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Medical centers location and specialists' allocation: a healthcare planning case study

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Abstract

Paper aims: To set the locations of new medical centers to meet the population's secondary care needs, the additional number of specialists, equipment, and an installation sequence at municipalities.

Originality: We developed descriptive cost functions models and adopted aggregate data from official sources to set parameters of an integrated MILP model.

Research method: A case study at the Brazilian state of Minas Gerais.

Main findings: For every scenario, the recommended locations set centers dispersed over the state area, in cities with the minimum required infrastructure. We also propose a scenario of secondary care network re-design and demonstrate the reduced cost of such a strategy.

Implications for theory and practice: To automate the decision process, we developed a web-based system, providing flexibility and scientific-based results. Finally, we propose a sequence for installing 43 new medical centers and improving the capacity of 27 existing infrastructure based on equality principles.

Keywords
Public healthcare planning. Facility location. Mixed integer linear programming.

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1. Introduction

In Brazil, decreasing economic progress imposes challenges to the deployment of good public healthcare planning. Setting the location of healthcare units in a hierarchical system, the size of hospitals, of medical centers or emergency units is critical since these decisions directly affect the population access to health services. Besides, cost-intensive procedures as computed tomography or nuclear magnetic resonance imaging technologies point to the promotion of inequalities in equipment access, which implies, in Brazil, a detachment from the principles of universality, integrality, and equity in health systems (Abreu, 2017).

The 1988's Brazilian Federal Constitution established a national health system subsidized by social security payments and taxes (Sistema Único de Saúde - SUS) to provide free healthcare at the primary, secondary and tertiary levels to all residents (Victora et al., 2011). The system follows principles of universalization, equity, and integrality. Every citizen can access primary, secondary and tertiary care in an integrated and decentralized public health system (Brasil, 2019a). Nonetheless, the Brazilian fast-aging community has raised services demand and increased the health system's requirements, but a recent federal law (Brasil, 2016) has established even tighter bounds on the public health budget. Consequently, the location of health units and the allocation of resources have been a topic of both political and methodological relevance, pressuring leaders to strive on setting priorities in allocating resources.

In this study, we evaluate and analyze the secondary care of Minas Gerais (MG), a Brazilian state, where the 2000 and 2010 census demonstrate the fast aging diagnostic (see Figure 1). We acquire health needs on demographic projections (Instituto Brasileiro de Geografia e Estatística, 2019) and the Ministerial Decree 1.631, and adopt mathematical programming models to solve an optimization problem of location and resource allocation (Brasil, 2015).

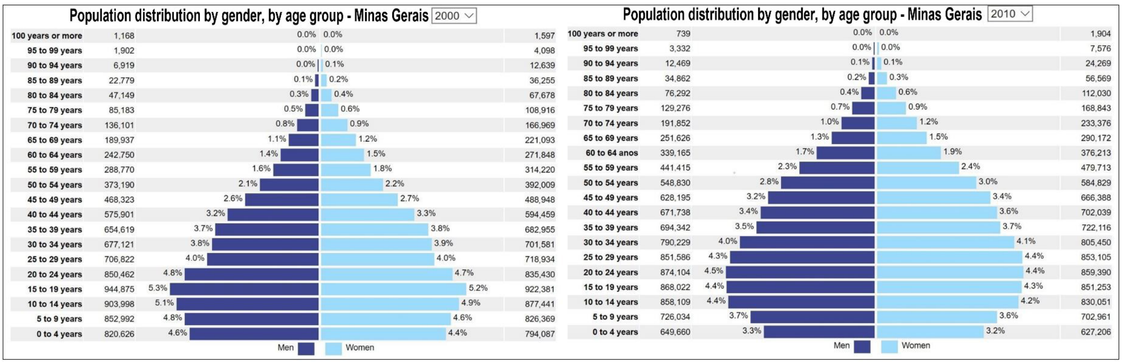


Figure 1. Demographic pyramid shows fast aging population of MG from 2000 to 2010 (Instituto Brasileiro de Geografia e Estatística, 2019).

Although SUS has improved access to primary and tertiary care over the past years, the provision of secondary is still problematic. The three service levels are interdependent (Macedo & Martin, 2014). The primary care consists of low-cost prevention events, reaching in 2010 nearly 98 million people in 85% of Brazilian municipalities. On the extreme side, public teaching hospitals and contracted private sectors providers execute tertiary care, paid by the SUS at about market value. With intermediate technological density between primary and tertiary care, secondary care is responsible for performing medium complexity procedures (Minas Gerais, 2019) and providing specialized services to outpatient at the hospital level.

The provision of secondary care is problematic. Medium complexity procedures are often restricted to patients with private health plans. Since there is little regulation at the second level, SUS is highly reliant on the private sector. In Brazil, only 24.1% of Computed Tomography (CT) scanners and 13.4% of Magnetic Resonance Imaging (MRI) scanners are public (Paim et al., 2011). Furthermore, the medical centers, qualified for healthcare on the second level, are not geographically dispersed, which motivates this study of medical centers' location and equipment allocation for health care.

Healthcare location problems have been an active research area (Rais & Viana, 2011). The models are an extension of the classic p-median, p-centers (Hakimi, 1964), set-covering (Toregas et al., 1971), and the max-covering model (Church & ReVelle, 1974), and the *location-allocation* model (Schilling et al., 1979). The p-centers and the location-allocation models are of particular importance to this work because, collectively, they address issues of equity, minimizing the distance between remote patients, and the equipment allocation to facilities.

From a historical perspective, we refer the interested readers to a comprehensive review (Hale & Moberg, 2003), successful case studies (Brandeau, 2016) and a recent survey (Ahmadi-Javid et al., 2017). Applications include modeling a 3-level location system of perinatal facilities (Galvão et al., 2002); the use of a genetic algorithm for a maximal covering location for health care (Shariff et al., 2012); and a facility location model for primary care system approaching physicians' preferences (Güneş et al., 2014). Following, Khodaparasti et al. (2016) address a hierarchical location model for community-based organizations with health care providers by applying multi-objective programming. Additional applications consists on the development of a system to optimize the equipment allocation (Treurnicht & Van Dyk, 2014); the tactical workforce planning and capacity allocation minimizing salary costs considering vacation and subcontracting opportunities (Van der Veen et al., 2015); and a performance evaluation of 87 private and public primary care health units (Novignon & Nonvignon, 2017). On health care location-allocation problem, examples include the location of preventive health care units (Gu et al., 2010), two-phase procedures to set the location and size of medical departments

(Stummer et al., 2004), and for improving spatial accessibility (Luo et al., 2017), and an integrated approach aiming inequality reduction (Sathler et al., 2019).

Despite the rich literature, most studies address primary care on the municipality level. Little attention, however, has been paid to location-allocation problems for health care on the secondary level, so there are potential gaps and open issues yet to investigate, besides, the literature presents few studies that address realistic problems (Güneş et al., 2014; Ahmadi-Javid et al., 2017). Our model: (i) adopts descriptive models of cost functions and dada aggregation to elaborate parameters; (ii) evaluates the existing equipment idle capacity on a hierarchical health care system; (iii) considers both the population requirements for local multiple medical services and physicians' preferences on living on municipalities with minimum infrastructure; and (iv) the government financial condition, as stated in objective function.

The authors developed the method following flexibility principles (De Neufville & Scholtes, 2011) for dealing with the problem faced in a project. Since we recognized that the context was of a generic style, representing an unstudied component of real health care location-allocation problems (Almeida et al., 2018), this work can directly contribute to general health care planning by supporting policymaking and providing scenario analyses.

In the following sections, we present a Mixed Integer Linear Programming (MILP) location-allocation model, a descriptive model based on cost functions for setting health care costs, and a strategy for installing health care units based on equality principles. Next, we provide a case study applying the proposed method to solve the problem in MG. We evaluate scenarios by distance, by budget availability are discuss a sequence for health units' installation. We finish the paper by providing conclusions and suggestions for future research.

2. Method

This paper presents a MILP model for healthcare planning at the state level, particularly, secondary care. Cost functions descriptive models and aggregate data are the base for the MILP model's parameters. The mathematical model aids the planner to select secondary care facilities locations and designate medical specialists, and equipment to them. The planner, here represented by the government health care management team, must combine patients' and physicians' inclinations, adequately size capacity, and guarantee service quality to justify the public infrastructure financing. As medical procedures often depend on equipment, we include these recourses and its' demands into the model considering official standards' amount of equipment per inhabitants and the actual available capacity.

The aim is minimizing the annual overall cost of a strategy that includes (i) the maintenance costs of medical centers; (ii) the cost of procurement of new equipment for existing infrastructure and new medical centers, and balance with (iii) a social opportunity cost of society, estimated by cost functions. We also evaluate available specialists and equipment in a hierarchical system. Secondary care specialists working in primary or tertiary care includes the available capacity. Their production is decreased from the estimated demand, set on Ministerial Decree 1.631. Datasus Outpatient and Hospital Information System and Applications (Departamento de Informática do SUS, 2018a, b) provides a history of outpatient and hospital production.

We denote a state with I municipalities, offering E medical specialties services and Q equipment. Patients move within their municipality or via available paths $(i,j) \in K \subset I \times I$ between pairs of municipalities to meet E medical specialties (see Table 1).

The number of inhabitants B_i per municipality i is sourced from Instituto Brasileiro de Geografia e Estatística (2019) projection to 2019. The observed physicians' preference for municipalities with a population higher than a minimum amount B_{min} and better infrastructure is considered. A *basic* measure for selecting acceptable distances is defining a lower bound parameter of the maximal allowed patients' displacement as $\max_i \left(min_{ij \in K | i \neq j} D_{ij} \right)$ for critical medical specialties services, like cardiology. Open Route online Services provides the distance between municipalities. The data helps setting candidates based on the maximum displacement DM_{eij} of patients, which results from the combination of medical specialty and distances (or time) to be established according to government parameters for service levels and budget availability. Therefore, the candidate municipalities $J = i \in N_i$ are a set of locations that meet the following requirements $N_i = j \,|\, (i,j) \in K, D_{ij} \leq \max_e \left(DM_{eij} \right) \wedge B_j \geq B_{min}$, and $|N_i|$ must not be empty for any municipality. Services often don't meet nominal capacities based on projections, therefore, the global efficiency of services E_j provided on municipality j can be adjusted based on observations combined with data envelopment analysis (DEA), moreover, the decision-maker may have the option to consider P_j municipalities that are provider of specialties services with available capacity on healthcare services.

The demand of patients for medical specialties services HE_{ie} and exams on equipment HQ_{iq} is available on official government publications; however, the decision-maker can estimate demand based on benchmarking indicators of OECD countries (Organisation for Economic Co-operation and Development, 2017), for instance.

Table 1. Input parameters of the facility location and resource allocation model.

