

Enhancing Urban Planning Through Improved Connectivity: A Genetic Algorithm Approach for Optimal Service Placement

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Abstract. In this paper, a review of existing methods for optimal service placement to meet demand has been conducted. A problematic issue was identified in the form of insufficient flexibility of existing solutions for urban planning and development tasks in terms of optimal coverage location problem. The hypothesis that small improvements in connectivity between neighborhoods can significantly reduce the number of optimally placed services was confirmed. A sub-optimal solution was obtained using a genetic algorithm. As a result, recommendations were proposed to improve the transport connectivity between specific neighborhoods for the calculated time interval, which will reduce needed amount of additional facilities to fulfill the demand. The main contribution of this paper is to apply connectivity optimization and optimal service location algorithms together, resulting in a reduction in the number of services required.

Keywords: Heuristic optimization · Location coverage problem · Spatial inequality · Spatial analysis

1 Introduction

In modern society, characterized by the rapid pace of urban development and the growth of industrial enterprises, the issue of improving the quality of life of industrial workers becomes more than relevant. Given the continuous variability of the city's infrastructure, the constant need to provide city dwellers with basic services, as well as the desire to improve the overall level of well-being, the development of a method for optimal placement of urban services is of particular importance.

The concept of well-being is an important aspect of assessing the quality of life of an individual and society as a whole. It includes many factors that together determine the level of comfort and satisfaction with life [1]. The concept of well-being has been studying for decades, but there is still no consensus on its definition or how it should be measured [2]. Thus, the article [3] reveals the concept of well-being through a person's social behavior, his interaction with other people and his interpersonal relationships; article [4] refers to other

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main characteristics of well-being reflecting its understanding through spatial dimensions. Such components include:

1) all types of security (financial, physical, environmental and others);
2) participation and involvement in nearby social activities;
3) economic affordability of housing for all segments of the population with different income levels;
4) spatial accessibility to all services necessary for living;
5) a sense of identity with the human environment.

A high level of employee well-being is a key resource for increasing productivity and competitiveness of the country's economy as a whole. In the context of the modern world, where technological progress and automation are of great importance, ensuring the most comfortable working conditions and improving the well-being of employees in industrial industries is a strategic step towards sustainable development and prosperity of the country.

Satisfied and motivated employees demonstrate higher quality of labor, which leads to increased quantitative performance of the entire enterprise. Such employees may face special working conditions, safety requirements and specific professional skills. A distinctive feature of industrial workers is their close connection to production activities, which are often located outside the central city districts, where the density of urban services is higher than on the outskirts. This can create additional challenges for these employees as they have to commute to work from other neighborhoods. A solution to this problem may lie in providing better public transportation infrastructure or affordable housing near businesses. Therefore, the pursuit of employee well-being in enterprises requires a holistic approach that includes not only a comfortable working environment, but also accessibility to housing, transportation and a variety of services.

Spatial inequality manifests itself in the uneven distribution of resources and opportunities in different neighborhoods. For example, according to [5], the spatial mismatch between housing and work depends on the level of wages and prices for rent / purchase of housing. Thus, articles [6,7] shows that middle-class residents pays more than comfortable amount of money for rent half of the time.

According to [8] the factors influencing the use of urban services are proximity to residence, affordability and usability. In addressing spatial inequality, at least one of these aspects can be improved, which in turn will lead to an increase in overall well-being.

It can be seen that there are three main factors that affect spatial inequality: affordable housing, quality of transit options and connectivity to certain facilities.

The main contribution of this paper is to combine changes in both connectivity and additional services placement, since they used to be considered separately.

The following paper structures as follows: Sect. 2 presents related work on optimal location coverage algorithms, Sect. 3 presents the developed method in detail, Sect. 4 presents the application of developed method on specific urban area.

2 Related Works

The problem of optimal service placement usually lies in the notion of business and emergency facility locations. The problem is well studied and includes variety of algorithms for many specific tasks. However, in recent years it gained more attention since new technologies appeared in the field. The main trend in this sphere is to solve the problem of optimal service placement, including more scenarios, variables, agents and constraints.

