A Solution Procedure for Fixed Mammography Unit Location-Allocation and Mobile Mammography Unit Routing Problems

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Abstract: This paper addresses the Mammography Unit Location-Allocation and Mobile Mammography Unit Routing problems. The objective is to maximize coverage of the target population and cover unmet demand with fixed mammography units by using mobile units. It is proposed a sequential solution procedure for solving, in which the first problem is solved by using an exact method, and the second one through a heuristic algorithm with the uncovered municipalities from the first problem as input. This proposal was tested in three scenarios from the State of Minas Gerais, Brazil. The results show that the coverage of this state can be fully met with 84 additional mobile units, considering the current location of the fixed equipment and the restriction of the municipalities' service to their healthcare micro-regions. However, if this requirement is not imposed, 42 units are sufficient. Finally, by allowing the equipment to be relocated, only nine units are needed.

1 INTRODUCTION

Breast cancer is, after skin cancer, the most common type of cancer in Brazil. According to (INCA, 2023), 73,610 new cases were estimated in the country in 2023, and that disease was responsible for 18,139 deaths in 2021. In 2022, statistics presented by (IARC, 2024), on a global scale, show that considering both sexes, breast cancer accounted for 11.5% of the cases, second only to lung cancer. When considering only the female population, the incidence reaches 23.8%, ranking first.

The most effective way to detect the disease is through mammography screening (Azevedo et al., 2019). According to (Ramos et al., 2018), when coverage exceeds 70% of the target group, mortality among women aged 50 years and older is reduced by 20% to 30%. However, mammography coverage rates vary significantly from one country to another, from one city to another, or even within regions of the same state. As an example, (Lages et al., 2012) described that, between 2010 and 2011, the access of women to screenings in Teresina, State of Piauí, Brazil, was higher than in cities like Rio de Janeiro, Recife, João Pessoa, and other municipalities in Brazil. Teresina's coverage also surpassed that of Turkey, where 56% of individuals are unaware of the exam, Mexico, where the coverage during this biennium was only 14.8%, and Australia, where 49% of women aged 40 to 49 have never undergone the exam. However, the study shows that, despite having

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a higher coverage than many municipalities in Brazil and worldwide, the coverage was only 62.1%, below the 70% suggested by (Ramos et al., 2018). This work also shows that more than half of the equipment in the Northeast region is installed in the capitals. Thus, the poor distribution of equipment is one of the reasons the coverage does not reach the desired percentage. This fact is also demonstrated by (Corrêa et al., 2011), as the authors state that the poor distribution of mammography units directly impacts the low production of the equipment. In addition to inadequate distribution, (Corrêa et al., 2011) point out that, for women who need to travel, the distance traveled is one of the factors influencing their decision to undergo the exam. The authors also state that, in 2015, the Ministry of Health established a maximum distance of 60 km to be traveled to perform the exam.

The Mammography Unit Location-Allocation Problem (MULAP) is proposed in light of these issues, such as the inefficient distribution of the mammography units, the significant impact of women's travel on coverage rates, and the importance of this exam for successful disease treatment. The MULAP objective is to improve the location of mammography units and, thus, increase the coverage rate of mammography exams. (Souza et al., 2019) used two mathematical formulations to solve MULAP. In one, full demand fulfillment for municipalities is considered, while the second formulation allows for partial demand fulfillment. In the conducted experiments, scenarios were considered where the existing mammography units were kept in their current locations and scenarios where there was the possibility of relocating those equipment. The results showed that relocating the equipment would result in greater coverage than that presented by the State Health Department of Rondônia, Brazil. (Sá et al., 2019), using the formulation of (Souza et al., 2019), addressed MULAP in an instance of the State of Espírito Santo, considering two scenarios: one keeping the existing location and the other allowing the relocation of the mammography units. The authors showed that the existing location met half of the state's demand, using 63.1% of the capacity of the mammography units, while relocating the equipment would allow for 83.5% demand coverage, increasing the equipment usage to 99.9%. (Souza et al., 2020) used the same model and developed a Variable Neighborhood Search (VNS) algorithm to solve an instance based on data from the State of Minas Gerais. In this case, the results obtained, both from the mathematical formulation and the proposed algorithm, showed superior coverage compared to the existing location of the mammography units. (de Campos et al., 2020) addressed MULAP using a Simulated Annealing algorithm. The algorithm was applied to instances from the state of Minas Gerais, considering partial demand fulfillment. In this way, a municipality is covered even if its demand is not fully met. Additionally, that work considered the acquisition of new equipment. The results indicated that, even under these conditions, not all municipalities had their demands fully met. Other studies in the literature, such as (de Assis et al., 2022), (de Campos et al., 2022), and (de Campos et al., 2024), also address MULAP. In all these works, full demand coverage is not achieved due to factors such as the maximum distance constraint between the demand point and the equipment's host municipality and/or the absence of hospital infrastructure.

