# A Mixed-Integer Linear Programming Model for Repeaters and Routers Location-Allocation Problem in Open-Pit Mines

Jéssica Cristina Teixeira da Costa[1] [a], Arthur Francisco Emanuel Borges Pereira[3], Higor Cassiano Sousa Milanês[3], Tatianna Aparecida Pereira Beneteli[2] [b] and Luciano Perdigão Cota[2] [c]

[1] *Programa de Pós-Graduação em Instrumentação, Controle e Automação de Processos de Mineração, Universidade Federal de Ouro Preto e Instituto Tecnológico Vale, Ouro Preto, Brazil*
[2] *Instituto Tecnológico Vale, Ouro Preto, Brazil*
[3] *Vale S.A., Parauapebas, Brazil*

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Abstract: In open-pit mines, communication network coverage is required throughout the operating area to ensure continuous operation of equipment such as drills, trucks, shovels, and loaders, in addition to communication between teams. Although the location-allocation problems have been widely studied in various contexts, there is a significant gap in its application to open-pit mines. This study proposes a Mixed-integer linear programming formulation based on the p-median problem to optimize the location-allocation of repeaters and routers. The objective is to minimize the number of network equipment installed and reduce distances between operating points and network equipment, increasing efficiency and coverage in mining environments. We use nine large instances to validate the mathematical formulation. These instances vary the number of candidate locations for installation and operation points, reflecting scenarios from large open-pit mines. The results demonstrate that the proposed method can find optimal solutions with low computational time, less than 5 minutes, ensuring efficient coverage of the operation area.

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## 1 INTRODUCTION

In open-pit mining environments, large-scale operations rely on a stable network to ensure the operation of equipment such as drills, trucks, and shovels. The lack of a reliable infrastructure can compromise the continuity of activities, generate operational failures, and increase risks to worker safety. In addition, constant communication between teams is essential for effective coordination of tasks and a rapid response to emergencies.

Currently, the location of repeaters and routers in mining environments is performed empirically through on-site testing. However, this manual approach has significant limitations, mainly due to the variation of operating points over time and the mobile nature of the facilities, which makes adjusting the location of devices time-consuming and often inefficient. In addition, the vast extension of the areas and the presence of physical barriers make it even more challenging to achieve adequate network coverage, resulting in operational failures that can compromise system performance and increase the risk of mining activities.

To mitigate these issues, adopting an efficient process to determine the optimal locations of repeaters and routers is necessary, ensuring continuous network coverage throughout the mining environment. The application of combinatorial optimization methods, such as the p-median problem, presents itself as a promising solution to strategically define the positions of these devices, maximizing coverage and minimizing costs.

P-median is a classical location problem, which aims to find the optimal location of $p$ facilities (Chappidi and Singh, 2023). This problem belongs to the NP-hard class (Liotta et al., 2005). In essence, this problem seeks the efficient distribution of resources to

[a] https://orcid.org/0009-0003-0759-8201
[b] https://orcid.org/0000-0001-6419-0286
[c] https://orcid.org/0000-0002-8385-7573



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optimize demand fulfillment, being widely applied in contexts such as logistics, infrastructure, urban planning, health, and education.

Although the p-median problem has been widely studied in various contexts, there is a significant gap in its application to mining environments, especially in open-pit mines, where only some studies address router location problems. Recently, in Mandarino *et al.* (Mandarino et al., 2024), the authors addressed the router location-allocation problem (RLP) in open-pit mines, in which they proposed a mixed-integer linear programming (MILP) formulation to represent it. In this work, the focus is on mines that use only routers to implement the communication network. However, it was identified that larger mines need to use repeaters in conjunction with routers to ensure network coverage throughout the territory. Basically, repeaters receive the signal generated by routers and amplify it, allowing the network to reach a larger area than would be possible without using these devices. Due to the lower cost and less operation complexity, repeaters are a good alternative to guarantee coverage in large areas, especially in large open-pit mines where a single router cannot guarantee complete connectivity. Including repeaters imposes new constraints, such as requiring each repeater to be within the coverage radius of at least one router.

Thus, this work proposes an extension of the study of Mandarino *et al.* (Mandarino et al., 2024), with a new MILP formulation to optimize the variant of the problem with repeaters, called repeaters and routers location-allocation problem (RRLP). This problem seeks to minimize the number of installed devices and reduce the distances between the operating points and the network equipment, providing greater efficiency and coverage in open-pit mining environments.

