

## Research Article

# A Mathematical Model for Locating the Medical and Emergency Centers considering the Failure Probability of Centers

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Enhancing the amount of industrial and chemical production is one of the most important effects of increasing rural people's migration to cities, which leads to many abnormalities in the healthcare domain. In this regard, one of the most important tasks of health sector managers is designing and implementing some programs to monitor and control the level of community health, which is one of the health organizations' strategic planning. On the other hand, the location of service centers is one of the most important problems in the area of strategic planning by any organization because selecting an appropriate site for constructing facilities can have a significant effect on reducing costs and increasing the coverage level. However, an appropriate site to construct the facilities must also have maximum reliability in addition to reducing costs and increasing the coverage level. This problem is important because many factors, such as natural disasters, result in failure of centers and influence the confidence level of system performance. Therefore, it is necessary to consider maximizing reliability in locating centers. For this purpose, an integer mathematical model is presented in this paper to select the optimum site for constructing the medical and emergency centers by considering the failure probability of each center. The research model's objective function minimizes the system costs, including the costs of construction, patient transfer, and failure of medical and emergency centers. Finally, a numerical example is designed and reviewed by real-world problems to ensure the performance accuracy of the proposed model.

## 1. Introduction

Nowadays, making managerial decisions to select an appropriate place for constructing medical and emergency centers is one of the most important strategic decisions in any organization and health policymakers [1–4]. This paper presents an integer mathematical model to locate the medical and emergency centers in an area. This model has been designed based on research by Degel et al. [5]. In this study, the gravity of the population is considered as the population symbol of the area, which is measurable and

recognizable using the distance criterion between population areas. Also, to consider the system costs and level of coverage, system reliability has been considered. Selecting a low-reliability site leads to an increase in the probability of destroying or deactivating a system. After that, it is necessary to remodel the system by spending a lot of time. Therefore, system reliability can be added to the objective function of the proposed model in the form of cost. Also, in the proposed model, the objective function includes the costs of construction, patient transfer between centers, and the failure of each center. Existing constraints include unique

allocations, capacity constraints, and system performance constraints.

The presented problem in this paper considers two important parts of strategic decisions: the first includes minimizing the operating costs of the system, such as the costs of construction and patient transfer, and the second includes minimizing the costs from the failure of medical and emergency centers, which leads to maximization of the level of system reliability (based on [6–10]).

In this paper, a comprehensive framework has been provided to select a site for medical and emergency centers, considering the reliability of each center. Wide areas are influenced by planning and implementing the presented plans by health sector managers to improve the general level of community health, and this will lead to different demands for health services. There is a significant difference between this model and recent models due to simultaneously considering patient transfer decisions between medical and emergency centers, as well as considering the reliability of medical and emergency centers that represents the actual conditions governing the health system. The structure of the research will be as follows: in Section 2, we explain the importance and necessity of research. In Section 3, we review some of the most important studies to examine more exactly the conducted studies in the area of location for medical and emergency centers. In Section 4, we present the research method and the mathematical model of the problem. In Section 5, we design and examine an example by real-world conditions to evaluate and ensure the proposed model's performance accuracy. Finally, the conclusion will be provided, and some limitations of the study are presented.

## 2. Importance and Necessity of Research

In health systems, planning to meet the society needs is a very challenging task because various types of health services must be provided at the right time and sufficiently to the community [11–13]. The planning includes a rigorous process to provide and distribute the services. Therefore, it is not possible to deny the effort to establish a comprehensive framework for health system management [14, 15].

On the other hand, location of medical and emergency centers is one of the most important decisions in the area of health system management [16–18]. Site selection for the facility construction can have a significant effect on reducing costs and increasing the coverage level. Thus, an appropriate site to construct the facilities must also have maximum reliability [19–21]. This problem is important because many factors, such as natural disasters, result in failure of centers and influence the confidence level of system performance. Therefore, it is necessary to consider maximizing reliability in locating centers [11, 17, 22].