In [9], the p-median problem is considered in detail, which is to choose the optimal location of facilities in the number of p units to serve the demand or cover the area with minimum cost. This problem is also considered in [10], which developed a location model for medical centers after analyzing their location, demand for medical services and road network in Jeddah city, Saudi Arabia. The study under review aims to optimize the network of medical services and provide location recommendations to maximize service coverage. The study [11] considers the p-median problem. However, in it, the object can serve any number of demand points, i.e., the problem is "uncapacitated P-Median".

The study [12] considers a problem, "the maximum coverage location problem" (MCLP), which is also one of the classical problems in resource allocation and facility location decision making. In contrast to the p-median problem, the MCLP considers a situation where a certain number of locations must be selected in order to maximize the total coverage of an area that is characterized by a set of customers or facilities. To solve that problem, a metaheuristic algorithm, AILS-PR, was proposed in [13]. Initially, there was an iterative local search (ILS). In ILS, the initial benchmark solution is iteratively refined by a local search followed by a perturbation phase. The perturbation phase aims to identify solutions that are "close" to the reference solution, but with a better local optimum within its neighborhood.

Optimal placement of various health care facilities is important for providing effective and timely medical care to the population. Therefore, it is their placement that is most often encountered in scientific articles. Thus, in [14] the above mentioned MCLP problem is considered to find the optimal placement of special health care facilities. For its solution, the proposed modified Particle Swarm Optimization (PSO) algorithm is used, which was compared with the results of the GAMS algorithm, where the former showed better results. PSO is a population-based stochastic optimization methodology (search algorithm). It simulates the social behavior of a flock of birds, where each particle represents a potential solution to the problem, i.e., a set of object locations.

However, not only the location of medical facilities is considered in scientific papers. For example, paper [15] presents a three-stage strategy to solve the cab stand location problem (TSLP). First, points with high cab demand are extracted from massive GPS cab data using a GIS platform, and the optimal area for cab parking locations is determined in the next steps. Then, the spatial interaction between cab demand and cab parking lots is investigated. Next, a cab stand location model (TSLM) is developed to minimize the total cost, which

includes passenger access cost and construction cost of cab stands. A program based on genetic algorithm is written to optimize the TSLM.

The application of the genetic algorithm for solving the MCLP problem is also discussed in the source [16]. However, in this paper, in addition to this algorithm, the implementation of a heuristic algorithm is presented, as well as a comparison of these methods with the software package "CPLEX". The proposed algorithms showed results both in terms of time and quality better than the considered solver. In turn, the heuristic method has superiority over the genetic method.

In [17], another problem is considered, namely the capacitated location-routing problem (CLRP), which is a combination of a facility location problem and a transportation routing problem. The problem consists of determining the location of warehouses, assigning each customer to one of the warehouses and determining the routes. The approach proposed by the authors consists of 3 phases. In the first phase, customers are clustered near warehouses based on distance and demand using the developed two-level CSOM teacherless learning method. In the second phase, the transportation routing problem for each cluster is solved by the Clarke and Wright algorithm. In the third phase, the routes are improved by exchanging clients between different routes using the "Or-Opt" method. The computational results show better performance of the proposed approach and demonstrate its effectiveness in solving large size problems.

Another example of a problem combining facility location and transportation assignment/routing issues is [18], which deals with an optimization approach in firefighting. They present a robust optimization problem formulation, the so-called Facility Location and Equipment Emplacement Technique with Expected Coverage (FLEET-EXC) model, which maximizes the demand with respect to vehicle utilization. The approach proposed by the authors iteratively improves the solution of the fire station location and transportation assignment problem. Testing was performed on a dataset provided by the national association of firefighters of Chile. The results show that the considered method gave a more accurate representation of the accident process than those commonly used in the literature.

The article [19] questions the concept of urban development where all necessary services for living are within walking distance. Such a development vector has an increased attention due to its advantages in health, economy and environmental sustainability. A mixed integer linear programming (MILP) model, a constraint programming (CP) model, and a greedy algorithm were used for optimization. The authors tested their solutions on data describing disadvantaged neighborhoods in the city of Toronto, Canada. As a result, MILP finds the best solutions in most scenarios, but scales poorly with network size. The greedy algorithm scales well and finds near-optimal solutions.