Parameters	Description	Unit
B_i	Inhabitants on municipality *i*	Inhabitants
B_{min}	Minimum number of inhabitants for a candidate municipality	Inhabitants
D_{ij}	Distance between municipalities (*i, j*)	Km
DM_{eij}	Maximum displacement (*i,j*) a patient can take to meet specialty *e*	Km
$J = N_i$	Candidate destinations of municipality *i.*	Municipality
E_j	Global efficiency of services provided on municipality *j*	Percent
P_j	Candidate municipality *j* that received a Medical Center	Binary
HE_{ie}	Demand of patients of municipality *i* by (*full time equivalent*) specialty *e*	FTE (40h)
HQ_{iq}	Demand of patients for exams on equipment *q (ex/1000inhab/year)*	Exams
KQ_{iq}	Available capacity of equipment *q* on municipality *i*	Exams
K_q	Nominal annual production capacity of equipment *q*	Exams
KE_{ie}	Availability of physicians of specialty *e* municipality *i*	Physicians
F	Minimum number of secondary health care facilities (Medical Centers)	Facilities
P_q	Minimum number of additional equipment of type *q*	Equipment
CI	Average annual cost of a Medical Center facility operations	Real (R$)
CQ_q	Average acquisition cost of equipment *q*	Real (R$)
S_e	Average annual salary of medical specialty *e*	Real (R$)
CD_{ij}	Average annual cost estimate of patients displacement from (*i,j*)	Real (R$)
α_{eij}	Average demand decay estimate due distance increase (*i,j*)	Percent
M_{eq}	Matrix assignment defining if equipment *q* is used by specialty *e*	Binary

The demand does not remain constant through every geographical region but decays proportionally to the distance. We propose a simplified decay function $\alpha_{eij} = \max\left(DM_{eij} - D_{ij}, 0\right) / DM_{eij}$ based on distance; however, this function can be improved by a floating catchment area (FCA) method based on real data (Bauer & Groneberg, 2016).

The (i) nominal capacity of the equipment K_q is different from the (ii) available capacity of the equipment KQ_{iq}. The first consists in the Original Equipment Manufacturer (OEM) information of annual production capacity of each equipment, individually, while the second is related to the municipality capacity on providing the service of exams on equipment, therefore, the information is obtained by the number of available equipment on healthcare units. The availability of physicians KE_{ie} of each specialty is based on historical data of similar periods in the past and consists of registries of the historical production of physicians on each municipality. A matrix M_{eq} assigns each type of medical specialty to the equipment used.

The government sets parameters of a minimum amount of secondary health care facilities F and equipment P_q according to its financial conditions and to the desired service level, it aims at providing to its population. The cost parameters of the average annual cost of Medical Centers operations, acquisition of equipment, and patients' displacement between municipalities guide the objective function that aims at minimizing the sum of government and population costs.

We propose the use of cost functions (Horngren et al., 2002) to estimate fixed and variable costs of the annual cost of medical center operations. Let S be a set of support team that enables the operations of health centers, N_s, the number of professionals of each team S, and S_s, the salary of each professional of support (Brasil, 2019b). The fixed costs FC include a periodic time t payment of salaries of multifunctional teams, as nurses, pharmacists, psychologists, social workers, and, administrative support, their corresponding social taxes T, and a General Costs (GC), therefore, $FC = \sum_s \sum_t TN_s S_s + GC$. The variable costs VC consist of the average number of hours provide by each medical specialty e and their category's average salary S_e (Brasil, 2019b), and divided by 40 to meet a full-time equivalent professional (FTE), therefore, $VC_e = \sum_t we_e S_e$, and the average annual cost of a medical center facility operations $CI = FC + \sum_e VC_e$.

The additional annual cost of new equipment is equivalent to the cost of the equipment divided by the depreciation period. General costs may include average operational equipment costs. The values of each type of equipment follow average market prices. To estimate the annual patients' displacement costs, let r be the average rate per kilometer of vehicle, s, the average speed vehicle, t, the annual number of trips, h, the time on queue and meeting physician, and m the average income of patient per hour. A medical care meet requires two trips (go, and return). The annual estimated number of meetings is base for setting the number of trips. For example, a physician that meets one patient per hour may meet $1 \times 8 \times 5 \times 4.25 \times 12 = 2{,}040$ meets per year, and $t = 2{,}040 \times 2 = 4{,}080$ trips per year. The opportunity cost spent by patients considers the time on round trips $2\left(D_{ij} / s\right)$, plus the average time h. This time is multiplied by the average hourly income of a patient (m), therefore, the displacement costs are represented by $CD_{ij} = \left(2(r)D_{ij} + \left(2\left(D_{ij} / s\right) + h\right)m\right)(t)$.

The data for parameters above are base for answering some questions, translated into model variables: Which municipality should receive a secondary level healthcare unit? How many physicians of specialty e should be hired to such municipalities and how many equipment of type q should be acquired for each of them? The demand of patients from municipality i for medical specialty e and their demand for exams on equipment q should be satisfied in which municipality? Table 2 presents the variables from the current questions.

Table 2. Input variables of the facility location and resource allocation model.

Variables	Description	Unit
x_{eij}	If demand of municipality i is met by specialty e on municipality j	Binary
y_{qij}	If demand of municipality i is met by equipment q on municipality j	Binary
z_j	Decide if candidate municipality j receive (or not) a healthcare unit	Binary
wq_{qj}	Number of equipment q to be acquired to municipality j	Integer
we_{ej}	Number of FTE physicians of specialty e to be hired to municipality j	Integer

$$minimize \sum_j \left(CIz_j + S_e we_{ej}\right) + \sum_{qj} CQ_q wq_{qj} + \sum_{eij} \alpha_{eij} CD_{ij} HE_{ie} x_{eij} \tag{1.0}$$

The objective function 1.0 minimizes the total annual cost composed of three classes of costs shared by the government and the society, that is (i) the maintenance of medical centers, (ii) the depreciation costs of newly acquired equipment of different types for each unit, and a social cost of patients' displacement for having medical care. This function is subject to constraints 1.1-1.17.

$$\sum_j x_{eij} = 1 \qquad \forall e \in E, i \in I \tag{1.1}$$

$$\sum_j y_{qij} = 1 \qquad \forall q \in Q, i \in I \tag{1.2}$$

In Equation 1.1 and Equation 1.2, the demand for medical services and the demand for exams based on equipment, respectively, of each district must be satisfied by only one medical center. Thus, the patient municipality does not have to assign the demand of every medical specialty nor every equipment to a single destination municipality, but it can be assigned to different municipalities, however, the split of demand of a patient municipality is not allowed for each medical specialty or equipment.

$$x_{eij} \leq z_j \qquad \forall e \in E, i \in I, j \in J \tag{1.3}$$

$$y_{qij} \leq z_j \qquad \forall q \in Q, i \in I, j \in J \tag{1.4}$$

Following, the demand for medical specialty, on the Constraint 1.3, or for medical equipment, on the Constraint 1.4, can only be assigned to a selected municipality, that is, the demand assignment is conditioned to the installation of a Medical Center on municipality j.

$$x_{ejj} = z_j \qquad \forall e \in E, j \in J \tag{1.5}$$

The Equation 1.5 establishes that the demand of a candidate municipality that was selected to receive a Medical Center must be locally satisfied since patients would not displace to different municipalities if its own municipality has healthcare units. Even if its health unit is overcrowded, the patient may not know nor may not accept being moved to different municipalities for healthcare services.

$$x_{eij} = y_{qij} \qquad \forall e \in E, q \in Q, i \in I, j \in J \mid M_{eq} = 1 \tag{1.6}$$

$$wq_{qj} \le z_j FP_q \qquad \forall q \in Q, j \in J \tag{1.7}$$

Constraint 1.6 link the medical specialty demand to the type of equipment each specialty depends on, such that the patient does not have to move to different municipalities to take exams. On Constraint 1.7, the number of equipment of type q is limited by an upper bound on selected municipalities or equal zero, if the municipality is not selected to receive a healthcare unit.

$$\sum_j z_j \ge F \qquad \forall j \in J \tag{1.8}$$

$$\sum_j wq_{qj} \ge P_q \qquad \forall q \in Q \tag{1.9}$$

The healthcare service level desired by the government is presented on Constraints 1.8 and 1.9 which defines the minimum number of Medical Centers and equipment, respectively. The more healthcare units, the higher is the healthcare service level, but the higher is the operating cost with administration, physicians, and equipment. Besides, the number of medical centers and equipment is dependent on the state's long-term financial conditions.

$$z_j \ge P_j \qquad \forall j \in J \tag{1.10}$$

Sometimes, an optimal solution may yield to municipalities with no infrastructure, which may be very close to other municipalities with available infrastructure and idle capacity. For such cases, Constraint 1.10 is interesting for decision-makers to force the selection of some candidates with better infrastructure, which may reduce the healthcare unit installation cost.

$$K_q E_j wq_{qj} \ge \sum_i max\left(HQ_{iq} - KQ_{iq}, 0 \right) y_{qij} \qquad \forall q \in Q, j \in J \tag{1.11}$$

$$we_{ej} \ge \sum_i max\left(HE_{ie} - KE_{ie}, 0 \right) x_{eij} \qquad \forall e \in E, j \in J \tag{1.12}$$

Constraints 1.11 and 1.12 project the minimum capacity to satisfy the demand of patients for exams and medical specialties, respectively. The above constraints consider the existing capacity of the available infrastructure of healthcare on the state to acquire only the extra recourses required to satisfy the demand. Finally, Constraints 1.13 to 1.17 set the domain of the model's variables.

$$x_{eij} \in \{0,1\} \qquad \forall e \in E, i \in I, j \in J \tag{1.13}$$

$$y_{qij} \in \{0,1\} \qquad \forall q \in Q, i \in I, j \in J \tag{1.14}$$

$$z_j \in \{0,1\} \qquad \forall j \in J \tag{1.15}$$

$$wq_{qj} \in \mathbb{Z}^+ \qquad \forall q \in Q, j \in J \tag{1.16}$$

$$we_{ej} \in \mathbb{Z}^+ \qquad \forall e \in E, j \in J \tag{1.17}$$

On solving the optimization problem, we obtain the number of municipalities, medical specialists, and equipment that satisfy all described constraints at a minimum overall cost. This solution, however, is static; therefore, we suggest a sequence for installing medical centers guided by inequality indexes. The inequality indexes are the Social Vulnerability Index (SVI) (Costa & Marguti, 2015), the Inequality-adjusted Human Development Index (IHDI) from the United Nations Development Programme (2018), or the Slope Index of Inequality (SII), and the Concentration Index (CIX), based on demographic health survey (Silva et al., 2018).

In this study, the authors propose the above methodology to aid Minas Gerais (MG) health care policy. MG is the Brazilian state with the largest number of municipalities, 853, the second most populous, with more than

20 million inhabitants, and fourth biggest, with 586,528 km^2. Solving this health care problem to MG indicates that the method can solve the health care problem for the remaining states of the country.

3. Results and discussion

Minas Gerais proposed in 2015 advances in health care including a decentralization process in the second level to increase the population access to specialized centers. The government inaugurated the first medical center, in this new arrangement, in 2016 (Jornal Estado de Minas, 2016). Some constraints were established. Candidate municipalities should satisfy a combination of requirements of least 30 thousand inhabitants to receive nine medical specialties services and equipment, which reveals physicians' preference on minimal infrastructure and on working with similar professionals. The patients' preference for minimal displacement establishes a maximal allowed distance from patients' municipalities to medical centers' municipalities.

The authors adopted open route services (Neis & Zipf, 2007) to obtain time and distance between the 853 municipalities (i,j) yielding 727,609 registries for each parameter. Following, we defined the lower bound parameter $\max_i \left(min_{ij \in K | i \neq j} D_{ij} \right) = 77km$ of the maximal allowed distance; however, 4.2% of municipalities do not meet these both requirements (more than 30 thousand inhabitants, and at most 77 km from candidate municipalities). Those municipalities that do not meet these requirements are an exception to a general rule and require a practical solution with special conditions. In general, we established a displacement ranging from one to three hours according to the accessibility need to health care services, setting 80 km for cardiology, and 120 km to 180 km to the remaining specialties resulting in the selection of 121 candidates.

