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An integrated framework to evaluate and improve the performance of emergency departments during the COVID-19 pandemic: A mathematical programing approach

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Abstract

The emergency department (ED) is one of the most critical and high-risk sections of the health system. Providing quality services at a fast pace is vital in this ward since it directly affects people's lives. The COVID-19 pandemic has turned into a serious challenge for physicians and emergency departments (EDs). The growing number of patients who refer to EDs creates congestion, which will reduce the quality of services. Consequently, managing and operating EDs will be more urgent during this pandemic. Considering this problem, we first used data envelopment analysis (DEA) to evaluate the performance of EDs in the central provinces of Iran. Then, sensitivity analysis was used to determine the main factors affecting the efficiency of this ward. Accordingly, the high number of admitted patients, the congestion of the ward, and the long time required to report the COVID-19 test results were found to be the most influential factors. Finally, drawing on the results of sensitivity analysis, we advance a number of measures to improve these three and other related indicators. Furthermore, appropriate strategies were presented for improving health, COVID-19 management, key performance indicators, and safety indicators in accordance with the results of strengths-weaknesses-opportunity-threat (SWOT) analysis.

Keywords

Emergency department, data envelopment analysis, performance evaluation, strengths-weaknesses-opportunities-threats, COVID-19

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Introduction and review literature

Healthcare systems are complex structures that provide the health and care required by patients.[1] The demand for health care services is on the rise in different societies due to technological advances, increased fertility, and greater life expectancy. In recent years, the average life expectancy of communities has increased with the development of treatment systems, such that according to the United Nation's reports, the ratio of people older than 60 to the total population is expected to double between 2007 and 2050, reaching two billion by 2050.[2] Medical care is more critical for the elderly. As such, the need for healthcare services among the elderly population is increasing. On the other hand, with the increasing pressure from governments to reduce costs in health systems, more attention has been directed to optimizing costs and increasing the performance of treatment systems.[3]

Hospitals are one of the influential pillars of healthcare systems. Due to congestion, a hospital's emergency department (ED) undergoes more pressure than other part of hospitals.[1,4] Therefore, it is beneficial, even necessary, to evaluate the ED, and improve its performance by considering its inputs and outputs.

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Severe Acute Respiratory Syndrome (SARS) spread in eastern Asia and subsequently worldwide in late 2002[5] and became a serious public health concern globally.[6] Since December 2019, the COVID-19 disease of the same SARS family[7] has posed a new challenge to the world's healthcare systems. The COVID-19 pandemic has led to large-scale changes in healthcare systems and people's lives.[8,9] One of these changes is the increased number of patients referring to the ED with respiratory symptoms and fever. As a result, it puts increasing pressure on the healthcare system, especially the ED, at the forefront. In these critical situations, healthcare systems have difficulty handling referrals.[10] We seek to evaluate and improve the performance of EDs by considering indicators that affect the COVID-19, such as the number of isolation rooms, equipment, such as the number of test kits, and the time needed to give test results.

In the ED, especially in the context of the COVID-19 pandemic, patient care is mostly provided by nurses. Accordingly, nurses are at the forefront of combating this crisis.[11,12] As such, it is imperative to consider the safety and protection of nurses and the recovery of patients. To assess the safety of the staff and their preparedness, we use safety and health indicators such as staff training and nurse-to-hospital bed ratio.

One of the common barriers to all parts of the healthcare system is the long waiting time of clients.[1] Identifying the threshold and optimizing patient flows help reduce costs and increase quality.[13] Increased crowding in the ED can lead to a higher mortality rate. Thus, it is important to examine KPIs such as waiting time until visit, ED beds, and nurse staffing per patient seen that exert a significant impact on making a precise evaluation of emergency centers and improving patients' satisfaction.[14] By comparing the mentioned indicators (i.e. key performance indicators, COVID-19, health, and safety), we compare and improve the performance of EDs in the context of critical COVID-19 pandemic.

Evaluating the performance of the ED has always been difficult due to the lack of transparency and controversy concerning the determinants of quality, efficiency, and sustainability.[15] To better define the criteria and sub-criteria related to the performance evaluation of EDs, we need experts and the participation of healthcare providers.[16] According to previous research, performance indicators are often used to evaluate and improve performance and increase the quality and safety of patient care.[17] Performance indicators can be classified into two types: quantitative and qualitative. Quantitative indicators can also be sub-divided into time-based, quality, and cost subcategories.[18] Due to the difficulties of measuring quality indicators, they are employed to a lesser degree. Sibbrit et al.[19] introduced and summarized a series of important performance indicators. Lindsay et al.[20] evaluated the performance of the ED by introducing 29 time-dependent qualitative indicators, including the rate of non-visited patient flow, length of hospital stay for patients with diseases such as pneumonia, chest pain, and thromboembolic disease. Some of the indicators used, such as the admission rate of pneumonia patients, were associated with the admission risk. Indicators were measured during or at the end of the process, and ultimately, the Delphi systematic method was used to evaluate performance. Although they considered the patient re-visit indicator as a safety indicator, it is not clear whether emergency patients were also included in the indicators.

Guttmann et al.[21] examined the quality of 12 pediatric EDs using 68 qualitative indicators. To improve the quality of services to children, they used a modified Delphi consensus technique to define more effective indicators and treatment processes. Although this method has been proven to contribute to developing service quality and patient safety,[22] the difficulty of determining qualitative indicators is especially visible for pediatric emergency care.

Alessandrini and Knapp[23] presented an organized method focusing on the waiting time and the time interval between arrival and visit to measure the ED quality. In this study, the authors believe they have used a wide range of indicators required for adequate measurement. Considering factors such as the return of patients before being seen and the sudden return of the patient has complicated this study. di Bella et al.[24] studied the performance evaluation and ranking of 19 EDs by considering qualitative and cost-related indicators. To rank the departments, the Theory of Partially Ordered Sets was built on to identify the best and worst departments as soon as possible. The authors believed that waiting time was the most influential indicator in determining the performance of EDs. Although this method ranks departments in a short time and is a suitable method for policymakers, it cannot assign weight to indicators. For example, duplicate profiles are dropped.