Despite the fact that there are many studies on the optimal location of facilities, the distance between the facilities that provide the service and those facilities that provide the demand for the service is considered to be constant. However, in the context of urban management, public transport routes and roads are changing due to urban development and transportation reforms.

The contribution of this paper is to apply heuristic optimization to improve the transport accessibility time between blocks to enhance the solution of the location coverage problem. The results of the algorithm is a recommendation for service placements in city blocks. If there are conditions in a block that do not allow the placement of the service, such blocks could be remove from the location allocation process.

3 Method

3.1 Hypothesis

The following hypothesis was investigated in this paper: improving connectivity between neighborhoods by no more than 40% can reduce the minimum number of optimally placed new polyclinics.

3.2 Location Coverage Problem Setting

In this paper, the quality of life of a person will be considered as an average assessment relative to the assessments of provision with various services and the assessment of spatial mismatch between housing and work. For experimental purposes, we will consider the service "Polyclinic", the location of which we will optimize. As it was shown in the part with the review of existing solutions, the MCLP algorithm provides solutions to maximize the demand coverage (provision of all people living in a given area). In this paper we will use an improved version of the MCLP algorithm - "CLSCP-SO" (Capacitated Location Set Covering Problem-System Optimal), which takes into account the demand and capacity of services. However, this algorithm works with the cost matrix as a constant. In this case, the cost matrix is the availability matrix between the selected neighborhoods, which will be optimized in this solution with respect to the number of located clinics.

3.3 Genetic Algorithm Adoptation

This paper considers changing the cost matrix values (availability time between selected blocks) in order to reduce the required number of services to cover the unsatisfied demand. The flexibility of the developed method lies in the ability to customize the limit to improve services availability, and to account for any distribution of demand quantities across blocks.

As an example, the Polyclinic service was considered as one of the vital services directly affecting the quality of life of residents. There are accessibility standards for different services that provide basic services. In this case, for the polyclinic service this standard is 15 min. Consequently, if a service does not fall within the accessibility zone of a residential building, its residents are considered unserved.

In order to improve the provision of the necessary service to the residents, it is necessary to make it accessible: improve accessibility to existing services and / or add new services. Since this paper considers accessibility to service by public transportation (which city managers can improve through reforms), it is proposed to slightly improve transportation accessibility between the selected neighborhoods.

Since the norm for the selected Polyclinic service is 15 min and the selected limit for improving accessibility is up to 40 %, it is necessary to consider those connections between neighborhoods that are greater than the established norm ($>$ 15 mins), but with improved connectivity could fall within the specified norm. Thus, it is necessary to consider connections between neighborhoods whose value does not exceed more than 25 min. (25 * 0.6 = 15)

Sample of cost matrix:
Colored cells indicate considered values to be optimized.

block id	0	1	2	3	4	5	6	7	8	9
0	0.0	11.3	21.0	25.0	27.6	26.5	34.6	32.4	26.1	25.0
1	11.3	0.0	24.5	27.3	29.9	28.8	36.9	34.7	28.4	27.3
2	17.3	20.4	0.0	13.8	22.8	21.8	29.9	27.7	21.3	20.2
3	25.9	29.0	13.8	0.0	17.2	29.0	37.3	35.1	20.3	19.2
4	26.3	29.4	26.6	18.6	0.0	21.2	35.6	33.4	25.8	24.4

In this case, the genetic algorithm is its standard implementation. It works by simulating the process of natural selection to optimize solutions to complex problems [20]. At its core, a genetic algorithm starts with a set of potential solutions presented as an initial population. These solutions are then evaluated based on their fitness function, which determines how well they do the task. Through the process of selection, crossover and mutation, the algorithm iteratively develops the population, contributing to the reproduction of individuals with higher fitness [21]. For several generations, the population has been striving for optimal or almost optimal solutions, which makes genetic algorithms especially effective in solving optimization problems in various fields, including urban studies. Figure 1 shows the block diagram of the algorithm.