We set the demand of patients from 853 municipalities for physicians of specialties HE_{ie} and exams HQ_{iq} on equipment as stochastic parameters $\mathcal{U}(a,b)$. Demands are uniformly distributed ranging from a to b. The parameters a,b range from a central value (central value – range, central value + range) which is selected on Ministerial Degree 1,631 (Brasil, 2015). We adopt a range variability of 0.26 based on indicators of Mexico physicians' density, which is a country included in Organisation for Economic Co-operation and Development (2017) and comparable to Brazil in indicators, like GDP.

The OEM information of standard equipment set base parameters of the nominal capacity of MRI scanners, Mammograph, CT scanners, Ultrasound, and Doppler. DATASUS database provides the municipality capacity on offering the service of exams for each type of equipment and the number of machines available on 853 municipalities (Departamento de Informática do SUS 2018a, b). We obtained 10 years of the historical production of physicians. We reached the information of availability of FTE physicians' specialists in angiology, cardiology, endocrinology, gynecology, mastology, nephrology, ophthalmology, pediatrics, and urology by dividing the average values of physicians' historical production from 2008 to 2017 on each municipality by a standard period of work of 40 hours of FTE physician.

The government sets the minimum number of secondary health care facilities and equipment according to its financial conditions and the desired service level it aims at providing to its population. This study evaluates the optimal strategy with minimum annual overall costs of heal care on the secondary level. The method considers simultaneously the installation of medical centers in different municipalities of MG, the provision of nine medical specialties services, and exams on five types of equipment.

The annual cost function of medical center operations considers the salary of multifunctional teams of nurses, pharmacists, psychologists, social workers, and, administrative support include fixed costs. The variable costs consist of the average number of hours provided by each medical specialty and their category's average salary, available at PDET (Brasil, 2019b). Following, we include the annual cost of new equipment, traditionally depreciated in 10 years. The values are based on average prices of catalogs of the standard equipment of each type, therefore, we set depreciation costs of R$300,000 for MRI scanner, R$41,000 for CT scanners, R$5,600 for mammograph, R$4,500 for ultrasound, and R$850 for doppler. Finally, the annual patients' displacement costs between municipalities of MG considered: (i) the average rate of Reals per kilometer (R$0.50/km) of bus companies for two (round trip) inter-municipal trips; (ii) the opportunity cost spent by patients; and (iii) the average number of trips, for health care with physicians, in a year. The number of trips is a stochastic parameter $\mathcal{N}(\mu,\sigma)$ based on the estimated number of meetings. Therefore, medical specialties meeting from one to two patients per hour yields about $\mathcal{N}(2000,300)$ trips per year. The opportunity cost considers the time on round trips at 60 km/h, plus an average time of 5 hours to arrive, wait on queues, receive the medical care, and return to the bus. This time is multiplied by the average hourly income of an MG's citizen (R$9.45), available at Instituto Brasileiro de Geografia e Estatística (2010a, b), therefore, displacement costs CD_{ij} depend on the distance and are represented by $R\$\left(2(0.50)D_{ij} + \left(2\left(D_{ij}/60\right)+5\right)9.45\right)\left(\mathcal{N}(2000,300)\right)$.

We evaluated eight optimized scenarios. The scenarios [1-3] consider the maximal patients' displacement, highlighting municipalities that need special treatment. The scenarios [4-6] takes the government budget availability into account. Following, the scenario [7] proposes a re-design of MG's network of medical centers, and finally, on scenario [8] we suggest a sequence for setting medical centers, based on equity principles. We implemented in MathProg (GLPK) and run the MILP models in a Linux Mint 17.3 64-bit, RAM of 8 GB, Intel Core I5 2.50 GHz x 2 processor. The mathematical programming problem comprises 1,445,574 constraints and 709,193 variables, all of which are integers, being 683,586 of them, binary. Instances were optimally solved within two hours.

The recent disclosure of MG State Secretary of Health shows that the health care policy of installing new medical specialties centers units has not been implemented yet (Ricardo, 2019). The state government has recently faced a serious financial crisis (Agência Minas, 2019), and much of the health resource has been used for working capital expenditures rather than investments (Assembleia Legislativa do Estado de Minas Gerais, 2018). The State government has transferred financial resources (R$19,350,970.03) to the existing 26 Specialized Care Centers (with Brazilian Portuguese initials CEAE) and 1 Medical Center (with Brazilian Portuguese initials CEM) (Minas Gerais, 2018). Since the 27 health units are dispersed over the state (see Figure 2), we adopt the plausible assumption that the model must capacitate the existing health care centers before creating new units.

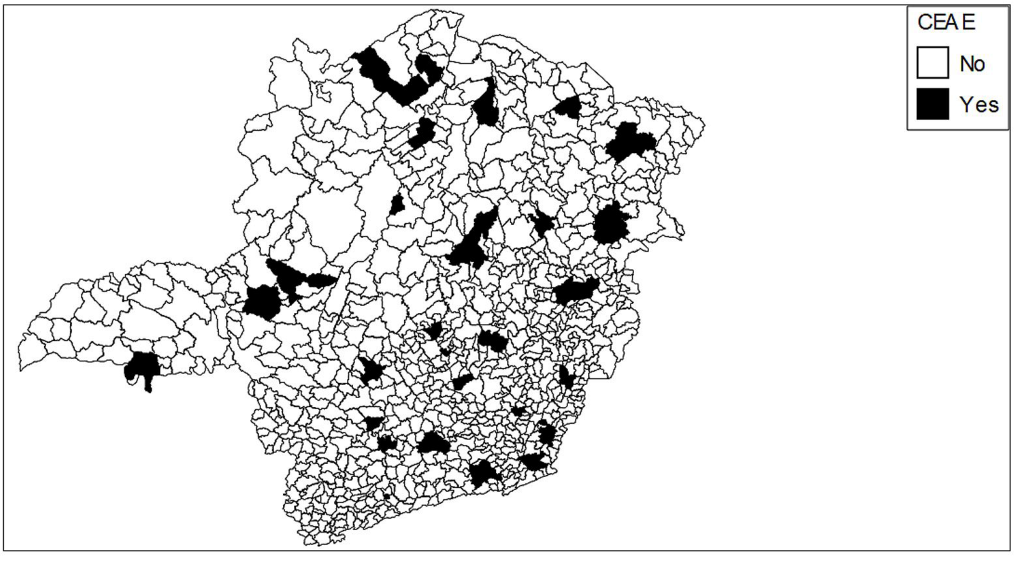


Figure 2. The 27 health units (Specialized Care Centers and a Medical Center) dispersed over the state area. Source: Software Tabwin 2019.

3.1. Scenarios [1-3] based on patients' displacement

Scenarios based on patients' displacement provides the minimum number of municipalities, equipment, and specialists that satisfy the maximum patients' displacement constraints. Therefore, we deactivate constraints 1.8 and 1.9 since parameter DM_{eij} imposes the limitation. We present three scenarios (see Figure 3) based on patients that move distances ranging from 180 km to 80 km (or take from 3 hours to approximate 1 hour). We describe the third scenario in more detail; evaluating the number of selected municipalities, the additional amount of each type of equipment, and the suggestion of hiring extra FTE specialists. Besides, we evaluate optimal overall costs and compare the state's costs with social costs.

In the **scenario [3]**, patients should move at most 80 km, or approximate 1 hour and 20 minutes to reach a health unit. In this scenario, 64 municipalities (in black and green, see Figure 4) offer secondary care at medical centers. Since 27 municipalities (in black, see Figure 4) already have a basic infrastructure (health units), the government should install 37 additional medical centers (in green, see Figure 4).

In this strategy, the government should hire 73 angiologists, 137 cardiologists, 69 endocrinologists, 183 gynecologists, 72 mastologists, 102 nephrologists, 160 ophthalmologists, 211 pediatrics, and 91 urologists (see Figure 5). Besides, it requires the procurement of 133 MRIs, 75 CTs, 142 mammograms, 957 ultrasounds, and

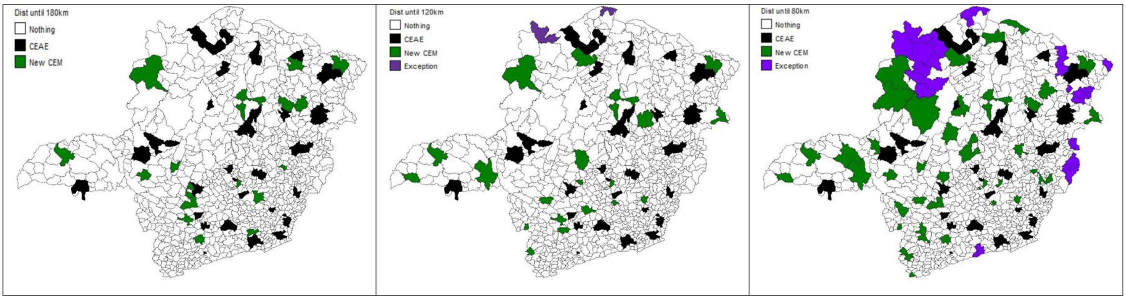


Figure 3. Municipalities selected (43, 45, and 64) for patients' displacement of at most 180, 120, and 80 km, respectively, to meet health care on medical centers. Municipalities in purple (scenarios 2 a 3) are exception requiring special treatment.

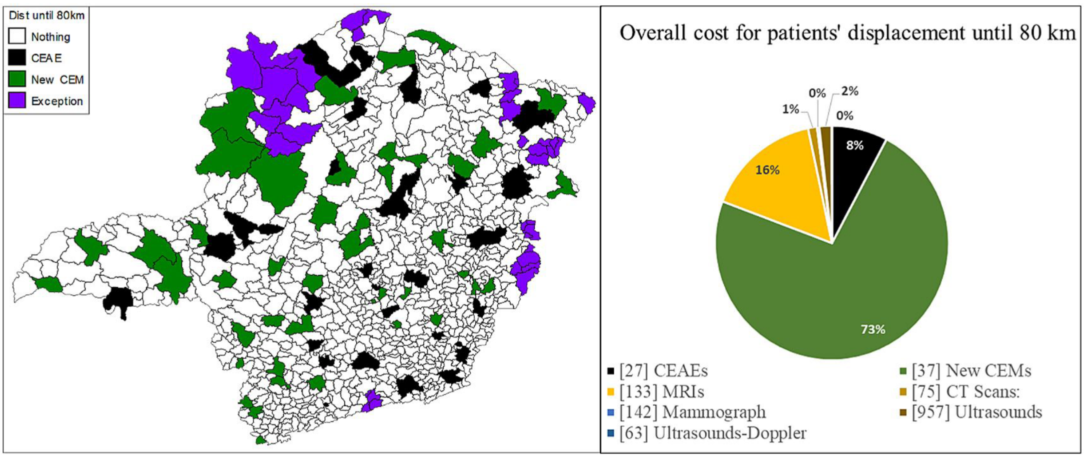


Figure 4. Municipalities selected in black and green enable the patients' displacement of at most 80 km to meet health care on medical centers. Municipalities in purple are exception requiring special treatment.

