecting target objects for laying the routes. Separate applications of such methods in GIS are studied very well. Therefore, this work solves the problems arising from their combined use when their consecutive application may be inefficient or impossible.

The conducted research has shown that to estimate the cost by using existing techniques, two different problems should be joined into one common problem. The
solution in this case is chosen by one criterion (3) containing two components: new power line layout costs and power reserve provision in the connection point of the chosen network.

GIS systems do not have tools to solve this problem and developing a complex procedure of spatial analysis is a sophisticated problem. The experiments have shown that algorithm A* can be used to solve such problem for a limited number of possible connection points. The number of path and aim point combinations can be reduced by introducing an empirically chosen number of nearest aim points under analysis (we used the number \( K = 6 \)). For networks where the connection is made at any point of linear objects, it is preferable to use an algorithm based on Dijkstra algorithm. In the modified Dijkstra algorithm, testing by the second condition of the additive criterion is realized within the main path finding cycle. Solving path finding and suitable source selection problems separately would lead to the necessity of taking into consideration a large number of path and connection point combinations and would unacceptably increase the time of the studied practical example calculation.

It is evident that application of path finding functions to distance calculation makes the problem more complicated. Many GIS-based solutions can be realized with simpler metrics. The paper \(^4\) represents the comparison discrepancies in results for geographical accessibility of selected health care services for residential areas computed using different distance types. Results of the comparison demonstrate that Cartesian distances (Euclidean and Manhattan distances) are strongly correlated with shortest network distances across the metropolitan area. However, important local variations in correlation between Cartesian and network distances were observed notably in suburban areas where Cartesian distances

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**Figure 7.** Example of zoning results on a city map.

**Figure 8.** Distribution of the number of connection points according to their remoteness from consumers at a straight distance.

**Figure 9.** Distance increase values distribution.
were less precise. In our case, the results of comparison of Euclidean distances and those obtained by the developed algorithms were notably different. An average length increase for our calculation method was about 30%. And the variations distribution lies within the range of 0–100% (Figure 9). This means that using Euclidean distances would greatly impact the distribution pattern. The model developed by us takes into account the evident fact that the more objects a certain area contains, the more complicated new communication line paths are and the greater their lengths differ from direct distances. It is evident that in sparsely populated areas with no obstacles for laying new lines, their lengths are close to Euclidean distances, which makes it impractical to use the complex method developed by us.

It should be noted that the problem solution required numerous calculations and considerable time. It took a PC with processor Intel Core i5 3450, 3.10 GHz, and memory 4 GB by using ArcGIS 10.1 up to several hours (depending on the model parameters) to calculate the results represented in Figure 7 for 9800 land parcels. The main factors influencing the calculation time and quality included the number of land parcels and the raster model resolution. Reducing the number of parcels (increasing their sizes) made the calculation results less adequate. A good solution was to use as the land parcels 2 × 2 m raster cells involved in the path-finding process; however, the calculation time dramatically increased.

The chosen 2-m sampling interval was a compromise between the calculation accuracy and speed. Reducing this interval improved the accuracy of the results but increased the calculation time, which was hardly reasonable in view of the assumptions made in the model. Reducing the sampling interval resulted in a “sticking together” of the raster model obstacles located close to each other. In general, the sampling interval should have been chosen with consideration of the object’s size when modeling obstacles and limitations.

The evaluation results showed that GIS can contribute to obtaining a general overview of the costs of consumers’ connections to utility networks within an urban area with consideration of real spatial conditions. The obtained values correspond approximately to the marginal costs of connection to utility networks determined by the documents of the government antimonopoly services. As the accurate values can only be obtained after accomplishing the design in accordance with the land parcels owners, these forecast data are an important reference point for investors in planning their activities and making decisions.

Based on the evaluation, it was evident that the evaluation adequacy of the proposed method can vary depending on the territory parameters and their use. The sufficiency of the method largely depends on the raster cell weight assignment method. In this paper, we accounted for only one factor: buildings as obstacles to laying paths. Depending on specific situations and conditions, other factors can be introduced in the model if they are shown on the map. For example, the algorithm can be adjusted so that paths do not penetrate private regions or expensive pavement areas by addition to the weight of the corresponding cells in the model. Conversely, it is possible to use existing pathways and dedicated channels to reduce the weight of the cells corresponding to them. However this requires collection of additional data. We used only open data and the data stored in the authorities of municipal management.

Using the studied evaluation method, a practical application of decision-making support systems includes plotting a set of thematic maps for different utility networks that accounts for the additional power capacity for every type of consumption resources. In this case, every map can show one criterion in a multicriterion problem of new object location selection.

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