A Decision Support System Based on a Mixed-Integer Linear Programming Model for Location of Routers in Open-Pit Mines

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Abstract: In open-pit mines, it is very important to ensure network coverage for equipment in operation, which is located in large areas. It should be noted that some of this equipment, such as trucks and drills, is autonomous; therefore, access to the network is essential. This work presents a mathematical model for solving it based on the p-median problem. The objective is to determine the location of the routers, minimizing the number of routers and the sum of the distances between the operating points and the installed routers. We use real data from the Fábrica Nova mine in Brazil to validate the mathematical model. The scenarios represent the mining planning for 2023, 2024, and 2025. The results showed that the proposed model found the optimal router location in a few seconds, providing more efficient coverage for mining equipment using fewer routers.

1 INTRODUCTION

Open-pit mining is an activity that requires the use of various high-tech equipment to ensure the safety and productivity of the operation. One of the main challenges mining companies face is ensuring equipment connectivity since the operation occurs in remote areas and often with limited access to communication networks. One solution to this problem is the use of mesh networks.

The mesh network is a wireless communication technology that stands out for its ability to increase network coverage and efficiency, offering more excellent stability and security (Taleb et al., 2022). This technology is an evolution of traditional networks, which use a single access point, such as a router, to connect to several devices. With the mesh network, devices connect, forming a communication mesh, which allows the network to be more robust and flexible.

According to Agrawal et al. (2023), mesh networks have several advantages over traditional networks, such as expanding the wireless network, covering remote areas, and solving connectivity problems where the signal is weak or non-existent. These advantages make the mesh network exciting for large environments like mining companies.

The location of routers in a mesh network is one of the main factors that influence the efficiency and signal quality of the network. Despite the economic and operational importance of providing efficient coverage for mining equipment, the installation points for routers in mines are generally determined empirically. This adopted strategy may cause a signal loss, putting operation and safety at risk. Figure 1 shows the structure used at the Fábrica Nova mine in Brazil to location routers.

Figure 1: Trailer used to install routers at the Fábrica Nova mine.

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The problem of locating routers in mesh networks can be classified as a p-median problem, where the routers are the facilities and the mine operating points are the customers. In the literature, the p-median problem is widely treated in several applications, aiming to minimize the distances between facilities and customers. However, no study was found on the problem of locating routers in open-pit mines. In this problem, there are additional constraints, such as delimiting the mine's operating areas by four extreme points, respecting the routers' coverage radius, and allowing redundancy of coverage, increasing network coverage's reliability. Furthermore, the objective function additionally deals with minimizing the number of routers since the installation adds cost to the mine infrastructure.

To fill this gap, this work proposes a mixed-integer linear programming model for router locations in open-pit mines based on the p-median problem. To validate the proposal, a case study was used with three scenarios at the Fábrica Nova mine from Vale S.A in Brazil. Scenarios represent mining planning for 2023, 2024, and 2025, respectively, and the results estimate the network infrastructure necessary for the operation.

The main contributions of this work are: *i*) characterization of the router locations in open-pit mines as a variant of the p-median problem class; *ii*) introduction of a mixed-integer linear programming formulation to solve the problem using a solver.

The article is organized as follows: Section 2 presents a literature review. Section 3 shows the characterization of the problem and provides a didactic example. Section 4 presents the proposed model for router location. Finally, in Section 5, the computational experiments are reported, while Section 6 shows the conclusions of the work.

2 LITERATURE REVIEW

This section presents a literature review of some topics related to the problem of the location of routers in open-pit mines.

2.1 Mesh Networks

The use of routers in mesh networks has been studied extensively in the literature. In particular, optimization algorithms to determine the optimal router location–allocation have proven effective in several contexts. In Zhang et al. (2009), the authors proposed an optimization model for router location–allocation in mesh networks in urban areas, aiming to minimize the total cost of the network.