The paper is organized into several sections that explore different aspects of the study. Section 2 presents a literature review about the repeaters and routers location-allocation problem. In Section 3, the location-allocation problem is described in detail, along with the definition of the parameters used in the MILP formulation. Section 4 discusses the proposed mathematical formulation, presenting the variables, constraints, and the objective function. Then, Section 5 examines the results of the computational experiments, and finally, Section 6 shows the conclusions and proposals for future research.

## 2 LITERATURE REVIEW

The strategic decision of facility location is crucial for both private companies and public organizations. In the public sector, this includes the selection of locations for essential services, such as healthcare centers, schools, and fire stations. In the private sector, location decisions pertain to productive facilities such as factories, warehouses, and distribution centers (Arenales et al., 2007).

Various approaches and algorithms have been applied to solve location problems across different sectors, such as healthcare, public safety, transportation, logistics, education, and electrical energy.

In the mining field, Lotfian and Najafi (Lotfian and Najafi, 2019) presented a solution to determine the optimal location of emergency facilities in underground mines based on a case study of a coal mine in Tabas, Iran.

From another perspective, Oyola-Cervantes and Amaya-Mier (Oyola-Cervantes and Amaya-Mier, 2019) proposed the design of a reverse logistics network for off-the-road tires discarded by the mining sector.

In the context of open-pit mining, Paricheh and Osanloo (Paricheh and Osanloo, 2016) investigated a case study of a copper mine in Iran. The study aims to determine the optimal location of in-pit crushers in open-pit mining operations.

The repeaters and routers location-allocation problem is often addressed using p-median problems. These problems seek to identify the optimal location of $p$ facilities to minimize distances or travel times between these facilities and demand points.

P-median problems have been applied in a wide variety of contexts, such as in the location of vaccination centers (Zapata et al., 2023) and public schools (Nascimento et al., 2023). Furthermore, several studies explore combining heuristic methods or hybrid approaches to solve complex problems, such as those investigated in Silva and Mestria (Silva and Mestria, 2018) and Pinto *et al.* (Pinto et al., 2023), which examined the use of metaheuristics combined with the p-median problem.

In addition to traditional location problems, optimizing connectivity in complex environments depends on advanced technological solutions such as mesh networks. Mesh networks are an advanced, self-configuring, and self-organizing wireless connection technology, offering advantages such as low initial cost, easy maintenance, robustness, and reliable coverage. (Akyildiz et al., 2005; Qian et al., 2023).

The use of routers in mesh networks has been widely studied in the literature. In particular, optimization algorithms to determine these routers' ideal location and distribution have proven highly effective in various contexts. Codato and Souza (Codato and de Souza, 2021) applied the Maximum Coverage Location Problem to the location-allocation of wireless network access points at the Federal Institute of Education, Science, and Technology of São Paulo, aiming to find the optimal positions for the access points and the maximum coverage of areas of interest.

Jansang *et al.* (Jansang et al., 2023) proposed an optimization mechanism based on MILP for the location of energy-aware wireless mesh routers. The objective is to determine the appropriate location of mesh routers and maximize network lifetime.

Wang *et al.* (Wang et al., 2017) proposed a method based on the p-median problem combined with heuristic methods to determine the location of nodes in a mesh network in an industrial context.

Oda (Oda, 2023), in turn, presented a solution for the location of mesh routers in evacuation centers, considering a disaster scenario in the city of Kurashiki, Japan. The objective is to maximize network connectivity and client coverage.

In the mining context, various approaches have been developed to optimize the placement of routers in mesh networks. Mandarino *et al.* (Mandarino et al., 2024) presented a recent approach to allocating telecommunications devices in open-pit mines. In a case study for the Fábrica Nova mine in Mariana-MG, the p-median problem was used to minimize the number of installed routers, ensuring necessary coverage and reducing costs. However, this study only considered the router location-allocation problem.

Although numerous studies focus on facility location in several contexts, were not found specific research addresses the simultaneous repeaters and routers location-allocation problem for open-pit mining applications. Including repeaters in the p-median problem formulation, especially in this context, represents a highly relevant and unexplored contribution to the literature. This approach will optimize network coverage and improve communication robustness and efficiency in challenging environments like large-scale open-pit mines. This methodology can reduce operational costs, increase safety, and improve operational efficiency when applied to open-pit mining projects.

