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Aydin Teymourifar (aydinteymurifar@gmail.com)
Catholic University of Portugal
Maria A. M. Trindade
SDA Bocconi, School of Management

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Dynamic Resectorization to Improve Utility of Healthcare Systems

Aydin Teymourifar[1,*], Maria A. M. Trindade[2]
[1]Católica Porto Business School, Centro de Estudos em Gestão e Economia, Porto, Portugal
[2]SDA Bocconi, School of Management, Milano, Italy
[*]Correspondence: aydinteymurifar@gmail.com

Abstract

This study discusses a regional healthcare system including several hospitals with different characteristics. We define a utility function for the system based on the sectorization concept to form a balance between hospitals in terms of important outputs such as waiting times and demands. Since the determined system is dynamic, the balance state is lost over time; consequently, resectorization is done over time. We simulate the system utilizing the data of a case study. We characterize multiple periods and calculate the utility of the system's current state. We design resectorization scenarios based on boosting the capacity and quality of hospitals. Numerical results demonstrate that substantial improvement of utility with resectorization is achievable.

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1. Introduction

In healthcare systems, besides less average waiting time and higher average quality, balancing between service centers in terms of quality and demand is desired. The balancing should be supplied with policies that benefit patients; otherwise, it cannot be valuable and applicable (Teymourifar, 2022a). The concept of sectorization can be used to characterize balancing. The goal of sectorization is to divide a large region into smaller and proportional sectors (Liu et al., 2020). Sectorization intersects with districting, accessibility (Bruno et al., 2022), and balancing (Diglio et al., 2020; 2021; 2022), but in this study, we focus on its balancing aspect. This work discusses a regional healthcare system that contains hospitals with different features. Each hospital and the patients who choose it are considered as a sector. Since service systems are generally dynamic, the desired condition may be lost over time, in which case resectorization can reform it (Teymourifar, 2022a). Resectorization is not a concept different from sectorization; it is just for balance over time. We define a utility function for the discussed system based on a multi-objective (MO) model (Mokni et al., 2023). We employ the simulation method to solve the model (Teymourifar, 2022b). The sectorization models designed based on integer programming techniques are non-convex. In this case, it can be challenging to find solutions for them (Teymourifar, 2021). Simulation models do not have this deficiency. Furthermore, simulation can be a practical tool for solving dynamic sectorization models (Teymourifar, 2022a) in healthcare management (Bouramtane et al., 2022; Do Amaral et al., 2022; Guo et al., 2020; Halawa et al., 2021; Troy et al., 2020). In the dynamic model of this study, scenarios such as closing a subset of hospitals and growing capacity and quality levels are analyzed to improve the utility.

The outlines of this work, its similarities and distinctions from earlier works can be summarized as follows:

- We determine a function for patients based on which they choose a hospital. Some studies in the literature have similar definitions (Kaya et al. 2020a,b; Teymourifar et al. 2021a). Unlike them, we don't include pricing decisions in the model but consider the decision of using or closing the hospitals in different periods. This kind of facility layout decision has been investigated deeply in the literature on healthcare management (Halawa et al., 2020; Taymaz et al., 2020). However, different than many of the works in this area, we regard the quality of hospitals and the distance of patients to them for the decisions. We indicate that closing a subset of hospitals can be beneficial in terms of providing a more balanced system.

- We define the utility of a healthcare system based on sectorization. Earlier studies specify utility for individuals and/or society, not for the healthcare system (Teymourifar, 2022a; Kaya et al. 2020a,b; Teymourifar et al. 2021a).

- Unlike previous studies, we aim to balance a healthcare system in terms of both demands and waiting times. Advancing average quality is also desired.

- We consider the number of patients that exit the system. This matter is neglected in most previous works (Teymourifar, 2022a,b).

- Unlike the former works (Teymourifar, 2022a), we do resectorization for more than one period. This point makes the model more suitable for real-life applications.

Other parts of the paper are organized as follows: Section 2 presents a literature review on the topic. Section 3 describes the proposed model. The case study, scenarios, and obtained results are presented in Section 4. The explanation of conclusions and future works in Section 5 constitutes the last part of the study.

2. Literature Review

Efficient and equitable access to hospitals is a critical challenge faced by societies worldwide. A challenging subject in healthcare systems is to provide a balance between hospitals of the system. Studies in the literature deal with this subject from different sight. An article by Taymaz et al. (2020) presents a stochastic optimization model for locating walk-in clinics in a network to cater to mobile populations. The authors model the continuum of care required for different diseases using coverage definitions that reflect the adherence protocols for the services (Taymaz et al., 2020). The objective is to maximize the total expected weighted coverage of the network, subject to a Conditional-Value-at-Risk measure (Taymaz et al., 2020). The article develops coverage definitions and an optimization model and presents a computational study carried out on a real-life case in Africa (Taymaz et al., 2020).

A study by Kaya et al. (2020a) investigates the coexistence of public and private hospitals and proposes subsidy mechanisms to balance their capacity utilization and improve overall access to healthcare. The authors develop a simulation model and analyze the effects of different public policies on patients' preferences, social utility, public healthcare spending, patient satisfaction, and waiting times (Kaya et al.,2020a). The study sheds light on the importance of balancing public and private hospitals to improve access to healthcare and patient satisfaction and provides insights into the impact of different policies on the healthcare system (Kaya et al.,2020a).

Similarly, a study by Kaya et al. (2020b) proposes new contract mechanisms based on pricing and subsidy policies to balance healthcare systems containing public and private hospitals. The study formulates a multi-objective problem and proposes analytical models to determine the best contract mechanisms and optimal contract parameters to maximize the total social utility (Kaya et al., 2020b). The study presents detailed numerical results and highlights that the proposed mechanisms can significantly improve the system performance, reduce waiting times and increase patient satisfaction.