## 3. Literature Review

A theoretical study for facility locating was formally initiated since 1909 when Alfred Weber proposed positioning a warehouse based on minimizing the total distance between the warehouse and various customers [12, 23, 24]. After that,

the theory of facility locating and its applications have been used by researchers in various areas, and various models have been proposed in this area. The facility's reliability has not been considered in early models, which considered the location of mobile facilities. Toregas et al. [25] and Church and ReVelle [26] presented models of full coverage and maximal covering, respectively, in terms of such an effect. In 2013, Degel et al. [27] presented an ambulance locating model to maximize the demand coverage where the demands are dynamic, and the travel time is dependent on different times. Then, Degel [28] presented another model for ambulances' locating and relocating in which variable environmental conditions, such as variable demand dependent on travel time and travel time depending on different times, were implemented in the model, and economic aspects of the problem were also considered including the number of personnel working at different hours (2014). Also, Mahmoud and Indriasari [29] presented a model that is titled "maximal covering areas" based on the assumption that service capacities are unlimited in each facility. In this model, which is the generalized form of the maximum coverage model, maximizing the covering areas is considered instead of maximizing the set of covering points. Limited capacity coverage models are also models that the assumption of the unavailability of servers has been ignored, but in contrast, the efficiency of these models has increased, considering the capacity constraint for facilities. Chung and Erdős [30] presented the first model of maximum limited capacity coverage. The limitations of this model ensure that the total demand allocated to each facility does not exceed the capacity of each facility. Ron Wei presented a coverage locating model that is titled "Continuous Space Maximal Coverage Problem (CSMCP)" in which the demands are continuously distributed in the whole coverage area, and the facilities can be located anywhere in the area (Wei et al. [31]). Demir et al. [32] presented a maximal quadratic covering a locating model for locating helicopters to maximize the demand point coverage, which was the place of occurring demands at nodes and paths. In the proposed model by Pirkul and Schilling [33], each customer achieves at least one facility, and therefore the facilities must be located in a way that at least one facility be at a standard distance of each customer [34–36].

Daskin [37] presented the first probabilistic covering model based on reliability that is entitled "maximum expected covering model." In this model, the workload of all service providers is considered to be the same, and each of them provides the service individually, it means that each service provider's activity or inactivity has no effect on the other's activity or inactivity [12, 14, 38]. ReVelle and Hogan [39] also presented a model that is titled "the maximum availability" in which each service provider can only serve specific local areas, and thus each service provider's workload is determined in terms of the volume of existing demand in that area. This model's objective function maximizes the total covered demand. Sorensen et al. [40] presented an expected maximum coverage model based on local reliability by integrating the two previous models. In this model, like the maximum availability model, local

serving areas are used to determine the workload of the service providers. This model's objective function, like the expected maximum coverage model, maximizes the reliability of customer coverage [41–43]. Furuta et al. [44] presented a model and applied it to test how different dispatch rules and geographical barriers can influence the optimal design of an EMS-helicopter service system. Inoue et al. [45] provided the maximal covering locating model for doctor-helicopter healthcare systems in which doctors are sent to the scene by helicopter to perform basic services. In this model, the optimum location of helicopter stations, ambulance stations, and transfer points are determined simultaneously, and two coverage criteria are used, and it represented that to what extent reducing and increasing time can influence the determination of helicopters' optimum location so that it is more reduced by dispatching a helicopter to the scene than dispatching ambulance [46, 47].

In the research of Rajagopalan et al. [48], the patients' demand for receiving ambulance services may vary at different times and even in different places. Therefore, using past data as well as future forecasting methods, it can locate and relocate ambulances and labor force in a way that involves the lowest cost and response time [49, 50].

According to the literature review, it can be seen that there is no study on the simultaneous locating of medical and emergency centers considering the failure probability of centers. However, according to the provided materials in the previous section, the need to review this matter cannot be ignored.