## 2.1 Comparison of Our Proposal with the Reviewed Papers

Table 1 provides a comparative view of the main characteristics of our proposal with the studies reviewed in the literature. The works are listed chronologically in the first column, from the oldest to the most recent publications. The subsequent columns (2 to 7) present the objective functions addressed in each study, column 8 identifies the application sector, and column 9 specifies the location-allocation facilities. Finally, the last three columns detail the solution methods applied in each work, classified as exact, heuristic, or hybrid.

Thus, the main differentiation of our proposal is the inclusion of repeaters in the localization problem, aiming to minimize two facilities simultaneously. In addition, little research focuses on the location of routers or repeaters in open-pit mining applications, highlighting the need for new studies in this context.

# 3 PROBLEM STATEMENT

This section presents the characteristics of the repeaters and routers location-allocation problem (RRLP) in open-mines, as follows:

1. An open-pit mining iron ore complex is formed by a set of mines ($\mathcal{M}$);
2. Each mine $k \in \mathcal{M}$ is formed by a set of mining fronts ($\mathcal{F}$);
3. Each mining front $z \in \mathcal{F}$ has a set of operation areas ($\mathcal{A}$):
   (a) Each operation area $a \in \mathcal{A}$ indicates a polygon of the mining front $z \in \mathcal{F}$ that is in operation;
   (b) In each area of operation $a \in \mathcal{A}$, a set of mining equipment needs connectivity to perform its activities adequately. The set of mining equipment consists of drills, trucks, cargo equipment (loaders and shovels), infrastructure and support equipment;
   (c) Each operation area $a \in \mathcal{A}$ is represented by a set of $J$ extreme points, or operation points;
   (d) Each operation point $j \in \mathcal{J}$ has a location $lp_j$;
   (e) Each operation point $j \in \mathcal{J}$ needs to be serviced by one or more network equipment $r \in \mathcal{E}$.
4. A communication network is composed of a set of network equipment ($\mathcal{E}$):
   (a) The set of network equipment ($\mathcal{E}$) has a subset of routers $\mathcal{R}$ and a subset of repeaters $\mathcal{T}$, which means that $\mathcal{E} = \mathcal{R} \cup \mathcal{T}$.
5. Set of routers ($\mathcal{R}$):
   (a) Each router installed has a location $LR_i \in I$;
   (b) Routers have a coverage radius identified as $RR$;
   (c) $PR_{max}$ indicates the maximum number of routers installed.
6. Set of Repeaters ($\mathcal{T}$):
   (a) Each installed repeater has a location $LT_i \in I$;
   (b) Repeaters have a coverage radius identified as $RT$;

Table 1: Summarizing the main characteristics of our proposal in comparison with the reviewed studies.

| Works | Objective Functions | | | | | | Application | Facility | Solution Methods | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | [1] | [2] | [3] | [4] | [5] | [6] | | | Exact | Heuristic | Hybrid |
| Paricheh and Osanloo (2016) | | | | ✓ | ✓ | | open-pit mining | in-pit crusher | ✓ | | |
| Wang *et al.* (2017) | | | | ✓ | | ✓ | industry | routers | ✓ | ✓ | |
| Silva and Mestria (2018) | ✓ | | | | | | - | service stations | | ✓ | |
| Lotfian and Najafi (2019) | ✓ | ✓ | | | ✓ | | underground mining | emergency stations | | | ✓ |
| Oyola-Cervantes and Amaya-Mier (2019) | | | | | ✓ | | open-pit mining | power generation plant | ✓ | | |
| Codato and de Souza (2021) | | | | | | ✓ | education | routers | ✓ | | |
| Nascimento *et al.* (2023) | ✓ | | | ✓ | | | education | municipal public schools | ✓ | | |
| Jansang *et al.* (2023) | | | | | | ✓ | rural area | routers | ✓ | | |
| Oda (2023) | | | | | | ✓ | evacuation center | routers | | ✓ | |
| Yang *et al.* (2023) | | | | ✓ | | ✓ | electrical energy | power stations | | ✓ | |
| Zapata *et al.* (2023) | ✓ | | | | | | healthcare | vaccination center | ✓ | | |
| Pinto *et al.* (2023) | | | | ✓ | | | transportation | hubs | | | ✓ |
| Mandarino *et al.* (2024) | ✓ | ✓ | | | | | open-pit mining | routers | ✓ | | |
| **Our Proposal** | ✓ | | ✓ | | | | open-pit mining | repeaters and routers | ✓ | | |

**Legend:** **[1]:** Minimize distance; **[2]:** Minimize one facility; **[3]:** Minimize two facilities; **[4]:** Minimize costs; **[5]:** Minimize losses or Maximize profit; **[6]:** Others.