The study of Teymourifar et al. (2020) addresses the challenge of balancing healthcare systems comprising both public and private hospitals. The study underscores the existing preference of patients towards public hospitals, resulting in overcrowding and dissatisfaction, despite the better services offered by private hospitals with shorter waiting times, albeit at higher prices (Teymourifar et al., 2020). The study proposes new pricing policies and contract mechanisms between the government and private hospitals to alleviate the situation (Teymourifar et al., 2020). A MO problem is formulated, and analytical models are presented to optimize the contract mechanisms and parameters to maximize the total social utility (Teymourifar et al., 2020). The study provides a detailed numerical analysis to compare the effectiveness of the different contract mechanisms. It highlights the significant improvements in the system performance, waiting times, and patient satisfaction with the proposed mechanisms (Teymourifar et al., 2020).

In a recent study, Teymourifar (2022a) proposes a new model for balancing the accessibility of healthcare services in a region based on resectorization. The study focuses on dividing a vast region into symmetric sectors and balancing the accessibility of healthcare units, which is a common goal of governments. The proposed model considers each hospital and the patients that choose it as a sector, and it defines a new bi-objective function that aims to improve quality and accessibility. The simulation-based optimization is used for resectorization, which is portrayed as a tool for policymaking based on contract mechanisms. The experimental results showed that it is achievable to balance the accessibility of healthcare units with a suitable contract mechanism.

As seen in Table 1, this work offers new insights into healthcare management and presents a more comprehensive framework for system balancing. It presents a novel approach to balancing a healthcare system by considering various factors. Specifically, we develop a function that captures patients' hospital preferences based on quality and distance, and we explore the impact of closing certain hospitals on system balance. Unlike some related studies, we do not include pricing decisions in our model but focus on facility layout decisions and their effects on demands, waiting times, and patient exits. Additionally, we define the utility of the healthcare system itself, rather than just individuals or society, and we sectorize for multiple periods to better reflect real-life applications.

Table 1: A comparison between studies in the literature and our study.

	Kaya et al. (2020a)	Kaya et al. (2020b)	Taymaz et al. (2020)	Teymourifar et al. (2020)	Teymourifar (2022a)	This paper
Patients oriented						√
System oriented	√	√	√	√	√	
Patients' preferences	√	√		√	√	√
Pricing	√	√		√	√	
Public expenditures	√	√		√	√	
Patient satisfaction	√	√		√	√	
Waiting times	√	√		√	√	√
Hospital distance					√	√
Quality of service	√	√		√	√	√
Utility function	√	√		√	√	√
Sectorization					√	√
Multiple hospitals	√	√	√	√	√	√
Multiple periods						√
Loss of demand						√

3. Description of the Model

The problem of this study can be summarized as follows: A regional healthcare system is considered, which is comprised of hospitals with different characteristics. Some hospitals are small and have low capacity and quality, while others are large and have high capacity and quality. Despite the fact that individuals have a shorter distance to smaller hospitals, larger hospitals are preferred since they are better in terms of quality. All hospitals in the model are thought to be administered by the government, which examines scenarios involving improving hospital capacity and quality as well as closing some hospitals to provide a more balanced system. The following parts of this section elaborate on the proposed model. The used notations are summarized in Table 2.

Table 2: Used notations

Notation	Description
SI^t	Set of patients in period t
SJ	Set of hospitals
SO^t	Set of open hospitals in period t
ST	Set of periods
i	Index of patients
j and k	indexes of hospitals
J	Number of hospitals
H_j	Hospital j
t	Index of period
T	Number of periods
y_j^t	Decision variable about opening H_j in period t
x_{ij}^t	Decision variable about selecting H_j by the i-th patient in period t
I_j^t	Number of patients selecting H_j in period t
I^t	Number of patients in period t
I	Number of patients in all periods
p_j^t	Probability of selecting H_j in period t
$\bar{p}^t$	Average probability of selecting hospitals in period t
I_{out}^t	Number of patients that the system loses in period t
q_j^t	Service quality level in H_j in period t
TQ_j^t	Total quality received by patients in H_j in period t
TQ^t	Total quality received by patients in period t
m_j^t	Capacity of H_j in period t
w_{ij}^t	Waiting time of the i-th patient in H_j in period t
$\bar{w}_j^t$	Average waiting time in H_j in period t
wd_{ij}^t	Time to reach H_j by the i-th patient in period t
$\overline{wd}_j^t$	Average time to reach H_j in period t
$\overline{TW}_j^t$	Average total time before examination in H_j (including reaching hospital and waiting for examination) in period t
$\overline{TW}^t$	Average total time before examination in all hospitals (including reaching hospital and waiting for examination) in period t
$sn_{qu_i}^t$	Quality sensitivity of a patient in period t
$sn_{wt_i}^t$	Waiting time sensitivity of a patient in period t
c_j	Fixed costs of H_j
c_j^{ca}	Cost of unit capacity in H_j
cq_j^t	Cost of increasing quality in H_j in period t
cq^t	Cost of increasing quality in all hospitals in period t
c_{max}^t	Upper level of the total cost in period t
U^t	Utility function in period t
o	Index of component o of U^t
f_o^t	Component o of U^t
U	Utility function for all periods
f_o	Component o of U
S_s^t	Scenario s in period t

We presume there are hospitals in a district, all managed by the government. The set of hospitals and the j-th hospital are shown as SJ and H_j, respectively. There are differences between hospitals in capacity, quality, and the average distance of patients to them. In period t, the quality and capacity of H_j are demonstrated as q^t_j and m^t_j, respectively.

In some periods, a subset of the hospitals may be closed. In period t, the decision variable about whether hospitals are open is expressed as in Equation 1.

$$y^t_j = \begin{cases} 1, & \text{if } H_j \textit{ is open in period t} \\ 0, & \text{otherwise.} \end{cases} \quad \forall j \in SJ, \forall t \in ST. \tag{1}$$

SO^t denotes the set of open hospitals in period t. It is obvious that $j \in SO^t$ if $y^t_j = 1, \forall t \in ST$. The sensitivity of patient i to distance and quality in period t, her distance from H_j and the related waiting time are respectively indicated as $sn^t_{wt_i}$, $sn^t_{qu_i}$, wd^t_{ij} and w^t_{ij} (Teymourifar, 2022a). Patient i selects H_j in period t if Inequality 2 is valid.