In Bueno (2021), the authors present a study on router location–allocation in mesh networks in rural areas. In this case, a mixed-integer linear programming model approach was used to determine the optimal router location–allocation, considering several constraints, such as installation cost and signal range.

Regarding the use of mesh networks in mining environments, a recent study by Shibalabala and Swart (2020) highlighted the importance of using mesh networks for data transmission in underground mines, aiming to improve the efficiency and safety of operations. However, more studies still need to be conducted on the installation of routers in mesh networks in open-pit mining environments.

2.2 The p-Median Problem

The p-median problem class is a combinatorial optimization problem that aims to find the optimal location of p medians in a set of possible locations, minimizing the distance between the medians and the demand points (Daskin and Maass, 2015). The p-median problem has been used in several areas. Below, we present some of these applications:

- **Distribution Center Optimization:** in logistics and supply chain management, the p-median problem is used to determine the strategic location of distribution centers, minimizing transportation costs and maximizing delivery efficiency of products (Ramadhanti et al., 2020).
- **Health Services Planning:** in healthcare, the p-median problem approach is applied to determine the ideal location of hospitals, clinics, or care centers, aiming to maximize access to medical services and minimize patient travel times (Murad et al., 2024).
- **Reduction of Carbon Emissions:** seeking sustainable transport solutions, the p-median problem is used to optimize charging point locations for electric vehicles, reducing carbon emissions and improving infrastructure urban mobility (Kim et al., 2022).
- **Urban and Spatial Planning:** the p-median problem approach is used in urban planning to determine the location of public services, such as schools, libraries, or parks, seeking to ensure an equitable distribution of these resources in the city (Chen et al., 2023).

Location-allocation problems seek to find the best configuration for installing one or more facilities to meet the demand of a population. The term facility can be replaced in the public sector by public service units (schools, libraries, hospitals, bus stops) and emergency services units (fire department, police stations, ambulance stations). In the private sector, the term facility can be replaced, for example, by factories, warehouses, telecommunications antennas, and routers (Barbosa et al., 2023; de Campos et al., 2020).

The problem of locating routers in mesh networks is a critical issue that aims to find the ideal location for installing routers in a geographic area to ensure maximum coverage and connectivity. This problem is complex and involves several restrictions, such as signal range, installation costs, and the limited number of routers to be installed. Several optimization approaches have been widely studied and applied to solve this challenge.

In Lorena and Pereira (2002), the p-median problem is applied to a facility location problem, simulating the installation of radio antennas for internet service in São José dos Campos, Brazil. Capdeville and Vianna (2013) also proposed the implementation of GRASP heuristics for the problem of locating access points in a wireless mesh network, which is treated as a problem capacitated p-median location based on the structure of a new network that will be implemented. Sandoval et al. (2021) consider the problem of maximizing user coverage for 5G/6G wireless communication networks subject to facility location and radial distance constraints through two models. The first model maximizes the total number of users. The second includes in the objective function the maximization of users and the minimization of the number of antennas to be activated. The numerical results obtained show that the increase in the number of radius allowed provides more flexibility and accuracy to the model, although at a higher computational cost. The authors indicate that proposed models can be used for future developments of 5G/6G networks to improve coverage.

Therefore, the p-median problem formulation can also solve the router location problem in mesh networks. In this context, the medians represent the locations of the routers, and the demand points are the devices or areas that require connectivity.

Using the p-median problem approach to solve the router location problem in mesh networks allows for determining strategic positions for installing routers to optimize network coverage and minimize associated costs. To that end, a new mathematical formulation was developed based on the p-median problem. The new objective function and problem constraints seek to represent the specific characteristics of the router location problem in open-pit mines. The proposed new formulation will be presented below.

3 PROBLEM STATEMENT

Open-pit mines generally have a vast geographic extension, and mining activities may exist simultaneously in different regions of that mine. The mining equipment used in the operation requires access to the communication network to guarantee the safety and productivity of the operation.