In the study by Yamani et al.,[25] using 360-degree evaluation, different parts of the ED were evaluated with a focus on the ED of Al-Zahra Hospital, Iran. In this study, quantitative indicators related to patients, including safety, are considered. Weaknesses involved issues such as lack of weight assignment to indicators and ambiguity concerning data accuracy; moreover, no specific strategy was suggested to improve performance. Zhao and Paul III[26] evaluated the performance and income of the ED; however, they have not proposed any improvement strategy while also the accuracy of the data has not been discussed. Yeh and Cheng[27] evaluated and proposed suggestions to improve the performance of EDs in Taiwan national hospitals. They used data envelopment analysis (DEA) with six input variables to evaluate the performance of EDs, concluding that approximately 60% of Taiwanese hospitals were inefficient and that the Taiwanese government should reconsider the allocation of resources to urban and non-urban hospitals to improve their performance. The factors considered in the study by *Yeh and Cheng* do not fully examine performance from varying perspectives. Ortiz-Barrios and Alfaro-Saiz[16] evaluated the performance and overall ranking of Colombian EDs by considering indicators such as human resources, facility, drugs, patient quality, and safety with 35 sub-criteria. The Fuzzy Analytic Hierarchy Process was initially used to determine the weight of the criteria and sub-criteria under uncertainty. FDEMATEL was subsequently used to determine the interdependency of the criteria. Ultimately, they employed the Technique for Order of Preference by Similarity to Ideal Solution for ranking purposes. After performance assessment, the weaknesses of each ED were pointed out and suggestions were made to improve them. However, the accuracy of the article information may not be easily guaranteed.

As mentioned earlier, emergency department is one of the critical departments of the hospital. As such, it is essential to evaluate and continuously improve the performance of this department. According to the reviewed research literature, most studies have used performance indicators to evaluate ED performance and have not used quantitative and qualitative indicators concurrently to evaluate ED performance. In this study, to fill this gap, we draw upon both quantitative and qualitative indicators to assess the more comprehensive performance of 63 different EDs.

The current primary challenge in EDs is how to manage and deal with COVID-19 cases. As such, this study is also distinguishable from previous research in that it examines the performance of EDs in the context of COVID-19 pandemic. Accordingly, we also consider COVID-19 indicators to evaluate the performance of EDs. In this study, 27 sub-indicators categorized under functional, COVID-19, patient health, and safety are used to analyze performance by using DEA. Hence, this is the first study that applies this method to evaluate the performance of EDs according to quantitative, qualitative, and COVID-19 indicators and to subsequently rank EDs based on the indicators.

Although evaluating the performance of EDs is significant, setting a policy and proposing to improve them will be of great help to policymakers of hospitals. In the end, strategic proposals based on strengths-weaknesses-opportunity-threat (SWOT) analysis to improve the performance of EDs will be presented. The combined use of DEA for quantitative and qualitative indicators and SWOT analysis leads to a better assessment of the actual performance of EDs under COVID-19 conditions.

The questions that will be addressed in this study are as follows:

- Ranking of EDs according to the indicators
- Ranking of EDs within their respective province
- Determining EDs with the best and worst performance
- Determining the province with the best and worst performance
- Introducing improvement measures for each department

The article's structure will be as follows: Section 2 will define the indicators and sub-indicators. Section 3 describes the problem and the methodology of the paper. Section 4 addresses the case study of EDs in Iran and the results of their performance evaluation and improvement actions. In the end, Section 5 draws conclusions based on the findings and offers some directions for future research.

Selection of indicators and sub-indicators

Considering the above introduction and review of the literature, we have selected the following indicators and sub-indicators:

Key performance indicators (KPIs)

EDs are one of the main wards for hospitalization, and congestion is always one of its chief concerns. The two main ways to deal with this problem are to analyze key performance indicators (KPIs) and to find solutions to improve them.[28] In this paper, we also apply a number of KPIs to appraise and enhance the performance of EDs. Below we describe these indicators: It is also necessary to mention that the KPIs are not limited to those used in the present research. While writing the present article, we aimed to select the most impactful sub-indicators related to each indicator in order to report the obtained results and avoid making the article too long at the same time. For this purpose, we used Principal Component Analysis (PCA). Based on this analysis as well as expert opinions, the degree of impact of each sub-indicator was calculated as a value within the range of 0–100. Then, the sub-indicators that had a degree of impact equal or less than 0.03 were eliminated, and the rest of the sub-indicators were used in the present study. The results obtained through PCA were examined by the specialists and they confirmed the output of the mathematical model. The indicators that were deleted during the selection of KPI sub-indicators included: waiting time for registration, percentage of ED patients accepted for admission, percentage of time the ED, percentage of patients initially assessed by a specialist physician, waiting time for nurse consultation, and waiting time for the results of laboratory or radiological examinations.

Length of hospital stay. A time indicator is usually incorporated in KPIs.[28] This is, among other reasons, due to the negative effect of overcrowding in EDs, which means spending more time in the ward. It is [relatively] easy to measure time-related indicators. The most frequently used indicator in this regard is the length of hospital stay, which is defined as the interval between the time of patient's admission and his/her discharge from the ED. Admission may be conducted by the patient himself/herself or by the ambulance staff. In this study, discharge was considered in the form of either the patient leaving the hospital or his/her transfer to another ward for, say, hospitalization. One of the disadvantages of using this criterion (i.e. length of hospital stay) is that it does not make it possible to identify and evaluate the ward with a deficient performance.[29] It can also be influenced by factors such as population or external factors over which the EDs has no control.[29,30] Therefore, although it is a practical criterion for evaluating performance, its measurement and interpretation should be carried out with enough care and sensitivity.[28]

Boarding time. Another time-related KPI is boarding time (BT), which refers to the interval between a physician's decision to admit [a patient] and the time that patient leaves the ED.[31] Prolonged BT poses several risks to patients; examples include exposure to nosocomial infections, drug shortage, or other care services provided by the hospital staff.[32] Indeed, this is one of the main causes of congestion in the ED,[33,34] which justifies the publication of many papers on reducing BT.

Ambulance diversion. Ambulance diversion (AD), another KPI, is expressed as a proportion index and refers to the percentage of ambulances that are not admitted and are, therefore, sent to nearby EDs.[29] It occurs when EDs are overcrowded.[35] In such conditions, ambulance diversion negatively affects the patients and leads to financial loss and a decrease in the number of patients admitted to the ED.

Left without being seen. Like AD, Left without Being Seen (LWBS) is a sub-indicator expressed as a proportion. It is defined as the percentage of patients who leave the ED before being visited by a physician. LWBS is affected by two factors: congestion and waiting time.[36] This KPI is also influenced by external factors such as the number of nearby EDs and demographic considerations. It is not easy to identify all patients who leave the center without being visited by a physician, which makes it difficult to compare the performance of emergency centers with the help of this indicator.[28] The reason for considering this factor in the present study is that in case patients' conditions exacerbate, the occurrence of this factor endangers their safety and health.[35]

Cancelations and ED occupancy. Like the previous two sub-indicators, the cancelations sub-indicator is a KPI that is expressed as a proportion. In fact, it is the most frequently used proportion indicator.[28] This factor shows how many admissions should be accepted or rejected at times of congestion,[37–39] hence its dependency on the ED occupancy (EDO).