## 4. Research Method

The present study is descriptive in terms of the purpose of research and exploratory and applied research in terms of data collection. The study population is a real example of locating in Tehran, Iran. It is important because about one-fifth of the population of Iran is living in Tehran. This paper presents an integer mathematical model to locate the medical and emergency centers in an area. This model has been designed based on the research work of Degel et al. [5]. In this study, the gravity of the population is considered as the population symbol of the area that is measurable and recognizable using the distance criterion between population areas. Moreover, in this model, we consider system reliability to analyze the system costs and level of coverage. Selecting a low-reliability site leads to an increase in the probability of destroying or deactivating a system. After that, it is necessary to remodel the system by spending a lot of time. Therefore, system reliability can be added to the objective function of the proposed model in the form of cost. Also, in the proposed model, the objective function includes the costs of construction, patient transfer between centers, and the failure of each center. Also, each location includes unique allocations, capacity constraints, and system performance constraints. Then, two examples have been designed based on real-world conditions to investigate the efficiency of the proposed model for solving a problem. We use GAMS software by CPLEX solver on a system with a 3.2 GHz processor and random access memory (RAM) 8 GB.

**4.1. Assumptions of Research.** The assumptions of research are as follows:

- (1) The cost of construction and patient transfer between specified centers
- (2) The cost of reconstructing the system is characterized that, indeed, it is the same cost of the centers' failure
- (3) The population of each population point is characterized
- (4) The distance between population patches is characterized
- (5) All model design criteria are under the rules of Iran's Ministry of Health and Medical Education

The mathematical model of the problem is provided below.

### 4.2. Symbols and Sets

$C$ : symbol of population points (population patches),  $c, c' \in C$

$D$ : symbol of medical center,  $d \in D$

$U$ : symbol of emergency center,  $u \in U$

### 4.3. Parameters

$CapD(d)$ : patient admission capacity in medical center ( $d$ )

$CapU(u)$ : emergency patient admission capacity in medical center ( $d$ )

$M_c$ : estimated number of patients in need of health services of population patch ( $c$ )

$DT_{c,c'}$ : the required cost for the distance between population spots ( $c$ ) and ( $c'$ )

$CD_c$ : the cost of construction of a medical center in a population point ( $c$ )

$CU_c$ : the cost of construction of an emergency center in a population point ( $c$ )

$DE_u$ : estimated demand for the emergency center ( $u$ )

$RD_c$ : the cost of reconstructing (restarting) a medical center if it is constructed in population patch ( $c$ )

$RU_c$ : the cost of reconstructing (restarting) an emergency center if it is constructed in population patch ( $c$ )

$M$ : an arbitrary positive and large enough number

### 4.4. Decision Variables

$Y_{ud}$ : it equals one if the emergency center ( $u$ ) is allocated to the medical center ( $d$ ); otherwise, it is equal to zero

$N_{ud}$ : the number of patients transferred from the emergency center ( $u$ ) to the medical center ( $d$ )

$Z_{dc}$ : it equals one if the medical center ( $u$ ) is constructed on population patch ( $c$ ); otherwise, it is equal to zero

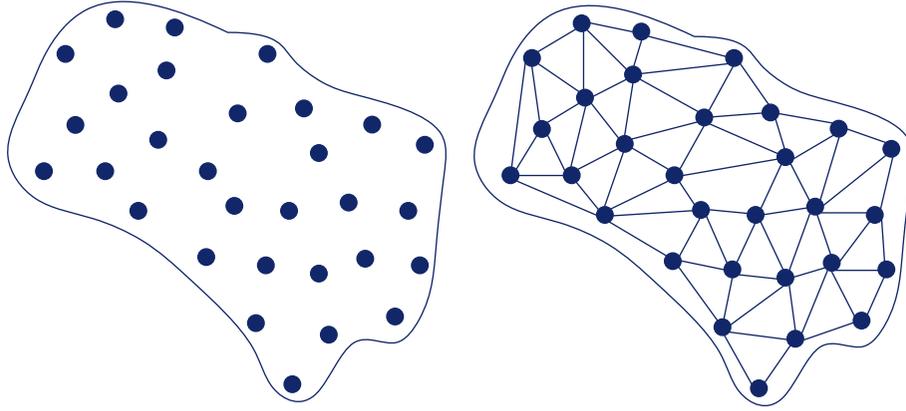


FIGURE 1: Point and graph structure of the studied area.