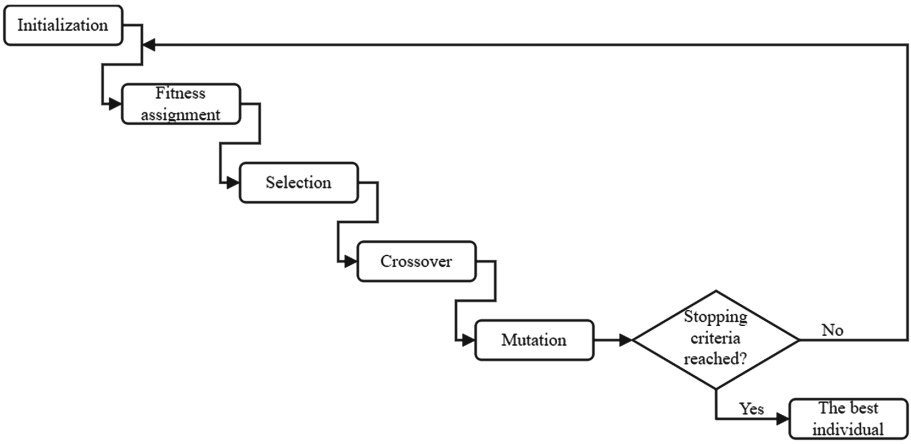


Fig. 1. The block diagram of the genetic algorithm

However, it is important to note how exactly the initial population and fitness function are specified.

Population initialization:
Matrices with modified considering values will be chosen as the initial population.

$$M_i \in \mathbb{R}^{n \times n} \quad \text{for } i = 1, 2, \ldots, \text{population_size}$$

$$M_{i,ij} = \text{random_uniform}(0.6, 1) \times \text{cost_matrix}_{ij}, \text{if } (i, j) \in \text{selected cells}$$

Fitness function:
In this case, the result of the optimal service placement algorithm (number of services placed) will be used as a fitness function.

$$F(M) = \text{count}(\text{clscpso.fac2cli}[M])$$

As a result, the algorithm selects the best solution that contains a minimum of new services to be placed.

The scheme representation of implemented genetic algorithm optimization is shown in Fig. 2.

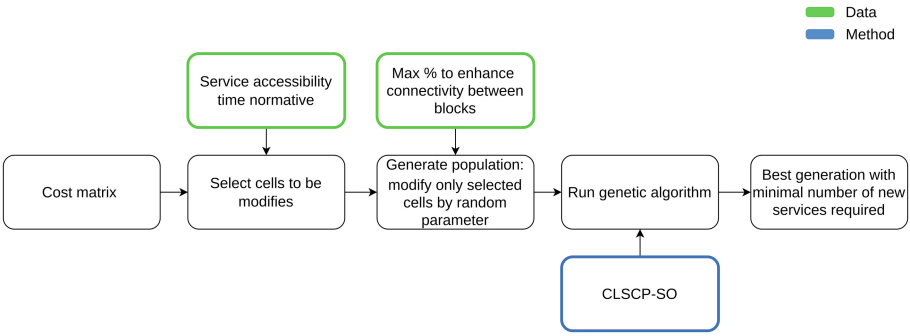


Fig. 2. Scheme of Genetic Algorithm implementation

4 Experiments

4.1 Study Area

This paper considers the scenario of new industrial enterprise location in the city within the development of priority industrial sectors according to the socio-economic development strategy of the city. This paper considers the location of an industrial enterprise in the port-industrial district of St. Petersburg. The placed enterprise and selected city blocks are presented in Fig. 3.



Fig. 3. Selected territory

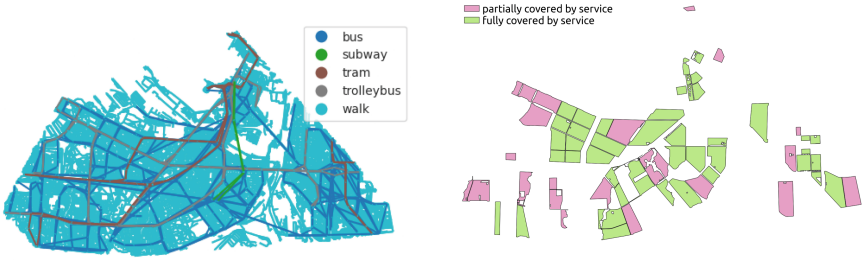
The neighborhoods to be considered were chosen as follows: according to the hypothesis of jobs-housing mismatch, a balance between employee salary, potential average rent, and distance from work is needed. The wages of potential employees were taken as the average for skilled industrial workers in the city.

