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EXPLORING TWO SOLUTION METHODS FOR THE TWO-STAGE LOCATION-ACTIVATION PROBLEM

This study highlights the importance of medical logistics research during crises that might stress the system. We formulated a practical problem statement for the organizational structure of the medical logistics system, which has three types of centers: regional, subregional, and distribution. We also proposed a mathematical model for the two-stage location-activation problem, which minimizes the costs of operation, delivery, location, and activation. For the proposed mathematical model, two solution approaches are presented. The first approach divides the process into two steps: locate the distribution centers by solving the continuous problem and then use the obtained coordinates to solve the second (discrete) part. The second approach is a combined solution technique combining continuous and discrete parts using full information during the algorithm's execution. Both can be used to solve the problem, the first is simpler and has a lower time complexity, and the second uses more information but has higher time complexity.

Keywords: discrete optimization, continuous optimization, effective decisions, evolutionary algorithms, transportation, medical logistics.

1. Introduction. Recent years have shown that the medical logistics system has some significant weaknesses and areas for improvement. The global pandemic in 2020 demonstrated how unprepared we were to handle the demand for large quantities of medicines and immunobiological products. It also highlighted the strain on the system when rapid and efficient action is needed during a crisis. The situation worsened with the full-scale invasion in 2022, which created an even greater need to move large quantities of medicines as part of the humanitarian response. This unprecedented demand put a lot of pressure on the existing infrastructure, underscoring the need for a strong and adaptable medical logistics system that can handle crises. These challenges have also highlighted the importance of modernizing and optimizing the way medical supplies are transported.

2. Literature review. The paper [1] describes a solution to the optimal warehouse location problem. A new model of mixed integer linear programming for solving the problem of warehouse location using linearization of Euclidean distance is proposed. The study [2] proposes a new approach to the location of manufacturing enterprises using fuzzy logic and inference systems. The study is useful for decision-makers in the manufacturing industry and allows for the effective use of fuzzy logic and inference systems to solve complex problems of manufacturing plant location. The proposed model can be applied in various industries, including the automotive, electronics, and food industries. The capacity allocation problem [3] with differentiated convex production costs is a variant of the classical capacity allocation problem, where the cost of production at each plant is modeled as a convex function of its production capacity. The authors propose a fast, accurate method based on the branch-and-price approach that exploits the structure of the problem and the convexity of production costs. The publication [4] describes the solution to the traveling salesman problem using swarm methods and highlights that evolutionary algorithms play a crucial role during logistics improvements. A combination of the particle swarm method and a genetic algorithm is used, using the output of one for the input of the other algorithm. An interesting aspect of the work is the study of the effectiveness of the roulette method and the multi-point cyclic crossover. When tested using samples of large sizes, the algorithm demonstrates 100% success for the clear case. Paper [5] deals with the two-stage transportation problem with fixed charges. They propose a fast, parallel-friendly solution method for real-world applications. Their iterative constructive heuristic reduces the solution space at each step. The problem of reasonable planning and optimization of shelter locations [6] aims to reduce losses from natural disasters and sustainable urban development. Paper considers a sequential solution to a two-criteria problem based on sequential decision logic to maximize economic sustainability and social utility. A two-stage transportation problem with a fixed route toll is researched in the publication [7]. To solve this problem, the authors transition to a different form of the problem, which is similar to the two-stage transportation problem with the cost of transportation per unit of goods. The cost of the goods is presented as a conditional expression depending on whether this route is used or not. A genetic algorithm is used to solve the problem. The chromosome is encoded using a matrix representation. The paper proves the robustness of the proposed algorithm using randomly generated entities. An alternative approach to deal with that problem is studied in [8]. The work described problem of optimizing evacuation logistics during emergencies to ensure the efficient distribution of resources and human flows. The proposed solution involves the introduction of a mathematical model and algorithm that optimize the location of rescue facilities and the zoning of territories to manage evacuation traffic effectively. The study [9] investigates the best location for a pharmaceutical warehouse in one of the major Turkish cities using the analytic hierarchy process and EDAS method, which evaluate locations around an average solution within a spherical fuzzy environment. This unique approach is applied for the first time to this problem. It identifies the most optimal location and comes with robustness analysis, ensuring the reliability of the method. Additive Manufacturing greatly enhances the flexibility of manufacturing networks. The paper [10] addresses a location-production routing problem for a distributed manufacturing platform, integrating decisions on location, production planning, and delivery routing. To solve this complex problem, the authors introduce a Neural Genetic Algorithm, which efficiently finds near-optimal solutions, reducing computation time by 99% compared to traditional methods. Sensitivity analysis shows that unit shortage costs heavily influence customer service and facility distribution.