$$\begin{aligned} sn^t_{qu_i} q^t_j - sn^t_{wt_i}(w^t_{ij} + wd^t_{ij}) \geq \\ sn^t_{qu_i} q^t_k - sn^t_{wt_i}(w^t_{ik} + wd^t_{ik}) \\ \forall i \in SI, \ \forall j \neq k \in SO^t \end{aligned} \tag{2}$$

A patient leaves the system when Inequality 2 is not valid for any j. This situation can be interpreted as preferring another hospital out of the region. The values of the variable defined in Equation 3 are determined by Inequality 2.

$$x^t_{ij} = \begin{cases} 1, & \text{if } \textit{patient i selects } H_j \textit{ in period t} \\ 0, & \text{otherwise.} \end{cases} \forall i \in SI^t, \forall j \in SO^t, \forall t \in ST. \tag{3}$$

The number of patients that prefer H_j in period t is acquired as in Equation 4.

$$I^t_j = \sum_{i \in SI^t} x^t_{ij}, \ \ \forall j \in SO^t, \forall t \in ST. \tag{4}$$

The probability of selecting H_j in period t is defined as in Equation 5.

$$p^t_j = \frac{I^t_j}{I^t}, \ \ \forall j \in SO^t, \forall t \in ST \tag{5}$$

Evidently, Equation 6 is valid for all periods.

$$\sum_{j \in SO^t} p^t_j = 1, \ \ \forall t \in ST \tag{6}$$

The average probability of selecting hospitals in period t is defined as in Equation 7.

$$\overline{p}^t = \frac{\sum_{j \in SO^t} p_j^t}{J}, \ \ \forall t \in ST \tag{7}$$

A balance between the probability of selecting hospitals is desired in each period. To measure this, $f_1^t, \forall t \in ST$ is determined as in Equation 8.

$$f_1^t = \sum_{j \in SO^t} |p_j^t - \overline{p}^t|, \ \ \forall t \in ST \tag{8}$$

$t = 1$ represents the current state of the system. Minimizing f_1^t for $\forall t > 1$, and satisfying Constraint 9 is expected.

$$f_1^t \leq f_1^1, \ \ \forall t > 1 \tag{9}$$

The balance between the probability of patients choosing hospitals during all periods is measured by f_1 defined in Equation 10, which is intended to be minimized. T is the number of all periods.

$$f_1 = \sum_{t \in ST} \frac{f_1^t}{T} \tag{10}$$

In period t, patients' average time to reach H_j is expressed as in Equation 11.

$$\overline{wd}_j^t = \frac{\sum_{i \in SI^t} wd_{ij}^t x_{ij}^t}{I_j^t}, \ \ \forall j \in SO^t, \forall t \in ST \tag{11}$$

In period t, the average waiting time before examination in H_j is as in Equation 12.

$$\bar{w}_j^t = \frac{\sum_{i \in SI^t} w_{ij}^t x_{ij}^t}{I_j^t}, \ \ \forall j \in SO^t, \forall t \in ST \tag{12}$$

Average total time before examination in H_j, including reaching the hospital and waiting time, in period t is indicated as in Equation 13.

$$\overline{TW}_j^t = \overline{wd}_j^t + \bar{w}_j^t, \ \ \forall j \in SO^t, \forall t \in ST \tag{13}$$

Average of $\overline{TW}_j^t$ for all hospitals is as in Equation 14.

$$f_2^t = \overline{TW}^t = \frac{\sum_{j \in SO^t} (\overline{wd}_j^t + \bar{w}_j^t)}{J}, \ \ \forall t \in ST \tag{14}$$

As defined in Constraint 15, the values of f_2^t in periods should be less than in the current state.

$$f_2^t \leq f_2^1, \ \ \forall t > 1 \tag{15}$$

Minimizing f_2, defined as in Equation 16, is aimed.

$$f_2 = \sum_{t \in ST} \frac{f_2^t}{T} \tag{16}$$

f_3^t is defined as in Equation 17 to measure the balance of $\overline{TW}_j^t$ between hospitals in period t, which is supposed to satisfy Constraint 18.

$$f_3^t = \sum_{j \in SO^t} |(\overline{TW}_j^t) - (\overline{TW}^t)|, \ \ \forall t \in ST \tag{17}$$

$$f_3^t \leq f_3^1, \ \ \forall t > 1 \tag{18}$$

The average of f_3^t for all periods is identified as in Equation 19, which is aspired to be minimized.

$$f_3 = \sum_{t \in ST} \frac{f_3^t}{T} \tag{19}$$

The total quality acquired by patients choosing H_j in period t is defined as in Equation 20.

$$TQ_j^t = q_j^t I_j^t, \ \ \forall j \in SO^t, \forall t \in ST \tag{20}$$

I^t, the number of patients in period t is calculated as in Equation 21.

$$I^t = \sum_{j \in SO^t} I_j^t, \ \ \forall t \in ST \tag{21}$$

In period t, the average quality level received by the patients is indicated as in Equation 22.

$$f_4^t = \frac{TQ^t}{I^t} = \sum_{j \in SO^t} \frac{TQ_j^t}{I^t}, \ \ \forall t \in ST \tag{22}$$

The average level of quality over all periods should be at least that of the current situation, which is satisfied by Constraint 23.

$$f_4^1 \leq f_4^t, \ \ \forall t > 1 \tag{23}$$

To be minimized, f_4 is determined as in Equation 24.

$$f_4 = \sum_{t \in ST} \frac{f_4^t}{T} \tag{24}$$

c_j and c_j^{ca} are, respectively, the fixed and unit capacity costs in H_j, while cq_j^t is the cost of the boost in quality in H_j in period t; thus, cq^t is calculated as in Equation 25.

$$cq^t = \sum_{j \in SO^t} cq_j^t, \ \ \forall t \in ST \tag{25}$$

The total cost of hospitals in period t is defined as in Equations 26.

$$f_5^t = cq^t + \sum_{j \in SO^t} (y_j^t (c_j + m_j^t c_j^{ca}), \quad \forall t \in ST \tag{26}$$

Due to an increase in capacity, there may be a growth in f_5^t. Constraint 27 is defined to manage this augmentation.

