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Ivan Peleshko, Mykhailo Hrubiy, Oleh Bilokur

FORMULATION OF THE OPTIMIZATION PROBLEM FOR UNDERGROUND ENGINEERING NETWORK ROUTES

Department of Construction Production,
Lviv Polytechnic National University
ipeleshko@hotmail.com

The article considers the implementation of methods for optimizing underground external engineering networks in order to reduce construction costs. For this purpose, the problem of optimizing the route of such networks is set in the form of a nonlinear programming problem. The route is modeled by a spatial polyline with rectilinear segments, and the coordinates of its vertices are considered design variables. The ground surface in the designated area is modeled as a continuous function of two coordinates in the plan using BIM technologies, which ensures the automated use of topographic information when calculating the volume of earthworks and checking compliance with constraints specified by standards requirements. The main result of the study is the formulation of the problem of optimizing the route of the engineering network taking into account the terrain.

Key words: engineering networks; optimal design; optimization task; design variables; objective function; constraints.

Introduction

Contemporary Building Information Modeling (BIM) technologies allow for the storage and analysis of large volumes of data, enhancing the accuracy of considering real-world conditions in the design process. Crucially, they enable the incorporation of terrain relief when determining optimal routes for underground engineering networks.

Advancements in external engineering network optimization have significantly benefited from the contributions of numerous scholars. Shatalov, Eremin, Sharapova and Vorotyntseva (2021) initiated a foundational study on BIM coordination for street engineering renovations. This methodology was further developed by Wei, Chen, and Wang (2018) with a focus on water supply and drainage design efficiency. Additionally, Honcharenko, Terentyev, Malykhina, Druzhynina, and Gorbatyuk (2021) highlighted the potential of BIM in early urban planning stages, showcasing its utility for digital modeling.

Further innovations were presented by Prasad, Khare, and Palod (2022), who introduced a multi-objective evolutionary algorithm for optimizing water distribution networks, aligning with the sustainable solution approaches emphasized by Marques, Savic, and Cunha (2015). The heuristic method advancements by Eusuff, Lansey and Pasha (2006), and the improvements to the harmony search algorithm by Geem (2014), marked significant progress in network design challenges.

Savic, Sultanova, and Mala–Jetmarova (2018) provided a comprehensive literature review outlining critical directions for water system optimization. This was complemented by Farmani, Walters, and Savic (2005), who offered evolutionary optimization perspectives. The discussions on metaheuristics by Maier et al. (2014), alongside the review on water distribution optimization strategies by Fayomi, Okolie, and Awe (2019), further enriched the academic dialogue.

Additional contributions from Babayan, Walters, and Savic (2007) focused on the challenges of uncertain demand and pipe roughness, while Cunha and Ribeiro (2007) explored tabu search methodologies, and Kapelan, Savic, and Walters (2005) developed decision-support frameworks. The field's current research frontier is represented by Ostfeld and Boindala (2022), who aimed for resilience in water distribution systems with their robust design optimization work.

Incorporating the work of Maier, Simpson, Zecchin, Foong, Phang, Seah, and Tan (2016) on Ant Colony Optimization techniques, the multiobjective optimization considerations by Maier, Simpson, and Wu (2013), and the sustainable urban development decision-support tools by Kapelan, Savic, and Walters (2005), these collective efforts have significantly pushed forward the dialogue on efficiency, sustainability, and adaptability in external engineering network optimization.

The purpose of the article is to formulate the problem of optimizing the route of underground engineering networks, taking into account construction costs and the use of BIM technologies for modeling the topography of the territory.