COVID-19

This paper investigates the performance of EDs under COVID-19 conditions, and we deal with those factors that are theoretically expected to affect the performance of this ward in these conditions.

Door-to-doctor time. Door-to-doctor time refers to the time interval between a patient's arrival at the ED and the time he/she is first visited by the physician.[29,40] This time-related sub-indicator is especially important for patients with acute conditions. The reason is that treatment can only start after the patient is visited and diagnosed by the physician.[41] Door-to-doctor time is particularly important for patients with acute conditions; on the other hand, other patients pay more attention to the total waiting time in the ED.[42] As a result, Door-to-doctor time is strongly associated with patient satisfaction, especially for people with acute conditions. Door-to-doctor time may also be grouped as a KPI indicator, but since it is especially important for patients with critical conditions, we examine it under COVID-19-related sub-indicators.

Number of admitted patients. During the COVID-19 pandemic, an increase in the number of patients who refer to the ED and are admitted, which resulting in more congestion.

Employee absenteeism rate. During the COVID-19 pandemic, ED staff are at the forefront of fighting the disease.[11] Indeed, these people are an invaluable and effective resource in dealing with this crisis. Due to the new difficult conditions, especially the increased need to care for patients with COVID-19, the congestion of EDs, and the risk of proximity to these patients, it is expected that the absence of the ED staff will have a considerably negative impact on the performance of the ward.

Percentage of complaints handled. Because EDs are not experienced in dealing with COVID-19 crisis, it is necessary to constantly monitor and improve their status and performance. One way to assess ED performance is to check the percentage of complaints handled (PCH) at the ward.

Number of patients waiting in a queue. The number of patients in line to receive services is an important factor that could also be considered as KPI. Congestion and dissatisfaction grow as this rate increases. Moreover, COVID-19 spreads faster in crowded places, which necessitates [social] distancing. This is why we consider this factor as a sub-indicator of COVID-19.

Number of test kits. A sufficient number of test kits are essential at every ED for diagnosing patients with

COVID-19. Therefore, we take account of this factor while examining the performance of emergency centers under COVID-19 conditions.

Time required for receiving the test results. The time required for obtaining the result of the COVID-19 test depends on how fast and congested the ED is. It is highly important to speed up COVID-19 diagnosis and take steps to improve it. Therefore, we will use this sub-indicator to evaluate the performance of EDs under COVID-19 conditions.

The ratio of isolation rooms to the ED area. There are unique care conditions for hospitalized patients with COVID-19. Special equipment is needed for the staff and patients at the ED. The isolation room separates COVID-19-infected patients from other patients.[1] Separate sections or rooms are also required for quarantining these patients. Clearly, the larger the ratio of isolation rooms to the ED area, the better the conditions for dealing with this crisis.

Health

In this study, the indicators that affect patients' physical health are also examined.

Delay in patient care (DPC). All EDs are concerned about excessive congestion, which leads to delays in patient care.[43] Delaying the provision of care services threatens patients' physical health and increases their dissatisfaction. This factor is especially vital for patients with severe conditions. Delay in patient discharge or transfer refers to the situation in which a patient remains in the emergency department for more than 4 h after a physician's decision to transfer him/her to another ward. This indicator has been selected based on expert opinions and considering the Joint Commission's standards of patient flow (Standard LD.04.03.11). According to Joint Commission perspectives,[44] the patient must not remain in the emergency department for more than 4 h after his/her admission or transfer to another ward has been decided. Enforcing this guideline ensures that prolonging this period does not put the patient's safety and health at risk. In some cases, the patient's stay in the emergency department is prolonged for more than 4 h, which is referred to as "boarding time."[45] However, following another definition of "boarding time" as a performance indicator, in the present research, we classify "boarding time" as a sub-indicator of performance indicators. In this study, a reduction in DPC is believed to improve patients' physical health and maintain their satisfaction.

Maximum capacity. EDs and their physicians face many patients; thus, they are under enormous pressure.[46] This pressure increases during COVID-19 pandemic. During the pandemic, due to considerable congestion in the emergency department and the lack of available rooms, the emergency department uses every available space (including the corridors) to place the additional beds. Consequently, maximum capacity refers to the maximum number of patients who can receive health services provided by the emergency department during the pandemic. It should be noted that this action is also referred to as full capacity protocol.[47] The details on the rules and regulations related to its implementation are beyond the scope of the present research. The researchers used the recorded system data in order to determine an emergency department's performance. Congestion occurs in such conditions because the resources and capacity of EDs are fixed. Insufficient capacity causes congestion and prolonged waiting time for patients, thus compromising their health.

Safety

Safety is one of the vital components of health systems,[48] and congestion is one of the factors that endanger patients' safety and reduce the reliability of EDs.[48] To evaluate and improve the performance of EDs in terms of safety, we have examined the following factors.

Nurse to hospital bed ratio. EDs are not designed for long-term care, and the lack or shortage of human resources to provide care services endangers patients' safety and health.[48] The higher the number of nurses per bed at the ED, the better the patient care and the lower the risk of compromising patient safety.

Mortality rate. Mortality rate (MR) can be due to various factors such as human error or lack of enough resources. In general, the lower this rate is, the safer the patients will be.

Errors due to pressure on nurses. Medical errors are one of the complex issues in hospitals. Increased congestion reduces the quality of services and increases human error.[48] As a result, one of the factors that threaten the safety of patients is related to accidents due to stress on nurses.

Number of equipment accidents. ED congestion increases both medical errors and the number of equipment accidents (NEAs). Therefore, we consider this indicator to evaluate the performance of EDs in terms of safety.

Hours of training per employee. Congestion is one of the main causes of medical errors and, regardless of employees' skills, endangering patients' safety.[48] The more skilled and experienced the employees are, the lower the risk of endangering patients' safety. Organizations hold training programs to enhance the

Figure 1. Selected provinces of Iran considered in the present study.

skills of their employees. In the health system, the longer and the more useful these training are, the more the employees' skills and experience will grow; consequently, the risk of compromising patients' safety will decrease. Therefore, we consider hours of training per employee as an effective factor on the performance of EDs as far as safety is concerned.