(Jewett et al., 2018) showed that the demand for the screenings is inversely proportional to the distance traveled to perform it. In this sense, (De Mil et al., 2019) suggested using Mobile Mammography Units (MMU) to serve women living in remote areas where the installation of a fixed unit is unfeasible. (Rosa et al., 2020) proposed a constructive heuristic algorithm to address the Mobile Mammography Unit Routing Problem (MMURP). In (Rosa et al., 2020), MMUs were routed to serve 444 locations, aiming to maximize the coverage of the demand and minimize the total distance traveled. In (Rosa et al., 2021), the authors presented an Iterated Greedy Search (IGS) algorithm to route 56 MMUs, departing from two depots, to serve 579 municipalities.

The aforementioned studies addressed MULAP and MMURP separately. In the present work, the objective is to solve them through a sequential procedure. Initially, it is proposed to generate a solution for MULAP and then, based on the municipalities not served or partially served in this solution, generate a solution via MMURP. To solve these two problems, the formulation by (Souza et al., 2019) will be applied for the solution of MULAP, and based on the results obtained, a constructive heuristic algorithm will be applied to route the MMUs to meet the remaining demand from MULAP. This solution procedure is applied to a case study addressing three scenarios in the State of Minas Gerais. The first scenario considers the freedom to relocate fixed mammography equipment. The second scenario considers the current location of fixed equipment and does not restrict the service of municipalities to their health micro-regions. Finally, the third scenario considers the current location of fixed equipment and restricts the service of municipalities to their health micro-regions.

The remainder of this work is organized as follows. Section 2 describes the problems addressed. Section 3 presents the application scenarios for MU-

LAP, as well as the main proposed changes in the mathematical formulation to meet the characteristics of these scenarios. Section 4 presents the constructive algorithm for MMURP. Finally, Sections 5 and 6 present the results achieved, conclusions, and indications for future work.

2 PROBLEM CHARACTERIZATION

This section is organized as follows. Subsection 2.1 presents the mathematical formulation of the MULAP problem used by (Souza et al., 2019) and an example illustrating this problem. In Subsection 2.2, the characteristics of the MMURP are presented along with an example.

2.1 Mammography Unit Location and Allocation Problem – MULAP

Table 1 describes the notation, parameters, and auxiliary and decision variables of the mathematical formulation for MULAP introduced by (Souza et al., 2020), which is given by:

$$\max \quad \sum_{i \in N} \sum_{j \in S_i} dem_j \cdot x_{ij} \quad (1)$$

$$\text{s. a} \quad \sum_{i \in S_j} x_{ij} \leq 1, \quad \forall j \in N \quad (2)$$

$$\sum_{i \in N} y_i = p \quad (3)$$

$$\sum_{j \in S_i} dem_j \cdot x_{ij} \leq cap \cdot y_i, \quad \forall i \in N \quad (4)$$

$$z_i \geq \frac{y_i}{p}, \quad \forall i \in N \quad (5)$$

$$z_i \geq x_{ij}, \quad \forall i, j \in N \quad (6)$$

$$x_{ii} = z_i, \quad \forall i \in N \quad (7)$$

$$y_i = 0, \quad \forall i \in N \mid Infra_i = 0 \quad (8)$$

$$x_{ij} \in [0,1], \quad \forall i, j \in N \quad (9)$$

$$y_i \in \mathbb{Z}^+, \quad \forall i \in N \quad (10)$$

$$z_i \in \{0,1\}, \quad \forall i \in N \quad (11)$$

The objective function (1) aims to maximize the coverage of the mammography demand. Constraints (2) ensure that the demand of each municipality j, if covered, is partially met by mammography units installed in municipalities within R km from it. Constraint (3) ensures that all p available units are installed. Constraints (4) ensure that the annual capacity of each mammography unit is respected. Constraints (5) force z_i to equal 1 if at least one unit is installed in municipality i. Constraints (6) ensure that a municipality j's demand can only be covered by a municipality i if there is a unit in that municipality. Constraints (7) state that if a municipality i has mammography units, all its own demand must be covered by its own units. Constraints (8) indicate that only municipalities with hospital infrastructure can host mammography units. Finally, constraints (9), (10), and (11) define the domain of the decision variables.