4.2 Data

All necessary data for services location, public transport networks, and residential building parameters (to calculate estimated population) were gathered from OpenStreetMap. The data on service capacity and demand were calculated according to the paper [22]. The implemented algorithm relies on gravitational model, limited number of residents and limited service capacities.

4.3 Method Implementation

The current estimation of availability "at the considered moment of time" was made with the help of the BlocksNet library [23]. The intermodal graph for the selected territory is presented in Fig. 4a. Estimation of availability of residents of the selected neighborhoods for the service "Polyclinic" is presented in Fig. 4b. Each service has its own standard of availability according to GOST (National Standard). For polyclinic the normative of accessibility is 15 min.

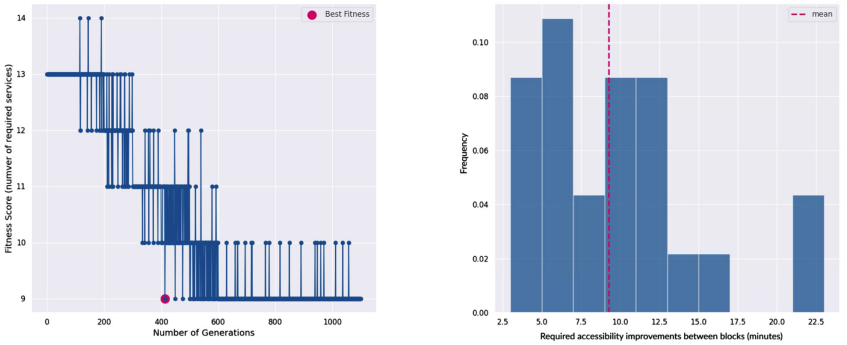


(a) Geolayer with intermodal graph of public transport

(b) Covered and not covered blocks by the service

Fig. 4. Input data

In this paper, all new polyclinics have a fixed (average) capacity of 400 people. It should be noted that a necessary but insufficient condition to consider a neighborhood as service-enabled is that it must fall within the service accessibility zone. The accessibility was calculated between neighborhoods on an intermodal graph built on OpenStreetMap public data.



(a) Fitness progression in genetic algorithm (b) Distribution of required accessibility improvements (in minutes)

Fig. 5. Results of genetic algorithm

Since the number of possible combinations in this case is large, a genetic algorithm was chosen as a tool to select a sub-optimal solution. The genetic algorithm receives a connectivity matrix as input and changes the values only in the specified cells (i.e., neighborhoods that do not fit the condition for optimization do not change the connectivity among themselves). As a result, the CLSCP-SO algorithm calculates the optimal number of new clinics needed to meet demand. The results of the algorithm are presented in Fig. 5a and 5b.

Figure 5a shows that by optimizing the accessibility time between blocks, the required number of new services was reduced from 13 to 9. The results of the distribution of the delta of connectivity change between quarters are shown in Fig. 5a. Figure 5b shows that the average time to improve transportation connectivity is 10 min.