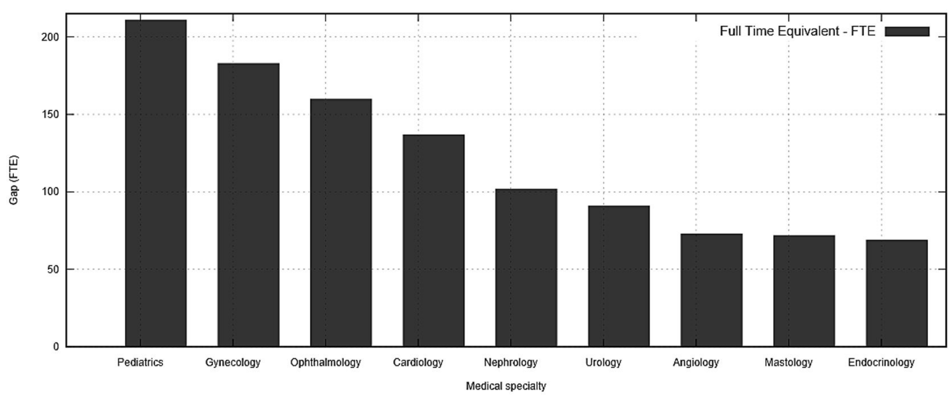


Figure 5. Additional hiring of medical specialties for patients' maximum displacement of 80 km.

63 ultrasound Doppler (see Figure 6). The strategy satisfies the demand of 816 municipalities, 95.8% of the state demand. The 37 municipalities in purple (see Figure 4) are Águas Formosas, Águas Vermelhas, Aimorés, Cachoeira de Pajeú, Arantina, Arinos, Bertópolis, Bom Jardim de Minas, Bonfinópolis de Minas, Brasilândia de Minas, Buritis, Chapada Gaúcha, Crisólita, Cuparaque, Divisa Alegre, Formoso, Fronteira dos Vales, Itabirinha, Itueta, Juvenília, Machacalis, Mantena, Medina, Miravânia, Montalvânia, Monte Formoso, Nova Belém, Passa-Vinte, Resplendor, Riachinho, Salto da Divisa, Santa Fé de Minas, Santa Helena de Minas, Santa Rita de Jacutinga, Santa Rita do

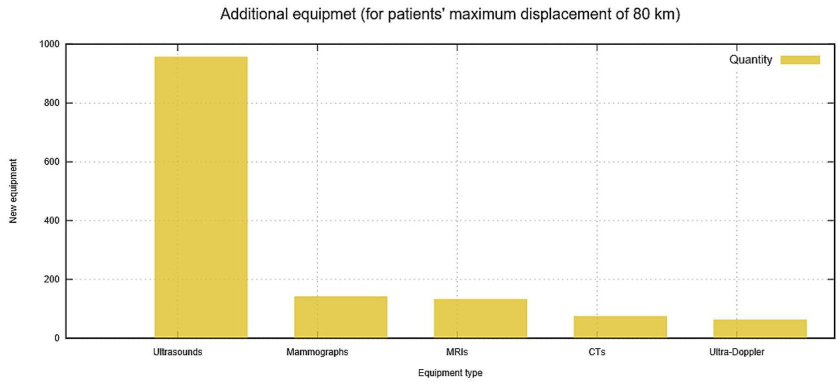


Figure 6. Additional equipment for patients' maximum displacement of 80 km.

Itueto, São João do Manteninha, and Urucuia. They represent 4.2% of municipalities that deviates the general rule, where patients move 110 ± 20 km to reach destination. To follow equality principles, these municipalities require special treatment, as dedicated public transport, for example.

The analysis revealed each medical center serving an average of 14 districts patients traveling on average 57 km and a standard deviation of 9 km from their municipality to the nearest medical center. The maximal distance is 80 km, limited by the scenario, while the shortest distance, excepting patients with medical center on their municipality, is 33 km. The Appendix A provides the number of equipment and specialist per municipality for this scenario in detail.

Figure 7 presents the financial results of the overall annual costs of 64 medical centers, equipment maintenance, and a comparison with social cost. The medical centers' costs include a maintenance cost for existing 27 health care units (SES Resolution 6563, 2018), the costs for expanding its capacity to meet patients' requirements, and the costs of additional 37 medical centers. Following, the results present the annual depreciation costs of equipment. The overall state annual costs are approximate R$250 M, which is comparable to the overall annual social opportunity cost, of R$259 M.

Cost [64]CEM	**R$**	**202.334.281,50**
Cost [27]CEAE+1CEM	R$	19.350.970,00
Cost [37]New CEMs	R$	182.983.311,50
Cost Equipment	**R$**	**48.130.250,00**
Cost MRIs	R$	39.900.000,00
Cost CTs	R$	3.075.000,00
Cost Mammographs	R$	795.200,00
Cost Ultrasounds	R$	4.306.500,00
Cost Ultra-Doppler	R$	53.550,00
State Cost	**R$**	**250.464.531,50**
Social Cost	R$	259.404.324,97

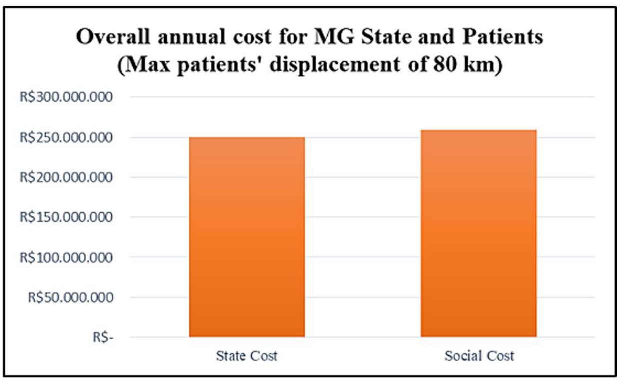


Figure 7. Financial results of overall annual costs of 64 medical centers and equipment maintenance, and a comparison with social cost.

3.2. Scenarios [4-6] based on budget availability

Scenarios based on budget availability focus on service offers. The government sets the number of municipalities and the minimum number of equipment it desires to provide according to its financial conditions. The model satisfies the patients' demand and government offer constraints. Therefore, we activate constraints 1.8 and 1.9. We present three scenarios (see Figure 8) based on requirements of 70, 60, and 50 medical centers and at least the number of equipment selected for the first scenario (maximum 180 km), that is 125 MRIs, 62 CTs, 134 mammograms, 952 ultrasounds, and 43 ultrasound Doppler. We describe the financial implications for scenario 4 [70 CEM]; evaluating the average patients' displacement, and the optimal overall costs and compare the state's costs with social costs.

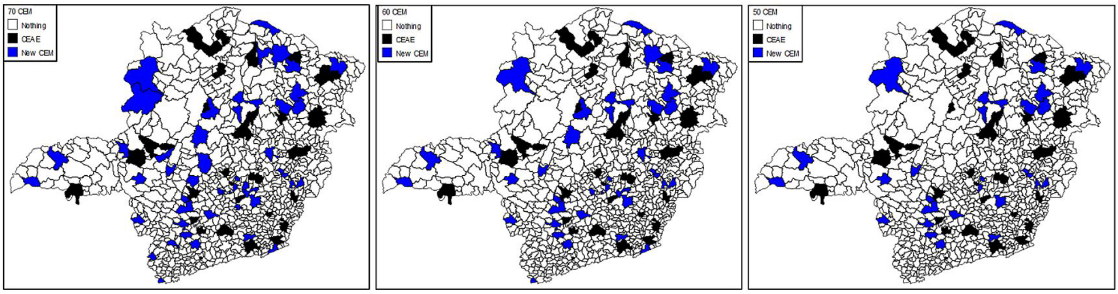


Figure 8. Municipalities selected to operate 70, 60, and 50 medical centers. Since 27 health units (in black) are fixed and available, the state would have to install 43, 33, and 23 new CEM.

With 70 medical centers of scenario 4, MG patients' displacement follows a normal distribution with $\mathcal{N}(156,50)$ km. As presented in Figure 9 and Figure 10, the number and cost of additional equipment are relatively similar to scenario 1, with 131 MRIs, 78 CTs, 147 mammograms, 961 ultrasounds, and 70 ultrasound Doppler. Figure 10 also demonstrates that when the MG state offers 70 medical centers, its costs are higher than the social opportunity cost.

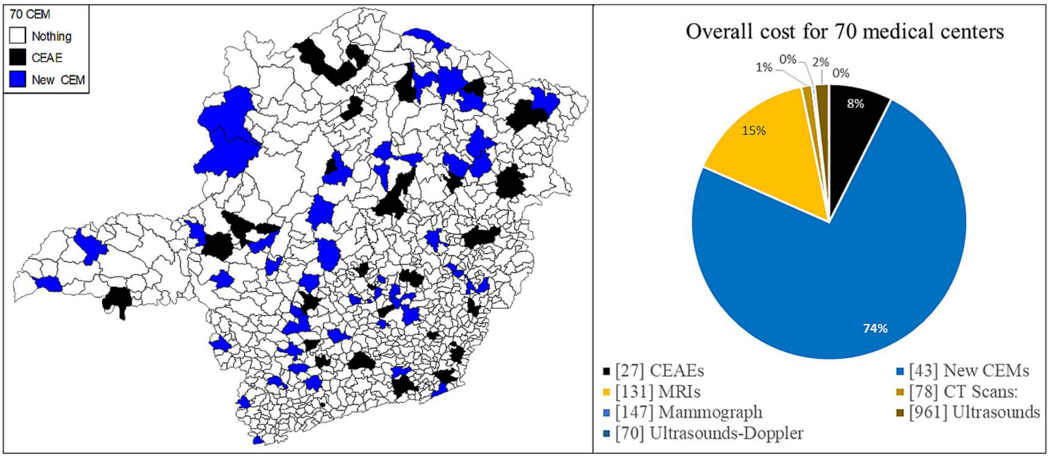


Figure 9. Municipalities (70) selected in black (27 CEAE) and blue (43 CEM). Patients' average displacement of 156 km. All municipalities demand are covered.

Cost [70]CEM	**R$**	**211.696.709,25**
Cost [27]CEAE+1CEM	R$	19.350.970,00
Cost [37]New CEMs	R$	192.345.739,25
Cost Equipment	**R$**	**47.705.200,00**
Cost MRIs	R$	39.300.000,00
Cost CTs	R$	3.198.000,00
Cost Mammographs	R$	823.200,00
Cost Ultrasounds	R$	4.324.500,00
Cost Ultra-Doppler	R$	59.500,00
State Cost	**R$**	**259.401.909,25**
Social Cost	R$	199.799.572,72

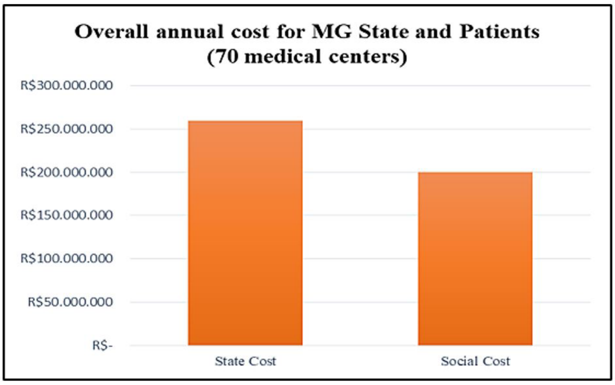
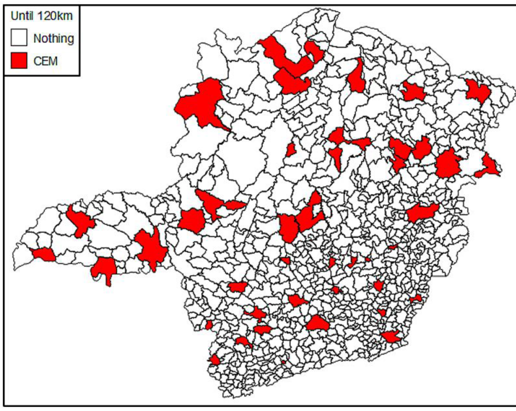


Figure 10. Financial results of overall annual costs of 70 medical centers and equipment maintenance, and a comparison with social cost.