3. Practical problem statement. In critical situations, such as emergencies, natural disasters, or military conflicts, there may be an urgent need for rapid and efficient distribution of essential medical supplies (medicines or medical devices) to the population. In such circumstances, the speed and accuracy of delivery can be critical to saving lives and health. To ensure such distribution, each region has a fixed number (N) of regional centers (RCs) and several (M) subregional centers (SRCs) that serve as distribution middle points for medical supplies. However, due to limited resources such as fuel, vehicles, personnel, or difficult logistical conditions, the government may decide to activate only a portion of these centers. To reduce costs and optimize the use of available resources, only L of the M subregional centers are activated. Schematically the practical problem statement is illustrated on Fig. 1.

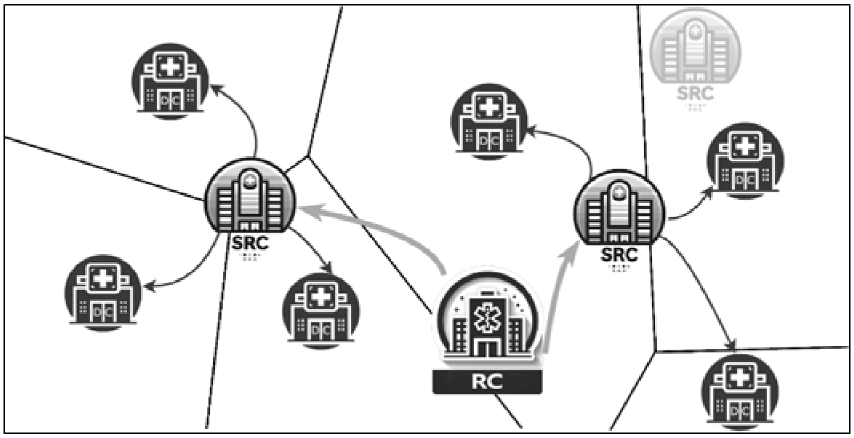

Figure 1. Diagram for practical problem statement.

The activated SRCs are responsible for redistributing medical supplies to distribution centers located throughout the region. In total, there are K such distribution centers (DCs) located at key points to ensure the fastest possible access to medical supplies for the population. These distribution centers serve as final delivery points from which medicines and medical supplies are distributed directly to consumers in their service areas. The primary goal of this process is to minimize overall transportation costs and delivery time while ensuring that the needs of each distribution center and consumer for necessary medical supplies are fully met. It is also important to consider factors that may affect logistics, such as the geography of the region, the state of the infrastructure, and potential risks that may arise during transportation. Achieving this goal is critical to ensuring the resilience and reliability of the medical logistics system during emergencies.

4. Mathematical model. Let's define the following:

- Ω — customer distribution area;
- Ω_i — customer service for i-th DC, $i = \overline{1, N}$;
- N — the required number of DCs;
- M — the total number of SRCs available for activation;
- L — the maximum number of possible activated SRCs;
- J — set of subregional centers available for activation;
- b_i^I — demand of the i-th DC, $i = \overline{1, N}$.
- b_j^{II} — capacity of the j-th SRC, $j = \overline{1, M}$;
- A_j — activation costs for j-th SRC;
- $c_i^I = c(x, \tau_i^I)$ — transportation cost between DC i and customer at x;
- $c_{ij} = c(\tau_i^I, \tau_j^{II})$ — transportation cost between SRC (τ_j^{II}) and DC (τ_i^I);

– $\rho(x)$ — demands from medicines in point x of the area Ω;
– $\tau_i^r = (\tau_{i1}^r, \tau_{i2}^r)$ — coordinates of DC(r=I) or SRC (r=II);
– v_{ij}^I — the volume weight units number of medicines and medical equipment transported from SRC j to DC i;
– $\theta_j = \begin{cases} 1, & \text{if SRC } j \text{ is activated,} \\ 0, & \text{otherwise.} \end{cases}$