$$f_5^t \leq c_{max}^t, \quad \forall t \in ST \tag{27}$$

The total cost of hospitals during all periods is determined as in Equations 28, respectively.

$$f_5 = \sum_{t \in ST} f_5^t \tag{28}$$

I_{out}^t is the number of patients that the system loses in period t; then the probability of patients not choosing the regional hospitals is identified as in Equation 29, which should satisfy Constraint 30.

$$f_6^t = \frac{I_{out}^t}{I^t} \tag{29}$$

$$f_6^t \leq f_6^1, \quad \forall t > 1 \tag{30}$$

The probability that patients do not prefer regional hospitals during all periods is as in Equation 31.

$$f_6 = \sum_{t \in ST} \frac{f_6^t}{T} \tag{31}$$

The defined utility for period t is an MO function, as in Equation 32.

$$U^t = (f_1^t, f_2^t, f_3^t, f_4^t, f_5^t, f_6^t) \tag{32}$$

f_o^t, $o = 1, 2, ..., 6$ is component o of U^t. The utility for all periods, i.e., the model's objective function, is identified as in Equation 33.

$$U = (f_1, f_2, f_3, f_4, f_5, f_6) \tag{33}$$

Similarly, f_o, $o = 1, 2, ..., 6$ is component o of U. As stated before, it is not intended to minimize $f_5^t, \forall t \in ST$, but only to satisfy Constraint 27. This point can be interpreted as the government tolerating the cost growth to improve the healthcare system but defining an upper limit.

4. Implementation and Experimental Results

The model described in Section 3 is implemented in the Rockwell Arena 14 software. We utilize a system with an Intel Core i5 processor, 2.4 GHz, with 12 GB of RAM. The patients' inter-arrival times are formed through the Exponential distribution in the Create module in Arena. The inter-arrival times, decision variable in Equation 1, quality levels, and costs are identified as variables. The quality and waiting time sensitivities and distances from hospitals are assigned to each patient as attributes. Capacities, i.e., the number of teams that do examinations in hospitals, are defined in the Set module.

Inequality 2 is defined in the Expression module of the Arena software. If patient i chooses H_j in period t, then $x_{ij}^t = 1$. This decision ensures in the Decide module of the Arena software. The patients that choose one of the hospitals in the region exit the system after going through a Process module of the Arena software representing the examination process. The simulation model's output is the waiting time, the number of patients, and the utility components for each period.

Data from a case study is employed in the simulation model conducted in the Eskişehir state in Turkey between 2015-2018. More details can be found in references (Kaya et al. 2020a,b; Teymourifar et al. 2021a). There are seven hospitals in the region, indicated as $H_j, \forall j = 1, ..., 7$. It should be noted that in the case study, H_1, H_2 and H_3 were public hospitals and H_4, H_5, H_6 and H_7 private hospitals. But in this study, we presume that all hospitals are public because otherwise, implementing scenarios, especially those about closing hospitals, can be challenging. Although, this assumption does not damage the model's generalizability, and if multiple hospitals with different characteristics have a unified administration, the proposed model can be applied.

Three periods are considered, denoted by t_1, t_2, and t_3. As seen in Table 3, the inter-arrival times of patients are the same in t_1 and t_2. However, t_1 represents the current state, while at t_2, the government decides to improve the utility by resectorization. t_3 represents the period in which the arrival rates of the patients are less. As seen in the first column of Table 3, based on the arrival rates, the hours of a day are divided into three intervals (Kaya et al. 2020a).

Table 3: Inter-arrival times, i.e., the average times between patient arrivals (in seconds).

	Inter-arrival times	
Time intervals	t_1 and t_2	t_3
02:00-08:59	65	130
09:00-16:59	30	60
17:00-01:59	19	38

Times to reach H_1, H_2, and H_3 by i-th patient in period t are considered to be according to the Normal distribution with mean and standard deviation equal to 45 and 15, respectively, which is stated as $wd^t_{ij}\sim$ NORM(45,15) $\forall j = 1, 2.3$, $\forall i \in SI^t$, $\forall t$ =1,2,3. Also, we supposed that $wd^t_{ij}\sim$ NORM(20,10), $q^t_j = 0.9$, $\forall j = 1, 2, 3$, $q^t_j = 0.7$, $\forall j = 4, 5, 6, 7$ $\forall t = 1, 2, 3$. This means that the average distance of patients from H_1, H_2, and H_3 is more than H_4, H_5, H_6, and H_7, while their quality level is alike more. In hospitals, H_1, H_2, and H_3, the capacity is supposed to be four, and for hospitals H_4, H_5, H_6 and H_7, it is assumed to be two. H_1, H_2, and H_3 are called large-sized hospitals, and others are called small-sized hospitals. The examination period for each patient is NORM(5,1.5) in all hospitals. If a negative examination time is generated from this distribution, it is assumed to be equal to zero. It is also supposed that there is just one examination process. Costs are defined as: $c_j = 10000$ and $c^{ca}_j = 15000$, $\forall j \in SO^t$. In addition, the cost of a unit increase in the quality level of each hospital is defined as 10000. For example, cq^t =70000 if there is one unit quality improvement in all hospitals in period t. The value of c^t_{max} in Constraint 27 is defined as 407,000, which is 10% more than f^1_5. Cost values are similar to the years when the case study was conducted, and the unit is Turkish Lira (Kaya et al. 2020a). Furthermore, we suppose that $sn^t_{qu_i}\sim$ NORM(300,10) and $sn^t_{wt_i} = 1$. $\forall i \in SI^t$ $\forall t \in ST$. The used parameters are also summarized in Table 4. As it is clear from the values of y^1_j, $\forall j \in SO^t$, at $t = 1$, all hospitals are available for service, and then $SO^t = SJ$.

The simulation model outputs for the current state are as in Table 4. All results are the average of ten replications, each lasting 720 hours, i.e., one month. As such, each period can also be assumed to be one month. It should be noted that similar outputs are obtained with more repetitions. For example, results similar to those in Table 4 are acquired with 100 replications. The warm-up period is three days.

Table 4: Parameters and outputs of the simulation model for the current state of the system, i.e., period $t = 1$.