In this work, the operating points determine the areas where mining activities are being performed and where mining equipment circulates and requires connectivity. For each operational area, four extreme points are defined.

Figure 2 illustrates a region in which two operation areas are represented by the areas delimited by the yellow lines. Each operating area is represented by four extreme points, called operating points, in red in the image.

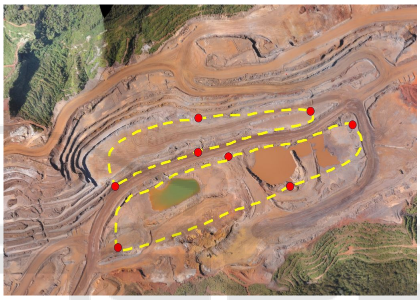

Figure 2: Mapping of operating points.

Therefore, the router location problem in open-pit mines consists of determining the minimum number of routers needed to ensure that all operating points are within the coverage radius of at least one router. The characteristics of this problem are presented below.

1. Operating points (J):
   (a) A mine can have several areas of simultaneous operation;
   (b) In each operation area, there is a variety of equipment that needs connectivity to perform its activities;
   (c) Each operating area is represented by four extreme points, called operation points;
   (d) Each operating point $j \in J$ has a location lp_j;
   (e) Each operating point $j \in J$ needs to be attended to one or more routers $r \in R$;
2. Routers (R):
   (a) A communication network is made up of n routers;
   (b) Each installed router has a location $lr_i \in I$;

(c) Each router $r \in R$ has a coverage radius, identified as *radius*;

(d) p_{max} indicates the maximum number of routers that can be installed.

3. Candidate locations for installing routers (I):

(a) There is a set of candidate locations for installing routers;

(b) Each location $i \in I$ has a location lr_i.

The objective is to locate routers $r \in R$ serving all operating points $j \in J$, seeking to minimize the number of routers installed and the sum of the distances between the operating points and the routers.

Next, a small example of the problem is presented to facilitate understanding.

In this example, represented in Figure 3, there are two operation areas, represented by the areas delimited in *yellow*. The two operating areas total eight operating points $j = \{J1, J2, \cdots, J8\}$, represented in *red*. There are six possible router installation points, $i = \{I1, I2, \cdots, I6\}$, represented in *blue*. Each router has an operating radius of 1000 meters, and the maximum number of routers that can be installed is four.

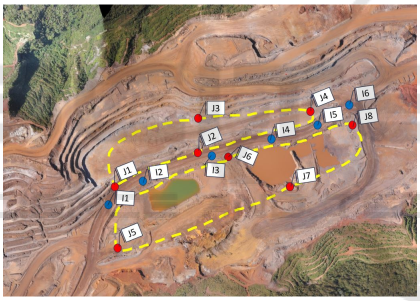

Figure 3: Operating points (J) and possible installation points (I).

Table 1 presents the location matrix of the operating points in Cartesian coordinates (XYZ), while Table 2 presents the location of possible router installation points.

Table 1: Operating points (J).

Points	Location X	Location Y	Location Z
J1	662924,60	7763976,10	857,60
J2	662944,60	7763855,45	855,87
J3	663103,26	7763667,44	863,62
J4	663085,39	7763452,97	861,33
J5	662745,07	7763950,46	850,35
J6	662983,63	7763629,94	857,03
J7	663025,22	7763378,73	844,49
J8	663157,37	7763180,37	852,08

Table 3 presents the distance matrix between the operating points and the possible router installation points in meters.

A possible solution for the didactic example is to install a router at point $I3$, which is show by Figure 4.

Table 2: Possible installation points (I).