Then mathematical model can be defined as:

$$\min_{\theta(\cdot)\in\Theta, \tau^I \in \Omega^N, v \in R^+_{NM}} \sum_{j=1}^{M} A_j \theta_j + \sum_{i=1}^{N} \int_{\Omega_i} c_i^I(x, \tau_i^I)\rho(x)dx + \sum_{i=1}^{N}\sum_{j=1}^{M} c_{ij} v_{ij}^I, \tag{1}$$

under the constraints:

$$\sum_{j=1}^{M} v_{ij}^I \theta_j = \int\limits_{\Omega_i} \rho(x)dx, \quad i = \overline{1, N}, \tag{2}$$

$$\sum_{i=1}^{N} v_{ij}^I \le b_j^{II}, \quad j = \overline{1, M}, \tag{3}$$

$$\sum_{j=1}^{M} \theta_j \le L, \tag{4}$$

$$\bigcup_{i=1}^{N} \Omega_i = \Omega, \tag{5}$$

$$mes(\Omega_i \cap \Omega_j) = 0, \quad i \ne j, \quad i, j = \overline{1, N}, \tag{6}$$

$$v_{ij}^I \ge 0, \quad \theta_j \in \{0; 1\}, \quad i, j = \overline{1, N}, \quad j = \overline{1, M}, \tag{7}$$

$$\tau^I = (\tau_1^I, \tau_2^I, \ldots, \tau_N^I), \quad \tau^I \in \Omega^N. \tag{8}$$

where: (1) — main optimization task of the two-stage location-activation problem which summarizes the total expenses for location and activation of distribution and subregional centers and transportation costs; (2) — the amount of medications shipped to the i-th distribution center is equal to its needs; (3) — the amount of medications shipped from the j-th subregional center not exceed its capacity; (4) — the number of activated subregional center is less or equal to specified non-negative value L; (5) — the service areas of the distribution centers encompass the entire region; (6) — each customer is served by only one distribution center; (7) and (8) are balance constraints;

Θ is defined as:

$$\Theta = \{\theta_1(\cdot), \theta_2(\cdot), \ldots, \theta_N(\cdot) : 0 \le \theta_i(x) \le 1; \sum_{i=1}^{N} \theta_i = 1 \text{ for almost all } x \in \Omega\}.$$

5. First solution approach. We propose to use a combination of evolutionary algorithms and the approach from the theory of optimal partitioning of sets. Given this, we can divide the solution of problems (1)–(8) into two stages. At the first stage, distribution centers are located and their service areas are determined by solving the problem of optimal partitioning of sets in formulation (9)–(11), where N is the required number of centers.

Minimize

$$\sum_{i=1}^{N} \int\limits_{\Omega_i} c_i^I(x, \tau_i^I)\rho(x)dx, \tag{9}$$

under the constraints:

$$\bigcup_{i=1}^{N} \Omega_i = \Omega, \tag{10}$$

$$mes(\Omega_i \cap \Omega_j) = 0, \quad i \neq j, \quad i, j = \overline{1, N}. \tag{11}$$

The (9)–(11) problem is a well-studied problem of optimal partition of sets. The paper [11] contains more information about the approaches and practical applications for such tasks. At the second stage, we solve the discrete location problem (12)–(16):

$$\sum_{j=1}^{M} A_j\theta_j + \sum_{i=1}^{N}\sum_{j=1}^{M} c_{ij}^I(\tau_i^I, \tau_j^{II})v_{ij}^I \to \min, \tag{12}$$

under the constraints:

$$\sum_{j=1}^{M} v_{ij}^I\theta_j = b_i^{*I}, \quad i = \overline{1, N}, \tag{13}$$

$$\sum_{i=1}^{N} v_{ij}^I \leq b_j^{II}, \quad j = \overline{1, M}, \tag{14}$$

$$\sum_{j=1}^{M} \theta_j \leq L, \tag{15}$$

$$v_{ij}^I \geq 0, \quad \theta_j \in \{0; 1\}, \quad i, j = \overline{1, N}, \quad j = \overline{1, M}, \tag{16}$$

where $\tau^I = (\tau_1^I, \tau_2^I, \ldots, \tau_N^I)$, $\tau^I \in \Omega^N$ — distribution centers location that was obtained during first stage; b_i^{*I} — determined capacity of distribution centers:

$$b_i^{*I} = \int\limits_{\Omega_i} \rho(x)dx, \quad i = \overline{1, N}.$$

Additionally, we define this solvability condition:

$$\int\limits_{\Omega} \rho(x)dx \leq \sum_{j=1}^{M} b_j^{II}\theta_j, \quad j = \overline{1, M}.$$