$K_{uc}$ : it equals to one if the emergency center ( $u$ ) is constructed on population patch ( $c$ )

$A_{cd}$ : it equals one if population patch ( $c$ ) is allocated to the medical center ( $d$ ), and otherwise, it equals zero

#### 4.4.1. Mathematical Model

$$\text{Min} \quad \sum_{d=1}^D \sum_{c=1}^C CD_c Z_{dc} + \sum_{u=1}^U \sum_{c=1}^C CU_c K_{uc} + \sum_{d=1}^D \sum_{u=1}^U \sum_{c=1}^C \left( \sum_{c'=1}^C K_{uc} N_{ud} Z_{dc'} DT_{c,c'} \right) + \left( \sum_{d=1}^D \sum_{c=1}^C RD_c Z_{dc} + \sum_{u=1}^U \sum_{c=1}^C RU_c K_{uc} \right), \quad (1)$$

subject to

$$\sum_{u=1}^U N_{ud} \leq \text{Cap}U_d, \quad \forall d, \quad (2)$$

$$\sum_{d=1}^D A_{cd} = 1, \quad \forall c, \quad (3)$$

$$\sum_{c=1}^C A_{cd} M_c M \text{Cap}D_d, \quad \forall d, \quad (4)$$

$$N_{ud} \leq MY_{ud}, \quad \forall u, d, \quad (5)$$

$$Y_{ud} \leq N_{ud}, \quad \forall u, d, \quad (6)$$

$$DE_u = \sum_{d=1}^D N_{ud}, \quad \forall u, \quad (7)$$

$$Z_{dc} \leq \sum_{c'=1}^C A_{c'd}, \quad \forall d, c, \quad (8)$$

$$\sum_{c'=1}^C A_{c'd} \leq MZ_{dc}, \quad \forall d, c, \quad (9)$$

$$\sum_{c=1}^C K_{uc} \leq \sum_{d=1}^D N_{ud}, \quad \forall u, \quad (10)$$

$$\sum_{d=1}^D N_{ud} \leq M \sum_{c=1}^C K_{uc}, \quad \forall u, \quad (11)$$

$$\sum_{u=1}^U K_{uc} \leq 1, \quad \forall c, \quad (12)$$

$$\sum_{c=1}^C K_{uc} \leq 1, \quad \forall u, \quad (13)$$

$$\{Y_{ud}, Z_{dc}, K_{uc}, A_{cd}\} \in \text{bin}, \quad \{N_{ud}\} \in \text{Int}, \forall c, d, u. \quad (14)$$

Objective function (1) of the problem has five sentences that are provided separately. The first, second, third, fourth, and fifth sentences state the cost of constructing the medical centers, the cost of constructing the emergency centers, the cost of patient transfer between centers, the cost of medical centers' failure, and the cost of emergency centers' failure. Since minimizing the cost of failure is the opposite of maximizing the reliability, thus minimizing these terms causes to maximization of reliability. Constraint (2) ensures that patient transfer will not deviate from the capacity of health centers. Constraint (3) ensures that every population patch is allocated to a medical center. These allocations will be made in a way that the problem is presented under full coverage.

Constraint (4) ensures that there is no deviation from the capacity of the emergency centers. Constraints (5) and (6) ensure that patient transfers are correctly allocated from emergency centers to medical centers. Constraint (7) ensures that the number of patients transferred to medical centers is equal to the number of demands for emergency centers.

TABLE 1: The costs of medical centers.