Figure 1 shows an example of the MULAP with 10 municipalities (A, B, C, D, E, F, G, H, I, J), each with a demand dem for mammography screenings. To meet this demand, there are 3 mammography units (M1, M2, M3) with a fictitious capacity of 1000 screenings annually, which can be installed in municipalities A, E, and H, as they have the infrastructure to host them. The lines connecting the municipalities indicate the distances between them. Note that mammography units M1 and M2 are installed in municipality A, and M3 is installed in H. Unit M1 fully meets the demand of municipality A, and the surplus covers the demand of municipalities B, D, and part of municipality C. Unit M2 covers the unmet demand of municipality C. Unit M3 fully meets the demand of municipalities H, I, and J, and partially meets the demand of municipality F. Although unit M2 has a non-used capacity of 950 mammography screenings, these screenings cannot meet the demand of municipality E, as it is located 90 km from municipality A, violating the maximum travel distance R of 60 km. Thus, the location of the mammography units in this scenario allows coverage of 2,050 women, with an unmet demand of 950 mammography screenings.

2.2 Mobile Mammography Unit Routing Problem – MMURP

Let there be a set of host municipalities, which are the starting points for a set of Mobile Mammography Units (MMUs), and a set of municipalities with a demand for mammography screenings. MMURP, introduced by (Rosa et al., 2020), consists of determining the routes of the MMUs to meet all the demands for mammography screenings while minimizing the total distance traveled.

The approach presented here considers that the starting point for each MMU is the reference municipality of each health macro-region, thus defining a multi-depot vehicle routing problem. In addition, the MMURP is treated based on the variant described by the Open Vehicle Routing Problem (OVRP), as presented in (Li et al., 2007), considering that the return of the MMU to the starting point should not be included. A maximum distance restriction of $D^{\max}$ km

Table 1: Parameters and decision variables.

Parameters	
N	set of municipalities
d_{ij}	distance from municipality i to municipality j
dem_j	demand for screenings from municipality j
cap	annual capacity of a mammography unit
p	number of mammography units to be located
R	maximum distance a woman can travel
$Infra_i$	binary parameter that equals 1 if municipality i has hospital infrastructure, 0 otherwise
S_i	set of municipalities that are at most R km from municipality i, that is, $S_i = \{j \in N \mid d_{ij} \leq R \text{ and } d_{ji} \leq R\}$
Auxiliary variables	
z_i	binary variable equal to 1 if a mammography unit is installed in municipality i and 0 otherwise
x_{ij}	Continuous variable in the range $[0,1]$ that indicates the fraction of the demand of municipality j met by mammography units installed in municipality i.
y_i	Integer variable representing the number of mammography units installed in municipality i

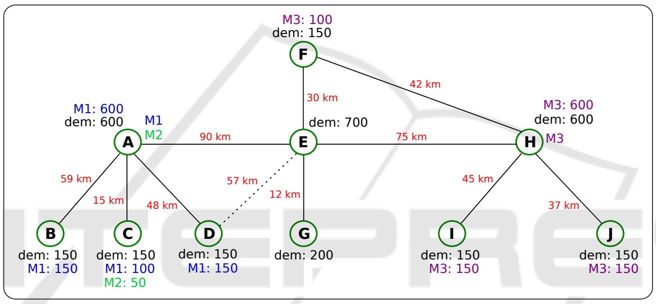

Figure 1: Example of location-allocation of mammography units.

between one municipality and another on the route is also defined.

For example, considering an MMU speed of 60 km/h, if $D^{\max} = 180$ km and the trip starts in the morning, it is possible to carry out mammography screenings in the destination municipality on the same day. This maximum distance restriction does not apply to MMUs leaving their departure points. Finally, a capacity of 4 mammography screenings per hour in each MMU is also considered.

To illustrate the MMURP, consider Figure 2, which presents the situation in the State of Rondônia after applying the MULAP. The municipalities shown in white color were fully covered by fixed mammography units, while those in green color had their demand only partially covered. The set of municipalities $\{$A, B, C, D, E, F, G$\}$ are those whose demand was not fully met by MULAP, and the set $\{1, 2, 3, 4\}$ includes the municipalities with hospital infrastructure. In this case, the problem is to determine the number of MMUs needed to serve the demand of municipalities A, B, C, D, E, F, and G, starting from municipalities 1, 2, 3, and/or 4 and covering the shortest possible distance.

In the scenario represented in Figure 2, detailed in Figure 3, three new routes are established to cover the demand of municipalities that were not fully served by the fixed mammography units, identified in green. There is one route departing from Municipality 1, covering Municipalities A, B, and C; another route departing from Municipality 2 and covering Municipalities D and E; and, finally, a third route starting from Municipality 3 and covering Municipalities F and G.