(c) Each repeater $t \in \mathcal{T}$ must be directly connected to a router $r \in \mathcal{R}$;

(d) $PT_{max}$ indicates the maximum number of repeaters installed.

7. There is a set of candidate locations for network equipment installation ($I$):

(a) Each place $i \in I$ has a location $l_i$.

The objective of this problem is to install repeaters $t \in \mathcal{T}$ and routers $r \in \mathcal{R}$ to meet all operation points $j \in \mathcal{J}$, seeking to minimize the number of network equipment installed ($r$ and $t$) and the sum of the distances between the operating points and the installed network equipment.

Figure 1 presents a didactic example to facilitate understanding of the RRLP. The scenario includes an operating area bounded by four operation points $j = \{J1, J2, J3, J4\}$, both shown in green. Eight candidate locations for installing network equipment $i = \{i1, i2, \cdots, i8\}$ are considered, indicated in red. In addition, the routers have a coverage radius of 140 meters and repeaters 80 meters, allowing the installation of one router and up to four repeaters.

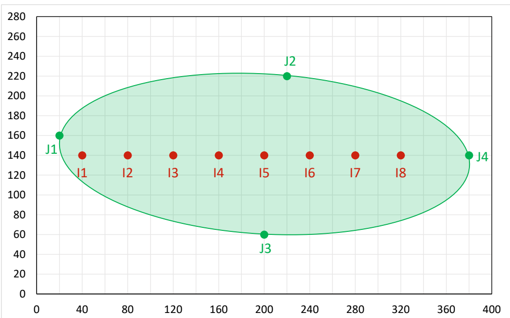


Figure 1: Mapping of operating points (J) and candidate locations for installation (I) for the didactic example.

Table 2 shows the Cartesian coordinates (X and Y) of the candidate locations for installing network equipment.

Table 2: Candidate locations for installing (I).

| Points | Location | |
|---|---|---|
| | X | Y |
| I1 | 40 | 140 |
| I2 | 80 | 140 |
| I3 | 120 | 140 |
| I4 | 160 | 140 |
| I5 | 200 | 140 |
| I6 | 240 | 140 |
| I7 | 280 | 140 |
| I8 | 320 | 140 |

Table 3 details the operation points that define the area that the network must meet.

Table 3: Operating points (J).

| Points | Location | |
|---|---|---|
| | X | Y |
| J1 | 20 | 160 |
| J2 | 220 | 220 |
| J3 | 200 | 60 |
| J4 | 380 | 140 |

Table 4 displays the matrix of distances between the operating points and the locations that are candidates for installing network equipment.

Table 4: Distance matrix.

| | **J1** | **J2** | **J3** | **J4** |
|---|---|---|---|---|
| **I1** | 28.3 | 197.0 | 178.9 | 340.0 |
| **I2** | 63.2 | 161.2 | 144.2 | 300.0 |
| **I3** | 102.0 | 128.1 | 113.1 | 260.0 |
| **I4** | 141.4 | 100.0 | 89.4 | 220.0 |
| **I5** | 181.1 | 82.5 | 80.0 | 180.0 |
| **I6** | 220.9 | 82.5 | 89.4 | 140.0 |
| **I7** | 260.8 | 100.0 | 113.1 | 100.0 |
| **I8** | 300.7 | 128.1 | 144.2 | 60.0 |

Table 5 also presents the distance matrix between all pairs of candidate locations for installing network equipment.