In the following (section 3), the above indicators and sub-indicators are represented with their corresponding signs and abbreviations.

Methodology

In this study, a new framework is proposed for evaluating and improving the performance of EDs in the central provinces of Iran (see Figure 1) by considering the effective indicators of this performance during the COVID-19 pandemic. The map of the proposed framework can be seen in Figure 2. This framework consists of five main steps, which are as follows.

Step 1.

- Determining important and effective factors on KPIs, COVID-19, health, and safety according to the literature review and the opinions of experts. A total of 15 separate interviews were held with the members of a committee composed of the managers and senior deputy managers of the National Medical Emergency Organization. The members that were present in this committee included the Manager and three Deputy Managers of the Development Department, the Manager and two Deputy Managers of the Resource Management Department, the Manager of the Support Department, the Manager and Deputy Manager of the Department of Accreditation, the Manager of the Department of Technical Support, and the Manager and three Deputy Managers of the Operations Department. The objective behind holding the interviews separately was to acquire the best indicators proposed by the managers and deputy managers of various emergency departments and to minimize the possible impact that the other managers and deputy managers could have on the obtained results. The indicators collected in this manner were eventually compared using Principal Component Analysis (PCA). Based on the conducted interviews, the indicators with calculated impact of less than 3% were discarded.
- Identifying hospitals with EDs that serve patients with COVID-19 in the central provinces of Iran

Step 2.

- Collecting the required data from the EDs that have already this data in their system for the period between March 2020 and October 2020, hence

obviating the need to check the reliability of the data
- Data normalization

Step 3.

- Determining the best DEA model
- Using the Selected DEA model to calculate the impact of each indicator on the performance of EDs
- Specifying efficient decision-making units (DMUs) by using the results of the DEA model
- Determining the province with the best ED performance

Step 4.

- Running the DEA model by removing indicators and sub-indicators one by one
- Conducting sensitivity analysis using the DEA model to identify the impact of each omitted factor on ED performance
- Identifying the most effective indicator(s)

Step 5.

- Discovering the reason for the positive or negative impact of each indicator on ED performance
- Conducting SWOT analysis to determine the appropriate strategy for improving ED performance

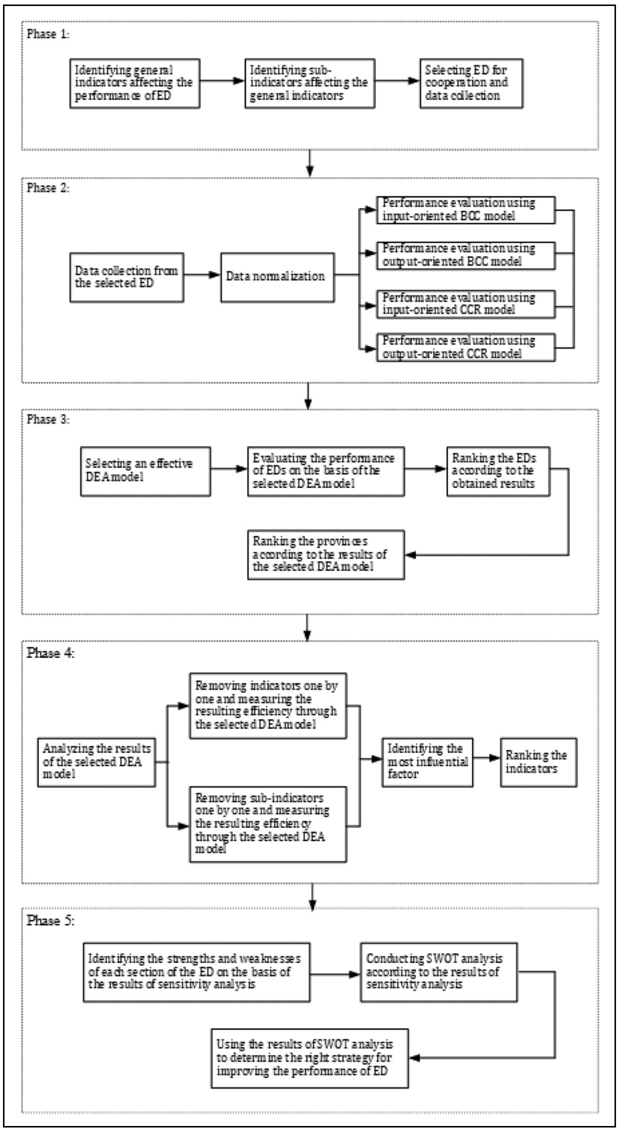

Figure 2. Overview of the proposed framework.

DEA

DEA is a non-parametric method, based on optimization and linear programing that compares the performance of decision-making units (DMUs).[9,49–57] This method was first proposed by Charnes et al.,[58] focusing on measuring key inputs and outputs related to decision groups. Indicators whose low levels/ranks are desirable, such as *Length of hospital stay* and *Boarding time*, are selected as input parameters of the DEA model. On the other hand, indicators whose high levels/ranks are desirable, such as *Number of admitted patients* and *Number of test kits*, are selected as output parameters of the DEA model. The group of decision-makers is called the DMUs. To calculate the efficiency of DMUs, one needs first to obtain the data production function. As it is difficult to identify and mathematically express the relationships held between the input and output parameters within a system,[51,53,56,59] researchers obtain a relative or empirical frontier, rather than computing a production frontier, based on observations. The concepts of empirical and theoretical production frontiers and the feasibility area of DMUs can be seen in Figure 3.

Researchers have recently considered this method in performance appraisal issues.[60,61] Although it does not require any assumptions,[62] making it simpler, the computation of the correlation between input and output indicators causes complexity when measuring and quantifying indicators.[63] The method is known as a valuable analytical tool with several advantages, including the simultaneous use of several inputs and outputs, the possibility of using different inputs and outputs with different measurement scales, non-use of a specific mathematical model to evaluate performance, and focus on all observations.[51] DEA has been demonstrated as a performance appraisal method to replace traditional multi-criteria decision-making approaches in the ED.[64] As a result, the features of DEA have led to its many applications in various fields, including healthcare systems.[65]

For example, DEA has been used to evaluate the performance of nursing home services[66] and to evaluate staff performance during specific diseases[67,68] in healthcare systems. DEA has also been used in many hospital evaluations and productivity studies.[69]

In the DEA model, the efficiency of the jth DMU for m inputs and s outputs is calculated as follows:

