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Assessing performance in health care: A mathematical programming approach for the re-design of primary health care networks.

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Highlights

-Model-based assessment and re-design of first-level health care networks.

-Medical consultations need is the driving force of the proposed changes.

-Geographic distance and perceived attention quality are explicitly considered.

-Satisfied medical consultations demand increases by re-distributing offer capacity within existing centers.

Title

Assessing performance in health care: a mathematical programming approach for the re-design of primary health care networks

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Authors' contributions

Maria Eugenia Elorza: Conceptualization, Methodology, Software, Investigation, Writing- Original draft preparation, Writing- Reviewing and Editing; **Nebel Silvana Moscoso**: Conceptualization, Writing- Original draft preparation, Writing- Reviewing and Editing. Funding acquisition; **Anibal Manuel Blanco:** Conceptualization, Methodology, Supervision, Software, Writing- Original draft preparation Writing- Reviewing and Editing.

Abbreviations

FL: First Level of Health Care

PHCC: Primary Health Care Centers

MILP: Mixed Integer Linear Program

CC: Census Cells

NC: Need Cells

OC: Offer Cells

Highlights

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Abstract

Mathematical models allow studying complex systems. In particular, optimal facility location models provide a sound framework to assess the performance of first-level of health care networks. In this work, a methodology founded on need/offer/demand quantification through a facility location-based mathematical model is proposed to assess the performance of existing networks of Primary Health Care Centers (PHCC) and assist in its re-design. The proposed re-design problem investigates the re-allocation of existing resources within the given infrastructure (existing PHCCs) to better satisfy the estimated health needs of the target population. This problem has not been widely addressed in the open literature despite its paramount importance in modern societies with fast demographic dynamics and constrained investment capacities. The model seeks to optimally assign the required type of service and the corresponding capacity to each PHCC (offer). The objective function to be maximized is the number of (needed) patients' visits effectively covered by the network (demand). The following constraints are explicitly considered: i) geographic accessibility from need centers to PHCCs, ii) maximum delivery capacity of each service in each PHCC, and iii) total budget regarding fixed, variable, and relocation costs. The proposed methodology was applied to a medium-size city. Results show that the non-attended necessity can be reduced by introducing capacity modifications in the existing network. Moreover, different solutions are obtained if budgetary restrictions or minimum attention volume constraints are included. This reveals how model-based decision support tools can help health decision-makers assessing primary health care network performance.

Keywords

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1. Introduction

Performance evaluation in the health care sector provides decision-makers with adequate information to improve the results achieved from the allocated resources. Different approaches have been proposed so far to address such a complex task. On the one hand, various methods have been devised and applied to evaluate the performance of health providers, mainly hospitals [1]. For example, a composite indicator that incorporates preference information of decision-makers has been developed to evaluate the overall performance of public hospitals [2].

On the other hand, a set of frameworks have been developed to evaluate the performance of the health system holistically [3]. In this line, Murray and Frenk [4] presented the first conceptual framework to evaluate the extent to which health systems achieve their goals with available resources. They included the different objectives that a health system must meet to improve the health status and distribution of the population, meet their expectations, and ensure equity in financing.

Likewise, the methods developed to measure the performance of healthcare providers have been adjusted to evaluate health systems established at the national level in countries around the world [5] [6].

Developments in this area have shown that performance evaluation in the health care sector is a valuable tool for health managers to design policies to improve their health systems [7].

In addition, performance assessment has been also probed to fit perfectly in urban contexts to evaluate local health systems, where local governments tend to play an active role in assuring first-level service delivery [8] [9].

Performance measurement is of paramount importance in the first level of health care (FL) because there is abundant empirical evidence that suggests that inefficiency is widespread at this attention level in developing countries [10]. The FL is the entry point into the health care systems and typically offers services through Primary Health Care Centers (PHCCs). In PHCCs, the needs related to the prevention of diseases are covered and activities are carried out to promote healthy lifestyles. Regardless of the specific organization of a health system, a critical issue is people´s ability to reach the specific medical service when needed, a condition known as accessibility [11].

Four dimensions of accessibility to healthcare can be distinguished: i) administrative; ii) economic; iii) cultural and iv) geographic [12]. In general, these dimensions are studied separately when assessing healthcare access. Particularly, the geographic factor, related to travel distances and times, can explain the greater or lesser accessibility of the population to the FL. Therefore, if the distribution of the PHCCs is well designed and the type and volume of the services offered in each PHCC are conveniently organized, better accessibility can be guaranteed.

The particular design of the FL infrastructure (number and size of PHCCs) determines the resulting accessibility. Health service network design is known as one of the most critical strategic decisions that affect the performance of health systems to the great extent [13]. Health systems around the world are currently facing the challenge of redesigning services to respond to the changing health needs of their populations and improve their performance.

Recently, the same methods used to evaluate the performance of health service provider units have been used in combination with other quantitative methods to generate information that assists decision-making in health linked to the redesign of care networks at the FL. For example, Shiri et al. [14] designed a network of PHCCs for a region of Iran based on the development of a new DEA technique to identify the best locations based on their efficient performance.

In Argentina, for example, the services of the FL are largely provided by the state government through PHCCs, which have the purpose of guaranteeing universal access to basic healthcare. These centers are essential to ensuring free access to low-complexity healthcare for people without health insurance (more than 30% of the population).

Since these services are typically managed by municipal governments, the quality of the service depends on the relative wealth of each district. The performance of the FL is constantly assessed by health managers to match the offer and the need as closely as possible as the cities change demographically and socioeconomically.

In this work, we explored the use of mathematical programming to study the performance of FL. Essentially; a mathematical model is proposed to determine the optimal capacities of the services to be offered in each PHCC of a FL public network, in order to maximize the coverage of needed consultations throughout the year. In this approach, the total demand of consultations in all services of all PHCCs of the network is adopted as the key assessment indicator of performance.

The model is quite general in scope. Specifically, it was used here to evaluate the base/current situation of the existing PHCC network and address its re-design. The re-design problem investigates the re-allocation of existing resources within the given infrastructure (existing PHCCs) to better satisfy the estimated health needs of the target population. According to our knowledge, this problem has not been widely addressed in the open literature despite its paramount importance in societies with rather fast demographic dynamics and constrained investment capacities.

The Bahía Blanca district, Buenos Aires Province (Argentina), PHCCs network is adopted as case study. This research is part of an ongoing collaboration with personnel from the Health Secretary, which is the office that coordinates the public health system in Bahía Blanca district. The staff of the secretary is interested in developing systematic decision support tools as part of a continuous informatization process taking place in the whole administration. We were provided with the available consultations database and complete information on the infrastructure at each PHCC. Additionally, the district's distribution in terms of census cells was analyzed with the assistance of the cadaster department staff.

This paper is structured as follows. In the next section, we present a review of the literature related to mathematical models for the optimal location of FL services. In Section 3, the problem under consideration and the corresponding mathematical model are described in detail. Section 4 presents the addressed case study together with a brief description of the most relevant parameters. The following section provides the results of four different computational experiments. A conclusions and discussion section closes the article.

2. Literature review

Mathematical programming modelling is a powerful approach to systematically investigating complex systems. Some of its major advantages are the possibility to expose all relevant variables simultaneously and to monitor the effect of the main parameters on the performance of systems. Current computing technology allows the programming and efficient resolution of mathematical models with thousands of variables and parameters in desktop computers. The main challenges arising from the effective model building of complex systems are the thorough understanding of the ongoing relations and the gathering of the required data, which is inevitably uncertain in most cases [15].

Mathematical programming has been widely applied to investigate different important issues of healthcare systems. Such activities can benefit from information systems and adequate analytic tools. One tool to assist in such process involves mathematical models for optimal location [16].

There are many types of location models [17]. Broadly speaking, some seek to minimize installation costs to cover the total demand, while others aim to minimize travel distances or times. Many works propose multi-objective approaches as well**.** The optimal configuration of the network of PHCCs to cover the needs depends on the performance metric adopted by the decision-maker. From a mathematical point of view, optimal location models typically assume a mixed integer linear formulation (MILP), where binary variables are used to decide, for example, to open or not a PHCC at a certain location, or to represent if a certain service should be provided or not at a given center [18].

The literature on optimal coverage applied specifically to healthcare facility location is vast. A comprehensive survey of health care facility location, is presented by Ahmadi-Javid et al. [19]. Very recent reviews are also provided in Mendoza-Gomez et al. [20][21].

The studies of location of healthcare facilities differentiate according to the considered type and number of objective functions, the inclusion or not of parameter uncertainty, the adoption or not of a multi-period analysis and the modeling and solution approaches, among other features.

Additionally, some studies also address finding a set of optimal sites from scratch (network design) while others aim at modifying the existing networks to improve the performance of the system (network redesign).

Finally, the contributions may address the location problem in one or more of the healthcare levels: First Level (basically PHCC networks), Second Level (basically hospitals) or Third Level (special services and complex diagnosis).

Next, most relevant contributions that have been specifically proposed to improve the performance of the existing system (network redesign approach) in the context of primary level of health care are briefly reviewed.

Baray et al. [22] combined maximum coverage and p-median models for the analysis and improvement of perinatal care in France, organized as a three-tier hierarchical network, including PHCCs. They use a bottom-up approach in which a maximum-covering model is used to locate PHCCs.

Mitropoulos et al. [23] developed an optimization model with which the best location of health facilities is determined, proposes which facilities should be expanded, improved or closed, and establishes which basic vital services should be provided in each center.

Pehlivan et al. [24] proposed a model for dynamic capacity planning and location of perinatal care units organized as a three-level hierarchical network and applies it for Paris (France). Their solution strategy, based on a nonlinear programming model, addresses decisions regarding opening/closing down facilities and capacity expansion/downsizing.