Parameters:

$y_1^1 = y_2^1 = y_3^1 = y_4^1 = y_5^1 = y_6^1 = y_7^1 = 1$, $q_1^1 = q_2^1 = q_3^1 = 0.9$, $q_4^1 = q_5^1 = q_6^1 = q_7^1 = 0.7$
$m_1^1 = m_2^1 = m_3^1 = 4$, $m_4^1 = m_5^1 = m_6^1 = m_7^1 = 2$

Outputs:

	H_1	H_2	H_3	H_4	H_5	H_6	H_7
I_j^1	25537	25840	24169	2996	3021	3076	2981
p_j^1	0.29	0.29	0.28	0.03	0.03	0.04	0.03
$\bar{w}_j^1$	22.49	22.15	22.16	0.46	0.46	0.44	0.51
$\overline{wd}_j^1$	30.23	30.52	30.04	3.67	3.41	3.61	3.39
$\overline{TW}_j^1$	52.72	52.67	52.20	4.13	3.87	4.05	3.9
TQ_j^1	22983.3	23256	21752.1	2097.2	2114.7	2153.2	2086.7
$c_j + m_j^1 c_j^{ca}$	70000	70000	70000	40000	40000	40000	40000
$cq^1 = 0, I_{out}^1 = 0$							

Comparing the values of p_j^1 and $\bar{w}_j^1$, $\forall j \in SO^t$ with the values of the real system in reference (Kaya et al. 2020a), the validation of the simulation can be confirmed. It should be remarked that the values $\overline{wd}_j^1$, $\forall j \in SO^t$ are not given in reference (Kaya et al. 2020a), and they are added in this study. In period $t = 1$, i.e., current state, the system is not balanced regarding waiting times and the probability of patients choosing hospitals. Also, $I_{out}^1 = 0$, meaning that all patients choose hospitals in the region.

Large-sized hospitals, namely H_1, H_2, and H_3, are more preferred by patients due to their quality. It should be considered that the value of $sn_{qu_i}^t$ is higher than $sn_{wt_i}^t$ in all three periods. It means that patients generally give more importance to quality than waiting time. As a consequence, these hospitals have higher average waiting times than others.

To improve the utility, the following scenarios are designed for period $t = 2$:

S_1^2: Closing H_4, H_5, H_6, H_7.
S_2^2: Closing H_4, H_5, H_6, H_7 and increasing the quality level of H_1, H_2, H_3 to 0.95.
S_3^2: Closing H_4, H_5, H_6, H_7 and increasing the capacity of H_1, H_2, H_3 to 5.
S_4^2: Closing H_4, H_5, H_6, H_7 and increasing the capacity of H_1, H_2, H_3 to 5 as well as increasing their quality level to 0.95.
S_5^2: Closing H_4, H_5, H_6, H_7 and increasing the capacity of H_1, H_2, H_3 to 6.
S_6^2: Closing H_4, H_5, H_6, H_7 and increasing the capacity of H_1, H_2, H_3 to 6 as well as increasing their quality level to 0.95.
S_7^2: Closing H_4, H_5, H_6, H_7 and increasing the capacity of H_1, H_2, H_3 to 7.
S_8^2: Closing H_4, H_5, H_6, H_7 and increasing the capacity of H_1, H_2, H_3 to 7 as well as increasing their quality level to 0.95.
S_9^2: Closing H_7.
S_{10}^2: Closing H_7 and increasing the quality level of H_1, H_2, H_3 to 0.95.
S_{11}^2: Closing H_7 and increasing the capacity of H_1, H_2, H_3 to 5.
S_{12}^2: Closing H_7 and increasing the capacity of H_1, H_2, H_3 to 5 as well as increasing their quality level to 0.95.

Similarly, the following scenarios are designed for period $t = 3$:

S_1^3: Using the parameters of current state for $t = 3$.
S_2^3: Closing H_4, H_5, H_6, H_7.
S_3^3: Closing H_4, H_5, H_6, H_7 and increasing the quality level of H_1, H_2, H_3 to 0.95.
S_4^3: Closing H_4, H_5, H_6, H_7 and increasing the capacity of H_1, H_2, H_3 to 5.
S_5^3: Closing H_4, H_5, H_6, H_7 and increasing the capacity of H_1, H_2, H_3 to 5 as well as increasing their quality level to 0.95.
S_6^3: Closing H_4, H_5, H_6, H_7 and increasing the capacity of H_1, H_2, H_3 to 6.
S_7^3: Closing H_4, H_5, H_6, H_7 and increasing the capacity of H_1, H_2, H_3 to 6 as well as increasing their quality level to 0.95.
S_8^3: Closing H_4, H_5, H_6, H_7 and increasing the capacity of H_1, H_2, H_3 to 7.
S_9^3: Closing H_4, H_5, H_6, H_7 and increasing the capacity of H_1, H_2, H_3 to 7 as well as increasing their quality level to 0.95.

The parameters of the scenarios designed for periods $t = 2, 3$ are summarized in Table 5.

Table 5: Parameters in scenarios.