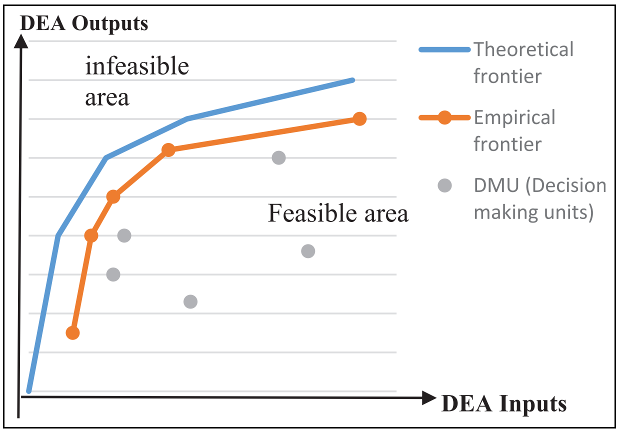

Figure 3. The frontiers of empirical and theoretical production.

$$max\theta_j = \frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \quad (1)$$

In this equation, v_i and u_r are the input cost and the output price. $\sum_{r=1}^{s} u_r y_{rj}$ and $\sum_{i=1}^{m} v_i x_{ij}$. represent the total weight of outputs and inputs, respectively. According to equation (1), the fractional linear programing model has been proposed to determine the efficiency:

$$\begin{aligned} & max\theta_0 = \frac{\sum_{r=1}^{s} u_r y_{r0}}{\sum_{i=1}^{m} v_i x_{i0}} \\ & \text{s.t} \\ & \frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \leqslant 1 \qquad j \in \{1,2,\ldots,n\} \\ & u_r,\ v_i \geqslant 0 \qquad i \in \{1,2,\ldots,m\} \end{aligned} \quad (2)$$

To obtain the relative efficiency of DMUs, the above model must be calculated n times for all DMUs. In the equation above, j is the number of decision units, i is the number of inputs, and r is the number of outputs. Also, y_{rj} denotes the outputs and x_{ij} represents the inputs. Besides, θ_0 is the efficiency of the Multiple-Criteria Decision Analysis)MCDM). Subsequently, using the method proposed by,[58] the above model is transformed into the following form of linear programing:

$$\begin{aligned} & max\theta_0 = \sum_{r=1}^{s} u_r y_{r0} \\ & \text{s.t :} \\ & \sum_{i=1}^{m} v_i x_{i0} = 1 \\ & \sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} \leqslant 0 \quad j \in \{1,2,\ldots,n\} \\ & u_r,\ v_i \geqslant \varepsilon \qquad i \in \{1,2,\ldots,m\},\ r \in \{1,2,\ldots,s\} \end{aligned} \quad (3)$$

In this equation, a non-Archimedean infinitesimal coefficient is defined to ensure that all weights are positive.

DEA models include the four basic models of Charnes, Cooper and Rhodes (CCR),[58] Banker, Charnes, and Cooper (BCC),[70] the multiplicative model,[71] and the additive model.[72] In DEA models, if we reduce the number of inputs without changing the number of outputs, it is called an input-driven model. If the output is increased without changing the number of inputs, it is called an output-driven model. Below, we will describe the CCR and BCC models.

CCR model. The first DEA model, known as CCR, was introduced to measure the efficiency of DMUs.[58] The obtained model (3) in the previous section is called the multiplier form of the CCR model. The dual problem of this model, known as the input-oriented CCR model and used more frequently than other DEA models in analyzing and interpreting results, is as follows:

$$\begin{aligned} & min\ y_0 = \theta_0 \\ & \text{s.t :} \\ & \sum_{j=1}^{n} \lambda_i y_{rj} \geqslant y_{r0} \qquad r \in \{1,2,\ldots,s\} \\ & \sum_{j=1}^{n} \lambda_j x_{ij} \leqslant \theta_0 \cdot\ x_i \qquad i \in \{1,2,\ldots,m\} \\ & \lambda_j \geqslant 0, \qquad j \in \{1,2,\ldots,n\} \\ & \theta_0 \in R \end{aligned}$$

where λ_j's constitute the dual variable corresponding to the second constraint, and θ_0 is the dual variable corresponding to the first constraint.

The CCR-output-oriented model, which increases the number of outputs without changing the number of inputs, is as follows:

$$\begin{aligned} & min\ = \theta \\ & \text{s.t :} \\ & \sum_{j=1}^{n} \lambda_i y_{rj} \geqslant \theta y_{r0} \qquad r \in \{1,2,\ldots,s\} \\ & \sum_{j=1}^{n} \lambda_j x_{ij} \leqslant\ x_i \qquad i \in \{1,2,\ldots,m\} \\ & \lambda_j \geqslant 0, \qquad j \in \{1,2,\ldots,n\} \end{aligned} \quad (5)$$

BCC model. The BCC model, introduced 6 years after the CCR model was introduced, deals with the total technical efficiency and the efficiency of DMUs under multifactorial conditions. The BCC model has one more constraint than the CCR model, which ensures that the sum of j is equal to one. The BCC output-oriented linear programing model is as follows:

$$
\begin{aligned}
& max\ \theta \\
& \text{s.t}: \\
& \sum_{j=1}^{n} \lambda_j x_{ij} \leqslant x_{i0} \quad i \in \{1, 2, \ldots, m\} \\
& \sum_{j=1}^{n} \lambda_i y_{rj} \geqslant \theta y_{r0} \quad r \in \{1, 2, \ldots, s\} \\
& \sum_{j=1}^{n} \lambda_j = 1 \\
& \lambda_j \geqslant 0 \quad j \in \{1, 2, \ldots, n\}
\end{aligned} \tag{6}
$$

The BCC input-oriented model, obtained by introducing the third constraint to the fifth model, is as follows:

$$
\begin{aligned}
& min\ = \theta \\
& \text{s.t}: \\
& \sum_{j=1}^{n} \lambda_i y_{rj} \geqslant y_{r0} \quad r \in \{1, 2, \ldots, s\} \\
& \sum_{j=1}^{n} \lambda_j x_{ij} \leqslant \theta x_{i0} \quad i \in \{1, 2, \ldots, m\} i \in \{1, 2, \ldots, m\} \\
& \sum_{j=1}^{n} \lambda_j = 1 \\
& \lambda_j \geqslant 0, \quad j \in \{1, 2, \ldots, n\}
\end{aligned} \tag{7}
$$

Given the inability of the original DEA model to rank efficient units, Anderson and Petersen modified the model to rank the efficiency of units.[73] They developed a new model by eliminating DMU_0 and solving the dual CCR for other DMUs.