Musazadeh et al. [25] addressed the problem of redesigning a multi-period three-level health service network (including the FL) by developing a mathematical model to study the northeastern area of Tehran (Iran). The model involves strategic decisions on locating, closing and expanding the capacity of network's facilities over the planning horizon to achieve an accessible, stable and equitable network.

Other contributions acknowledge that different types of services are typically provided in the PHCCs and take this aspect into account in the model.

Griffin et al. [26] proposed a maximal covering location model for optimizing the primary healthcare network of the State of Georgia (USA). The purpose of this work is to identify the number and location of centers, together with the services provided in each one.

Mestre et al. [27] proposed a hierarchical and multiservice mathematical programming model to decide upon the location and structure of hospital's supply when their main objective is to improve access to hospital services. The model considers the multiservice structure of hospital production (inpatient care, emergency care, and external consultations, such as those provided at FL) and the costs associated with reorganizing the network.

Ahmadi-Javid et al. [28] designed a network of health posts that, through a nonlinear model that simultaneously determines the location of the facilities, the mix of labor in each open center and the appropriate number and capacity of the facilities.

Mendoza-Gómez et al. [20] proposed a model to define the regionalization of primary health care services that allows improving access to health services in the State of Mexico (Mexico). They employ a MILP model to minimize the total travel distance in a trained facility location problem. Capacity is measured in units called basic kernels (a standard group of health personnel). This approach aids on the location of new PCHHs and the change of capacity of the existing ones within a multi-institutional system.

Mendoza-Gómez et al. [21] used a variation of the maximum coverage problem to address the problem of locating new facilities or improving existing ones aimed at maximizing the coverage of a set of complementary services (nutritional counseling, dental care, mental health and clinical tests) available in the PHCCs. The model contemplates that the cost of opening new facilities and improving existing ones is restricted to a budget. They apply it to the case of the Mexican public health system in the State of Mexico.

Davari et al. [29] presented a mixed-integer programming model to design PHCC networks that maximize accessibility subject to budget constraints and congestion considerations. They developed a biased variable neighborhood search algorithm to solve their model.

Zhang et al. [30] designed a multi-objective health centers allocation model that was applied to the case of Hong Kong. Among the objectives considered in the problem it is the cost of building new centers, and among the decision variables, the capacity level of each one.

Dogan et al. [31] developed a strategic level multi-objective mixed integer linear programming model for locating PHCC facilities to ensure maximum participation and providing timely service under a budget constraint. They apply the model to the case of Istanbul (Turkey) and solve it considering the forecasted population for the next 15 years.

Another group of works stand out for taking into account that users of the FL have different characteristics.

Shariff et al. [32] considered the effects of population growth when studying the maximal coverage problem applied to healthcare facilities in one Malaysian district through a genetic algorithm approach.

Kim et al. [33] addressed the problem of redesigning a network with two types of health centers (public and private) that provide services to two types of patients (low and high income). Their model, applied to the Korean healthcare system, has the objective of maximizing the number of patients covered by both types of health centers, with a budget constraint for the establishment of new public facilities.

Graber-Naidich et al. [34] took into account the heterogeneous health profiles of the population in the design of a FL network with different types of healthcare facilities through a mixed integer programming model.

In Argentina, the systematic use of mathematical optimization models for decision support in the planning of the FL is still scarce. Remarkably, Buzai [35] implemented a maximum coverage model to establish the actual coverage provided by the twelve PHCCs of Luján city (Buenos Aires). In that study, the city was partitioned according to census cells and it was established that no inhabitant should be farther than 1500 m from the nearest PHCC. According to such criteria, only 33% of the population had optimal accessibility to the preventive level.

According to the studies reviewed, the mathematical models developed to evaluate the performance of the re-design of networks of primary health care centers always consider the possibility of closing and opening health centers to improve accessibility or reduce costs. However, in health care systems such as Argentina's, this is often not a possibility, due to cultural, political, or economic issues.

In this sense, it is essential to design tools that allow evaluating the performance of different reorganizations of the services provided in established health centers, to bring supply closer to need. Our contribution addresses this particular issue. The main challenge of this endeavor is the appropriate estimation of the population healthcare needs, which depends on social demography. In order to this, our approach relies on a very disaggregated representation of the population healthcare needs in terms of gender, age, socioeconomic level and territorial distribution.

Although the problem is motivated and stems from a specific problem in Argentina, the methodological framework can be adopted in a wide range of applications where the location of the supply centers cannot be modified in the short term, but where it is feasible to modify the type and volume of the services provided in each one.

3. Problem statement and formulation

A variant of the maximum coverage problem is proposed to establish the optimal increment or decrement of offered consultations of each medical service available in each center of an existing network. The objective is to maximize the coverage of needed consultations of the target population yearly. Capacity, budgetary, and geographic constraints are taken into account. This “service capacity problem” is addressed instead of the “PHCC location problem”, since evidence suggests that, in Bahía Blanca, PHCCs are reasonably well distributed from a geographic point of view, but the service volume offered in each center does not necessarily match the needs of the target population [36].

This work assumed that the existing PHCCs cannot be closed and that only the number of offered consultations of each service for each center can be changed to adapt to the needed consultations. It may happen, for example, that the offer of certain services in some PHCC is set to zero if there is a very low need for such service in the covered region, while other services may require a larger volume of offered consultations in the same center due to the need profile of the target population.

The population is classified according to its distribution in census cells (CC), which is the most desegregated level of detail available in geographic information systems in Argentina. Each CC comprehends some 300 households on average. Each CC is also defined as a need cell (NC) since its population is considered to have health needs to be fulfilled by the FL network. In addition, some of the CCs are offer cells (OC) if a PHCC (or hospital) is located at the specific CC.

The medical services considered are those usually provided by the FL in Argentina: i) nursing, ii) general family medicine, iii) pediatrics, iv) gynecology, v) obstetrics, vi) mental health and vii) odontology. For modelling purposes, each service in each PHCC is considered to have one of three possible capacities, according to the number of consultations that can be offered by the available personnel and the installed infrastructure: low, medium and high.

To summarize, this work used estimations of health necessity in each census cell calculated as the number of consultations required of each preventive service according to the gender and age profiles of the target population. The actual demand for consultations was modelled as a function of the distance between each NC and OC, being large in the surroundings of the healthcare center, but rapidly decreasing as moving away.

Next, the proposed model is presented. Sets, parameters, variables and equations are listed, defined, and described in detail in the following subsections. Since the involved constraints and objective functions are linear, and binary variables are necessary to represent some of the required logic, the resulting model is a MILP.

3.1. Sets

i *Need Cells (Census Cells).* $i \epsilon (1, nNC)$

z *Offer Cells (PHCCs and hospitals).* $z \epsilon (1, nOC)$

j *Services offered at the OC* $j \epsilon (1, m)$

k *Capacity levels of services in OC*

3.2. Parameters

n_{ij} *Annual needed consultations of service j by patients located in NC* i

g_{iz} *Proportion of patients located in NC i willing to travel to OC* z

d_i *Proportion of patients from NC* i *willing to perform preventive consultations*

CAP_{jk} *Maximum annual consultations of service* j *that can be attended with a capacity level* k

B *Total network budget*

τ_{zj} *Minimum proportion of consultations to be necessarily attended*

CFm_{jk} *Fixed material costs of service* j *at capacity* k

CFh_{jk} *Fixed personnel costs of service* j *at capacity* k

CV_j *Consultation costs of service j*

CR_{jk} *Relocation costs of service* j *at capacity* k

$c_z = 1$ *If an OC is located in OC*z*,* 0 *otherwise*

$si_z = 1$ *If a PHCC or hospital is located in OC*z*,* 0 *otherwise*

o_z *Proportion of patients willing to perform consultations in OC* z

β_i *Proportion of patients from NC* i *that demand attention*

3.3. Variables

y_{izj} *Consultations of patients from NC* i *attended by service* j *of OC* z

$sn_{ijk} = 1$ *If service* j *at capacity* k *should be provided in OC*z*;* $= -1$ *if service* j *at capacity* k *should be removed from OC* z*;* $= 0$ *if no modification of service* j *at capacity* k *should be performed in OC* z

$s_{zjk} = 1$ *If service* j *at capacity* k *is provided in OC*z, 0 *otherwise*

$sf_{zjk} = 1$ *If service* j *at capacity* k *is offered in OC*z, 0 *otherwise*

D *Annual deficit or surplus*

3.4. Equations

Equation (1) represents the objective function of the model to be maximized. It stands for the total number of preventive consultations attended by patients of all NCs, in all services in all OCs.

$$Max \qquad \sum_{i=1}^{nNC} \sum_{z=1}^{nOC} \sum_{j=1}^{m} y_{izj} \qquad (1)$$

Equation (2) introduces a constraint that reflects barriers to accessibility. Specifically, the consultations demanded in OC z of service j of patients from NC i are considered a fraction of the total needed consultations in NC n_{ij}

$$y_{izj} \leq g_{iz} * n_{ij} \qquad \forall\, i, z, j \qquad (2)$$

Parameter g_{iz}, which modulates the actual demand for the services, is a function of the distance between NC i and OC z.

Therefore, the separation between supply (i.e., health care providers) and need (i.e., population) is used to model the attractiveness of OC z. This work considers that the geographic barrier is the most relevant determinant of attractiveness [37] [38].

In this context, g_{iz} is modelled as a function of the distance between the cells (Eq. 2.1).

$$g_{iz} = ae^{-\frac{(d_{iz}-b)^2}{2c^2}} \qquad (2.1)$$

There is no consensus regarding the "best" function to model the relationship between need and travel distance [39]. We adopted a Gaussian function because it provides a large amount of flexibility to adapt to different scenarios, provided that enough information is available to estimate its parameters with reasonable accuracy in different situations (Eq.2.1).