$t = 2$	
S_1^2:	$y_1^1 = y_2^1 = y_3^1 = 1, y_4^1 = y_5^1 = y_6^1 = y_7^1{=}0,\ q_1^1 = q_2^1 = q_3^1 = 0.9,\ m_1^1 = m_2^1 = m_3^1 = 4$
S_2^2:	$y_1^1 = y_2^1 = y_3^1 = 1, y_4^1 = y_5^1 = y_6^1 = y_7^1{=}0,\ q_1^1 = q_2^1 = q_3^1 = 0.95,\ m_1^1 = m_2^1 = m_3^1 = 4$
S_3^2:	$y_1^1 = y_2^1 = y_3^1 = 1, y_4^1 = y_5^1 = y_6^1 = y_7^1{=}0,\ q_1^1 = q_2^1 = q_3^1 = 0.9,\ m_1^1 = m_2^1 = m_3^1 = 5$
S_4^2:	$y_1^1 = y_2^1 = y_3^1 = 1, y_4^1 = y_5^1 = y_6^1 = y_7^1{=}0,\ q_1^1 = q_2^1 = q_3^1 = 0.95,\ m_1^1 = m_2^1 = m_3^1 = 5$
S_5^2:	$y_1^1 = y_2^1 = y_3^1 = 1, y_4^1 = y_5^1 = y_6^1 = y_7^1{=}0,\ q_1^1 = q_2^1 = q_3^1 = 0.9,\ m_1^1 = m_2^1 = m_3^1 = 6$
S_6^2:	$y_1^1 = y_2^1 = y_3^1 = 1, y_4^1 = y_5^1 = y_6^1 = y_7^1{=}0,\ q_1^1 = q_2^1 = q_3^1 = 0.95,\ m_1^1 = m_2^1 = m_3^1 = 6$
S_7^2:	$y_1^1 = y_2^1 = y_3^1 = 1, y_4^1 = y_5^1 = y_6^1 = y_7^1{=}0,\ q_1^1 = q_2^1 = q_3^1 = 0.9,\ m_1^1 = m_2^1 = m_3^1 = 7$
S_8^2:	$y_1^1 = y_2^1 = y_3^1 = 1, y_4^1 = y_5^1 = y_6^1 = y_7^1{=}0,\ q_1^1 = q_2^1 = q_3^1 = 0.95,\ m_1^1 = m_2^1 = m_3^1 = 7$
S_9^2:	$y_1^1 = y_2^1 = y_3^1 = y_4^1 = y_5^1 = y_6^1 = 1, y_7^1{=}0,\ q_1^1 = q_2^1 = q_3^1 = 0.9,\ q_4^1 = q_5^1 = q_6^1 = 0.7$ $m_1^1 = m_2^1 = m_3^1 = 4,\ m_4^1 = m_5^1 = m_6^1 = 2$
S_{10}^2:	$y_1^1 = y_2^1 = y_3^1 = y_4^1 = y_5^1 = y_6^1 = 1, y_7^1{=}0,\ q_1^1 = q_2^1 = q_3^1 = 0.95,\ q_4^1 = q_5^1 = q_6^1 = 0.7$ $m_1^1 = m_2^1 = m_3^1 = 4,\ m_4^1 = m_5^1 = m_6^1 = 2$
S_{11}^2:	$y_1^1 = y_2^1 = y_3^1 = y_4^1 = y_5^1 = y_6^1 = 1, y_7^1{=}0,\ q_1^1 = q_2^1 = q_3^1 = 0.9,\ q_4^1 = q_5^1 = q_6^1 = 0.7$ $m_1^1 = m_2^1 = m_3^1 = 5,\ m_4^1 = m_5^1 = m_6^1 = 2$
S_{11}^2:	$y_1^1 = y_2^1 = y_3^1 = y_4^1 = y_5^1 = y_6^1 = 1, y_7^1{=}0,\ q_1^1 = q_2^1 = q_3^1 = 0.95,\ q_4^1 = q_5^1 = q_6^1 = 0.7$ $m_1^1 = m_2^1 = m_3^1 = 5,\ m_4^1 = m_5^1 = m_6^1 = 2$
$t = 3$	
S_1^3:	$y_1^1 = y_2^1 = y_3^1 = y_4^1 = y_5^1 = y_6^1 = y_7^1{=}1,\ q_1^1 = q_2^1 = q_3^1 = 0.9,\ q_4^1 = q_5^1 = q_6^1 = q_7^1 = 0.7$ $m_1^1 = m_2^1 = m_3^1 = 4,\ m_4^1 = m_5^1 = m_6^1 = m_7^1 = 2$
S_2^3:	$y_1^1 = y_2^1 = y_3^1 = 1, y_4^1 = y_5^1 = y_6^1 = y_7^1{=}0,\ q_1^1 = q_2^1 = q_3^1 = 0.9,\ m_1^1 = m_2^1 = m_3^1 = 4$
S_3^3:	$y_1^1 = y_2^1 = y_3^1 = 1, y_4^1 = y_5^1 = y_6^1 = y_7^1{=}0,\ q_1^1 = q_2^1 = q_3^1 = 0.95,\ m_1^1 = m_2^1 = m_3^1 = 4$
S_4^3:	$y_1^1 = y_2^1 = y_3^1 = 1, y_4^1 = y_5^1 = y_6^1 = y_7^1{=}0,\ q_1^1 = q_2^1 = q_3^1 = 0.9,\ m_1^1 = m_2^1 = m_3^1 = 5$
S_4^3:	$y_1^1 = y_2^1 = y_3^1 = 1, y_4^1 = y_5^1 = y_6^1 = y_7^1{=}0,\ q_1^1 = q_2^1 = q_3^1 = 0.95,\ m_1^1 = m_2^1 = m_3^1 = 5$
S_6^3:	$y_1^1 = y_2^1 = y_3^1 = 1, y_4^1 = y_5^1 = y_6^1 = y_7^1{=}0,\ q_1^1 = q_2^1 = q_3^1 = 0.9,\ m_1^1 = m_2^1 = m_3^1 = 6$
S_7^3:	$y_1^1 = y_2^1 = y_3^1 = 1, y_4^1 = y_5^1 = y_6^1 = y_7^1{=}0,\ q_1^1 = q_2^1 = q_3^1 = 0.95,\ m_1^1 = m_2^1 = m_3^1 = 6$
S_8^3:	$y_1^1 = y_2^1 = y_3^1 = 1, y_4^1 = y_5^1 = y_6^1 = y_7^1{=}0,\ q_1^1 = q_2^1 = q_3^1 = 0.9,\ m_1^1 = m_2^1 = m_3^1 = 7$
S_8^3:	$y_1^1 = y_2^1 = y_3^1 = 1, y_4^1 = y_5^1 = y_6^1 = y_7^1{=}0,\ q_1^1 = q_2^1 = q_3^1 = 0.95,\ m_1^1 = m_2^1 = m_3^1 = 7$

The simulation model is run for each scenario. The outputs of the scenarios are presented in Table 6, where the selected ones for each period are bolded. Also, the results from Table 4 are summarized in Table 6. As stated before, for $f_5^t, t = 1, 2, 3$, they are only checked to be valid in Constraint 27 instead of minimization. For instance, f_5^2 for S_8^2 is more than S_9^2, but S_8^2 is chosen because it has better values for other utility components. Note that the values of f_5^2 for both S_8^2 and S_9^2 are less than f_5^1 because the number of hospitals in both is less than that in the current situation.