Materials and methods

The task is to optimally design the route of the engineering network that extends continuously from point $O(x_0; y_0; z_0)$ to point $N(x_N; y_N; z_N)$. The positions of points *O* and *N* are fixed in a certain three-dimensional Cartesian coordinate system, immutable, and specified by the design task. The route has the shape of a spatial polyline without self-intersections, consisting of *N* line segments, meaning there are *N*–1 vertices of the polyline between points *O* and *N* (Fig. 1). The route labeled as *a* should be restricted to the territory outlined in the permitting documents and bounded by two polygonal chains *b* and *c* (Fig. 2), where the coordinates of their vertices are known. Additionally, the elevations $H(x, y)$ of ground surface points within this specified territory have been identified.

Among all permissible route options, it is necessary to select the one that ensures the global extremum of the objective function.

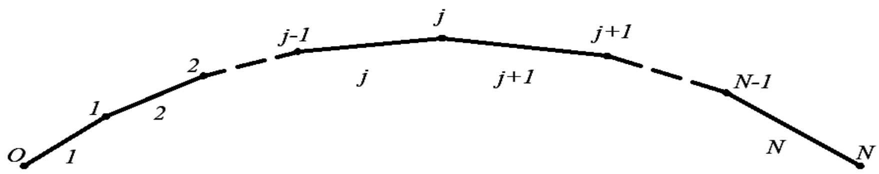

Fig. 1. Scheme of numbering the elements of the route

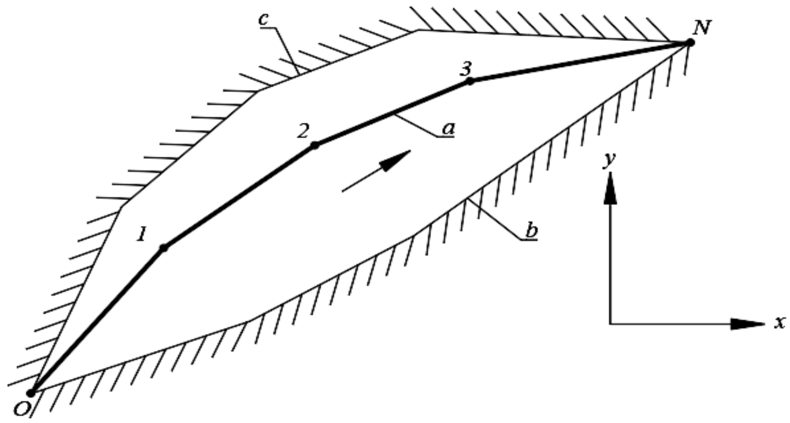

Fig. 2. Schematic plan of the territory with the route: 0 – starting point of the route;
N – endpoint of the route; 1, 2, ..., N–1 – vertex numbers of the route; b, c – boundaries of the territory

Route optimization design variables include plan coordinates (x_j, y_j) as well as elevation z_j at vertices of the route $j = \overline{1, N-1}$ (Fig. 3).

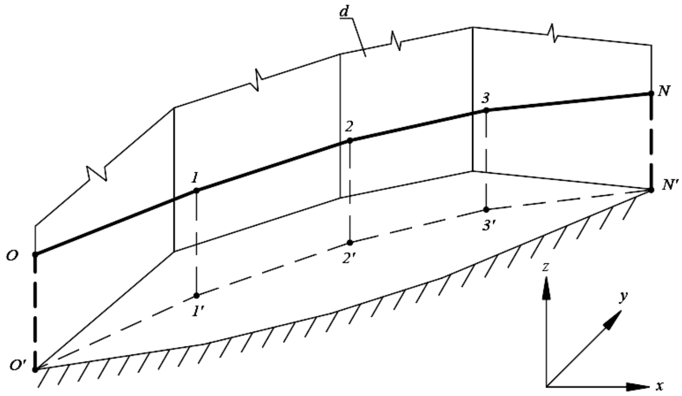

Fig. 3. Spatial representation of the route: d – constraint surface for one of the boundaries (other surfaces are conventionally not shown)

During the optimization problem solving, the values of design variables are selected in a way to achieve the extreme value of the objective function while considering all specified requirements.