The solution for discrete task (12)–(16) is more deeply investigated by authors in [12]. The example of program implementation for the first solution approach can be found in [13]. Despite the successful location and activation of the centers, the proposed approach has several drawbacks:

– the located distribution centers are independent of chromosomes, which reduces variability and does not fully correspond to the idea of the genetic algorithm;
– when solving the location problem, the transportation plan is not taken into account, which leads to a more uniform distribution of centers, which can lead to inefficient placement of distribution centers.

To eliminate these drawbacks, we propose to use a different approach.

6. Second solution approach. We propose to use a genetic approach to solving the two-stage location-activation problem. The proposed modifications compared to the first approach:

– In the objective function (1), we additionally take into account the transportation plan between centers. This will add influence links between the placed centers and the activated ones, making the approach more rational in considering all the links and constraints.
– Each chromosome or other solution from evolutionary algorithm represents a transportation plan between certain centers. Therefore, the encoding and decoding procedure depends on the actual coordinates of the corresponding centers. We propose to modify the chromosome estimation procedure (and decoding procedures) in the form of solving the placement problem to build a more complete transportation plan.

Using the evolutionary algorithms, we can formulate the second solution approach:

1. We will use the mathematical model (1)–(8). The general scheme of the genetic algorithm is the following:
2. The population $P(t)$ is initialized using priority-based encoding. We get the first generation of potential solutions to the problem.
3. We evaluate the fitness of each chromosome in the population by solving the location problem on the model (1)–(8) with a transportation plan included in the optimization task. After solving the problem, the DCs' location, capacity, and transportation plan are obtained for each chromosome.
4. Chromosomes are selected for reproduction using the roulette method.
5. The selected chromosomes are crossed to produce offspring.
6. Some chromosomes undergo mutation to introduce variations.
7. A new population $P(t+1)$ is formed from the offspring and possibly some individuals from the current population. The new generation replaces the old one.
8. Check whether the stopping requirement is met. If so, go to the next step. Otherwise, return to step 2 with the population value $t+1$.
9. Finish the algorithm. Decode the effective chromosome and return the value of the objective function and the transportation plan. The algorithm is described.

The second approach proposes a more connected solution for the problem (1)–(8) where we consider the actual determined locations of the centers. We also improved the decoding procedure to ensure that the decision on where to place the center was made under full information. One of the drawbacks of such an approach is that we create circular dependency for minimization functional and chromosome evaluation procedure that requires more computation and time complexity for the algorithm's implementation.

7. Experiments. Let us run some experiments to demonstrate and compare different approaches. To illustrate the work of the proposed mathematical model and proposed approaches, we developed a software implementation using C++ (location module) and Python (UI module) technologies. For the experimental environment, we use an Apple M3 Max chip featuring a 12-core CPU and 18-core GPU, 36 GB of unified memory, a 512 TB SSD, and running macOS Sequoia 15.1. To demonstrate differences in performance between the two described methods, we run a set of experiments: the problems will have sizes 4×10, 7×20, 10×25, 12×30, 15×35. As random generation plays a crucial role during the solution, we will rerun each experiment 20 times and find the average value for these parameters: algorithm execution time and fitness function value. These comparisons are illustrated in Fig. 2.