In this study, the four DEA models, including BCC input-oriented, BCC output-oriented, CCR input-oriented, and CCR output-oriented, are compared to find the best model for performance evaluation. We have used perceptron correlations for comparison. To determine the desired DEA model, we induce noise to 10% of the DMU data and subsequently select the DEA model by comparing the perceptron correlation.

Sensitivity analysis

We used sensitivity analysis to illustrate the effect of each indicator on the performance of EDs.[74] To this end, considering all the above-mentioned indicators and sub-indicators, we used sensitivity analysis and ran the selected DEA model. Then, the model was re-run according to the number of indicators, such that one indicator was removed in each iteration. The final average efficiency score of DMUs (i.e. when one selected factor is removed) was compared with the average efficiency score of DMUs obtained in the initial situation when no indicator had been eliminated. Next, we recorded the results regarding the appropriate or inappropriate performance of the ED after removing each indicator. For a more accurate analysis, the obtained results were statistically examined. It should be noted that there are two different categories of statistical tests, namely parametric and non-parametric. To use parametric tests, the simultaneous existence of two conditions in the efficiency values must be checked, and if even one of these is not met, the parametric test cannot be used: (1) normal distribution, (2) homogeneity. Kolmogorov-Smirnov (K-S) and Levene's tests are used to check the normal distribution and homogeneity of data. After determining the most effective indicators and the ED with the weakest performance, one can adopt and implement improvement measures based on the obtained results to boost efficiency and improve the performance of the ED in question.

SWOT analysis

SWOT (strengths, weaknesses, opportunities, and threats) analysis is a simple yet powerful tool for developing improvement strategies for different organizations. Using this analysis, as its name suggests, one can create a strategic balance between strengths and opportunities.[75–78] Four types of strategies could be developed using this analysis: SO (strengths-opportunities), ST (strengths-threats), WO (weaknesses-opportunities), and WT (threats-weaknesses).[79]

Numerical results

In this study, we considered 72 EDs that were located in nine central provinces of Iran and provided services to patients with COVID-19. The purpose of this study was to compare and evaluate the performance of EDs in terms of KPIs, health, safety, and COVID-19 considerations using the actual data in these centers.

The first step in calculating efficiency via the DEA model is to select inputs and outputs.[80] In this study, indicators whose low levels/ranks are desirable are selected as input, and other indicators whose high levels/ranks are desirable are selected as output.

Each ED (total = 72) was considered as a DMU, and the quantitative data recorded in the system of each ED were used to collect the required information.

Results of determining the preferred DEA model

We used noise analysis to determine the preferred DEA model. In this method, 10% of DMUs were randomly selected 10% of DMUs were randomly selected by following "Random sample of cases" from the "Select cases" menu in SPSS 26 before calculating efficiency. In some of these randomly selected DMUs, −10% to 10% is randomly added to or subtracted from the numbers, and efficiency is then measured using these four DEA models.

The Spearman's correlation test was used to evaluate the effect of the noise generated on each DMU. Finally, the model with a higher correlation between the results obtained before and after noise generation was selected as the optimal DEA model for efficiency analysis. The results are given in Table 1. Accordingly, the output-

Table 1. Spearman correlation test results.

Model	CCR input-oriented	CCR output-oriented	BCC input-oriented	BCC output-oriented
Spearman's correlation	0.969	0.969	0.877	0.979

Table 2. Results and ranks of DMU performance within each province and across all considered provinces.

Province	DMU	BCC output-oriented	Rank	Rank in province	Province	DMU	BCC output-oriented	Rank	Rank in province
Tehran	1	46	47	7	Isfahan	37	110	11	9
Tehran	2	31	65	10	Isfahan	38	139	6	4
Tehran	3	58	36	6	Isfahan	39	172	2	2
Tehran	4	67	27	2	Isfahan	40	91	14	11
Tehran	5	61	33	5	Isfahan	41	156	3	3
Tehran	6	46	47	7	Isfahan	42	91	14	11
Tehran	7	41	57	9	Qazvin	43	57	38	6
Tehran	8	64	31	4	Qazvin	44	59	35	4
Tehran	9	23	68	12	Qazvin	45	72	25	2
Tehran	10	27	66	11	Qazvin	46	64	31	3
Tehran	11	76	22	1	Qazvin	47	140	4	1
Tehran	12	67	27	2	Qazvin	48	53	42	7
Alborz	13	33	64	5	Qazvin	49	43	52	9
Alborz	14	39	59	4	Qazvin	50	58	36	5
Alborz	15	76	22	2	Qazvin	51	45	49	8
Alborz	16	55	40	3	Qom	52	86	20	1
Alborz	17	17	70	6	Qom	53	56	39	2
Alborz	18	110	11	1	Qom	54	52	43	3
Yazd	19	52	43	5	Qom	55	10	72	4
Yazd	20	88	16	2	Markazi	56	74	24	2
Yazd	21	36	61	7	Markazi	57	49	46	5
Yazd	22	61	33	4	Markazi	58	72	25	3
Yazd	23	38	60	6	Markazi	59	11	71	9
Yazd	24	34	62	8	Markazi	60	25	67	8
Yazd	25	23	68	9	Markazi	61	34	62	7
Yazd	26	66	29	3	Markazi	62	88	16	1
Yazd	27	140	4	1	Markazi	63	44	51	6
Isfahan	28	117	10	8	Markazi	64	55	40	4
Isfahan	29	119	9	7	Chaharmahal and Bakhtiari	65	43	52	1
Isfahan	30	180	1	1	Chaharmahal and Bakhtiari	66	43	52	1
Isfahan	31	86	20	15	Chaharmahal and Bakhtiari	67	40	58	3
Isfahan	32	88	16	13	Semnan	68	45	49	3
Isfahan	33	87	19	14	Semnan	69	43	52	4
Isfahan	34	110	11	9	Semnan	70	43	52	4
Isfahan	35	131	7	5	Semnan	71	66	29	1
Isfahan	36	121	8	6	Semnan	72	50	45	2
average efficiency of all ED							67.95		

oriented BCC model is the choice model because it is less sensitive to the generated noise.

Results of the preferred DEA model

The performance of each ED was calculated and ranked using the selected DEA model. The indicators, which were introduced in Section 2 (Length of hospital stay, Boarding time, etc.), were fed into this model for calculation. Table 2 presents the results and ranks of all EDs within each province and across all considered provinces.