Parameter $\mathrm{d_{iz}}$ represents the distance in meters between NC i and OC z. Parameters a, b, and c were arbitrarily chosen such that $\mathrm{g_{iz}}$ has values close to 1 in a few blocks around the OC, but decreases steeply with distance ($\mathrm{a} = 1, \mathrm{b} = 0,$ and $\mathrm{c} = 1000$). Figure 1 shows the shape of the adopted function.

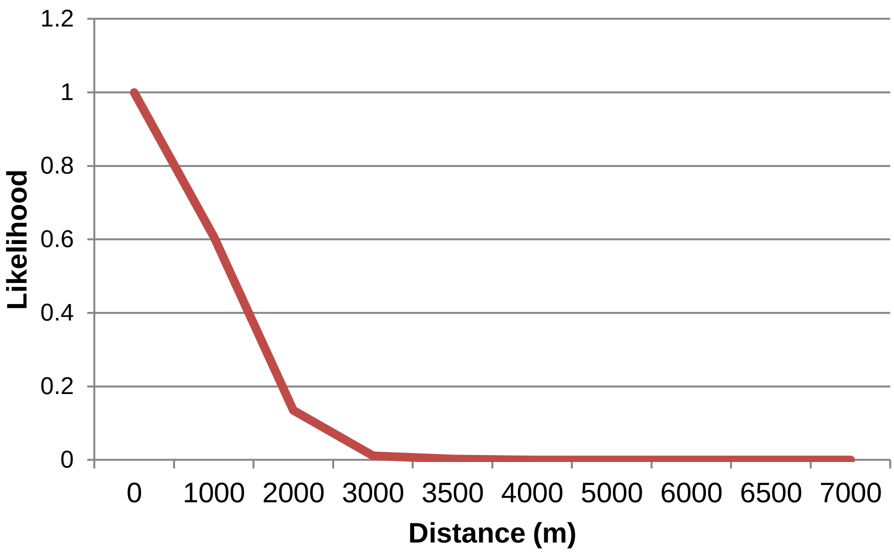


Fig 1. Travelling likelihood between NC i and OC z

This means that a relatively large percentage of the population is predisposed to visiting a PHCC in a location close to their residence, but for distances greater than 3000m, this predisposition approaches zero.

Equation (3) introduces an access barrier from the demand side. It is considered that the demand for consultations of the total necessary consultations is modulated by parameter β_i, which quantifies the proportion of people of a NC who will effectively visit a PHCC. Some studies suggest that spatial interactions between patients and health centers are also affected by patients' socioeconomic status [40].

Proportion β_i is a function of the socio-economic characteristics of the population of the NC, such as educational level, poverty level, proportion of foreign people, etc. It is usually difficult to be estimated and can be inferred from censual data.

$$y_{izj} \leq \beta_i * n_{ij} \qquad \forall\, i, z, j \qquad (3)$$

In this work β_i, were estimated from the proportion of three categories of people living in a specific NC: i) unemployed individuals, ii) illiterate individuals (people who cannot read and write), and iii) foreign individuals. Because no standard model exists to our knowledge to relate demand predisposition to such social profile, the following approach was adopted in this work (Eq. 3.1):

$$\beta_i = 1 - \frac{FP_i + IP_i + UP_i}{TP_i} \qquad \forall\, i \qquad (3.1)$$

FP_i: $foreign\ people\ in$ NCi

IP_i: $people\ who\ cannot\ read\ and\ write\ in$ NCi

UP_i: $unemployed\ people\ in$ NCi

TP_i: $total\ population\ in$ NCi

It should be noted that the fraction of the population that will not voluntarily seek consultations in the FL for the aforementioned reasons is worth quantifying, since it would typically require additional state efforts to make healthcare accessible for those individuals.

Equation (4) models potential barriers to accessibility from the offer side by considering that the number of consultations demanded in a certain OC is only a fraction of the total needed consultations in the NC.

$$y_{izj} \leq o_z * n_{ij} \qquad \forall\, i, z, j \qquad (4)$$

Proportion o_z limits the actual demand on OC z and is a function of the perception of the overall quality of attention provided in the PHCC. In general, this feature is related to issues such as the waiting times required to receive attention, the extension of the working period of the PHCC and the possibility of performing multiple consultations during the same visit. Although such a characteristic is difficult to quantify, this work assumed that a large center with many services is more "attractive" to the population than smaller ones. This approach was adopted based on certain work that showing the availability of qualified staff is an important determinant of FL utilization [40].

Arbitrarily, Equation (4.1) is proposed to calculate the value of such parameter.

$$o_z = \frac{\sum_{j=1}^{m} \sum_{k=1}^{q} \varphi_k * s_{z,j,k}}{7} \qquad \forall z \qquad (4.1)$$

This equation intends to estimate the "attraction" generated by the center as an average of the existing services, weighted by the corresponding capacities. Parameter φ_k takes values 0.5, 0.75 and 1.0 for low ($k = 1$), medium ($k = 2$), and high ($k = 3$) capacities, respectively. For example, if a PHCC offers the seven services at the highest possible capacity each, then, proportion o_z equals one. On the contrary, if a center offers only the nursing service at the lowest capacity, o_z equals 0.07 and the center is regarded as low attractive.

Thus, Equations 2 to 4.1 provide a way to integrate spatial access and non-spatial factors into the mathematical model by adjusting the definition of demand using non-spatial factors.

Equation (5) establishes that the total number of consultations of a particular service j that can be attended in a specific OC z cannot exceed the capacity of that service in that OC.

$$\sum_{i=1}^{n} y_{izj} \leq \sum_{k=1}^{q} CAP_{jk} * s_{zjk} \qquad \forall z, j \qquad (5)$$

The number of consultations is determined by the existence or not of service j in OC z. If the service exists, it is provided at a specific capacity (k) of the q possible standard capacity levels (high, medium and low). Equation (6) ensures that a specific level of capacity (CAP_{jk}) is adopted or that the service is not available in the node.

$$\sum_{k=1}^{q} s_{zjk} \leq 1 \qquad \forall\, z, j \qquad (6)$$

Since the closure of an existing PHCC is not allowed, every OC is required to provide at least the nursing service at a convenient capacity (Eq. 7).

$$\sum_{k=1}^{q} s_{zjk} = 1 \qquad \forall\, z \in (1, nc), j = 1 \qquad (7)$$

Equation (8) is the budgetary constraint. It determines that the total costs (CT) equal the available budget (B) plus a slack variable (D) that quantifies the possible deficit or surplus of the system. Variable D is introduced because, although there typically exists a municipal budget for the FL system (B), if justified, additional resources could be assigned to health care from, for example, other governmental sources. In other words, budget B may not necessarily act as a hard constraint on the system. Therefore, variable D was used in this study to evaluate tradeoffs between accessibility and economics.

$$CT = B + D \qquad (8)$$

Variable costs and relocation costs were considered (Equation 9). The former include operational costs of the facilities (rent, energy, insurance, etc.)(CFm_{jk}) (Eq. 9.1), and the latter are associated with the professionals of each service in each center(CFh_{jk}) (Eq. 9.2). Additionally, there are variable costs (CV_j) corresponding to the expense generated by each consultation in each service (Eq. 9.3).

$$CT = C_1 + C_2 + C_3 + C_4 \qquad (9)$$

$$C_1 = \sum_{z=1}^{n} \sum_{j=1}^{m} \sum_{k=1}^{q} CFm_{jk} * s_{zjk} \qquad (9.1)$$

$$C_2 = \sum_{z=1}^{n} \sum_{j=1}^{m} \sum_{k=1}^{q} CFh_{jk} * s_{zjk} \qquad (9.2)$$

$$C_3 = \sum_{i=1}^{n} \sum_{z=1}^{nc} \sum_{j=1}^{m} CV_j * y_{izj} \qquad (9.3)$$

Finally, relocation costs (CR_{jk}) represent the expense (or saving) on the equipment required for the opening (or closure) of service in the different PHCCs (9.4). Equation (9.4.1) defines the variable sn_{zjk} as the difference between the situation after and before the re-design in each PHCC (z) regarding service j at capacity k.

$$C_4 = \sum_{z=1}^{n} \sum_{j=1}^{m} \sum_{k=1}^{q} CR_{jk} * sn_{zjk} \qquad (9.4)$$

$$sn_{zjk} = s_{zjk} - sf_{zjk} \qquad \forall\, z, j, k \qquad (9.4.1)$$

If $sn_{zjk} = 0$, no changes in the capacity are introduced in service j in OC z. If the variable takes value 1, it means that the OC incorporates such service at such capacity. Similarly, if the variable takes value -1, service j at capacity k is closed in the OC. It is possible, for example, that, in a certain PHCC, a specific service at capacity, say $k1$, is closed and, at the same time, the same service is opened at capacity $k3$, meaning that an overall increase in the capacity took place in that particular OC.

$$sn_{zjk} \in \{-1, 0, 1\} \qquad (9.4.2)$$

Equation (10) ensures that the number of consultations attended by service$j$, which is available in OC z, represents at least a fraction τ_{zj} of the total volume of consultations offered in the center.

$$\sum_{i=1}^{n} y_{izj} \geq \tau_{zj} * \sum_{k=1}^{q} CAP_{jk} * s_{zjk} \qquad \forall\, z, j \qquad (10)$$

This constraint ensures that a minimum number of consultations is effectively provided in a center in order to justify the maintenance of the offered service. Parameter τ_{zj} might depend on the service and the center and is defined by the decision-maker to avoid excessively restrictive solutions. For example, this work assumed that τ_{zj} equals zero for all the nursing services in the network. Moreover, clinical and pediatrics are also set to zero in OCs where there are no other close public attention alternatives.