Figure 2 illustrates a possible solution for this didactic example. In this configuration, the router was

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Table 5: Equipment distance matrix.

| | I1 | I2 | I3 | I4 | I5 | I6 | I7 | I8 |
|---|---|---|---|---|---|---|---|---|
| **I1** | 0 | 40 | 80 | 120 | 160 | 200 | 240 | 280 |
| **I2** | 40 | 0 | 40 | 80 | 120 | 160 | 200 | 240 |
| **I3** | 80 | 40 | 0 | 40 | 80 | 120 | 160 | 200 |
| **I4** | 120 | 80 | 40 | 0 | 40 | 80 | 120 | 160 |
| **I5** | 160 | 120 | 80 | 40 | 0 | 40 | 80 | 120 |
| **I6** | 200 | 160 | 120 | 80 | 40 | 0 | 40 | 80 |
| **I7** | 240 | 200 | 160 | 120 | 80 | 40 | 0 | 40 |
| **I8** | 280 | 240 | 200 | 160 | 120 | 80 | 40 | 0 |

allocated at point I5, shown in red, while the repeaters were installed at points I2 and I8, shown in blue, ensuring coverage of all operating points. In addition, it is noteworthy that the repeaters installed in I2 and I8 are within the coverage radius of the router installed in I5, as delimited by one of the problem's constraints.

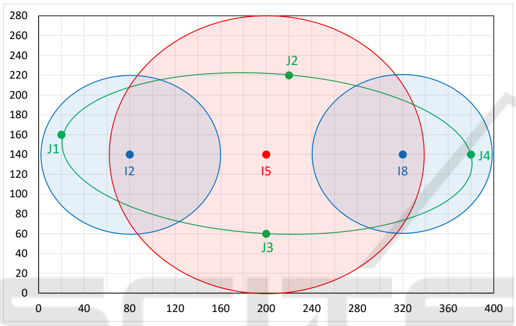


Figure 2: Possible solution for the didactic example.

## 4 MILP FORMULATION

This section presents the proposed MILP formulation to represent the RRLP. The input sets, indices, parameters, and decision variables are described below.

- Sets:

$\mathcal{A}$ : set of the areas of operation;

$\mathcal{R}$ : set of routers;

$\mathcal{T}$ : set of repeaters;

$\mathcal{E}$ : set of network equipment ($\mathcal{E} = \mathcal{R} \cup \mathcal{T}$);

$\mathcal{J}$ : set of operation points that must be met;

$I$ : set of candidate locations for installing network equipment.

- Indexes:

$j$ : index for a element of the set $\mathcal{J}$;

$i, a, k$ : index for a element of the set $I$.

- Parameters:

$D_{ij}$ : distance from the operating point $j$ to the candidate location $i$ for installation of a network equipment;

$DE_{ki}$ : distance between all pairs $k$ and $i$ of candidate locations for the installation of a network equipment;

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

$PT_{max}$ : maximum number of repeaters that can be installed;

$RR$ : coverage radius of each router;

$RT$ : coverage radius of each repeater.

- Decision variables:

$pr$ : number of routers installed;

$pt$ : number of repeaters installed;

$$x_{ij} : \begin{cases} 1, & \text{if the operating point } j \text{ is attended by the network equipment installed in } i; \\ 0, & \text{otherwise;} \end{cases}$$

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

$$yt_k : \begin{cases} 1, & \text{if the repeater is installed at location } k; \\ 0, & \text{otherwise;} \end{cases}$$

The objective function of the proposed formulation is composed of two parcels. The first parcel minimizes the number of open installations, that is, the number of network equipment installed. The second parcel minimizes the sum of the distances between the operating points and the installed network equipment. The Equations (1) to (3) represent the objective function.

$$\min \alpha \left( \sigma \frac{pr}{|\mathcal{R}|} + \phi \frac{pt}{|\mathcal{T}|} \right) + \beta \left( \frac{\sum_{i \in I} \sum_{j \in J} d_{ij} x_{ij}}{|\mathcal{J}| \max(RR, RT)} \right) \tag{1}$$

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

where $\alpha$ indicates the weight of the first parcel and $\beta$ indicates the weight of the second parcel of the objective function.

$$\sigma + \phi = 1 \tag{3}$$

where $\sigma$ indicates the weight in the objective function of router installation and $\phi$ indicates the weight of repeater installation.

The constraints (4) ensure that all operating points are within the coverage radius of installed network equipment.

$$D_{ij}\, x_{ij} \leq RR\, yr_i + RT\, yt_i \qquad \forall i \in I, \forall j \in \mathcal{J} \tag{4}$$

The constraints (5) ensures that each operating point is attended by at least one network equipment.