3.3. Scenario [7] based on patients' displacement with no fixed infrastructure

So far, we have evaluated scenarios considering the available infrastructure. In the following scenario, we propose a maximum patient's displacement of 120 km (or two hours) and we relax the constraint 1.10 that fixes medical centers to existing infrastructure. The goal in this scenario is to evaluate a re-design option of the MG secondary care network. Under this strategy, the MG state requires 41 municipalities with medical centers (see Figure 11). The solution requires the procurement of 119 MRIs, 61 CTs, 136 mammograms, 946 ultrasounds, and 41 ultrasound Doppler. Besides, the government should hire 60 angiologists, 124 cardiologists, 59 endocrinologists, 176 gynecologists, 61 mastologists, 90 nephrologists, 152 ophthalmologists, 199 pediatrics, and 80 urologists. MG patients' average displacement takes 1.5 hours, following a normal distribution with $\mathcal{N}(95,31)$ km.



Cost [41]CEM	**R$**	**158.038.154,62**
Cost Equipment	**R$**	**43.254.450,00**
Cost MRIs	R$	35.700.000,00
Cost CTs	R$	2.501.000,00
Cost Mammograph:	R$	761.600,00
Cost Ultrasounds	R$	4.257.000,00
Cost Ultra-Doppler	R$	34.850,00
State Cost	**R$**	**201.292.604,62**
Social Cost	R$	210.356.216,06

Figure 11. Financial results of overall annual costs of 41 medical centers, equipment maintenance, and social cost.

From the 41 municipalities selected to receive medical centers, 12 municipalities already have the available infrastructure, that is Capelinha, Frutal, Governador Valadares, Janaúba, Januária, Leopoldina, Patos de Minas, Patrocínio, Pirapora, São João del Rei, São Lourenço, and Teófilo Otoni. Municipalities without services are assigned to one of the 41 municipalities. The model generates this strategy for all scenarios. The strategy is aligned with the Intermunicipal Health Consortiums and provided for in the organic law of the SUS (Law 8,080/1990) to assure integral care to the population of the connected municipalities (Brasil, 1990).

3.4. Priority-base schedule of medical centers installation

A *time-based schedule* for creating new medical specialties centers depends on the government budget and its priorities, therefore, for the future health units, we suggest the *priority-based schedule* adopting the SVI index (Instituto de Pesquisa Econômica Aplicada, 2019) for the selected municipalities. We designated 70 municipalities of the previous scenarios from which 43 are new medical centers, and 27 are available health units. Table 3 presents the proposed sequence based on SVI for installing new medical centers and improving the existing health units' capacity.

Table 3. Proposed sequence for installing medical centers in MG, and improve CEAE's capacity.

Sequence	Municipality	SVI	Sequence	Municipality	SVI
1º	Bom Despacho	0.18	36º	Unaí	0.288
2º	Extrema	0.185	37º	Sarzedo	0.31
3º	Araxá	0.187	38º	Pompéu	0.31
4º	Guaxupé	0.189	39º	Nanuque	0.32
5º	Nova Serrana	0.199	40º	Salinas	0.324
6º	João Monlevade	0.202	41º	Bocaiúva	0.331
7º	Timóteo	0.204	42º	Várzea da Palma	0.34
8º	Uberaba	0.206	43º	Guanhães	0.353
9º	Formiga	0.207	CEAE 1º	São Lourenço	0.164
10º	Passos	0.213	CEAE 2º	Santo Antônio do Monte	0.178
11º	Machado	0.216	CEAE 3º	Lavras	0.181
12º	Alfenas	0.217	CEAE 4º	Viçosa	0.187
13º	Ouro Fino	0.217	CEAE 5º	Patos de Minas	0.194

Table 3. Continued...

Sequence	Municipality	SVI	Sequence	Municipality	SVI
14º	Monte Carmelo	0.22	CEAE 6º	São João del Rei	0.201
15º	Ituiutaba	0.222	CEAE 7º	Itabirito	0.207
16º	Três Pontas	0.222	CEAE 8º	Muriaé	0.216
17º	Oliveira	0.224	CEAE 9º	Frutal	0.229
18º	Andradas	0.225	CEAE 10º	Sete Lagoas	0.233
19º	Uberlândia	0.225	CEAE 11º	Campo Belo	0.235
20º	Visconde do Rio Branco	0.226	CEAE 12º	Governador Valadares	0.243
21º	Piumhi	0.237	CEAE 13º	Patrocínio	0.246
22º	São Gotardo	0.241	CEAE 14º	Itabira	0.248
23º	Carangola	0.246	CEAE 15º	Juiz de Fora	0.248
24º	Ponte Nova	0.247	CEAE 16º	Manhuaçu	0.254
25º	Boa Esperança	0.248	CEM 17º	Pirapora	0.259
26º	Ouro Branco	0.251	CEAE 18º	Leopoldina	0.262
27º	Três Marias	0.253	CEAE 19º	Teófilo Otoni	0.302
28º	Congonhas	0.258	CEAE 20º	Janaúba	0.313
29º	Barão de Cocais	0.261	CEAE 21º	Diamantina	0.318
30º	Iturama	0.264	CEAE 22º	Taiobeiras	0.329
31º	Três Corações	0.27	CEAE 23º	Capelinha	0.337
32º	Belo Horizonte	0.276	CEAE 24º	Ribeirão das Neves	0.358
33º	Caratinga	0.276	CEAE 25º	Brasília de Minas	0.405
34º	Curvelo	0.277	CEAE 26º	Januária	0.426
35º	Paracatu	0.278	CEAE 27º	Jequitinhonha	0.442

The authors and the IT lab team developed a system to provide flexibility and automate the analysis of the secondary care planning process. The system provides the results of optimizations run, with the location of medical centers, the number of medical specialties, the assignment of patients' demand to medical centers on municipalities. Simultaneously, the analyst can evaluate the assignment of patients' demand for exams to medical centers and the number of the equipment for procurement within a maximum distance. The system, presented in Figure 12, enables scenario investigations by changing the quantity of new equipment and a maximum distance of coverage.

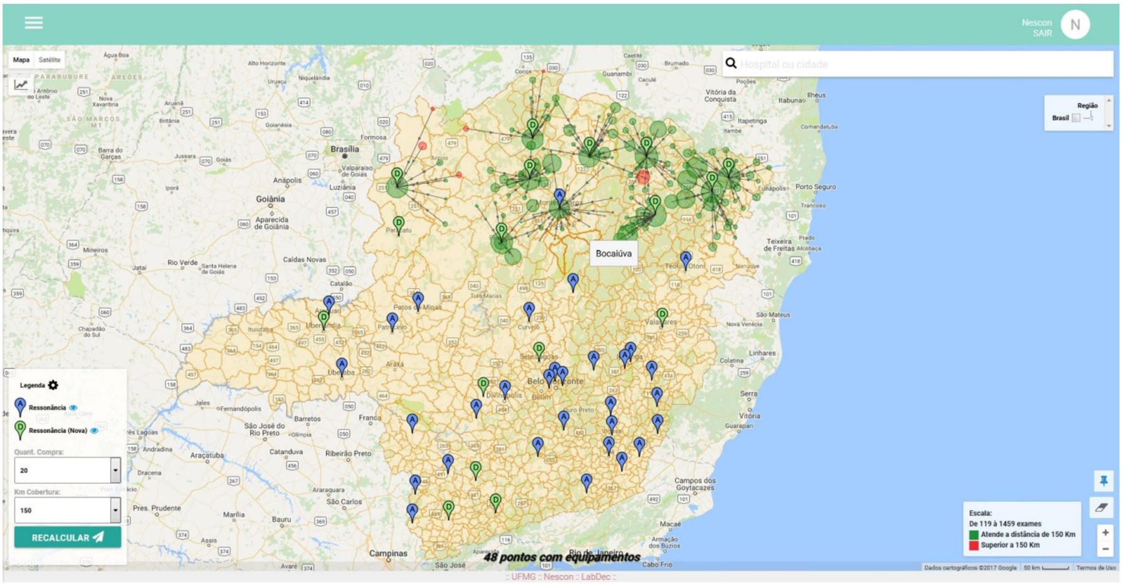


Figure 12. General view of the web-based system interface (text in Portuguese). Location and demand coverage of new 20 MRI scanners considering available MRI scanners on MG for a maximum distance of 150 km. (the connections show municipalities and services of the northern region of the state). Source: Nescon (2018).

4. Conclusion

This study proposed an optimization method for simultaneously setting out the location of medical centers and the equipment allocation for secondary care taking into account the tradeoff between patients' desire for minimum displacement, and physicians' inclination for working on settled MG municipalities. The proposed method considered existing infrastructure on 27 municipalities of MG and developed analysis based on patients' displacement, government budget availability.

For patients' displacement scenarios, we observed that it is possible to implement a solution where a patient may meet secondary care at most one hour and a half from its residence. For this scenario, the social opportunity cost is equivalent to government costs. For budget availability scenarios, we observed that the service level can increase in quality (with numerous medical centers and equipment), however, with 70 medical centers, for example, patients would take longer to reach such services, besides, the government costs would be higher than the citizens' opportunity costs. Following, we presented a scenario that re-designs the secondary care network of MG and demonstrated that 41 municipalities would be enough to satisfy the state's demand. Finally, the authors presented a table with 70 municipalities and a sequence for installing medical centers and increasing the capacity of the available infrastructure based on the SVI index. The table took into account 43 similar municipalities of optimization runs and the 27 municipalities of MG that already offer specialized care.

In general, the outcomes suggested that this integrated optimization modeling approach is a prospective method to endorse the integration of professionals of public health, medicine, and engineering, to support the decision-making process. We consulted specialists offer for decades and provided a deep financial evaluation of a wide system projected to ensure universality, equity, and long-term sustainability.

The developed system is a potential tool to provide knowledge-based policymaking. It is also fundamental to highlight that both descriptive models, as cost functions, as the mathematical model do not replace managers. Its' contribution resides on aiding decision-makers interacting to find the best solution by consensus by evaluating scenarios.

Some limitations of the study are worth mentioning. First, physicians move among municipalities, therefore, the offer of medical specialties is not accurate when we evaluate the values by municipalities. Micro or macro-regions describes better medical specialties' offer. Second, we did not consider the possibility of physicians of a municipality meet the requirements of other municipalities. This strategy would increase the dynamics of patients' and physicians' movement increasing considerably the model complexity. Such an analysis would have provided answers to questions of political aspects. Finally, a common adoption is to consider population coverage in static computations. Although it is desirable, we did not consider such a parameter since it trades-off maximum distance, but both parameters can be evaluated simultaneously in future works.