In order to represent the results, different maps were generated with the aid of the QGIS 3.4 software. Each CC is depicted with a color tone proportional to the corresponding necessity level. Classes were obtained with the Natural Breaks method, which produces the maximum homogenization within each class and the maximum dispersion between classes. PHCCs are shown with different forms and colors according to the optimal re-design for the different services. Possible options include: i) to open the service, ii) to close the service, iii) to increase the current capacity, iv) to decrease the current capacity, and v) no changes performed.

4. Case study: application of the model to a district of Argentina

Bahía Blanca district comprehends three communities: Bahía Blanca city, Gral. Daniel Cerri and Cabildo. According to the national census of the year 2010, the total population was 301 572 inhabitants, 27% of which did not have health insurance.

The district is organized into 369 CCs. The CCs are considered NCs in this study. In specific CCs, the local governments installed PHCCs over the years in order to provide service to the FL. Such CCs are also OCs.

Specifically, the current FL network of the district has 56 PHCCs of different sizes and attention hours, offering all or a subset of the seven mentioned health services. Moreover, there are also two large public hospitals in the system. Although hospitals are supposed to provide mainly healthcare attention of the second and third levels, in practice, they also operate as PHCCs providing consultations of the preventive type. Figure 2 shows a map of the district under study divided into CC. Dots represent PHCCs.

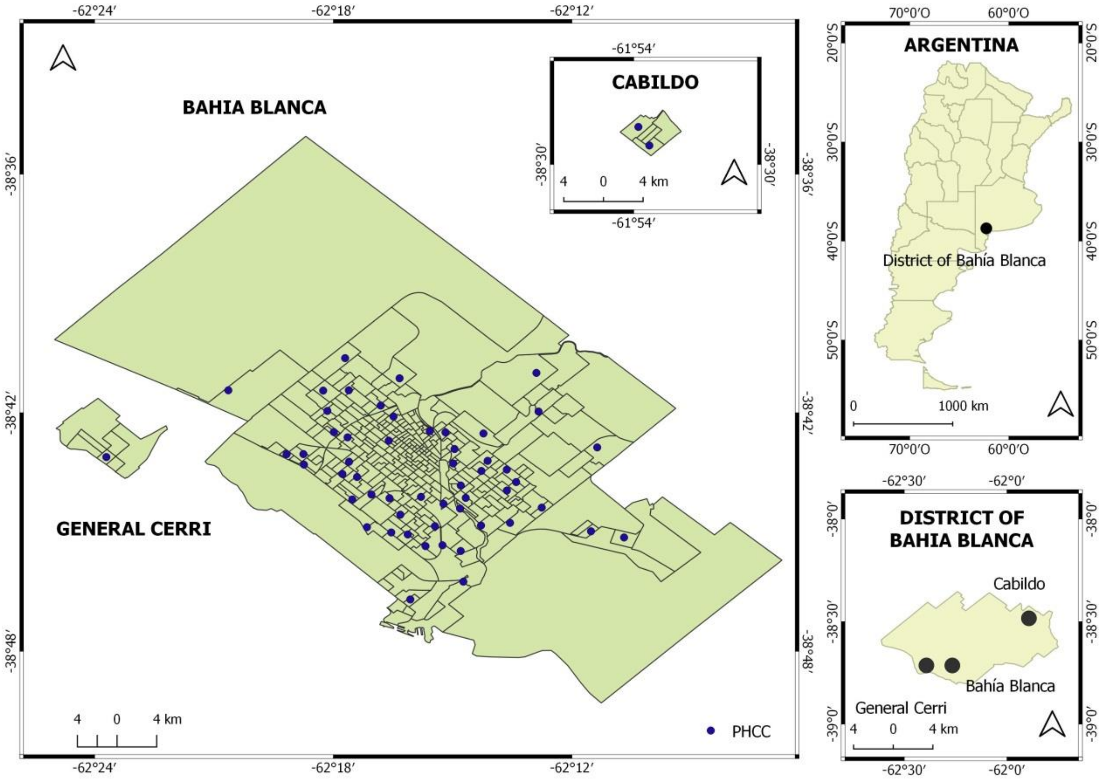


Fig.2. Geographic distribution of CCs (NCs) and OCs in Bahía Blanca District (2015)

For the year 2015, the total needed consultations of services in the FL network in Bahía Blanca city were estimated at 299 772. On average, each NC required 812 consultations, although a large dispersion among NCs exists. The NC with the lowest necessity theoretically required 81 consultations, while the NC with the largest volume might have demanded 3 095 consultations.

The distribution per service was as follows: nursing 41.34%, odontology 25.05%, pediatrics 17.44%, gynecology 4.90%, mental health 4.64%, clinical practice and family medicine 3.69%, and obstetrics 2.96%. A strong positive correlation exists among services in the different NCs, as well as between the needs and the population in each NC, as expected.

The data on the need and offer of consultations were estimated using the approach adopted by Elorza et al. [36]. These data, as well as those related to costs and budget, are provided in Appendix I, together with information on locations and distances in the system. Additionally, Appendix II summarizes the statistics of the data for: (i) the necessary consultations of each service by RC and (Table II.1) (ii) the supply capacity of each service by PHCC in the current situation of the network (Table II.2).

The model was implemented in the GAMS modelling platform using the CPLEX solver for mixed integer models. Excel spreadsheets were interfaced with the GAMS system to facilitate the intensive data entry and result visualization.

The model spans a MILP that possesses: 35 198 equality constraints, 2 885 580 inequality constraints, 7 749 binary variables, and 988 638 continuous variables. Typical solution times are about 53 minutes (wall clock) on a regular laptop computer.

5. Results

This section reports the results corresponding to the optimal re-design of the PHCC network in Bahía Blanca district.

In the first place and for comparative purposes, the current network was simulated. Then, as previously established for optimal re-design purposes, the number and location of the existing PHCCs were kept fixed, but the type and capacity of each service in each center were allowed to be modified.

Next, the results for two scenarios are shown: i) re-design subject to tight budgetary constraint, and ii) re-design with relaxed budgetary constraint. In both cases, each PHCC is required to attend at least 75% of the available consultations ($\tau_{zj} = 0.75$), except nursing in all cases and for clinical practice-family medicine and pediatrics in two particular OCs far from other OCs.

On the one hand, the fixed budget scenario was chosen, because it is probably the most likely situation any system faces. On the other, the flexible budget one is also investigated to visualize the best possible result in terms of coverage of needs and quantify the gaps, both in infrastructure and budget, towards such a desirable situation.

5.1 Current network vs. re-design under given budget

Major results for this experiment are reported in Table 1, where the current network is simulated and compared with the optimized one. It is observed that, due to re-design actions, 26 864 consultations could be additionally offered regarding the simulated original situation. Interestingly, the current total offer of consultations largely exceeds the expected demand (514 080 vs. 242 993). The proposed re-design reduces the total offer by 41% while increasing the expected consultations by 11%.

In this scenario, the increased coverage responds to a re-distribution between variable costs and operational costs. Variable costs increase by 11%, while operational costs are reduced by 40%. It is worth noting that, the re-design frees resources to be used in other centers, which is reflected in the negative value of relocation costs (USD -7 967).

Table 1. Comparison of main variables and metrics before and after re-design under given budget

Variables	Current network	Re-designed network	Difference (%)
Total annual consultations	242 993	269 857	26 864 (11%)
Material costs (USD)	36 777	20 075	-16 702 (-45%)
Personnel costs (USD)	145 6400	883 180	-573 220 (-39)
Variable costs (USD)	5 410 400	6 008 300	597 900 (11%)
Relocation costs (USD)	0	7 967	-7 967
Total costs (USD)	6 903 600	6 903 600	0 (0%)
Total offered/available consultations	514 080	305 690	-208 390 (-41%)

After the re-design, the cost structure remains quite the same, since relocation costs represent only 0.25% of the total costs. The original cost structure was as follows: operating costs 0.53%, personnel costs 21.1%, and variable costs 78.4%. After the re-design, material operating costs constitute 0.29%; personnel costs, 12.8% and; variable costs, 87.0%. Figure 3 describes the effects of the optimized re-design on each service as follows: i) opens service, ii) closes service, iii) decreases capacity, iv) increases capacity, and v) remains without change.

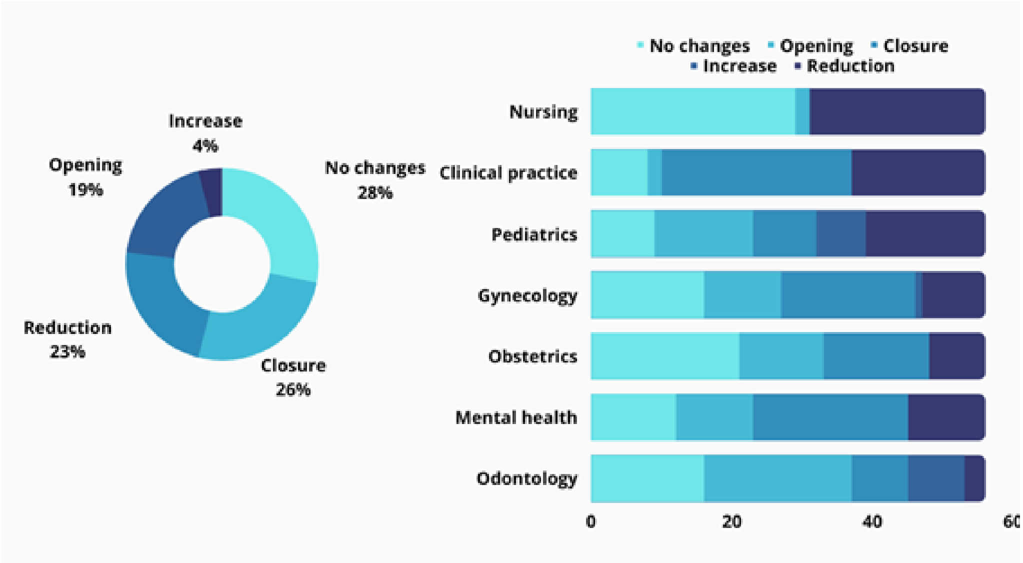


Fig. 3 Changes resulting by service from the optimal re-design problem under constrained budget

In this scenario, the optimal solution proposes to close 26% of the services, mostly at medium and low capacity levels, and to reduce capacities in 23% of the services, mostly to the lowest level. These reductions are compensated by 19% of openings, most of them at the lowest capacity level. About 28% of the services remain without modifications and there are very few cases where capacities are expanded (4%).