This way, we allow coverage redundancy, increasing the network reliability.

$$\sum_{i \in I} x_{ij} \geq 1 \qquad \forall j \in \mathcal{J} \tag{5}$$

The constraints (6) defines that each operating point can only be attended by a location where it has a repeater ($yt_i = 1$) or a router ($yr_i = 1$) installed.

$$x_{ij} \leq yr_i + yt_i \qquad \forall i \in I, \forall j \in \mathcal{J} \tag{6}$$

The constraints (7) ensures that in each candidate location can be installed at most one network equipment, a repeater ($yt_i = 1$) or a router ($yr_i = 1$).

$$yr_i + yt_i \leq 1 \qquad \forall i \in I \tag{7}$$

The constraint (8) determines the number of routers installed, while the constraint (9) defines that the number of routers installed must be less than the number of available routers $PR_{max}$. The constraint (10) ensures that at least one router will be installed.

$$\sum_{a \in I} yr_a = pr \tag{8}$$

$$pr \leq PR_{max} \tag{9}$$

$$pr \geq 1 \tag{10}$$

Similarly, the constraint (11) determines the number of repeaters installed, while the constraint (12) defines that the number of installed repeaters must be less than the number of available repeaters $PT_{max}$.

$$\sum_{k \in I} yt_k = pt \tag{11}$$

$$pt \leq PT_{max} \tag{12}$$

The constraints (13) ensure that the repeater installed in $k$ is within the coverage radius of a router installed in $a$. The term $(M \times (1 - yr_a))$ ensures that this equation is only valid if there is a router installed on $a$. Otherwise, the Big M will be activated, and the equation will be respected.

$$DE_{ka}\, yt_k \leq RR yr_a + (M \times (1 - yr_a)) \qquad \forall k, a \in I \tag{13}$$

Finally, the Equations (14), (15) and (17) define the domain of the variables.

$$x_{ij} \in \{0,1\} \qquad \forall i \in I, \forall j \in \mathcal{J} \tag{14}$$

$$yr_a \in \{0,1\} \qquad \forall a \in I \tag{15}$$

$$yt_k \in \{0,1\} \qquad \forall k \in I \tag{16}$$

$$\alpha,\ \beta,\ \sigma,\ \phi\ \geq 0 \tag{17}$$

# 5 COMPUTATIONS EXPERIMENTS

We implement the proposed MILP formulation in Lingo 10.0, version 4.01.100. The computational experiments were conducted on a computer with an 11th Gen Intel(R) Core(TM) i5-1135G7 CPU @ 2.40GHz, 8.0 GB of RAM, and the Windows 11 Pro operating system.

To evaluate the proposed method, we used nine instances varying the number of candidate locations for installing network equipment and the number of operating points.

## 5.1 Instances

Table 6 presents the data of the instances used in detail. Column one shows the number of instances, while columns two and three show, respectively, the number of candidate locations for network equipment installation and the number of operating points. Finally, columns four and five show the maximum number of repeaters and routers available for installation in each experiment. In these scenarios, the number of routers was restricted to one unit due to the higher cost and complexity of operation compared to repeaters.

Table 6: Characteristics of the instances.

| Instances | #Installation Points | #Operating Points | #Max Repeaters | #Max Routers |
|---|---|---|---|---|
| 1 | 150 | 20 | 10 | 1 |
| 2 | 300 | 20 | 10 | 1 |
| 3 | 450 | 20 | 10 | 1 |
| 4 | 150 | 35 | 10 | 1 |
| 5 | 300 | 35 | 10 | 1 |
| 6 | 450 | 35 | 10 | 1 |
| 7 | 150 | 50 | 10 | 1 |
| 8 | 300 | 50 | 10 | 1 |
| 9 | 450 | 50 | 10 | 1 |

In all the experiments performed, we adopted the coverage radius of the repeaters as 120 meters and the routers as 140 meters.

To illustrate the set of instances, we detailed the largest them (Instance 9). This instance has 450 candidate locations for the installation of network equipment and 50 operating points. The mapping of the operation points and the candidate locations for installation of the network equipment are shown in Figure 3. In this scenario, five operation areas were delimited, each with 10 points of operation, totaling 50 points $j = \{J1, J2, J3, \ldots, J50\}$, highlighted in green. Additionally, this instance has 450 candidate locations for the installation of network equipment, identified as $i = \{I1, I2, \ldots, I450\}$ and highlighted in red.