For future works, we recommend (i) a study about municipalities' efficiency on providing secondary care using Data Envelopment Analysis (DEA) scores (Mitropoulos et al., 2013); (ii) evaluating further decades' projection of both, population (Instituto Brasileiro de Geografia e Estatística, 2019), and specialists' offer. For this last, we recommend systems dynamics, since it is dependent on several causal variables with data not readily available. Finally, (iii) the decision of installing medical centers can be modelled by two-stage stochastic programming (Errarhout et al., 2016; Zarrinpoor et al., 2017), where the first stage decision is the installation of medical centers, and on the second stage, the uncertain demand and offer of medical specialties are revealed.

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Appendix A. Equipment assignment and number of specialists for each municipality of MG.

This appendix presents the scenario [3] selection of medical centers and equipment considering the 853 municipalities of MG. We compute the gap of each medical specialty for each municipality, considering both, its demand and the assignment of specialists and equipment to the 63 medical centers. Figure A1 to Figure A5 propose assignment of equipment, while Figure A6 to Figure A14 suggest the number of specialists for each municipality.

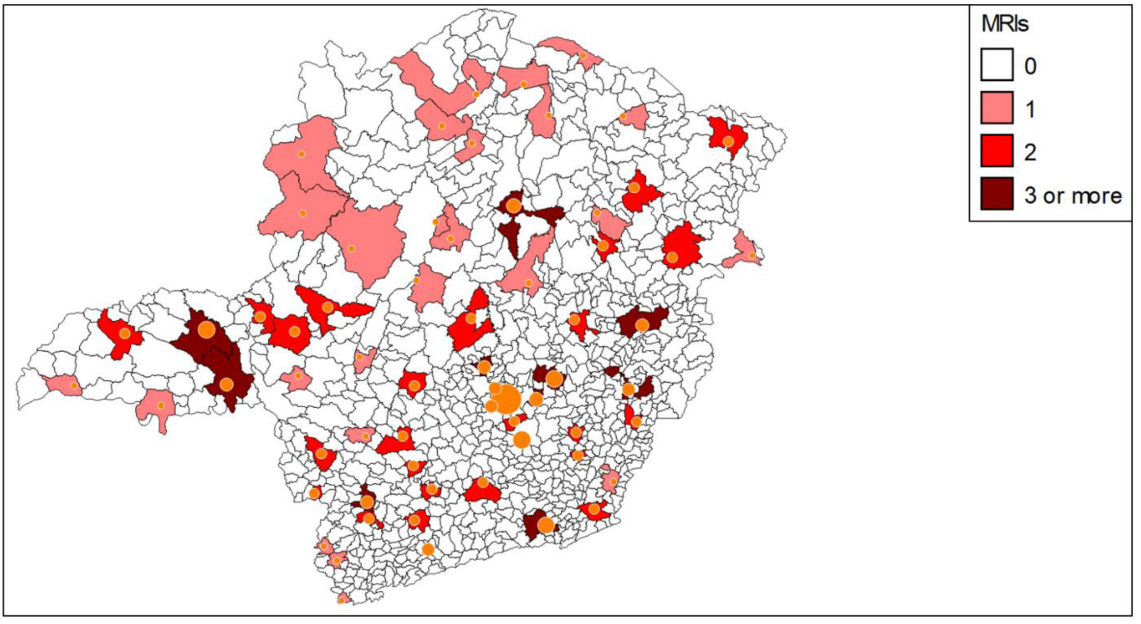

Figure A1. MRIs procurement for scenario [3].

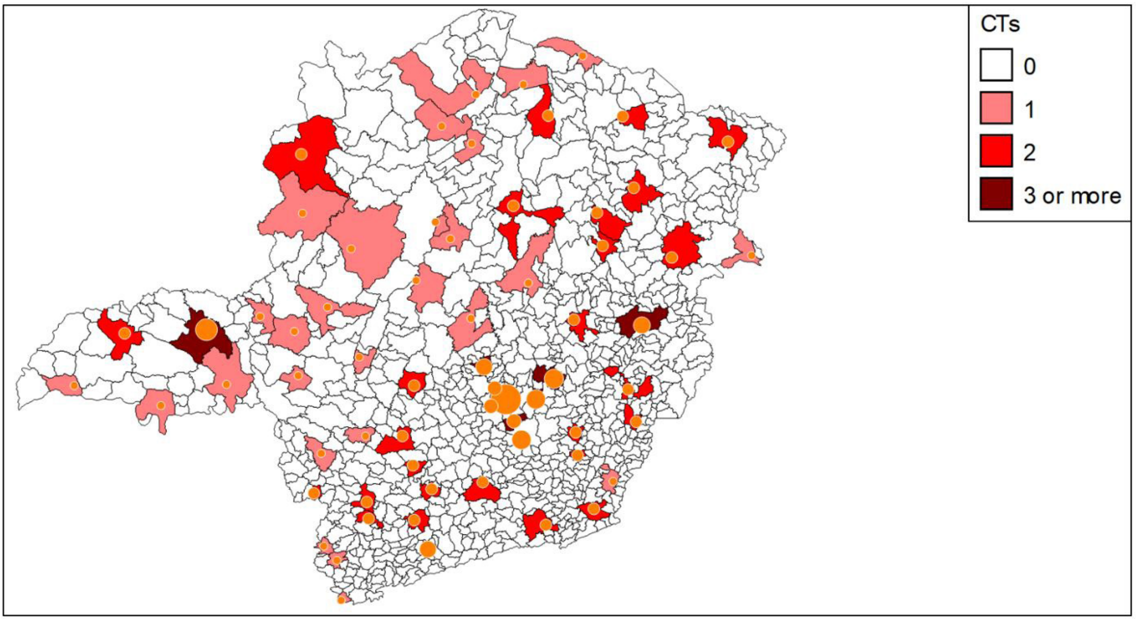

Figure A2. CTs procurement for scenario [3].

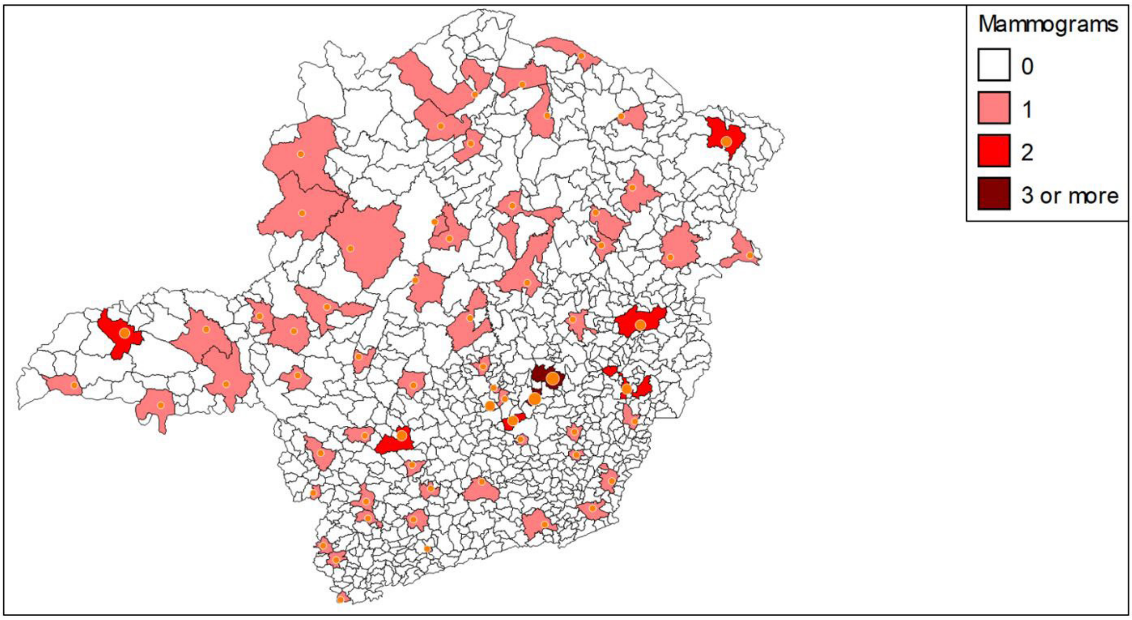

Figure A3. Mammograms procurement for scenario [3].

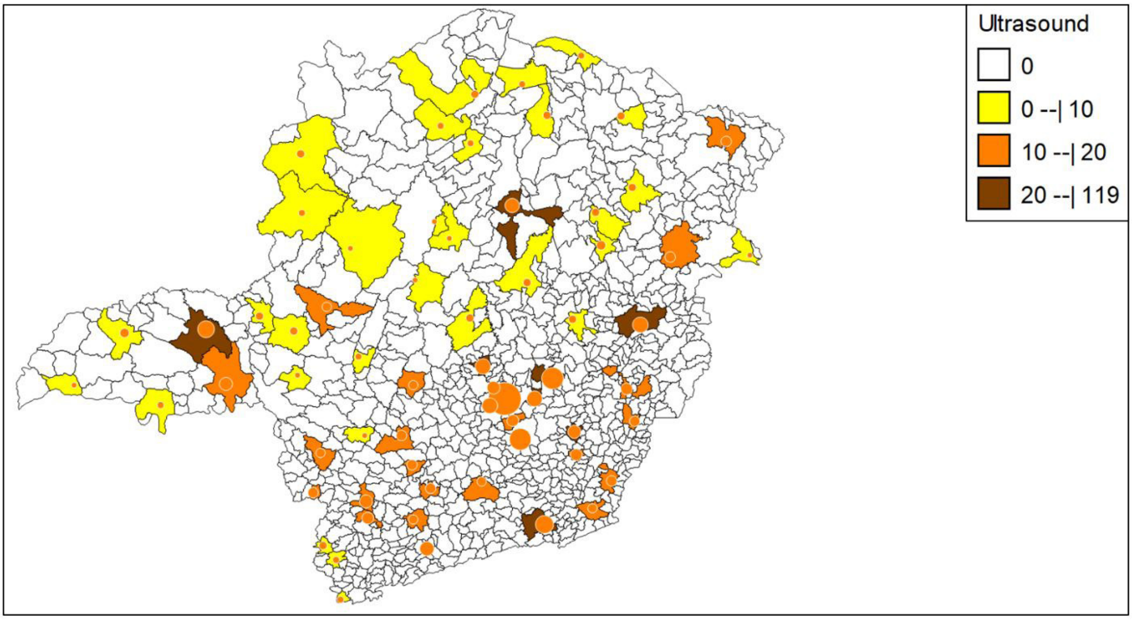

Figure A4. Ultrasound procurement for scenario [3].