To illustrate the time required to complete each route, consider in Figure 3 that each MMU is capable of performing 6758 mammography screenings annually. Furthermore, assume that the number above the arrow between the base of an MMU and a municipality, or between two municipalities, represents the travel time. Also consider that the first number in brackets, above each municipality, represents the setup time, and the second number indicates the required time to perform all the screenings in the municipality under consideration. Regarding the setup time, a value of zero indicates that there is no setup time, a situation that occurs when the MMU arrives at the end of the day.

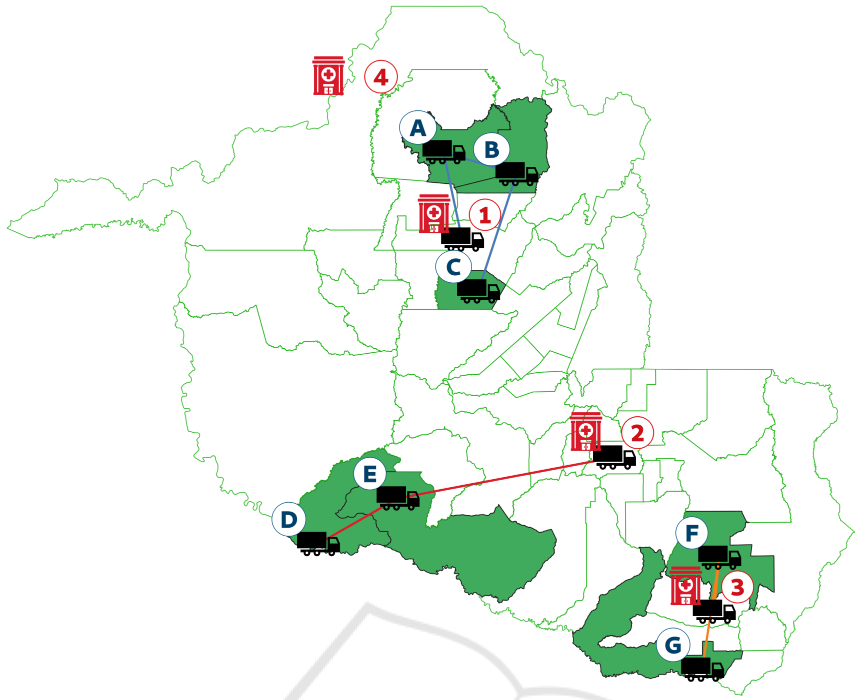

Figure 2: Example of MMU routing: situation in the State of Rondônia after applying the MULAP.

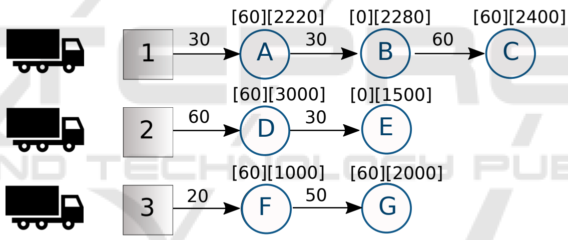

Figure 3: Routing relative to Figure 2.

3 A SOLUTION FOR MULAP

The main works in the literature for solving MULAP use the formulation proposed by (Souza et al., 2019). The current work also uses that formulation. In this article, three scenarios are considered. Scenario 1 allows the relocation of mammography units, and the assignment of exams is made without considering the health micro-regions. In Scenario 2, the current location of the equipment is kept; however, the assignment of exams does not observe the micro-regions. Scenario 3, in turn, maintains the current location of the equipment and respects the health micro-region of the municipalities.

To meet the requirements of Scenarios 2 and 3 and prevent the mammography units from being relocated, the set of constraints (12) is added, as follows:

$$y_i \geq pe_i \quad \forall i \in N. \qquad (12)$$

where pe_i represents the number of mammography units installed in municipality i. To meet Scenario 3, it is also necessary to restrict the service of a municipality to the health micro-region it belongs to. Thus, it is necessary to update S_i to include only the municipalities whose distances to municipality i are less than or equal to R km and are in the same health micro-region. In this case:

$$S_i = \{j \in N \mid d_{ij} \leq R \text{ and } d_{ji} \leq R \text{ and } reg_i = reg_j\}.$$

4 PROPOSED ALGORITHM FOR MMURP SOLUTION

The solution for MMURP proposed in this work is based on the construction phase of the GRASP metaheuristic, where a restricted candidate list with the α best candidates is generated. At each iteration, an element is randomly selected from this restricted list of the best candidates and inserted into the solution. The method developed is described by Algorithms 1 and 2.