There are differences according to service: while nursing is the one that requires the fewest changes, others, such as clinic practice and pediatrics, require changes of various types (openings, closures, increases and reductions). In particular, the clinic practice service is the one that should be closed the most. At the other extreme, the service that should open the most and increase its capacity is odontology.

In addition, in Table III.1 of Appendix III it can be observed that, in 24 of the 56 PHCCs, nursing ($j = 1$) was reduced to the lowest capacity level, followed by clinical practice ($j = 2$) in 18 cases. Clinical practice is also closed in 27 PHCCs. For odontology ($j = 7$), on the other hand, openings are suggested in 21 PHCCs. In general, it can be concluded that more services are closed than opened (100 vs 73) and capacity reductions are more frequent than capacity increments (92 vs 16).

This suggests that, given a limited budget and unmovable locations, the re-design tends to distribute small capacity services throughout the network rather than concentrating large services in a few OCs.

5.2 Constrained vs. flexible budget re-designs

If the budgetary constraint (USD 6 903 571 in the year 2015) is relaxed, the optimal solution changes in several aspects. In Table 3, the “constrained budget” and the “relaxed budget” re-design solutions are compared. In the latter case, the re-design allows increasing by 3 203 the coverage of needed consultations regarding the optimal situation for the given budget.

Table 3. Comparison of the main variables and metrics in the constrained and flexible budget scenarios

Variables	Flexible budget	Constrained budget	Difference
Budgetary slack D (USD)	1 075 400	0	1 075 400
Total annual consultations	273 060	269 857	3 203
Material costs (USD)	48 784	20 075	28 709
Personnel costs (USD)	1 809 700	883 180	926 520
Variable costs (USD)	6 100 200	6 008 300	91 900
Relocation costs (USD)	20 327	-7 967	28 294

Total costs (USD)	7 979 000	6 903 600	1 075 400
Total offered/available consultations	752 250	305 690	446 560

The re-design generates a 46% rise in the total available consultation capacity, at the expense of an increase of USD 1 075 400 in the total costs (about 15% of the available budget). This is explained by a 32% rise in material expenses and 24% in those concerning personnel, plus the relocation costs (USD 20 327) generated by the overall opening and closing of services along the network. The variable cost due to the higher number of consultations increases by about 10%.

In the flexible budget re-design case, the cost structure is as follows: material costs0.61%, personnel costs 22.7%, and variable costs 76.4%. This structure resembles that of the existing network rather than that of the re-design with the constrained budget case, even though more than USD 28 000 is assigned to relocation expenses of services along the network.

The changes in these variables are explained by the reconfiguration of the services' capacities in the different PHCCs. Figure 4 summarize the changes introduced by the re-design process in aggregate terms and by service. It is observed that, in 25% of the cases, no changes are produced, while, in 24% of them, new services are opened. The other 19% of the changes involve reductions from high/medium to medium/low capacities. In 16% of the changes, the optimal re-design recommends an increase of capacity in the existing services (from low to medium or high). In the remaining 16% of cases, the recommendation is to close the services.

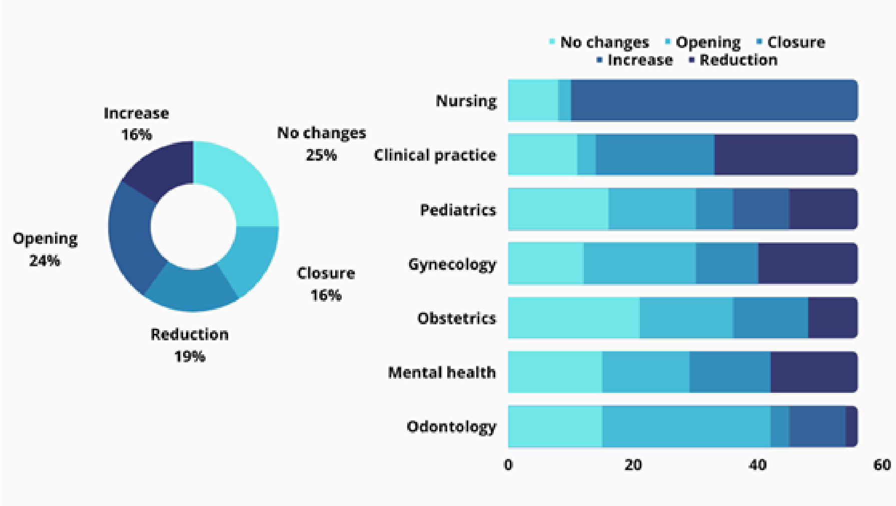


Fig. 4 Changes resulting by service from the optimal re-design problem under flexible budget

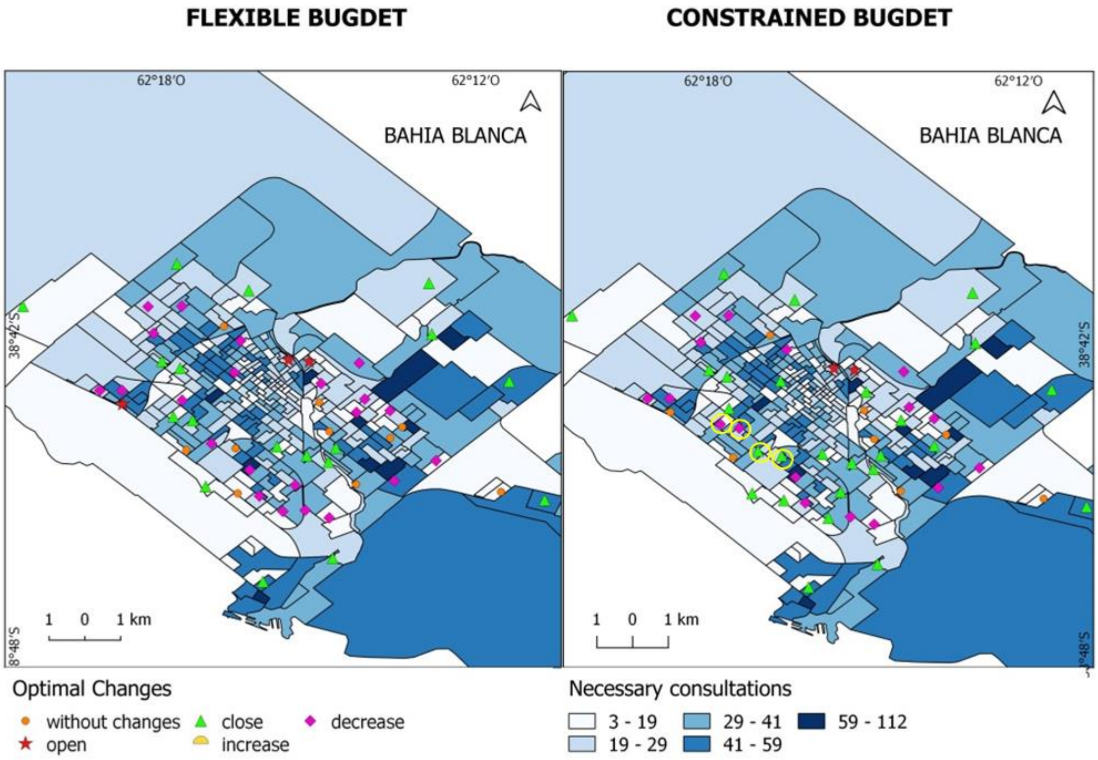
As in the previous scenario, there are differences by service. However, with a flexible budget: the nursing service should increase its capacity in most centers, the clinic practice service should reduce its capacity or close in most centers, the odontology service should mostly open in centers that they don't have it.

Table III.2 of Appendix III summarizes the changes introduced by the re-design process to the 56 existing centers in the network regarding the delivery capacity of consultations for the seven offered services.

In general, there are more openings than closures (93 vs. 63 cases), but more capacity reductions than increments take place (74 vs. 64 cases). This suggests that the re-design tends to distribute the services along the network by decreasing the capacity of many existing services and opening new ones at low capacities (except nursing and odontology). This is a natural response of the model, since if the traveling distance to the PHCC is the main barrier for demand, the most straightforward solution is to bring the services closer to the NC.