According to Table 2, EDs 30 and 55 had the best and the weakest performance, respectively. Figure 4 shows the average performance of EDs in each province separately. According to Figure 4, EDs in Qom province show the lowest average efficiency and, as a result, the weakest performance. On the other hand, EDs in Isfahan province are marked by the highest average efficiency and, therefore, the best performance.

Results of sensitivity analysis of EDs in all considered provinces

As mentioned in Section 3-2, we used sensitivity analysis to understand and evaluate the impact of each indicator on the performance of all EDs and to identify the

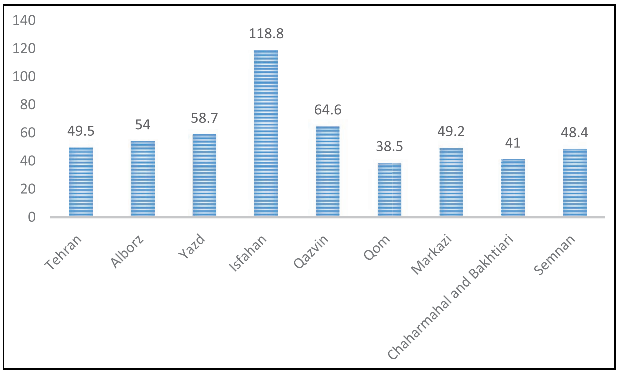

Figure 4. The average efficiency of EDs in each considered province.

most effective indicator in this regard. To do this, efficiency was calculated before and after removing each indicator and sub-indicator. The obtained intuitive results were then statistically examined. For statistical tests, parametric methods are used if the two conditions of normality and data homogeneity are met; otherwise, non-parametric methods are employed.[51] Since the normality of data collected from all considered provinces was not confirmed (Table 3), we ran the non-parametric Kruskal–Wallis test to examine the hypothesis of if the data follow a normal distribution versus if they do not follow a normal distribution in order to evaluate and conduct sensitivity analysis on the ED performance of the provinces (Table 4).

According to the results of sensitivity analysis, removing indicators A, C, and sub-indicators a2, a3, a4, b4, b5, and d4 will reduce deviation from efficiency. Based on the performed statistical tests, this reduction is significant at $\alpha = 0.05$, which confirms ED performance is appropriate as far as these indicators are concerned. Therefore, it can be concluded that EDs do not perform well in terms of these indicators, which will negatively influence their overall performance. EDs showed a good performance in terms of indicators B and D and sub-indicators b2, b3, d3, and d5; removing these factors will reduce the efficiency of these centers. This reduction was also found to be significantly valid at $\alpha = 0.05$. Furthermore, according to the results of Table 4, sub-indicators b2 and d4 revealed the most negative and positive impact on the performance of EDs, respectively.

Table 3. Results of Shapiro-Wilk (S-W) test and Kolmogorov-Smirnov (K-S) test for all indicators.

Omitted indicator	*p*-Value K-S	*p*-Value S-W	Omitted indicator	*p*-Value K-S	*p*-Value S-W
None	0.000	0.000	b3	0.005	0.000
A	0.000	0.000	b4	0.007	0.000
B	0.000	0.000	b5	0.001	0.000
C	0.001	0.000	b6	0.006	0.000
D	0.001	0.000	b7	0.007	0.002
a1	0.000	0.000	b8	0.007	0.001
a2	0.000	0.000	c1	0.001	0.000
a3	0.001	0.000	c2	0.011	0.001
a4	0.000	0.000	d1	0.005	0.000
a5	0.002	0.000	d2	0.004	0.001
a6	0.001	0.001	d3	0.002	0.000
b1	0.001	0.000	d4	0.008	0.001
b2	0.007	0.003	d5	0.000	0.000

Table 4. Results of sensitivity analysis of all nine provinces considered in the present study.

Omitted indicator	$\mu_1 - \mu_2$	*p*-Value	Omitted indicator	$\mu_1 - \mu_2$	*p*-Value
A	2.3	0.000	b4	1.20	0.007
B	−3.79	0.040	b5	3.49	0.000
C	1.88	0.000	b6	−1.41	0.000
D	−2.18	0.000	b7	−9.45	0.030
a1	−2.73	0.000	b8	−2.93	0.000
a2	2.49	0.007	c1	−5.94	0.000
a3	4.18	0.000	c2	−1.15	0.004
a4	−0.99	0.008	d1	−5.80	0.001
a5	−3.37	0.000	d2	−1.58	0.000
a6	−7.36	0.000	d3	−3.90	0.000
b1	1.07	0.020	d4	5.56	0.003
b2	−49.57	0.000	d5	−1.65	0.000
b3	−4.09	0.008			

Table 5. Results of sensitivity analysis of general indicators for all considered provinces.

Omitted indicator / province		A	B	C	D
Tehran	$\mu_1 - \mu_2$	2.38	2.301	−3.92	−1.76
	p-Value of paired *t*-test	0.000	0.000	0.000	0.000
Alborz	$\mu_1 - \mu_2$	2.8	2.89	−3	0.6
	p-Value of paired *t*-test	0.000	0.001	0.002	0.000
Yazd	$\mu_1 - \mu_2$	3.11	3	−4.44	−2.55
	p-Value of paired *t*-test	0.000	0.000	0.000	0.000
Isfahan	$\mu_1 - \mu_2$	1.26	1.6	−5.22	−2.3
	p-Value of paired *t*-test	0.000	0.000	0.000	0.000
Qazvin	$\mu_1 - \mu_2$	0.77	2.1	−3.56	−4.6
	p-Value of paired *t*-test	0.000	0.000	0.002	0.000
Qom	$\mu_1 - \mu_2$	1.25	0.75	−1.5	−2.25
	p-Value of paired *t*-test	0.008	0.002	0.014	0.007
Markazi	$\mu_1 - \mu_2$	2.6	−−0.6	−3.3	−1.2
	p-Value of paired *t*-test	0.000	0.000	0.000	0.000
Chaharmahal and Bakhtiari	$\mu_1 - \mu_2$	4.6	2.7	−3.6	−2.6
	p-Value of paired *t*-test	0.005	0.009	0.007	0.000
Semnan	$\mu_1 - \mu_2$	5	2.76	−1.8	−2
	p-Value of paired *t*-test	0.001	0.003	0.004	0.007

According to the tables, Isfahan, Markazi, and Qazvin provinces have the best ED performance in terms of indicators C, B, and D; and Semnan, Yazd, and Alborz provinces have the weakest EM performance in terms of indicators A, B, and D.