Algorithm 1: buildMMURPSolution (CL, α).

```
   Data: CL: List of cities, α: Parameter to control the greediness
   Result: s: Solution generated
1  s ← ∅ ;                          // Solution to be generated
2  j ← 1 ;                          // Route counter
3  R_1 ← ∅ ;                        // Initial route
4  newRoute ← TRUE
5  while CL ≠ ∅ do
6      if newRoute then
7          StartNewRoute(j,R,s,CL,newRoute) ; // Starts a
             new route.
8      else
9          RCL ← generateRestrictedCandidateList(CL,α)
10         i ← Randomly chosen city from RCL
11         R_j ← Add city i to route R_j
12         Update the time of route R_j
13         Update the demand of city i
14         if Time of R_j reached the limit then
15             s ← Add route R_j to the solution s
16             j ← j+1
17             newRoute ← TRUE
18         else
19             newRoute ← FALSE
20         end
21         if i has no demand left then
22             CL ← CL \ {i}
23         end
24     end
25 end
26 return s
```

Lines 1 to 4 of Algorithm 1 initialize the method variables. Lines 5-25 construct the solution by inserting a municipality at each iteration while there are still municipalities in the Candidate List (CL) to be served. Line 7 creates a new route to be added to the solution when necessary, as described by Algorithm 2. In lines 8-24, cities are added to the current route according to the number of exams to be performed. In line 9, a Restricted Candidate List (RCL) is generated with the α municipalities from CL closest to the last city added to the route. In line 10, a city is randomly selected from the RCL, and in lines 11-13, this city is added to the route, updating the route's time and the demand of this city. The route time update involves calculating the time spent attending to the municipality's demand, including travel and preparation time. The demand update determines how many screenings can be performed within one year. In lines 14-20, it is verified whether the MMU's capacity (route time) is exhausted after adding a new municipality to the route. If so, the route is added to solution s, and the *newRoute* variable is set to *TRUE*. Finally, in lines 21-23, the selected municipality is removed from CL if its demand is fully met.

Algorithm 2: StartNewRoute($j, R, s, CL, newRoute$).

```
Data: CL: List of municipalities, j: Route counter, R: Routes, s:
      Solution, newRoute: Indicates if it's a new route
Result: newRoute: Returns whether a new route should be
        started
i ← Municipality with the highest demand in CL
D ← closest depot to municipality i
if D ∈ CL then
    R_j ← Add depot D to route R_j
    Update the time of R_j
    Update the demand of D
    if Time of R_j reached the limit then
        s ← Add route R_j to the solution s
        j ← j+1
        newRoute ← TRUE
        if D has no demand left then
            CL ← CL \ {D}
        end
    else
        R_j ← Add city i to route R_j
        Update the time of R_j
        Update the demand of i
        if Time of R_j reached the limit then
            s ← Add route R_j to the solution s
            j ← j+1
            newRoute ← TRUE
        else
            newRoute ← FALSE
        end
        if i has unmet demand then
            CL ← CL \ {i}
        end
    end
else
    R_j ← Add depot D to route R_j
    R_j ← Add city i to route R_j
    Update the time of R_j
    Update the demand of i
    if Time of R_j reached the limit then
        s ← Add route R_j to the solution s
        j ← j+1 newRoute ← TRUE
    else
        newRoute ← FALSE
    end
    if i has no demand left then
        CL ← CL \ {i}
    end
end
return newRoute
```

Algorithm 2, in turn, describes the procedure for opening new routes. In lines 1 and 2, the municipality *i* with the highest demand is used to determine the depot for the new route, which is the closest to this municipality *i*. The steps described in lines 3 to 43 of Algorithm 2 are very similar to the steps previously described in Algorithm 1. These lines insert cities into the route, update times and demands, and, if necessary, close the route.

5 RESULTS

The mathematical formulation was executed using the CPLEX solver, version 20.1. The constructive MMURP algorithm, in turn, was implemented in C++. The experiments were conducted on a DELL *Inspiron* 153511 laptop, with an Intel Core i7-1165G7 processor, 16 GB of RAM, and Ubuntu 20.04 Operating System.

The instances used in this work utilize population data from the 2022 Brazilian Census. The group of candidate municipalities to host the equipment consists of municipalities that currently have hospitals and/or host mammography units in the existing configuration. The number of available mammography units was obtained from the DATASUS system in December 2023.

The experiments considered three distinct scenarios. The first scenario assumes there is freedom to relocate mammography units. The second scenario considers that mammography units must remain at their current locations, serving any municipalities located up to 60 km away. The third scenario differs from the previous one in terms of target population coverage; in this scenario, coverage is restricted to municipalities within the same health micro-region.

For the constructive MMURP algorithm, instances were formed using data from municipalities not covered by the MULAP solution. Additionally, these instances consider the reference municipalities for each health macro-region in the State as depots. Furthermore, for each scenario, two values for the maximum distance traveled were tested: 180 km, as proposed by (Rosa et al., 2020), and 545 km, to evaluate the consequence of relaxing this maximum distance traveled.