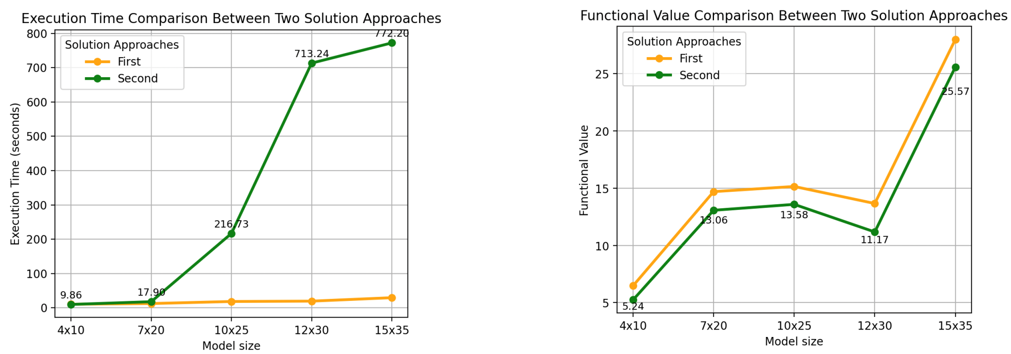

Figure 2. Comparison of first and second solution approached for execution time (left) and functional value (right).

From the results obtained from experiments, we can state that, as expected, the solution time for the second solution approach is significantly greater (starting from 10×25 size) than for the first one. This is expected, as we apply the location of the centers for each chromosome for the second solution approach while doing it only once in the first solution approach. At the same time, as we are solving the minimization problem, the second solution approach gives more efficient results where the average functional value of the second solution approach is 13.44% lower than the first one. We can conclude that the first solution approach is more usable when fast and approximate solutions for the location-activation process are required (e.g. real-time routing of medical supply vehicles or points in a city where quick decisions are critical to ensure the timely delivery of medicines) and the second solution approach gives a more efficient solution but takes drastically more time to execute (e.g. long-term planning for the establishment of new centers of medical logistics to optimize coverage and resource allocation across a region). As the decision about location or opening some centers from a practical problem statement is usually something more like a strategic one rather than short-term, the second solution approach should be utilized to manage medical logistics efficiently.

8. Conclusions. In the paper, we highlighted the importance of medical logistics research. The topic's relevance becomes more vital during the crises that put the system under challenge. We formulated a practical problem statement that represents the organizational structure of the medical logistics system and it contains several types of centers: regional, subregional and distribution. We also propose a mathematical model for the two-stage location-activation problem and this model minimizes the expenses for operation, delivery, location, and activation. For the mentioned mathematical model, two solution approaches are introduced. The first one contains the idea of dividing the process into two steps, wherein in the first step, we only locate the distribution centers by solving the continuous optimization task. We use the obtained coordinate to solve the second (discrete) part in the second step. The second solution approach proposes a combined solution technique where continuous and discrete parts are linked together so that we use full information during the algorithm run. For the first and the second methods, we run a set of experiments that demonstrate that both ways can be used to solve the mentioned problem, with the difference that the first one is significantly faster and can be used in areas where solutions are required during runtime or live mode, while the second one uses more information and has longer execution time but provides more efficient solutions that can greatly optimize costs and can be used during strategic and long-term planning for location or activation of centers of different levels. Both approaches can be used to solve the mentioned problem and the first one is simpler and has simpler time complexity while the second one uses more information but has longer execution time.

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Сергєєв О. С., Ус С. А. Дослідження двох підходів до розв'язання двоетапної задачі розміщення-активації.

У роботі досліджується система медичної логістики під час кризових ситуацій, що спричиняють надмірне навантаження. Авторами сформульовано практичну постановку задачі для структури медичної логістики, яка включає три типи центрів: регіональні, субрегіональні та дистрибуційні. Також було запропоновано математичну модель для двоетапної задачі розміщення-активації, що мінімізує витрати на експлуатацію, доставку, розміщення та активацію відповідних центрів. Для цієї математичної моделі було представлено два підходи до розв'язання. Перший підхід розділяє процес на два етапи: спочатку визначаються місця розташування дистрибуційних центрів шляхом розв'язання неперервної задачі, а потім використовуються отримані координати для розв'язання другої (дискретної) частини. Другий підхід є комбінованою методикою, яка поєднує як неперервну, так і дискретну частини, використовуючи всю доступну інформацію під час виконання алгоритму із застосуванням еволюційної теорії. Обидва підходи можуть бути використані для розв'язання задачі: перший є простішим і має меншу обчислювальну складність, а другий використовує більше інформації, але має вищу обчислювальну складність.

Ключові слова: дискретна оптимізація, неперервна оптимізація, ефективні рішення, еволюційна теорія, транспортування, медична логістика.

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