Points	Location X	Location Y	Location Z
I1	662672,16	7764069,48	854,63
I2	662848,54	7764001,51	857,08
I3	663018,54	7763651,51	862,22
I4	663101,99	7763358,01	865,70
I5	663176,98	7763235,03	871,57
I6	663262,39	7763096,90	876,83

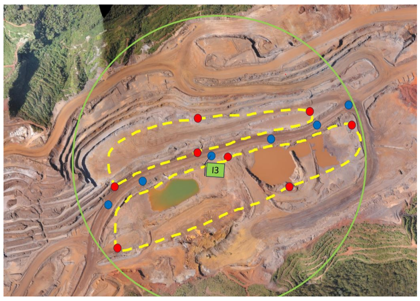

Figure 4: Possible solution.

4 PROPOSED MATHEMATICAL MODEL

In this section, we present the mixed-integer linear programming model to solve the addressed problem based on p-median. The main contributions of this model are: *i*) minimize the number of installed routers; *ii*) delimitation of mine operating areas by extreme points; *iii*) respect the routers' coverage radius; *iv*) allow redundancy of router coverage.

Next, the input sets, indexes, parameters, and decision variables used in the proposed formulation are described.

- Sets:

  J : set of operating points that must be met;

  R : set of routers;

  I : set of candidate locations for router installation.

- Indexes:

  j : index of the set J;

  i : index of the set I.

- Parameters:

  d_{ij} : distance from the operating point j to the router located at i;

  p_{max} : maximum number of routers that can be installed;

  $radius$: coverage radius of each router.

- Decision variables:

  p : number of routers that will be installed;

Table 3: Distance matrix.

	J1	J2	J3	J4	J5	J6	J7	J8
I1	277,72	347,99	670,29	787,10	157,96	544,46	878,69	1019,42
I2	80,40	176,29	462,85	615,55	160,79	395,36	806,04	902,36
I3	359,54	257,19	88,18	210,27	546,07	67,90	587,14	593,94
I4	709,21	618,35	313,71	115,42	927,43	371,70	529,54	371,72
I5	979,04	908,97	501,79	341,15	1286,16	651,06	942,44	438,00
I6	1313,17	1261,83	766,80	637,82	1699,66	993,61	1414,54	746,96

$$x_{ij} : \begin{cases} 1, & \text{if the operating point } j \text{ is assigned to} \\ & \text{the router located at } i; \\ 0, & \text{otherwise;} \end{cases}$$

$$y_i : \begin{cases} 1, & \text{if the router is installed at location } i; \\ 0, & \text{otherwise;} \end{cases}$$

The objective function of the formulation is composed of two parcels. The first parcel minimizes the number of open facilities, that is, the number of routers installed. The second parcel minimizes the sum of the distances between the operating points and the installed routers. The equations (1) and (2) represent the objective function.

$$min\ \alpha \frac{p}{|R|} + \beta \left(\frac{\sum_{i \in I} \sum_{j \in J} d_{ij} x_{ij}}{|J| radious} \right) \tag{1}$$

$$\alpha + \beta = 1 \tag{2}$$

where α indicates the weight of the first parcel and β indicates the weight of the second parcel of the objective function.

A set of constraints (3) has been implemented to ensure that all operating points are within the coverage radius of the routers.

$$d_{ij}\, x_{ij} \leq radius \qquad \forall i \in I, \forall j \in J \tag{3}$$

The set of constraints (4) ensures that each operating point is assigned to at least one router.

$$\sum_{i \in I} x_{ij} \geq 1 \qquad \forall j \in J \tag{4}$$

The set of constraints (5) guarantees that each operating point can only be assigned to installed routers.

$$x_{ij} \leq y_i \qquad \forall i \in I, \forall j \in J \tag{5}$$

The constraint (6) determines the number of installed routers. The constraint (7) defines that the number of installed routers must be less than the number of routers available p_{max}.

$$\sum_{i \in I} y_i \leq p \tag{6}$$

$$p \leq p_{max} \tag{7}$$

Finally, the set of constraints (8) and (9) define the domain of the decision variables x_{ij} and y_i, respectively.

$$x_{ij} \in \{0,1\} \qquad \forall i \in I, \forall j \in J \tag{8}$$

$$y_i \in \{0,1\} \qquad \forall i \in I \tag{9}$$

5 CASE STUDY

The proposed mathematical model was implemented in *Lingo* 10.0, version 4.01.100, and the computer used in the computational experiments was an Intel(R) Xeon(R) W-10885M CPU @ 2.40 GHz notebook, 64.0 GB RAM, and Windows 11 operating system.