Table 2 reports the results obtained from applying the mathematical formulation to the MULAP. The first and second columns consist of the identifier and description of each analyzed scenario, respectively. The third and fourth columns show, respectively, the number and rate of exams covered by the MULAP. Finally, the fifth and sixth columns show, in this order, the number and rate of demand not covered by the MULAP.

As can be observed in Table 2, as the restrictions in the MULAP increase, the demand coverage rate decreases. In the first scenario, the coverage approaches totality, considering the freedom to relocate the equipment. In the second and third scenarios, while preserving the current mammography unit locations, the coverage rate decreases substantially. By restricting the service of a municipality to its health micro-region (third scenario), this rate falls to 72.08%. These results show that the current location-allocation of the mammography units in the State of Minas Gerais is inefficient, and the configuration of the health micro-regions in the state further limits the coverage of the demand.

Table 3 reports the results obtained by applying the constructive algorithm to the MMURP. The first column presents the ID of the scenario analyzed in the MULAP and the maximum distance traveled between two cities in MMURP; the second column reports the number of MMUs required to meet the remaining demand for each of these scenarios; the third column displays the total distance traveled by the MMUs; the fourth column presents the total demand covered by the MMUs, and, finally, the fifth and sixth columns show, respectively, the average occupancy and the occupancy rate of the MMUs.

As can be observed in Table 3, the remaining demand from the MULAP in Scenario 1 is fully met by 9 MMUs, which travel 2164 km. The remaining demand in the second Scenario requires 42 MMUs, covering a total of 14937 km to perform 182754 exams, while the remaining demand in the third Scenario is covered by 84 MMUs, which travel a total of 30578 km, serving 484987 patients. Considering that an MMU can serve 6758 patients, Scenario 3 made the best use of its capacity, achieving an average utilization of 85.42%. On the other hand, in Scenario 1, due to the geographical locations of the served municipalities and the maximum distance restriction imposed on the MMU between cities, the average utilization reached a rate of 17.15%.

Illustrating a solution for the MULAP, Table 4 presents the routes of the MMUs required to meet the remaining demand in scenario blue1. The first column identifies the route of each MMU described in the second column, while the third and fourth columns report, in this order, the distance traveled by each and the demand covered by them.

As can be observed in Table 4, to meet the remaining demand from the MULAP in Scenario 1, Algorithm 1 generated a solution with 9 MMUs needed to cover the target population. These 9 MMUs cover a

Table 2: Characteristics of the MULAP solution for the State of Minas Gerais.

ID	Scenario	Demand Covered	Coverage Rate	Remaining Demand	Uncovered Rate
1	Freedom to relocate and allocate	1,728,037	99.40%	10,435	0.60%
2	Maintains current location, changes allocation	1,555,710	89.49%	182,754	10.51%
3	Maintains current location, imposes health micro-region	1,253,482	72.08%	484,987	27.92%

Table 3: Characteristics of the MMURP solution of the State of Minas Gerais.

Scenario	# Routes	Total Distance Traveled	Total Demand Covered	Average MMU Occupation	MMU Occupation Rate
1 (180 km)	9	2,164	10,435	1,159	17.15%
2 (180 km)	42	14,937	182,754	4,351	64.38%
3 (180 km)	84	30,578	484,987	5,773	85.42%
1 (545 km)	2	3,339	10,435	5,217.5	77.20%
2 (545 km)	29	17,020	182,754	6,301.9	93.25%
3 (545 km)	74	32,392	484,987	6,553.9	96.98%

Table 4: Detailed solution of the MMURP in Scenario 1 (180 km).

ID	Route	Distance (*km*)	Coverage
1	Patos de Minas → Brasilândia de Minas → Dom Bosco → Natalândia	364	1,549
2	Diamantina → Buenópolis → Joaquim Felício → Augusto de Lima → Santo Hipólito → Monjolos → Santana de Pirapama → Santana do Riacho	429	3,025
3	Teófilo Otoni → Novo Oriente de Minas	71	728
4	Teófilo Otoni → Mata Verde	345	631
5	Montes Claros → Claro dos Poções → Jequitaí → Francisco Dumont → Ibiaí → Santa Fé de Minas	362	2,279
6	Patos de Minas → São Gonçalo do Abaeté → Varjão de Minas	139	1,020
7	Governador Valadares → São Geraldo da Piedade → São José da Safira	167	585
8	Montes Claros → Itacambira	99	313
9	Montes Claros → Padre Carvalho	188	305
	Total	**2,164**	**10,435**

Table 5: Detailed solution of the MMURP in Scenario 1 (545 km).