Table 6: The results of scenarios for periods $t = 1, 2, 3$.

$t = 1$ (Current state)						
	f_1^1	f_2^1	f_3^1	f_4^1	f_5^1	f_6^1
S_1^1	0.87	24.79	166.43	0.87	370000	0

$t = 2$						
	f_1^2	f_2^2	f_3^2	f_4^2	f_5^2	f_6^2
S_1^2	0.01	22.21	177.68	0.90	210000	0.02
S_2^2	0.01	22.21	177.68	0.95	225000	0.02
S_3^2	0.00	16.47	131.75	0.90	255000	0.01
S_4^2	0.00	16.47	131.75	0.95	270000	0.01
S_5^2	0.00	14.13	113.02	0.90	300000	0.00
S_6^2	0.00	14.13	113.02	0.95	315000	0.00
S_7^2	0.00	13.96	111.69	0.90	345000	0.00
S_8^2	**0.00**	**13.96**	**111.69**	**0.95**	**360000**	**0.00**
S_9^2	0.79	23.70	169.35	0.88	330000	0.04
S_{10}^2	0.79	23.70	169.35	0.93	360000	0.04
S_{11}^2	0.99	16.34	130.75	0.90	375000	0.00
S_{12}^2	0.99	16.34	130.75	0.95	405000	0.00

$t = 3$						
	f_1^3	f_2^3	f_3^3	f_4^3	f_5^3	f_6^3
S_1^3	1.14	13.98	111.86	0.90	370000	0.00
S_2^3	0.01	13.97	111.74	0.90	210000	0.00
S_3^3	0.01	13.97	111.74	0.95	225000	0.00
S_4^3	0.01	13.88	111.02	0.90	255000	0.00
S_5^3	**0.01**	**13.88**	**111.02**	**0.95**	**270000**	**0.00**
S_6^3	0.01	13.83	110.66	0.90	300000	0.00
S_7^3	0.01	13.83	110.66	0.95	315000	0.00
S_8^3	0.01	13.82	110.53	0.90	345000	0.00
S_9^3	0.01	13.82	110.53	0.95	360000	0.00

For $t = 2$, S_8^2 is chosen, in which hospitals with less capacity and quality, i.e., H_4, H_5, H_6 and H_7 are closed, and the capacity and quality of H_1, H_2 and H_3 are raised. In this case, all the utility components improve, and even the cost is reduced compared to the current state. For $t = 3$, S_5^3, which is a similar scenario to S_8^2, is chosen. However, compared to S_8^2, in S_5^3, the capacities of H_1, H_2, and H_3 are increased by a smaller amount. The reason is that, at $t = 3$, there are fewer arrival rates and, therefore, lower patients than $t = 1, 2$.

Using Equations 10, 16, 19, 24, 28, 31, 33 the results of selected scenarios are summarized in Table 7. These outputs satisfy all Constraints 9, 15, 18, 23, 27 and 30. Also, Table 7 gives the results of using the current state's parameters for all three periods. As seen, all components of the utility function improve, and even cost reduces.

Table 7: The value of the objective functions at the end of the third period, with the proposed scenarios (for three periods).

f_1	f_2	f_3	f_4	f_5	f_6
With proposed scenarios (S_8^2, S_5^3 as well as S_1^1)					
0.29	17.54	129.71	0.92	1000000.00	0.00
With the parameters of current state					
0.96	21.19	148.24	0.88	1110000.00	0.00

Managerial Implications

The study's findings have noteworthy managerial implications for balancing and enhancing the performance of local healthcare systems. The outcomes show the importance of regular resectorization to keep healthcare systems balanced in terms of key outcomes such as waiting times and demands. Managers can proactively adapt to changing dynamics and maintain an effective system over time by regularly performing resectorization depending on patient arrival rates.

The study outlines some precautions that may considerably boost the utility of the system. Notably, closing minor hospitals while improving the capacity and quality of larger hospitals can have a substantial positive impact. This is a strategy that policymakers may employ to improve resource allocation and system performance. The study also highlights a challenge that might be interpreted as a lack of demand for local healthcare systems. Administrators may create focused initiatives to attract and keep patients by comprehending the factors influencing patients' hesitation to select local hospitals, thereby enhancing hospital usage and system effectiveness.

5. Conclusion and Future Works

This study addresses a regional healthcare system that includes hospitals with dissimilar characteristics in terms of quality, capacity, and average distances to patients. Some hospitals are small-sized with low capacity and low quality, while others are large-sized with higher quality and capacity. Though patients have a less average distance to small hospitals, large-sized ones are preferred because of their better quality. We suggest a new model for this system to balance patients' average waiting times and improve quality. Since balancing is one of the noteworthy objectives of the sectorization concept, the model is characterized based on it. Each hospital and patients that choose it are considered as a sector. The foundation of the proposed model is the definition of a new utility function for the system. Scenarios based on raising the capacity and quality of hospitals to improve utility are designed. In addition, since all of the hospitals in the model are supposed to be managed by the government, closing a subset of them is analyzed in the scenarios. This matter has not been dealt with enough in previous studies. Since the discussed system is dynamic, it is essential to do resectorization over time to improve utility. Therefore, different scenarios should be analyzed in different periods.

We utilize simulation, which is suitable for the analysis of dynamic systems. Model and designed scenarios are implemented within the Rockwell Arena software. In the experimental results section, data from a case study is used. Three periods are defined based on the patients' arrival rates, one of which is assumed to represent the system's current state. In the second period, arrival rates are the same as the first one, i.e., the current state, but the government does resectorization to improve the defined utility. In the third period, the arrival rates are less than the previous ones for which the government applies resectorization too.

Unlike most of the studies in the literature, we consider the case where patients did not choose any of the regional hospitals. This situation can be regarded as a loss of demand for regional hospitals. In the analysis of scenarios, the cost component in the utility function is handled with a constraint of the upper limit. This means that limited increases in cost can be tolerated if it benefits society. Results demonstrate that the defined scenarios can remarkably improve the utility. The outputs indicate that closing small hospitals and increasing the capacity and quality of large hospitals can improve the defined system. Even in this case, it is possible to reduce the cost. This matter is a noteworthy consequence from the managerial viewpoint.