We used real data from three scenarios of the Fábrica Nova mine in Mariana, Brazil, to evaluate the proposed model. The operating points were collected using geographic coordinates. The possible installation points were defined in the existing roads from the mine using the *Deswik* software.

5.1 Scenarios

Currently, in the Fábrica Nova mine, there are 12 routers available for implementing the network. In this study, each router has a coverage radius of 1,000 meters. We used three scenarios to validate the proposal: the first represents the operations for 2023, while the others represent the projection of the operations for the following years, 2024 and 2025.

- **Scenario 01**: the first scenario evaluated reflects the mining planning for the year 2023. This scenario has 12 operating areas represented by four extreme points each, totaling 48 operating points. Figure 5 shows the operating points for this year.
- **Scenario 02**: the second scenario analyzed represents mining planning for the year 2024. This scenario is presented in Figure 6 and has nine operation areas, totaling 36 operation points.
- **Scenario 03**: the last scenario analyzed is presented in Figure 7 and represents the mining planning for the year 2025. This scenario has six operation areas, totaling 24 operation points.

In open-pit mines, the installation of routers is only permitted at the mine's access points, that is, on the existing roads within the mine. To determine the possible installation points for the routers, we use the

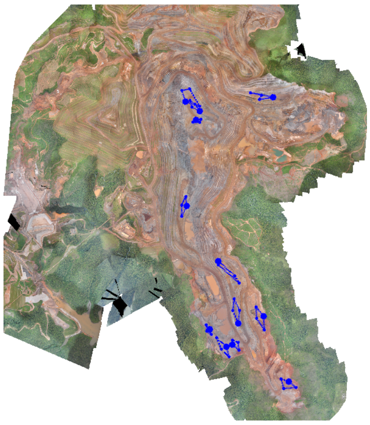

Figure 5: Operating points for the scenario 01.

Figure 6: Operating points for the scenario 02.

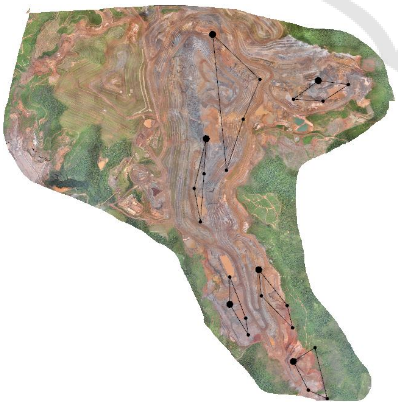

Figure 7: Operating points for the scenario 03.

Deswik software, version 2023.2.953. The topography of the area with indications of existing accesses is inputted into the software, as showed the red lines in Figure 8. Thus, the software returns the number of possible installation points to better the characterization of these accesses, as well as their geographic coordinates. In the studies, we used the same access topography across all scenarios and the software identified 101 possible router installation points in the mine.

A distance matrix, *nxm*, was created for each scenario, where *n* is the number of operating points for each scenario and *m* is the number of possible installation points. Due to the amount of data, a spreadsheet with the matrices is available at https://encr.pw/alocacao-roteadores

Figure 8: Possible installation points (in red).

5.2 Results

Table 4 summarises the results. As the objective function of the proposed mathematical model is composed of two parcels, it was evaluated in three weight combinations for each scenario.

In all scenarios, the proposed mathematical model quickly found the optimal solution (GAP = 0). It can be seen that when one of the parcels has a weight equal to 0, it is not considered in the optimization process. Therefore, for this problem, it is suggested to use a weight of 0.5 for each parcel of the objective function.