ID	Route	Distance (*km*)	Coverage
1	Patos de Minas → Brasilândia de Minas → Dom Bosco → Natalândia → Santa Fé de Minas → Ibiaí → Jequitaí → Francisco Dumont → Claro dos Poções → Itacambira → Joaquim Felício → Buenópolis → Augusto de Lima → Santo Hipólito → Monjolos → Santana de Pirapama	1,378	6,657
2	Teófilo Otoni → Novo Oriente de Minas → São José da Safira → São Geraldo da Piedade → Santana do Riacho → Santana de Pirapama → São Gonçalo do Abaeté → Varjão de Minas → Padre Carvalho → Mata Verde	1,961	3,778
	Total	4,158	10,435

total of 2164 km and serve 10435 patients. The routes described in Table 4 are graphically presented in Figure 4. It can be observed that the geographical distribution of the municipalities required a greater number of MMUs to fully meet the mammography demand. Table 5, in turn, shows that the flexibility (from 180 to 545 km) of the maximum distance traveled between two cities reduces the number of necessary routes and, consequently, increases the occupancy rate of MMUs. Figure 5 exhibits the routes described in Table 5.

6 CONCLUSIONS

This work addressed the MULAP and MMURP using a sequential solution procedure. The MULAP was solved using a mathematical formulation from the literature and applied to three different scenarios. In Scenario 1, the possibility of relocating equipment was considered; in Scenarios 2 and 3, the current location of the equipment was kept, and, by turn, in scenario 3, the service of a municipality was restricted to its health micro-region. The MMURP was addressed by a constructive algorithm applied to the remaining

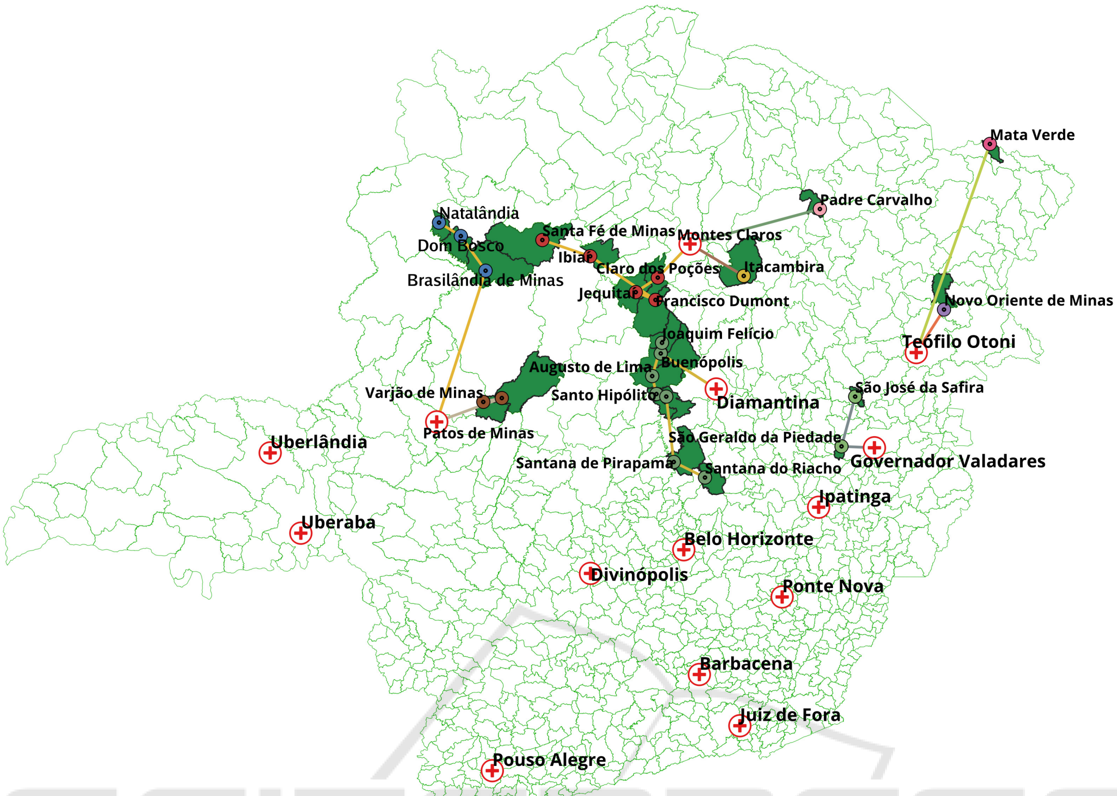

Figure 4: MMURP Routes - Instance MMURP-MG-Flexible.

demand resulting from the MULAP solution.