Results and discussion

The length L_j of the route segment between the route's turn points $j-1$ and j is calculated using the formula:

$$L_j = \sqrt{(x_j - x_{j-1})^2 + (y_j - y_{j-1})^2 + (z_j - z_{j-1})^2}, \quad (1)$$

where x_{j-1}, x_j, y_{j-1}, y_j, z_{j-1}, z_j are coordinates of the endpoints of segment j.

The length of the route L:

$$L = \sum_{j=1}^{N} L_j. \quad (2)$$

The slope of section j is calculated using the formula:

$$i_j = \frac{z_{j-1} - z_j}{L_j}. \quad (3)$$

The objective function aims to minimize total costs in engineering network design, covering material, installation, and operational expenses. The formula for the objective function may look as follows:

$$C = \sum C_s \to \min, \quad (4)$$

where $\sum C_S$ is the sum of all expenses: the cost of all construction materials, components, and consumables used during the construction process; expenses for paying the labor of workers and engineering and technical staff directly involved in the construction; costs for renting or operating construction machinery, machines, and equipment. Fixed costs like management, safety, permits, and design are independent of design variables.

Network laying costs are calculated using route geometry, considering length, depth, terrain type, and more. Material costs C_m:

$$C_m = L \cdot p_m, \quad (5)$$

where p_m is material price per route unit length is based on current construction material prices data.

Wages C_l:

$$C_l = V \cdot p_l, \quad (6)$$

where p_l is unit cost for the volume of work (Guidelines for determining direct costs in construction costs, DSTU, 2013).

Cost of machinery rental C_{mac}:

$$C_{mac} = V \cdot p_{mac} \cdot T, \tag{7}$$

where p_{mac} is cost of machinery rental (Guidelines for determining the cost of operating construction machines and mechanisms in the cost of construction, DSTU, 2013); *T* is the time required for laying the route, which is found by the formula:

$$T = \frac{V}{N_h}, \tag{8}$$

where N_h is standard work time, which are determined from the regulatory document (Sectoral norms. Collection 2. Issue 1. Mechanized and manual earthworks).

To calculate the volumes of earthworks, we divide the route into segments of small length l_k, the sum of which equals the length of the route *L*. Let the *k*-th segment be located within section *j* at a distance L_k from its beginning (from point $j-1$ of the route turn). Then, the total volume of earthworks for trench construction V_k can be determined as the sum of volumes of earthworks on individual segments:

$$V = \sum_{k=1}^{K} V_k, \tag{9}$$

where *K* is the number of segments into which the trench for laying the route is divided.

$$V_k = S_k \cdot l_k, \tag{10}$$

where l_k is length of the *k*-th segment; S_k is the average cross-sectional area of the trench in the *k*-th segment. The average area of the trench segment is calculated using the formula:

$$S_k = h_k \frac{b_b + b_{t,k}}{2}, \tag{11}$$

where h_k is depth of the *k*-th segment; b_b, b_{tk} are lower and upper width of the trench segment. The upper width of the trench segment is calculated using the formula:

$$b_{t,k} = b_b + 2 \cdot b_{u,k}, \tag{12}$$

where $b_{u,k}$ is the slope width (Safety in construction. Earthworks. General safety requirements, 2009), depending on the type and condition of the soil. The height of the trapezoid is calculated as the difference between the surface elevation marks and the bottom of the trench using the formula:

$$h_k = H_k(x, y) - z_k, \tag{13}$$

where z_k is elevation mark of the bottom of the trench for the *k*-th segment; H_k is elevation mark of the surface for the *k*-th segment of the trench.

BIM and auto-interpolation determine the *k*-th segment's surface elevation, using geodetic data for accurate depth calculation and optimal network routing. The elevation mark of the bottom of the trench for the *k*-th segment is calculated using the formula:

$$z_k = z_{j-1} - L_k \cdot i_j, \tag{14}$$

where z_{j-1} is elevation mark of the trench bottom at the turning point of the route $j-1$; i_j is the slope of section *j* between the turning points of the route $j-1$ and *j*.