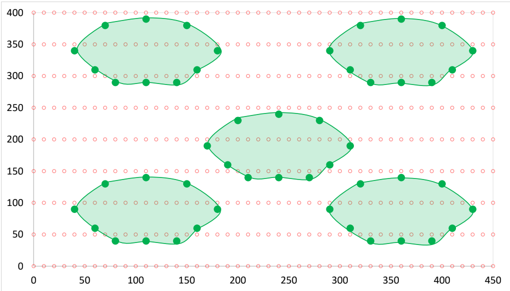
Figure 3: Mapping of operating points (green) and candidate locations for installation (red) for the Instance 9.

A distance matrix, *nxm*, and an equipment distance matrix, *mxm*, were generated for each instance, where *n* represents the number of operating points and *m* indicates the number of candidate locations for installation. All instances are available at https://github.com/tatiannabeneteli/ICEIS2025/blob/main/Instances.zip.

## 5.2 Results

Table 7 summarizes the results. Column one shows the instance, while column two shows the best bound value. Columns three and four indicate the number of repeaters and routers installed in the found solution. Finally, columns five and six report the GAP and execution time in seconds for each instance. The weights adopted for the objective function parcels were: $\alpha = 0.5$, $\beta = 0.5$, $\sigma = 0.1$, and $\phi = 0.9$.

Table 7: Results for instances.

| Instances | Best Bound | Repeaters Installed | Routers Installed | GAP | Execution Time (s) |
|---|---|---|---|---|---|
| 1 | 0.31047 | 2 | 1 | 0 | 2 |
| 2 | 0.31008 | 2 | 1 | 0 | 14 |
| 3 | 0.31008 | 2 | 1 | 0 | 56 |
| 4 | 0.41486 | 3 | 1 | 0 | 8 |
| 5 | 0.41486 | 3 | 1 | 0 | 84 |
| 6 | 0.41345 | 3 | 1 | 0 | 458 |
| 7 | 0.46351 | 4 | 1 | 0 | 13 |
| 8 | 0.46351 | 4 | 1 | 0 | 111 |
| 9 | 0.46291 | 4 | 1 | 0 | 381 |

In all instances, the solver found the optimal solution (GAP = 0) in low computational time, less than five minutes.

We chose Instance 9, which was detailed in the previous section, to analyze the results. Figure 4 presents the optimal solution found by the solver for this instance. In this solution, the router was allocated to point I224, highlighted in red, while the repeaters were positioned at points I115, I133, I315, and I333, indicated in blue. Thus, the solution of this instance requires one router and four repeaters to ensure coverage of all operating points. The best objective function found was 0.46291 and the computational time was 381 seconds.

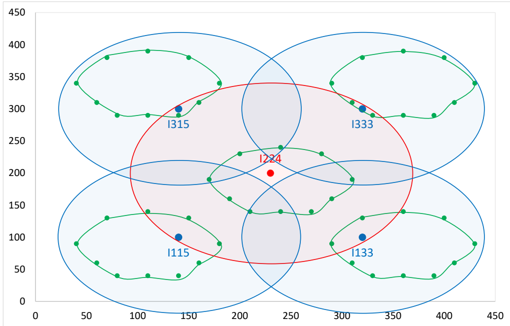

Figure 4: Optimal solution for the Instance 9.

These results demonstrate the feasibility of the proposed mathematical modeling to determine the optimal location-allocation of repeaters and routers in open-pit mines, ensuring an efficient coverage even in large-scale scenarios.

# 6 CONCLUSIONS

This study explores a new variant of the p-median problem, the repeaters and routers location-allocation problem in open pit mines. We proposed a MILP formulation to minimize the number of network equipment installed and the distances between operating points and network equipment. The proposed formulation was tested in nine instances, using different combinations of operation points and candidates location for installation. The results demonstrate the solver's effectiveness in finding optimal global solutions with low computational times in all instances. These results reinforce that the proposed model is a strategic tool to support decisions, enabling a network infrastructure capable of covering the entire area of operation of large open-pit mines. Additionally, the proposed model can be adapted to other industrial sectors, reinforcing its applicability in large-scale operations and under diverse operational conditions. In future work, we intend to adapt the proposed model to other industrial environments, such as ports and railways. We also suggest to explore other optimization approaches, such as using metaheuristics to solve this problem.

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