In Figure 5, the changes introduced under flexible and constrained budgets regarding the original structure for two of the services (clinical/family medicine and odontology) are graphically shown. These changes are represented with specific symbols in each case. Since both graphics look quite alike, circles indicate some of the differences between both solutions.

a. Clinical practice and family medicine case



b. Odontology case

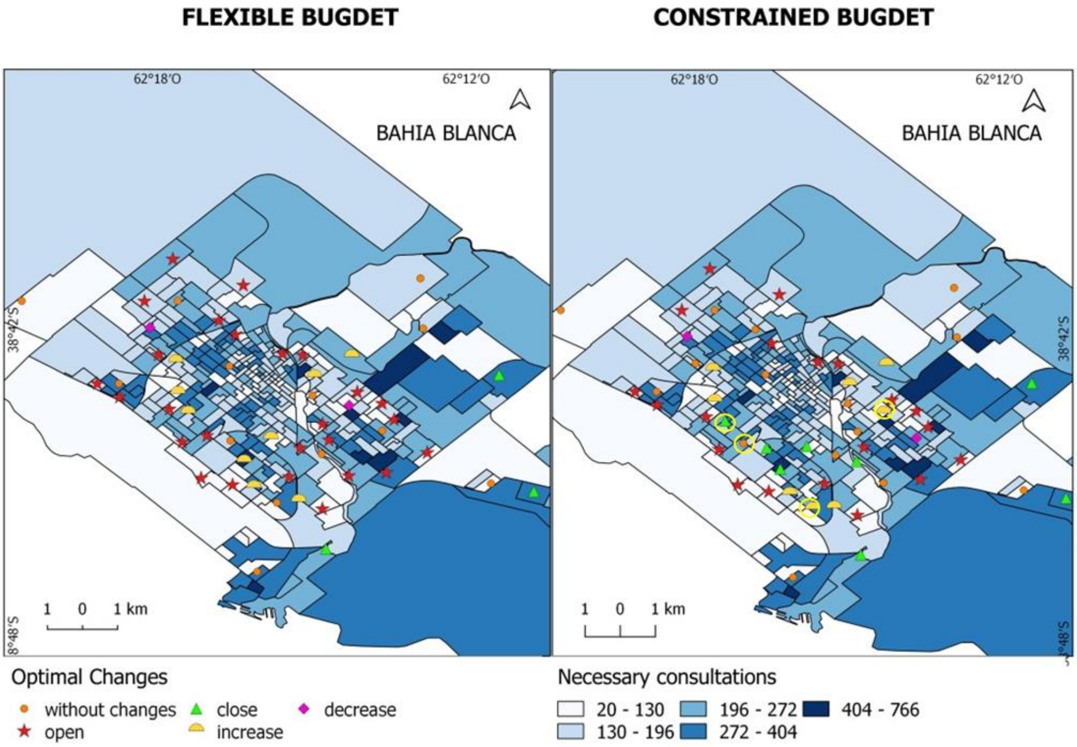


Fig.5. Geographic distribution of changes resulting from the optimal re-design problem under flexible and constrained budgets (circles show some of the differences between both graphics in each case)

5.3 Budget vs. Accessibility

When the re-design is performed under the constrained budget scenario, the achievable coverage reaches 89%, while in the flexible one, it increases to 92%. The number of consultations effectively demanded due to the optimal network re-design varies with the allowed complementary budget D. This tradeoff is shown in Figure 6, where several re-designs were run for fixed values of parameter D.

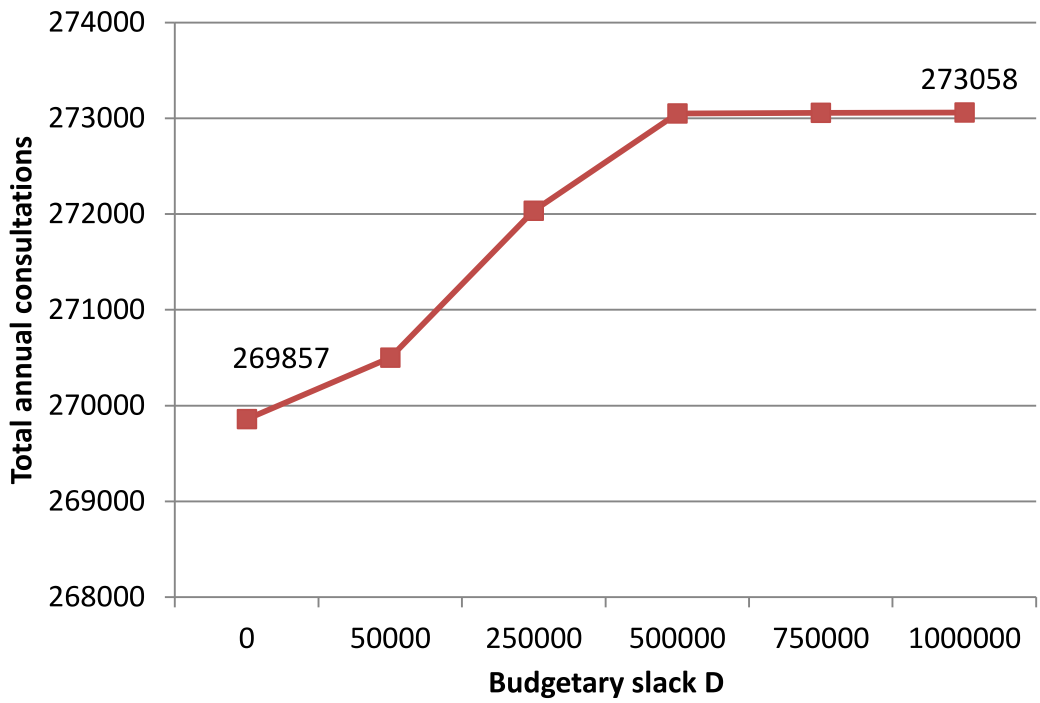


Fig. 6: Relationship between the total number of demanded consultations and budgetary slack D

It is observed that an improvement on the total annual consultations of the optimized network (original budget) for an additional USD 500 000 increase is rather modest (3 194) and becomes practically insignificant to even larger amounts. This suggests that the system is close to its full provision capacity and that additional consultations could only be obtained through the inclusion of new PHCCs in the network.

5.4 Accessibility vs. Minimum service attention

Finally, we analyzed how the system responds to different constraint levels on the minimum number of consultations required to be effectively delivered in a specific service. This constraint is modelled through parameter τ_{zj}, assigned by the decision-maker, which imposes the minimum proportion of the offered capacity that has to be effectively delivered to justify the opening (or a capacity increase) of a certain service in a particular OC. The idea behind this constraint is to enforce that at least τ_{zj} of the offered consultations are effectively delivered. This ensures a minimum activity level of the professionals in the center, in order to keep the personnel trained in the required activity. In the previous experiments, τ_{zj} was set to 0.75 for all the services in all OCs, except for nursing in all OCs and for general medicine and pediatrics in a few specific OCs, where they were set to zero to ensure the public delivery of these services.

Figure 7 shows how the total number of demanded consultations varies with parameter τ_{zj}. Nursing in all OCs and general medicine and pediatrics in specific OCs were kept at zero and the additional budget variable (D) was set free for this experiment. It is observed that, if $\tau_{zj} = 0$, the largest possible coverage is obtained. This is achieved at the expense of a 33% increase in the service capacity and the opening of new services in 32% of the OCs where they were not previously available. At the other end of the spectrum, the minimum delivery constraint is very restrictive ($\tau_{zj} = 0.9$) and thus, as expected, fewer consultations are demanded. This last case suggests quite congested PHCCs, while the previous one might correspond to excessively overdesigned services with relatively low attendance.

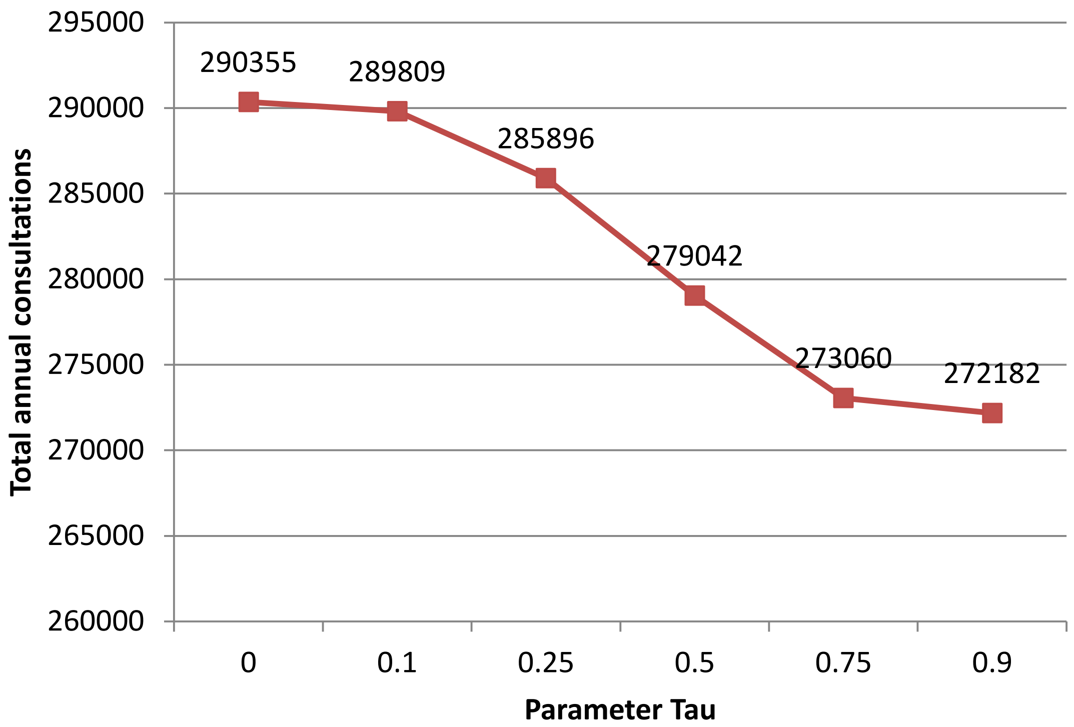


Fig. 7. Relationship between the total number of demanded consultations and parameter τ_{zj}

6. Discussion and Conclusions

The operations of existing public health systems respond in many cases to historical, cultural, political and economic constraints and might not be adequate for the current health needs. Furthermore, rapid changes in the socioeconomic and demographic profiles of populations can make existing healthcare networks less efficient than when they were first designed [41].

Currently, the importance of performance assessment of the health system for its continuous improvement is globally recognized. In particular, the FL health system has been extensively evaluated using traditional methods [42]. However, the methodologies designed to date are difficult to apply comprehensively in countries with financial issues, mainly due to limitations in the availability of data [43].