In this work, a high-level and simplified discrete event simulation model is employed to assess a strategic-level problem. Future work will develop more sophisticated techniques to define multiple decision variables. The values of the used parameters, which are selected from a case study (Kaya et al., 2020a, 2020b; Teymourifar et al., 2021a, 2022a), affect the managerial implications. In order to provide more broadly applicable managerial consequences, it is intended to analyze a wide variety of parameters in future studies.

The model described in Section 3 is not a mathematical programming model; it is just a formulation for understanding the problem and also to be implemented in the Rockwell Arena software. The model is developed based on the choices of each individual patient. However, while this approach can be implemented in a simulation model, it can be complicated to define it in a mathematical programming model. Patients may become ill for many reasons that affect their choices, which should be considered in the simulation model. However, closing a hospital can be interpreted as capacity sharing between healthcare units; in reality, it has managerial complexities. All of these limitations will be considered in future work to develop a more broad-scale model.

This study assumes that the government manages all hospitals in the region; otherwise, hospitals' closure scenarios are not functional. This matter does not affect the model's generalizability, and it can be applied to hospitals with different characteristics managed by the same authority. Future works will discuss which policies can improve utility where public and private hospitals co-exist in the region. In addition, in this study, we considered just an examination process in the centers. We plan to model complex healthcare systems with diverse processes for future work.

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Supporting Information

All implemented codes models are accessible via the author's email address.

References

Bouramtane K, Kharraja S, Riffi J, Elbeqqali O. A Decision-Making System for emergency service design and management during pandemic COVID-19. In 2022 International Conference on Intelligent Systems and Computer Vision (ISCV), IEEE 2022:1-8.

Bruno G, Cavola M, Diglio A, Piccolo C. Geographical accessibility to upper secondary education: an Italian regional case study. The Annals of Regional Science 2022;69(2):511-536.

Diglio A, Nickel S, Saldanha-da-Gama F. Towards a stochastic programming modeling framework for districting. Annals of Operations Research 2020;292(1):249-285.

Diglio A, Peiró J, Piccolo C, Saldanha-da-Gama F. Approximation schemes for districting problems with probabilistic constraints. European Journal of Operational Research

2022.

Diglio A, Peiró J, Piccolo C, Saldanha-da-Gama F. Solutions for districting problems with chance-constrained balancing requirements. Omega 2021;103:102430.

Do Amaral J V S, Montevechi J A B, De Carvalho Miranda R, De Sousa Junior W T. Metamodel-based simulation optimization: A systematic literature review. Simulation Modelling Practice and Theory 2022;114:102403.

Guo H, Gu H, Zhou Y, and Peng J. A data-driven multi-fidelity simulation optimization for medical staff configuration at an emergency department in Hong Kong. Flexible Services and Manufacturing Journal, 2020:1-25.
Halawa F, Madathil S C, Gittler A, Khasawneh M T. Advancing evidence-based healthcare facility design: a systematic literature review. Health Care Management Science 2020;23:453-480.

Halawa F, Madathil S C, Khasawneh M T. Integrated framework of process mining and simulation–optimization for pod structured clinical layout design. Expert Systems with Applications 2021;185:115696.

Kaya O, Teymourifar A, Ozturk G. Analysis of different public policies through simulation to increase total social utility in a healthcare system. Socio-Economic Planning Sciences 2020;70:100742.

Kaya O, Teymourifar A, Ozturk G. Public and private healthcare coordination: An analysis of contract mechanisms based on subsidy payments. Computers and Industrial Engineering 2020;146:106526.

Liu H, Erdogan A, Lin R, and Tsao H S J. Mathematical models of political districting for more representative governments. Computers and Industrial Engineering 2020;140:62-65.

Mokni M, Yassa S, Hajlaoui J E, Omri M N, Chelouah R. Multi-objective fuzzy approach to scheduling and offloading workflow tasks in Fog–Cloud computing. Simulation Modelling Practice and Theory 2023;123:102687.

Taymaz S, Iyigun C, Bayindir Z P, Dellaert N P. A healthcare facility location problem for a multi-disease, multi-service environment under risk aversion. Socio-Economic Planning Sciences 2020;71:100755.

Teymourifar A, Kaya O, Ozturk G. Contracting models for pricing and capacity decisions in healthcare systems. Omega 2021;100:102232.

Teymourifar A, Rodrigues A M, Ferreira J S, Lopes C. A Comparison Between Optimization Tools to Solve Sectorization Problem. In International Conference on Modelling, Computation and Optimization in Information Systems and Management Sciences, Springer, Cham 2021:40-50.

Teymourifar A, Rodrigues A M, Ferreira J S. A comparison between simultaneous and hierarchical approaches to solve a multi-objective location-routing problem, in: Graphs and Combinatorial Optimization: from Theory to Applications. Springer 2021:251-263.

Teymourifar A, Rodrigues A M, Ferreira J S. A comparison between NSGA-II and NSGA-III to solve multi-objective sectorization problems based on statistical parameter tuning, in: 2020 24th International Conference on Circuits, Systems, Communications and Computers (CSCC), IEEE 2020:64-74.

Teymourifar A, Simulation-based optimization for resectorization in healthcare systems. Journal of Simulation 2022a:1-20.

Teymourifar A. A Simulation-Based Approach to Reduce Waiting Times in Emergency Departments. In Innovations in Mechatronics Engineering II, Cham: Springer International Publishing 2022b:232-244.

Troy P, Lahrichi N, Porubska D, and Rosenberg L. Fine-grained simulation optimization for the design and operations of a multi-activity clinic. Flexible Services and Manufacturing Journal, 2020;32:599-628.

Conflict of interest
The authors have no relevant financial or non-financial interests to disclose.

Ethical approval
The authors declare compliance with the Ethical Standards required by this journal.

Appendix

Table of abbreviations

Abbreviations	Definition
MO	Multi-objective
NORM	Normal distribution