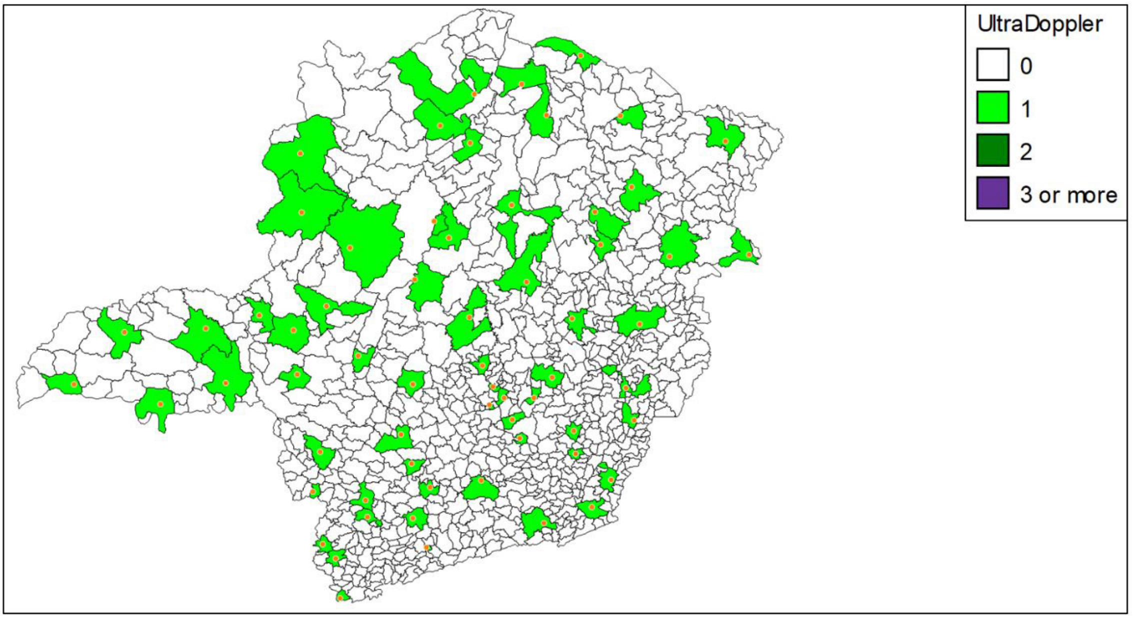

Figure A5. Ultrasound Doppler procurement for scenario [3].
Specialists hiring suggestion for scenario [3].

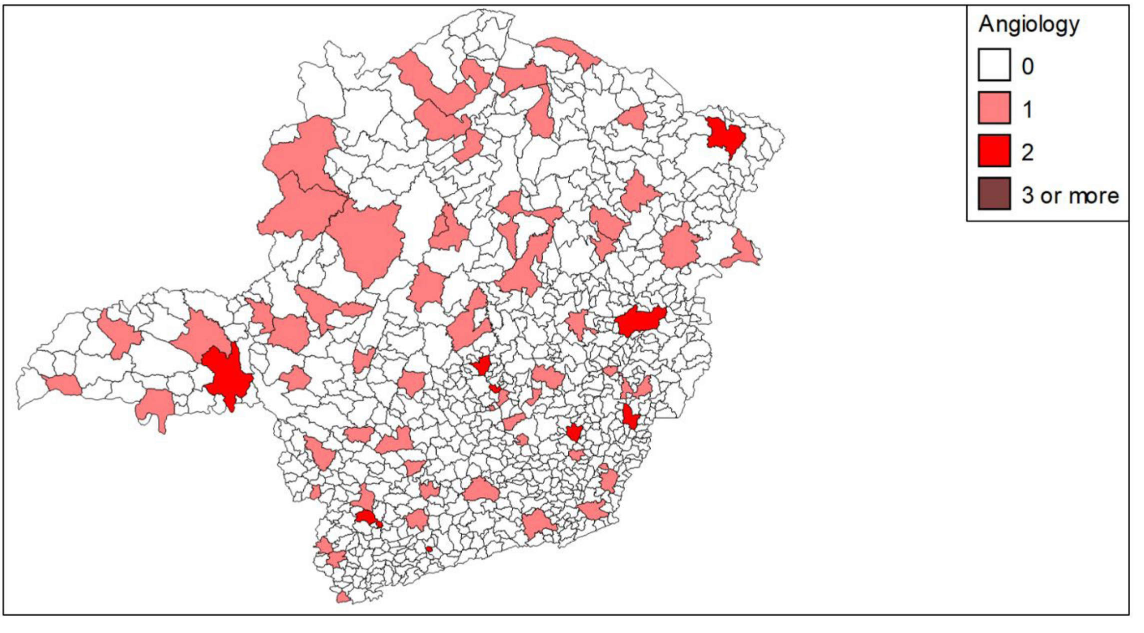

Figure A6. Andiology hiring suggestion for scenario [3].

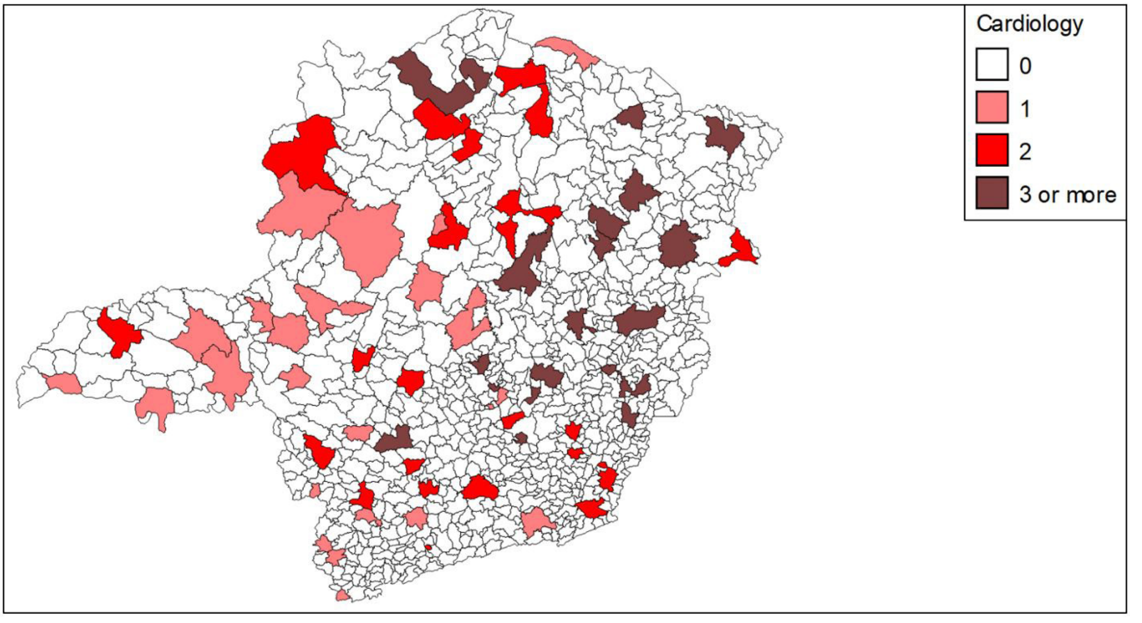

Figure A7. Cardiology hiring suggestion for scenario [3].

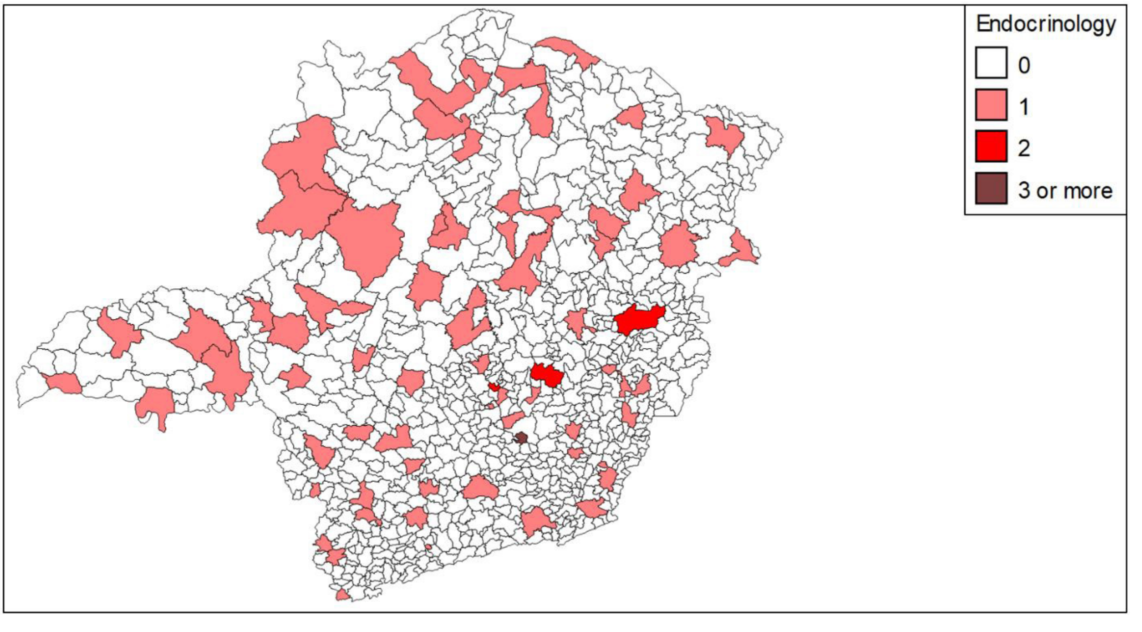

Figure A8. Endocrinology hiring suggestion for scenario [3].

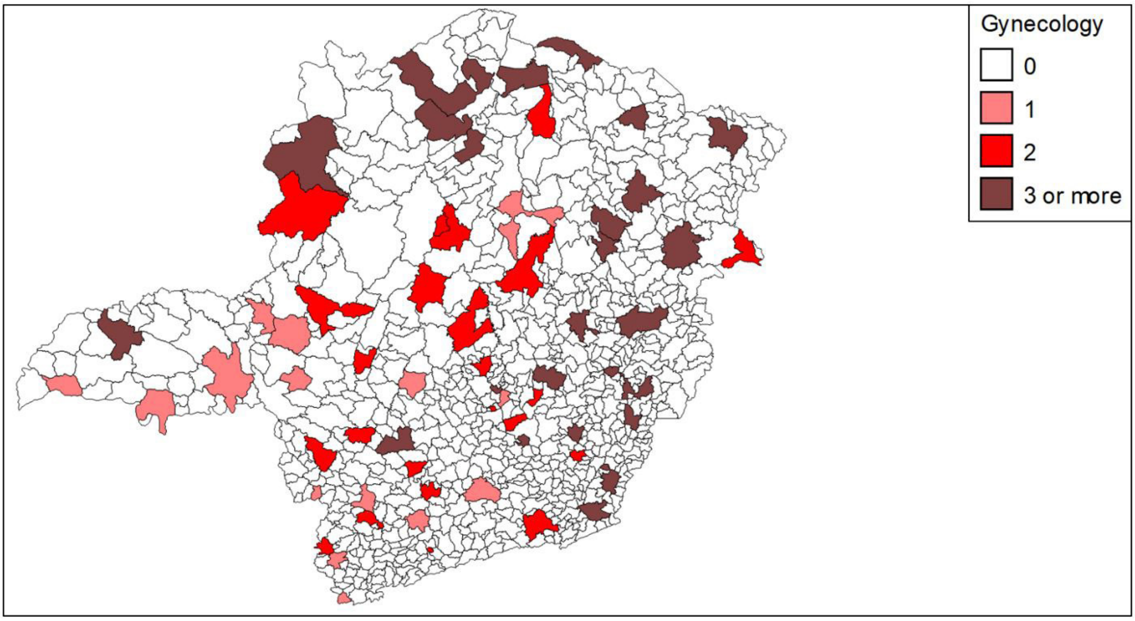

Figure A9. Gynecology hiring suggestion for scenario [3].