Mathematical modeling applied to resource assignment problems provides a framework to systematize the use of the available information, assess overall performance and assist in the decision-making process of the public health care sector of the FL. Several works have shown the efficacy of mathematical models for the services provided by the FL network when applied to real case studies.

A distinctive feature of the model presented in this article is the possibility of modifying the service types and capacities provided in the existing facilities with fixed locations. This reflects a common situation in developing countries, where, for different reasons, the closure of existing centers is not a viable option and the opening of new ones requires investments that usually exceed the available budgets. The natural response of the model is to distribute as many services of relatively small volume as possible across the territory, in order to maximize access.

The type of problem addressed in this contribution (redesign of a network of PHCCs) has been little studied in the indexed literature. In fact, in a recent survey [19], the authors suggest that future research in the field of health systems location problems should be oriented towards developing a holistic model to optimally design (redesign) a health system's physical network for a new (existing) city or district.

Applications to real cases of medium cities in Latin American countries are scarce. A somewhat close related reference is Flavio de Freitas et al. [44]

who proposed a mathematical model to study the problem of redesigning the second level of care (hospitals) in the state of Minas Gerais (Brazil).

Additionally, our work uses estimations of health necessity in each census cell, calculated as the number of consultations required of each preventive service according to the gender and age profiles of the target population. This represents an important difference regarding previous approaches like Musazadeh et al. [25], which are mostly based on the whole target population without considering the detailed composition of the community, which is a strong determinant of the basic healthcare requirements.

Moreover, differently from other similar studies based on demand records, like Griffin et al. [26], who proposed an approach based on demand estimations, our approach relied directly on necessity estimations, as demand data may introduce limitations in the planning of health systems since necessity not automatically translates into demand in all cases.

In this sense, it is important to note the difference between the demand and the necessity of a health service for infrastructural planning purposes. Frequently, health necessity is not perceived as such and, therefore, it does not manifest into demand or, although properly identified, access barriers, such as those discussed in the previous sections, may hinder effective access to the FL.

However, the main limitation of this study is also precisely related to the effective estimation of necessity, since a rather large amount of updated demographic and socioeconomic data is required for proper projections. Although somewhat easier to estimate than necessity, the calculations of the costs and the health delivery capacity are too a challenging endeavor. This problem was also reported in similar works applying mathematical models for health systems in developing countries, where it is difficult to gather trustworthy information from poorly organized registering systems [45]. In this respect, recent research has proposed to apply the optimal location models to the case of the FL network using open source data. These studies obtain good but limited results, because they only consider the distribution of the population and distances [46].

Therefore, several simplifying assumptions were adopted in issues of difficult evaluation, such as the willingness of people to travel to reach the service or the perception of the user towards the service quality of a PHCC. However, the most significant access barriers, not only geographic but also cultural and those related to the perceived quality of the offer, were introduced to consider all the important factors affecting accessibility to preventive health services.

The proposed model constitutes, hopefully, a practical tool to perform a systematic assessment of the healthcare system of the FL based on reasonably obtainable information. Because of the fast dynamics in the demographic and socioeconomic development of the population in large districts all around the world, and specifically in Argentina, this type of tool allows the continuous evaluation of the system and provides quantitative elements for informed decision making aimed at adapting the provided infrastructure to the actual needs.

The model also provides information on the coverage level for the existing infrastructure, which can be used to identify bottlenecks that limit access and to assess the impact of changes in costs and population demographic redistributions across the territory.

The proposed model/approach can systematically address the analysis of primary healthcare networks of cities and easily adapts to different management strategies. Through the proper setting of constraints, “the best” possible network, according to certain adopted performance metrics can be identified. In the case of the district under study, all existing centers were maintained open, but the type and volume of services offered in each one, were adapted to improve the coverage provided to the population. It should be mentioned that it is possible that one or many of the existing facilities could not adapt its infrastructure to enlarge the volume of attended patients or include new services. In this case additional facilities to complement the existing ones should be installed in the nearby of the centers or whole new buildings with improved infrastructure should be built/adapted. Additionally, if such options could not be implemented, due, for example, to budgetary or other type of constraints, alternative solutions could be easily explored by allowing the feasible changes in the specific PHCC (the possible types of services that can be provided and their maximum allowed volume) and investigate how the nearby PHCCs adapt their offer to this situation. Several other what-if type studies can be performed to aid decision-makers in adapting the current network to new population configurations when required.

The proposed model is general in scope with a large level of disaggregation in terms of population strata, medical services and territorial granularity. Although this approach requires an important amount of data, one of its main strengths is that it can easily adapt to many different situations and health systems. It should be also mentioned that the number of variables and equations scales with the number of census cells, PHCCs and services offered in each center. Although the combinatorics may turn some very large instances intractable, since each PHCC can serve only a limited number of need cells within reasonable travelling distances, additional constraints could be easily included to eliminate unfeasible demands and keep the solution times compatible with practical user interaction.

A related problem to be addressed in the future is the possibility to modify the infrastructure but not only reassigning services and capacities in existing facilities but also incorporating new centers and closing existing ones. Moreover, the tool may be used to investigate the effect of adding new services to the FL, for example, activities devoted to the wellbeing of the elderly.

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Appendix I: Data estimation

1. Annual Necessity Estimation

The total number of needed consultations of each service j in each NC i is calculated based on the specific preventive health requirements of each age and gender group through the following formula (I.1):

$$n_{ij} = \sum_{g=1}^{G} P_{gi} * SC_g * DS_r * (pn_{gi} * fn_{gi}) \qquad \text{(I.1)}$$

n_{ij} : annual consultations required of service j in NC i

P_{ig}: number of people belonging to group g in NC i

SC_g : proportion of people of group g *without health coverage*.

DS_i: proportion of people exposed to unfavorable living conditions in NC i

pn_{gj} : proportion of people of group g that require consultation of service j

fn_{gj} : annual consultation frequency of service j required by group g

Fourteen groups were considered depending on gender and age: children (younger than one-year-old; between one and two years old, between two and three years old, between three and four years old and between five and nine years old); women (between 10 and 14 years old, between 15 and 19 years old, between 20 and 39 years old, between 40 and 64 years old, older than 65 years old) and men (idem women). Services are required by people in each group of the NC (P_{ig}) modulated by: i) proportion of people without insurance in each group (SC_g), and ii) a higher number of consultations are required in those NC with unfavorable living conditions (DS_i).

The proportion of the population that uses each service according to gender and age (pn_{gj}) and the number of annual consultations per service recommended for each group (fn_{gj}) were established following data founded on prevalence and evidence-based medicine.

2. Offer calculation

The number of offered consultations per year of each service at each PHCC located in an OC z was estimated based on the annual working hours of the staff affected by each service and on the number of consultations that can be hourly delivered per specialty (2):

$$O_{zj} = \beta_j * \left(Hs_{zj} * Sa\right) * \alpha_j \qquad \text{(I.2)}$$

O_{zj}: consultations of service j offered in OC z

β_j : consultations offered per hour of service j

Hs_{zj} : weekly hours of service j in center z

Sa : weeks per year

α_j: service j modulator index

The number of weekly hours of each service in each PHCC (Hs_{zj}) is calculated as the number of hired people delivering the service in the PHCC

(RH_{zj}) multiplied by the number of weekly hours (C_j) worked by each professional (3):

$$Hs_{zj} = RH_{zj} * C_j \qquad \text{(I.3)}$$

RH_{zj} : number of people delivering service j in PHCC z

C_j : weekly hours delivered by personnel of service j

Hired weekly hours C_j are calculated as the daily hours (Hd_{zj}) multiplied by the days per week (Ds_{zj}) each professional is in service j in the PHCC in OC z. The total number of hours calculated in this way is finally affected by parameter (β_j), which represents the number of consultations per hour typically delivered in the specialty. Table I.1 summarizes parameters that represent the typical operations adopted in this work.

Table I.1. Parameters adopted to estimate the capacity per service

	Capacity level			*Low* $k = 1$	*Medium* $k = 2$	*High* $k = 3$
Service	*Nursing* *($j = 1$)*	β_j		4	4	4
		RH_{zj}		1	2	2
		C_j	Hd_{zj}	5	5	7
			Ds_{zj}	4	5	6
	Clinical practice and family medicine *($j = 2$)*	β_j		4	4	4
		RH_{zj}		1	1	2
		C_j	Hd_{zj}	3	3	3
			Ds_{zj}	2	5	6
	Pediatrics *($j = 3$)*	β_j		4	4	4
		RH_{zj}		1	1	2
		C_j	Hd_{zj}	3	3	3
			Ds_{zj}	2	5	6
	Gynecology *($j = 4$)*	β_j		2	2	2
		RH_{zj}		1	1	2
		C_j	Hd_{zj}	4	4	4
			Ds_{zj}	2	4	5

	Obstetrics ($j = 5$)	β_j		2	2	2
		RH_{zj}		1	1	2
		C_j	Hd_{zj}	4	4	4
			Ds_{zj}	2	4	5
	Mental health ($j = 6$)	β_j		1	1	1
		RH_{cj}		1	2	3
		C_j	Hd_{cj}	4	4	4
			Ds_{cj}	4	4	4
	Odontology ($j = 7$)	β_j		2	2	2
		RH_{cj}		1	1	2
		C_j	Hd_{cj}	4	4	4
			Ds_{cj}	3	5	4

Based on the parameters detailed in Table I.1, the maximum number of consultations that can be delivered by each service at each capacity level was calculated. Finally, a modulator parameter α_j $(0 \leq \alpha_j \leq 1)$ was incorporated to adjust the estimations since not all the available time is devoted to patient attention, but assigned to other activities (administrative and teaching and health promotion, among others). In general, this modulator is difficult to estimate. Some illustrative figures were gathered by direct consultation with professionals of the different services. Results are summarized in Table I.2.