The slope is calculated using the formula:

$$i_j = \frac{z_{j-1} - z_j}{L_j}, \tag{15}$$

where L_{j+1} is the distance between points $j-1$ and *j* of the route.

Designing routes for external engineering networks with BIM involves establishing constraints that prevent crossing boundaries to mitigate conflicts and adhere to environmental zones. Furthermore, specific laying depths are determined in accordance with regulatory values to ensure safety and durability

$$h_k - D \geq [h]_{min}, \tag{16}$$

where $[h]_{\min}$ is regulatory depth for protection against freezing; D is the diameter (height) of the pipeline.

$$h_k - D \geq [h]_m, \tag{17}$$

where $[h]_{\mathrm{m}}$ is regulatory depth for protection against mechanical damage.

The slope is expressed using the inequality:

$$[i]_{\max} \geq i_j \geq [i]_{min}, \tag{18}$$

where $[i]_{\min}$, $[i]_{\max}$ are regulatory slopes.

Values for $[h]_{\min}$, $[h]_{\mathrm{m}}$, $[i]_{\min}$ and $[i]_{\max}$ are specified in the document (Sewerage. External networks and structures. Basic design provisions, DBN, 2013).

Conclusions

The optimization problem for the engineering network route, comprising multiple segments represented as a spatial polyline with vertices, is defined. Design variables encompass planar coordinates (*x*, *y*) and elevation (*z*) at these vertices.

An objective function, expressed in terms of design variables, are devised to minimize costs, incorporating material expenses, labor, and equipment rental, while considering earthworks during trench construction.

Constraints for the optimization task are specified, ensuring network traversal within specified limits, along with the requisite depth and slopes for route segments, also expressed in terms of design variables.

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І. Д. Пелешко, М. І. Грубий, О. М. Білокур
Національний університет “Львівська політехніка”,
кафедра будівельного виробництва

ФОРМУЛЮВАННЯ ЗАДАЧІ ОПТИМІЗАЦІЇ ТРАСИ ПІДЗЕМНИХ ІНЖЕНЕРНИХ МЕРЕЖ

У сучасному будівництві зовнішні підземні інженерні мережі широко застосовують, проте планування ефективного використання ресурсів під час їх проєктування залишається складним завданням. У статті вирішено актуальне питання упровадження методів оптимізації інженерних мереж у практику їх проєктування і мінімізації комплексу затрат на будівництво.

Як передумову економії затрат розглянуто формулювання задачі оптимізації траси зовнішніх інженерних мереж із підземним прокладанням, у формі задачі нелінійного програмування. Траса моделюється просторовою полілінією із прямолінійними сегментами. Змінними проєктування прийнято просторові координати точок зміни напрямку траси. Поверхня землі на території, виділена для будівництва траси, моделюється неперервною функцією двох координат у плані. Для моделювання поверхні землі передбачено використання BIM-технологій, які забезпечують задавання необхідної топографічної інформації та її використання під час розрахунку параметрів для варіантів траси, що розглядають, виконуючи оптимізацію. Шукані координати точок у плані повинні забезпечувати проходження траси у межах виділеної території, а висоти цих точок – забезпечувати дотримання нормативних вимог щодо ухилів ділянок траси, а також щодо необхідної глибини прокладання траси з урахуванням нормативної глибини промерзання ґрунту та забезпечення цілісності конструкції самої мережі.

Основним результатом виконаного дослідження є формулювання цільової функції та обмежень задачі оптимізації траси інженерної мережі з урахуванням нормативних вимог і реальної поверхні землі, яку можна задати за допомогою BIM-технологій. Цю інформацію використовують під час підрахунку значення обсягів земляних робіт для визначення критерію оптимальності та для розрахунку потрібних значень під час перевірки обмежень.

Ключові слова: інженерні мережі; оптимальне проєктування; задача оптимізації; змінні проєктування; цільова функція; обмеження.