Center number	2	5	8	12	26
CapD ( $d$ )	20	30	50	40	45
CapU ( $d$ )	10	12	15	40	45
$CD_c$	100	120	150	130	160
$RD_c$	0.25	0.20	0.18	0.22	0.3

TABLE 2: The costs of emergency centers.

Center number	1	3	7	15	20	24	28	30
$DE_u$	5	8	5	4	5	6	8	5
$CU_c$	80	85	90	75	65	70	95	80
$RU_c$	0.20	0.30	0.35	0.18	0.22	0.35	0.33	0.28

TABLE 3: The system costs from the exact solution by software.

The cost of the emergency center's failure	The cost of a medical center's failure	The cost of patient transfer between centers	The cost of constructing an emergency center	The cost of constructing a medical center
108	67	1458	67	108

Constraints (8) and (9) ensure that population patches are correctly allocated to medical centers. Constraints (10) and (11) ensure that population patches are properly allocated to emergency centers and emergency centers to medical centers. Constraints (12) and (13) also guarantees for the unique allocation of population patches to emergency centers. Ultimately, constraint (14) expresses the variables used in the model.

**4.5. The Efficiency of the Proposed Model.** In this section, an example has been designed based on real-world conditions to investigate the efficiency of the proposed model. In this example, an area was considered with 30 populated patches in Tehran, where health sector managers try to select the appropriate sites to construct the medical and emergency centers. The decision was to construct three medical centers and five emergency centers. The population patches 2, 5, 8, 12, and 26 were identified as potential sites for the construction of medical centers, and the population patches 1, 3, 7, 15, 20, 24, 28, and 30 were identified as potential sites for the construction of emergency centers. The distance was characterized between centers and populations of each population point, the cost of constructing centers, and patient transfer between centers. Figure 1 shows the basic system structure, and Tables 1 and 2 provide the required information to solve the provided problem.

After solving a problem using GAMS software by CPLEX solver on a system with a 3.2 GHz processor and random access memory (RAM) 8 GB, the results are illustrated in Table 3.

The optimal structure of the system is shown in Figure 2.

It can be seen that the medical and emergency centers are constructed in such a way that all population patches in the studied area have the least possible distance to the centers, and also the centers' selection meets all the needs of the application areas.

To further review the model, the effect of changes in some model parameters will be reviewed in the responses from the solution. Sensitivity analysis is important because it

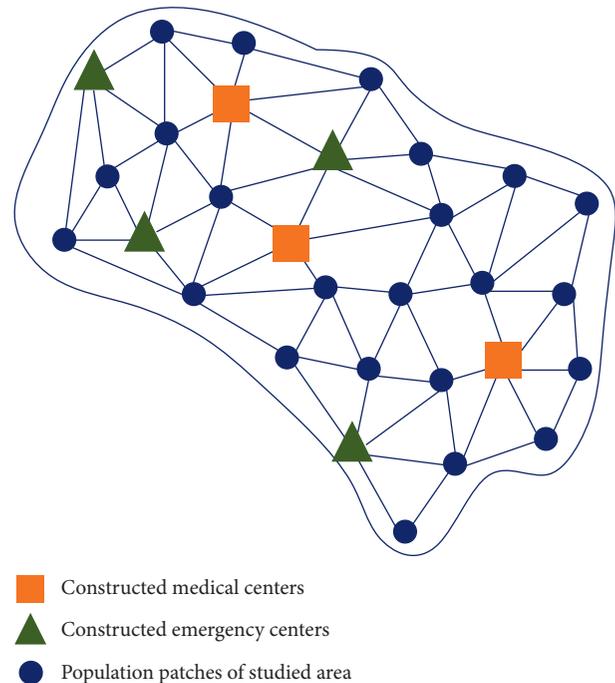


FIGURE 2: The optimal structure of the problem after solving by software.

can assess the stability of the model against changes caused by the values of the effective parameters.