The solution generated in each scenario is illustrated as follows, considering $\alpha = 0.5$ and $\beta = 0.5$. Figure 9 presents the solution for scenario 01. Five routers were installed at the points indicated in green.

The solution for scenario 02 is presented in Figure 10. For 2024, nine routers were installed at the points indicated in green. When finding solutions for mine planning in the coming years, the model has shown to be a valuable tool for predicting the infrastructure necessary for implementing the communication network in mine expansion.

Finally, for 2025, the installation of eight routers was indicated. Figure 11 represents the solution for scenario 03.

In scenarios 2 and 3, the installation of routers overlaps more than in scenario 1. These situations are due to the projection of the mine for 2023 and 2024,

Table 4: Results.

Scenario	Weight Parcel 1 (α)	Weight Parcel 2 (β)	# Operation Areas	# Operation Points	# Possible Installation Points	Installed Routers	Maximum Distance	Average Distance	GAP	Execution Time (s)
1	0.0	1.0	12	48	101	12	592,019	219,684	0	13
	0.5	0.5				5	836,646	360,746	0	12
	1.0	0.0				5	908,457	588,192	0	21
2	0.0	1.0	9	36	101	12	958,006	388,08	0	1
	0.5	0.5				9	958,006	465,878	0	1
	1.0	0.0				9	958,006	657,681	0	7
3	0.0	1.0	6	24	101	12	972,767	622,021	0	0
	0.5	0.5				8	972,767	659,385	0	0
	1.0	0.0				8	992,281	774,993	0	3

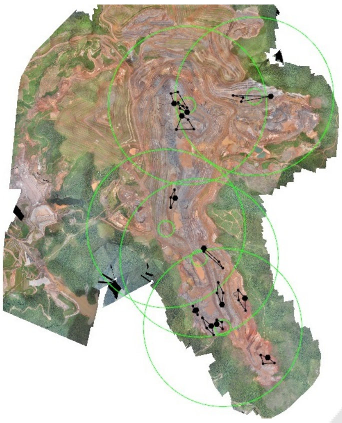

Figure 9: Solution for scenario 01.

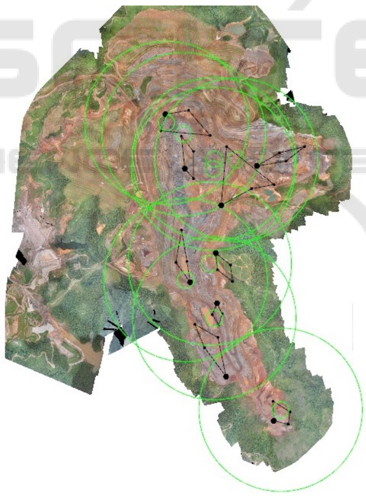

Figure 10: Solution for scenario 02.

Figure 11: Solution for scenario 03.

in which the front mining will be more profound.

For all the scenarios evaluated, the proposed mathematical model was able to find the optimum solution quickly, demonstrating that it is a suitable tool for decision-making.

6 CONCLUSIONS

This work proposed a mathematical model based on the p-median class to solve a router location problem in open-pit mines. Open-pit mining is an activity that requires the use of various high-tech equipment in large areas. In this problem, it is necessary to define the installation points for the routers, guaranteeing network coverage for all the mine's equipment. The objective is to minimize the number of routers installed and the sum of the distances between the operating points and the installed routers.

The proposed mathematical model brings the following new features: *i*) all equipment must be within the overage radius of the routers; *ii*) one or more routers can attend each mining equipment, i.e., coverage redundancy is allowed; *iii*) and the objective function involves additionally minimizing the number of routers since a cost is associated with their installations.

We use real data from the Fábrica Nova mine in computational experiments to validate the proposed model. The results showed that the model found the optimal router location in all scenarios, minimizing the number of installed routers and providing more efficient coverage for mining equipment. Therefore, the proposed mathematical model proved to be suitable for supporting decision-making in the locating of routers in open-pit mines.