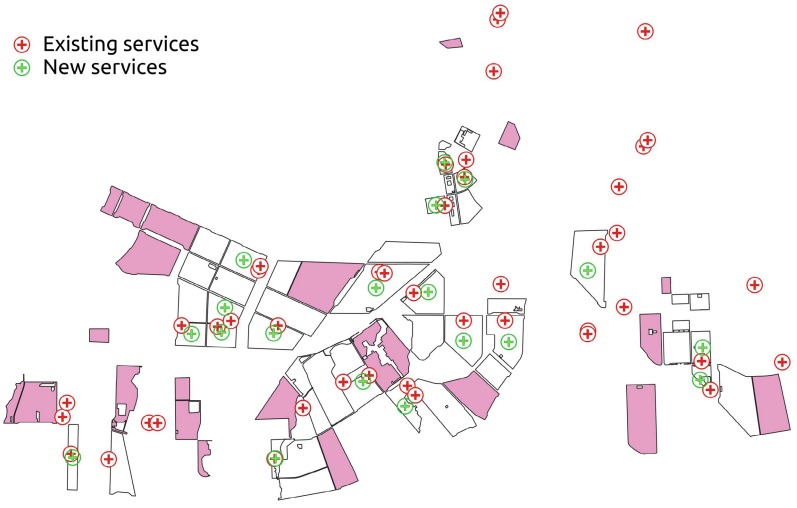


Fig. 6. The location of existing and additional services (Color figure online)

Figure 6 shows the blocks in which the service should be placed (the service is represented by a green marker), the blocks in which the service has already been previously (marked with red marker), and the uncovered blocks before optimization and placement of additional services (marked in red). Figure 7 shows reduce of travel time between blocks (lines, with gradient coloring depending on the required value of change).

It can be noted that in some cases the new service is placed in neighborhoods where the service already exists. This indicates that there is a need to expand or optimize the existing service. It can also be observed that due to the nature of the routes and road network, in some cases. Only a slight improvement in connectivity between distant neighborhoods is needed (2 to 4 min) and conversely, between spatially close neighborhoods a reduction in accessibility time may be required (10 to 13 min).

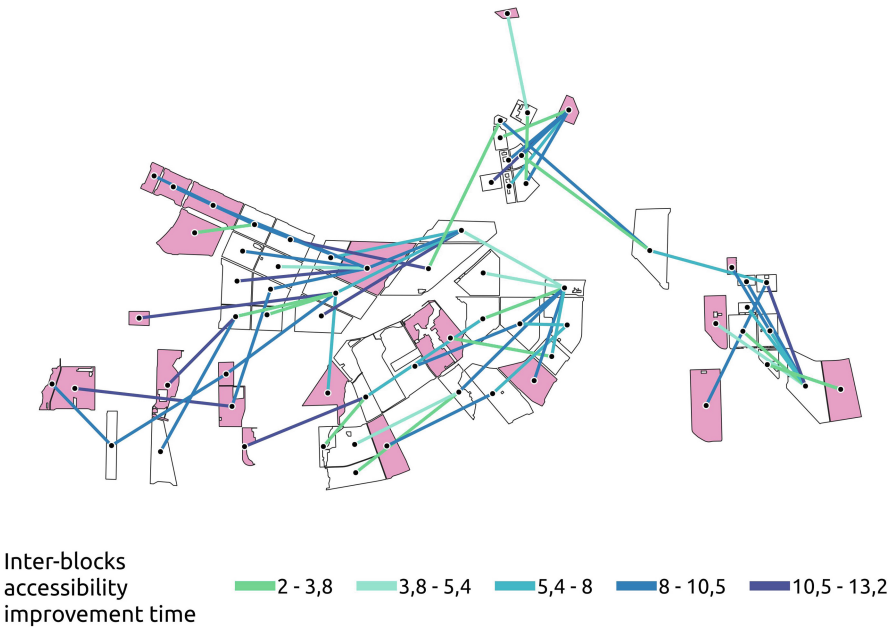


Fig. 7. Distribution of change in transportation connectivity between neighborhoods in a given area

5 Conclusion

Through the application of heuristic optimization, it was found that by improving transportation connectivity between blocks by applying optimal service placement algorithms, it is possible to reduce the required number of services. However, it should be noted that in order to fully solve the task, it is necessary

to tackle the problem considering the entire city's data. In this case, the loads on services, including new ones, will be redistributed between all the neighborhoods both in case of adding new services and in case of changing the connectivity only on a given territory and on the whole city area. The flexibility of the developed method lies in the ability to customize the limit to improve availability, and to account for any distribution of demand quantities across quarters. Since any of the services, be it a kindergarten, school, polyclinic or multifunctional center, can be described through such criteria as demand and capacity, the developed algorithm is applicable to any type of urban service. The further work in this direction may include multi-criteria optimization of transportation and landuse types of urban blocks to consider changes in the scale of the whole city.

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