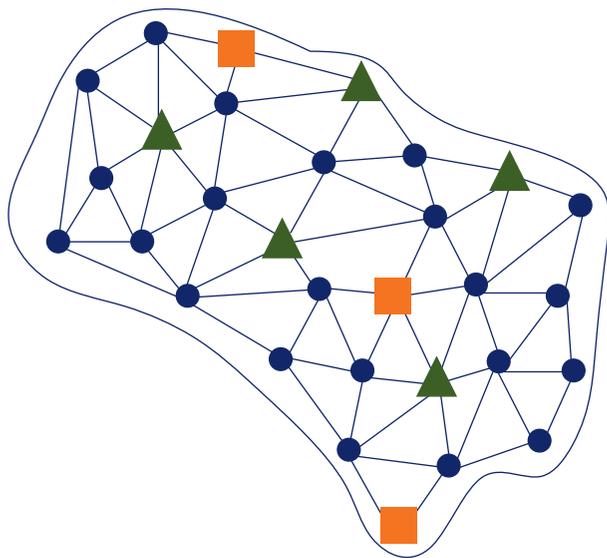
**4.5.1. Case One: Reconstruction Costs.** According to the model presented in this paper, the cost of reconstructing centers is one of the effective parameters which leads to some changes in the system structure. In this section, to investigate more precisely the influence rate of this parameter, the proposed model is solved and examined under various categories of possible values. In the following, the problem data are presented in Tables 4 and 5, and the problem structure is presented under different values of reconstruction cost.

TABLE 4: Reconstruction costs of emergency centers in population patch (c).

Center number	1	3	7	15	20	24	28	30
$RU_c$	0.60	0.40	0	0.5	0	0.55	0	0.4

TABLE 5: Reconstruction costs of medical centers in population patch (c).

Center number	2	5	8	12	26
$RD_c$	0	0.4	0	0.22	0



- Constructed medical centers
- ▲ Constructed emergency centers
- Population patches of studied area

FIGURE 3: The model structure under new values of the reconstruction cost parameter.

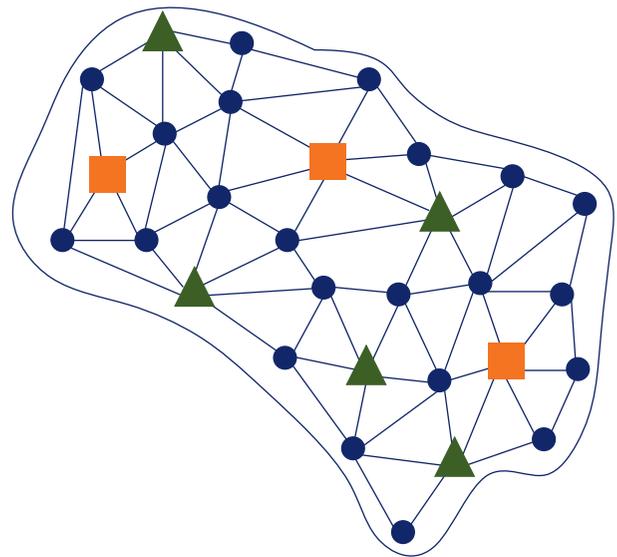
TABLE 6: Patient admission capacity in medical and emergency centers.

Center number	2	5	8	12	26
$CapD(d)$	100	10	100	100	10
$CapU(d)$	100	10	100	100	10

After solving the model by the desired values, the system structure will change to the structure shown in Figure 3.

According to Figure 3, it can be seen that the medical and emergency centers are constructed in areas where the cost is zero for reconstruction or center failure. This indicates the effectiveness and importance of this parameter.

**4.5.2. Case Two: Centers Capacity.** To review the effect of changes in the centers capacity on the optimal system restructuring, Table 6 illustrates the centers capacity under different values.



- Constructed medical centers
- ▲ Constructed emergency centers
- Population patches of studied area

FIGURE 4: The model structure under new values of centers capacity parameter.