In future work, we suggest analyzing the uncertainties present in the coverage radius of routers in large areas and network interference. In addition, we also aim to explore other objective functions.

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REFERENCES

Agrawal, R., Faujdar, N., Romero, C. A. T., Sharma, O., Abdulsahib, G. M., Khalaf, O. I., Mansoor, R. F., and Ghoneim, O. A. (2023). Classification and comparison of ad hoc networks: A review. *Egyptian Informatics Journal*, 24(1):1–25.

Barbosa, R. P., Souza, M. J. F., and de Miranda Junior, G. (2023). Mammography unit location: Reconciling maximum coverage and budgetary constraints. In *ICEIS (1)*, pages 187–194.

Bueno, H. d. O. (2021). *Optimization of transmission parameter selection for single channel LORA Mesh gateway networks in rural environments (in Portuguese)*. Master's Thesis, Universidade Federal de Uberlândia.

Capdeville, R. M. A. and Vianna, D. S. (2013). Grasp heuristics for the access point allocation problem in an indoor wireless network (in portuguese). *Sistemas & Gestão*, 8(1):86–93.

Chen, Y., Lai, Z., and Huang, C. (2023). Optimizing spatial location and service capacity of new schools toward maximum equity in the distribution of educational resources. *Journal of Urban Planning and Development*, 149(3):04023027.

Daskin, M. S. and Maass, K. L. (2015). The p-median problem. In *Location science*, pages 21–45. Springer.

de Campos, M. V. A., de Sá, M. V. S. M., Rosa, P. M., Penna, P. H. V., de Souza, S. R., and Souza, M. J. F. (2020). A mixed linear integer programming formulation and a simulated annealing algorithm for the mammography unit location problem. In *ICEIS (1)*, pages 428–439.

Kim, K., Jeon, M., Shin, S., and Kim, S.-W. (2022). Finding second hierarchy point for cooperative multi-vehicles using p-median and voronoi diagram vertices. In *2022 International Conference on Electronics, Information, and Communication (ICEIC)*, pages 1–4. IEEE.

Lorena, L. A. and Pereira, M. A. (2002). A lagrangean/surrogate heuristic for the maximal covering location problem using hillman's edition. *International Journal of Industrial Engineering*, 9:57–67.

Murad, A., Faruque, F., Naji, A., Tiwari, A., Qurnfulah, E., Rahman, M., and Dewan, A. (2024). Optimizing health service location in a highly urbanized city: Multi criteria decision making and p-median problem models for public hospitals in jeddah city, ksa. *Plos one*, 19(1):e0294819.

Ramadhanti, N. S., Ridwan, A. Y., and Pambudi, H. K. (2020). Feasibility study of determination a new distribution warehouse location using p-median and analytical network process methods in one of the cement industries. In *IOP Conference Series: Materials Science and Engineering*, volume 982, page 012057. IOP Publishing.

Sandoval, C., Adasme, P., San Juan, E., Soto, I., and Firoozabadi, A. D. (2021). Novel p-median-based formulations for maximizing coverage in 5g/6g wireless networks. In *2021 Third South American Colloquium on Visible Light Communications (SACVLC)*, pages 01–05. IEEE.

Shibalabala, J. and Swart, T. G. (2020). Performance analysis of wireless mesh networks for underground mines. In *2020 International Conference on Artificial Intelligence, Big Data, Computing and Data Communication Systems (icABCD)*, pages 1–6. IEEE.

Taleb, S. M., Meraihi, Y., Gabis, A. B., Mirjalili, S., and Ramdane-Cherif, A. (2022). Nodes placement in wireless mesh networks using optimization approaches: A survey. *Neural Computing and Applications*, 34(7):5283–5319.

Zhang, Y., Berman, O., and Verter, V. (2009). Incorporating congestion in preventive healthcare facility network design. *European Journal of Operational Research*, 198(3):922–935.