Table I.2. Number of annual consultations of service j at capacity level k

Capacity level	Service						
	$j = 1$	$j = 2$	$j = 3$	$j = 4$	$j = 5$	$j = 6$	$j = 7$
α_j	*0,55*	*0,35*	*0,40*	*0,55*	*0,55*	*0,55*	*0,75*
$k = 1$	2 244	428	490	449	449	449	918
$k = 2$	5 610	1 071	1 224	898	898	898	1 530
$k = 3$	9 425	2 570	2 938	2 244	2 244	1 346	2 448

From Table I.2, it is observed, for example, that a PHCC with a low capacity $(k = 1)$ in the nursing service $(j = 1)$ can deliver a maximum of 2 244 annual consultations, while at the highest possible capacity ($k = 3$), 9 425 consultations are available.

3. Costs and budget

Table I.3 summarizes the annual operating costs due to personnel (CFh_{jk}) for each service and capacity level. Such figures were estimated from the annual hours available per service per capacity level (Table I.1) and the price per hour of professionals, estimated from the average salaries of one of the public hospitals in the year 2015 (nurse: 6.90 USD/h and professionals of the other services: 8.93 USD/h).

Table 3. Personnel operating costs per service per capacity level (USD/year)

Capacity level	Service						
	$j = 1$	$j = 2$	$j = 3$	$j = 4$	$j = 5$	$j = 6$	$j = 7$
$k = 1$	3 759	957	1 094	2 005	2 005	4 010	4 101
$k = 2$	9 399	2 392	2 734	4 010	4 010	8 020	6 835
$k = 3$	15 790	5 742	6 562	10 025	10 025	12 030	10 937

Material costs for PHCC operations (CFm_{jk}) due to expenses such as energy and gas bills, insurances, rents, etc., were also considered. It was assumed that such costs vary according to the number, type and capacity level of the offered service. For simplicity, they were calculated as a fraction of the personnel costs (π_k). Estimations from fieldwork suggest that π_k can be assumed to be approximately 2.5%.

Variable costs (CV_j) are associated with expenses generated by the attention of each patient in each consultation in each service. Three main types of variable costs were identified: i) nursing service ($j = 1$): the average cost of the vaccines included in the national vaccination calendar was considered (USD 40); ii) obstetrics ($j = 5$): basically, disposable materials such as gloves were regarded (USD 10); and iii) odontology ($j = 7$): basically, disposable materials such as gloves and needles were taken into account (USD 22). For the rest of the services, costs were set to zero. Standard prices set by the Health Ministry of the Buenos Aires province for the year 2015 were adopted.

Relocation costs (CR_{jk}) stand for expenses associated with the installation of the equipment required for the opening of a new service in a PHCC. This work assumed that these costs only depend on the capacity level at which the service is provided. It was also considered that the closure of a service in a center will set equipment free that can be reused if the same service is opened in another center. The values, summarized in Table I.4, were estimated from the buying costs of the equipment required for each service. In general, they are quite low because the services provided in a PHCC are labor-intensive rather than infrastructure dependent, with the possible exception of some specialties, such as odontology or gynecology.

Table I.4. Relocalization costs per service and capacity (USD)

Capacity level	Service						
	$j = 1$	$j = 2$	$j = 3$	$j = 4$	$j = 5$	$j = 6$	$j = 7$
$k = 1$	223	74	74	372	149	74	447
$k = 2$	298	149	149	447	149	74	521
$k = 3$	447	223	223	521	223	74	596

The annual budget available for maintenance of the FL healthcare network was estimated as a fraction of the total budget assigned to the Bahía Blanca

Public Health System. In the year 2015, the budget for the re-design, maintenance and operations of PHCCs was determined in USD 6 903 571.

4. *Other data*

The actual locations of OCs were associated with specific CCs through geographic coordinates using Google Maps from the postal addresses of the different PHCCs. The Euclidean distances in meters between the centroids of each NC (CC) and each OC were adopted for this work, although more sophisticated models are possible. The cartographic information provided in shape format corresponding to the National Census 2010 was downloaded and processed with the QGIS software.

Appendix II: Summary statistics of data

Table II.1. Descriptive statistics of the needed consultations of each service j per NC i (N=369)

Service	Average	Standard deviation	Minimum value	Maximum value
$j = 1$	336	154	34	1 285
$j = 2$	30	14	3	112
$j = 3$	142	65	14	544
$j = 4$	40	18	4	153
$j = 5$	24	11	2	92
$j = 6$	38	17	4	142
$j = 7$	203	93	20	766
Total NC	812	372	81	3 095

Services: nursing: j1, clinical practice and family medicine j2, pediatrics: j3, gynecology: j4, obstetrics: j5, mental health: j6, odontology: j7

Table II.2. Descriptive statistics of the offer capacity of each service j per PHCC in the current scenario (N=56)

Service	Average	Standard deviation	Modal value*	Minimum value*	Maximum value*
$j = 1$	4 264	2 591	2 244 (27 PHCC)	0 (2 PHCC)	9 425 (7 PHCC)
$j = 2$	1 377	1 023	2 570 (22 PHCC)	0 (7 PHCC)	2 570 (22 PHCC)
$j = 3$	1 102	1 115	0 (16 PHCC)	0 (16 PHCC)	2938 (13 PHCC)
$j = 4$	625	694	0 (23 PHCC)	0 (23 PHCC)	2 244 (6 PHCC)
$j = 5$	536	914	0 (33 PHCC)	0 (33 PHCC)	2 244 (9 PHCC)
$j = 6$	617	510	0 (17 PHCC)	0 (17 PHCC)	1 346 (12 PHCC)
$j = 7$	667	866	0 (32 PHCC)	0 (32 PHCC)	2448 (6 PHCC)
Total PHCC	9 187	9 252	5 610 (4 PHCC)[1]	3315 (i=102)[2]	25 393 (i=352)[3]

Services: nursing: j1, clinical practice and family medicine j2, pediatrics: j3, gynecology: j4, obstetrics: j5, mental health: j6, odontology: j7

* Between parentheses it is indicated in how many PHCC the same value is recorded.

[1] These are 4 PHCCs (i=3, i=196, i=242, i=338) that only offer the nursing service with medium capacity (k=2).

[2] This PHCC offers only nursing (j=1) and clinic practice and family medicine services (j=2) with the minimum capacity (k=1).

[3] This PHCC offers the 7 services with maximum capacity (k=3).

Appendix III: Results

Table III.1. Changes resulting from the optimal re-design problem under constrained budget by type de change and service

Type of change		Service							Subtotal	Total
		$j = 1$	$j = 2$	$j = 3$	$j = 4$	$j = 5$	$j = 6$	$j = 7$		
No changes		29	8	9	16	21	12	16	111 (28.7%)	111 (28.7%)
Opening	$k = 1$	2	1	11	10	11	10	5	50 (12.8%)	73 (18.6%)
	$k = 2$	0	1	2	1	1	1	7	13(3.3%)	
	$k = 3$	0	0	1	0	0	0	9	10(2.6%)	
Closure	$k = 1$	0	10	5	5	7	7	3	37(9.4%)	100 (25.5%)
	$k = 2$	0	9	2	12	5	9	5	42(10.7%)	
	$k = 3$	0	8	2	2	3	6	0	21(5.4%)	
Increase	$k = 1$ to $k = 2$	0	0	2	1	0	0	1	4(1%)	16

	$k = 1$ to $k = 3$	0	0	2	0	0	0	3	5(1.3%)	(4.1%)
	$k = 2$ to $k = 3$	0	0	3	0	0	0	4	7(1.8%)	
Reduction	$k = 2$ to $k = 1$	19	5	7	5	2	5	0	43(11%)	92 (23.5%)
	$k = 3$ to $k = 1$	5	13	4	3	6	6	1	38(9.7%)	
	$k = 3$ to $k = 2$	1	1	6	1	0	0	2	11(2.8%)	
Total PHCC		56	56	56	56	56	56	56	392 (100%)	392 (100%)

Capacities: low: k1, medium: k2, high: k3.
Services: nursing: j1, clinical practice and family medicine j2, pediatrics: j3, gynecology: j4, obstetrics: j5, mental health: j6, odontology: j7

Table III.2. Changes resulting from the optimal re-design problem under flexible budget by type de change and service

Type of change		Service							Subtotal	Total
		$j = 1$	$j = 2$	$j = 3$	$j = 4$	$j = 5$	$j = 6$	$j = 7$		
No changes		8	11	16	12	21	15	15	98 (25%)	98 (25%)
Opening	$k = 1$	0	3	3	17	13	13	7	56 (14%)	93 (24%)
	$k = 2$	0	0	7	0	0	0	7	14 (4%)	
	$k = 3$	2	0	4	3	2	1	13	23 (6%)	
Closure	$k = 1$	0	8	2	2	5	4	1	22 (6%)	63 (16%)
	$k = 2$	0	4	2	7	5	6	2	26 (6%)	
	$k = 3$	0	7	2	1	2	3	0	15 (4%)	
Increase	$k = 1$ to $k = 2$	0	0	4	0	0	0	3	7 (2%)	64 (16%)
	$k = 1$ to $k = 3$	26	0	1	0	0	0	2	29 (7%)	
	$k = 2$ to $k = 3$	20	0	4	0	0	0	4	28 (7%)	
Reduction	$k = 2$ to $k = 1$	0	10	3	12	2	8	1	36 (8%)	74 (19%)
	$k = 3$ to $k = 1$	0	12	4	3	5	6	0	30 (7%)	
	$k = 3$ to $k = 2$	0	1	4	1	1	0	1	8 (2%)	
Total PHCC		56	56	56	56	56	56	56	392 (100%)	392 (100%)

Capacities: low: k1, medium: k2, high: k3.
Services: nursing: j1, clinical practice and family medicine j2, pediatrics: j3, gynecology: j4, obstetrics : j5, mental health: j6, odontology: j7

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