According to Figure 4, it can be seen that the medical and emergency centers are constructed in sites with the highest capacity. Of course, this is not true for all centers. This is due to the high cost of construction in some population patches despite lower capacity. However, the capacity of the constructed center is sufficient for the level of demand.

## 5. Conclusion

As mentioned, decision making about the appropriate location for constructing the medical and emergency centers is one of the most important strategic decisions in any organization. This is important because of that selecting an appropriate site for constructing facilities can have a significant effect on reducing costs and increasing the coverage level. However, an appropriate site to construct the facilities must also have maximum reliability in addition to reducing costs and increasing the coverage level. This is important because of that many factors, such as natural disasters, result in failure of centers and influence the confidence level of system performance. Therefore, it is necessary to pay attention to maximize the centers' reliability in their locations. For this purpose, an integer mathematical model is presented in this paper to select the optimum site for constructing the medical and emergency centers by considering the failure probability of each center. The model's objective function minimizes the system costs, including the costs of construction, patient transfer, and failure of medical and emergency centers. Existing constraints include unique allocations, capacity constraints, and system performance constraints. To examine the proposed model's performance accuracy, an example is a review under real-world

conditions. According to the results, this model tries to divide the medical and emergency centers across the studied area so that all population patches can be in the shortest possible distance to the centers. These divisions, of course, involve the cost of construction and the costs of system failure, considering the distance. To examine more accurately the model behavior, we discuss the effect of changes in some problem parameters on the system structure.

In this paper, a comprehensive framework is provided to select a site for medical and emergency centers, considering the reliability of each center. Wide areas are affected by the planning and implementation of the plans presented by health sector managers to improve the general level of community health, and this will lead to different demands for health services. There is a significant difference between this model and recent models due to simultaneously considering patient transfer decisions between medical and emergency centers, as well as considering the reliability of medical and emergency centers that represents the actual conditions governing the health system.

Research works such as Toregas et al. [25] and Church and ReVelle [26] have only examined the costs of constructing health centers, whereas this study considers the costs of the reconstruction as reliability. Degel et al. [27, 28] and Rajagopalan et al. [48] considered construction and reconstruction cost only for emergency centers. In addition to emergency centers, the study also considers medical centers to be normal. Mahmoud and Indriasari [29] studied medical center equipment only indefinitely, whereas the present study analyzes variable service capacity. Chung et al. [30] considered maximum coverage of the area, but this study also focuses on the coverage based on population patch availability. Demir et al. [32] and Furuta et al. [44] have addressed the cost of reconstruction and reliability solely for rescue helicopters, but this study has modeled for demographic variable-capacity treatment centers. Pirkul and Schilling [33], ReVelle and Hogan [39], Sorensen et al. [40] have only examined the standard of access, but there is no mention of cost constraints and the type of healthcare facility, whereas this study considers these two issues.

According to the results, it can be concluded that the change in the cost of reconstructing the centers (the cost of the center failure) has a significant effect on the system structure. In contrast, changes in the centers capacity may not make much difference in some cases, because for constructing centers, the cost of construction has a higher priority than additional capacity.

## 6. Limitations of the Research

In this study, we attempted to examine real variables and constraints comprehensively, but there were limitations in the research work performed. These include the time constraint that led to the disaggregation of public and private centers and their policy constraints, which will be addressed in future research.

Limiting the cost and access to the local community is limited to the city of Tehran (though it accounts for about

one-fifth of the population of Iran daily). Other metropolises or smaller cities could also be considered in future research.

Also, there were problems such as access to information in conduction of the research, which we access through the efforts of the researchers in this study.

## Data Availability

The data used to support the findings of this study are included within the article and supplementary file.

## Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

## Supplementary Materials

Supplementary file: all data of emergency centers and their other quantitative data that are necessary for analysis. Every parameter and decision variable data, same as entitled in the manuscript, are in one column. (*Supplementary Materials*)

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