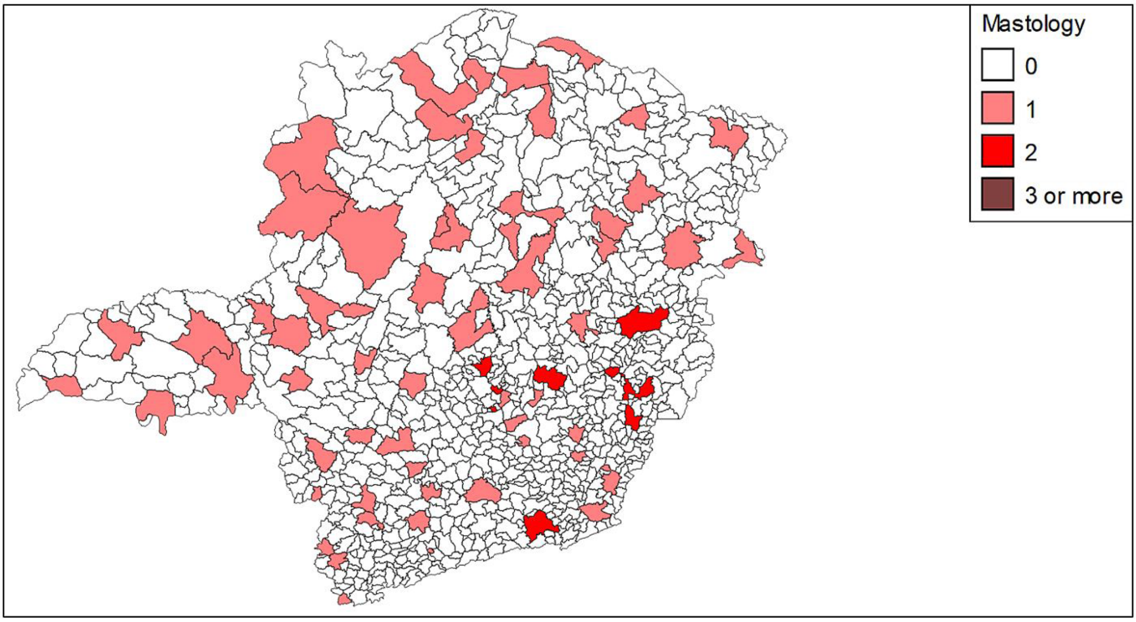

Figure A10. Mastology hiring suggestion for scenario [3].

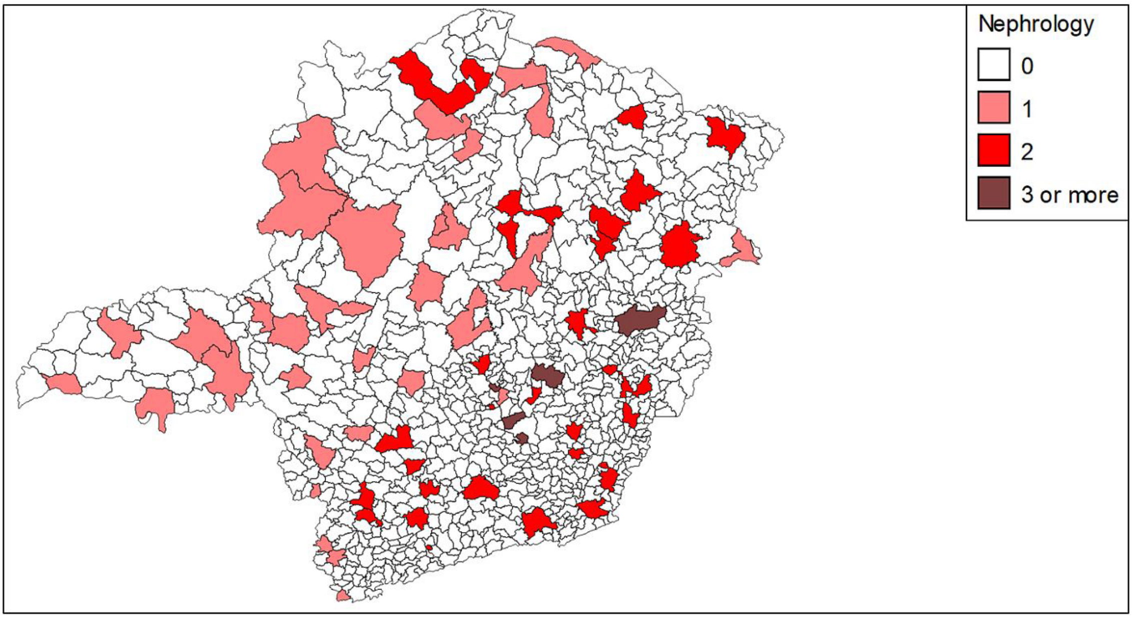

Figure A11. Nephology hiring suggestion for scenario [3].

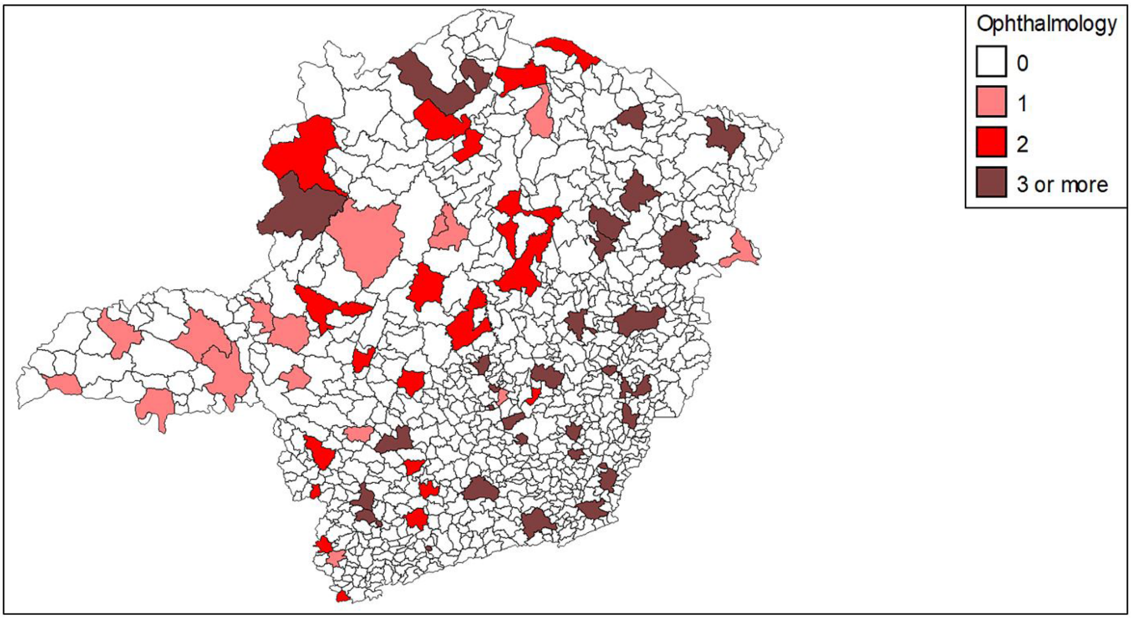

Figure A12. Ophthalmology hiring suggestion for scenario [3].

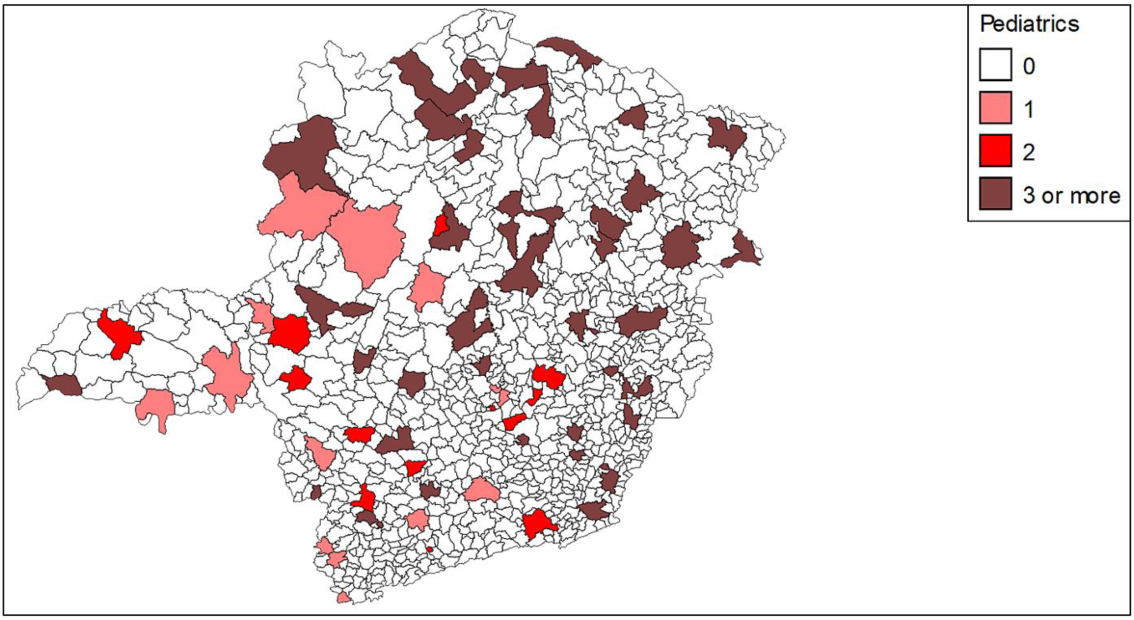

Figure A13. Pediatrics hiring suggestion for scenario [3].

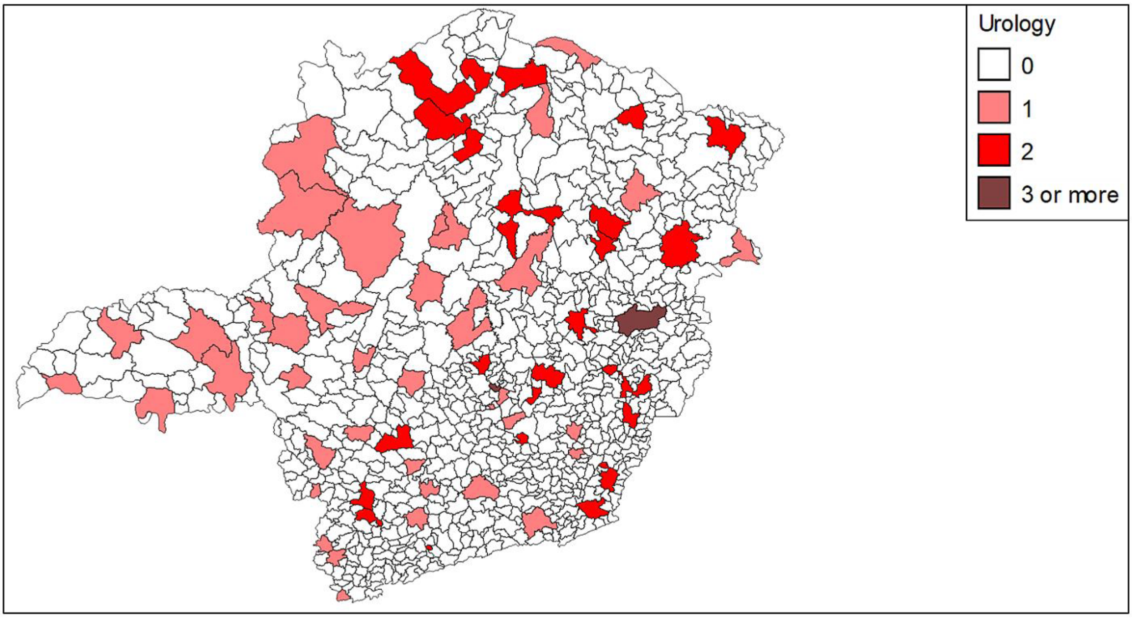

Figure A14. Urology hiring suggestion for scenario [3].