Among the three scenarios analyzed in the MULAP solution, the result obtained in Scenario 3 had the lowest coverage, 72.08%, followed by Scenario 2, with 89.49% of the demand met, and Scenario 1 with 99.40% coverage. These results were expected, once Scenario 3 represents the situation closest to reality. In fact, in this scenario, the current location of the existing equipment is considered, and the obligation for the target population to be covered only within the health micro-region to which each municipality belongs is imposed. Scenario 2 is somewhat more flexible since it allows services to be provided outside the health micro-regions. The result in Scenario 1 shows that, with the current mammography units, it would be possible to meet almost all the demand in the State of Minas Gerais.

Regarding the MMURP, the solution in Scenario 3 was also the worst, requiring 84 MMUs. The solution in Scenario 1 was the best, requiring only 9 MMUs, with most of these MMUs making short routes and serving a small set of municipalities. Many of these routes depart from the same home municipality to a single destination municipality due to the distance limitation imposed on MMUs, which cannot travel more than 180 km from one municipality to another. Given this result, the MMURP solution in Scenario 1 could be improved by allowing the distance traveled between municipalities to be greater. Finally, these results from the MULAP and MMURP show that when mammography units are not well-located, coverage is lower, consequently requiring more MMUs to meet the demand from uncovered municipalities.

For future work, it is suggested to develop refinement heuristics to reduce the number of MMUs and make better use of each MMU's capacity.

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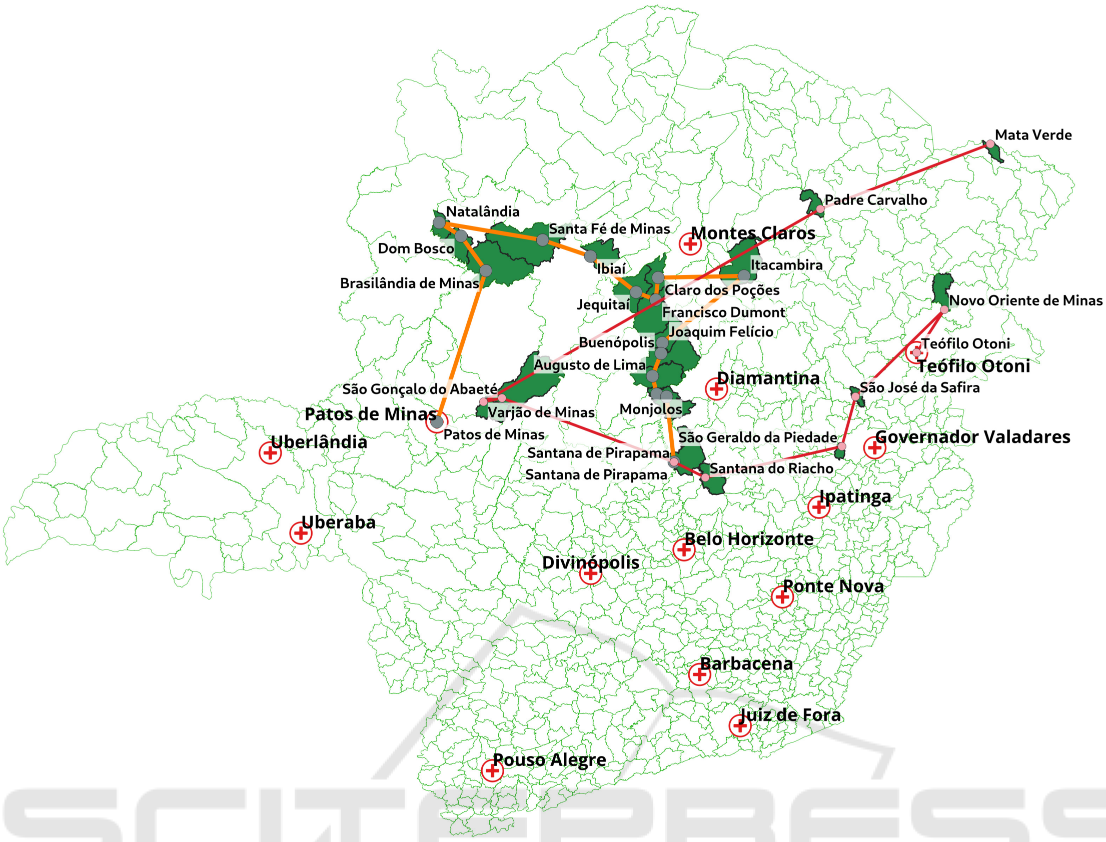

Figure 5: MMURP Routes - Instance MMURP-MG-Flexible.

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