Results of sensitivity analysis of EDs in each single province

In this section, the results of sensitivity analysis on each of the provinces are examined separately, and the intuitive results are statistically analyzed. In this section, to make pairwise comparisons for each single province (testing the hypothesis $H_0 : \mu_1 = \mu_2$ vs $H_1 : \mu_1 \neq \mu_2$), we used paired t-test because the two conditions of data normality and homogeneity were met (See Tables A1–A9 of Appendix). The results of paired t-test for each province are presented in Table A10–A18 of Appendix.

According to Table 5, which shows the results of sensitivity analysis of the general indicators in each province, it can be concluded that all provinces have a good performance in terms of indicator A and a weak performance in terms of indicator B. Also, the performance of all provinces except Markazi province was good in terms of indicator C, and the performance of all provinces except Alborz province was weak in terms of indicator D.

Appendix Tables A10 to A18 shows the results of sensitivity analysis of sub-indicators in all considered provinces . According to these tables, at $\alpha = 0.05$, all *t*-pair tests are valid, and the following results are noteworthy.

- The ED performance of Tehran province was weak in relation to sub-indicators a4, b2, b3, a5, b7, a1, a6, b8, c1, c2, d1, d2, d3, and d5, but it was good in relation to sub-indicators b1, a2, a3, b4, b5, b6, and d4. Also, sub-indicators b2 and d4 had the most negative and the most positive impact on the ED performance of Tehran province, respectively.
- The ED performance of Alborz province was weak in relation to sub-indicators a4, b2, b3, b7, d2, d3, a1, a6, b8, c1, c2, and d1, but it was good in relation to sub-indicators b1, a2, a3, b4, a5, d4, and d5. Sub-indicators b2 and a2 had the most negative and the most positive impact on the ED performance of Alborz province, respectively.
- The ED performance of Yazd province was weak in relation to sub-indicators b2, b3, a6, a5, b7, a1, c1, c2, d2, d3, d1, and d5, but it was good in relation to sub-indicators b1, a2, a3, b4, b5, b8, b6, and d4. Sub-indicators b2 and d4 had the most negative and the most positive impact on the ED performance of Yazd province, respectively.
- The ED performance of Isfahan province was weak in relation to sub-indicators a4, b2, b3, a5, b7, a1, a6, b8, c1, b6, c2, d1, d3, and d5, but it was good in relation to sub-indicators b1, a2, a3, b4, b5, d2, and d4. Sub-indicators b2 and b5 had the most negative and the most positive impact on the ED performance of Isfahan province, respectively.
- The ED performance of Qazvin province was weak in relation to sub-indicators a4, b2, b3, a5, b7, a1, a6, b8, c1, b6, c2, d1, d2, d3, and d5, but it was good in relation to sub-indicators b1, a2, a3, b4, b5, and d4. Sub-indicators b2 and b5 had the most negative and the most positive impact on the ED performance of Qazvin province, respectively.
- The ED performance of Qom province was weak in relation to sub-indicators a4, b2, b3, a5, b7, a1, a6, b8, c1, b6, c2, d1, and d5, but it was good in relation to sub-indicators b1, a2, a3, b4, b5, d2, d3, and d4. Sub-indicators b2 and a2 had the most

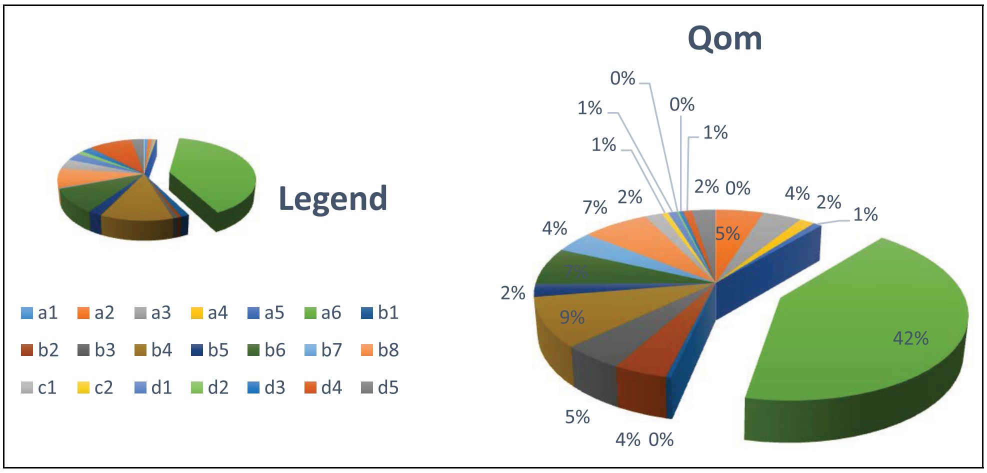

Figure 5. Weight of each sub-indicator in ED efficiency in Qom province.

negative and the most positive impact on the ED performance of Qom province, respectively.

- The ED performance of Markazi province was weak in relation to sub-indicators a4, b2, b5, AR, Ca, b7, a1, a6, b8, c1, b6, c2, d1, and d5, but it was good in relation to sub-indicators b1, a2, a3, b4, and d4. Sub-indicators b2 and a3 had the most negative and the most positive impact on the ED performance of Markazi province, respectively.
- The ED performance of Chaharmahal and Bakhtiari province was weak in relation to sub-indicators a2, a4, b4, b2, Ca, b7, a1, a6, c1, d1, d2, d3, and d5, but it was good in relation to sub-indicators b1, b5, b3, b6, c2, and d4. Sub-indicators b2 and d4 had the most negative and the most positive impact on the ED performance of Chaharmahal and Bakhtiari province, respectively.
- The ED performance of Semnan province was weak in relation to sub-indicators b2, b4, a4, A5, b7, a1, a6, b8, c1, b6, c2, d1, d2, d3, and d5, but it was good in relation to sub-indicators a2, b1, a3, b5, and d4. Sub-indicators b2 and d4 had the most negative and the most positive impact on the ED performance of Semnan province, respectively.

Weighing the sub-indicators

In this section, we use the results of sensitivity analysis to calculate the impact of each sub-indicator on ED performance in each province. The resulting weights show the percentage change in the efficiency of the EDs after removing each sub-indicator. This study uses the average efficiency of EDs in each province to calculate the percentage change in efficiency. Figure 5 and A1 have been used in the paper in order to better schematically demonstrate the percentage change in the initial efficiency of the emergency departments after removing each sub-indicator. These figures demonstrate the changes in average efficiency scores before and after removing each sub-indicator, as presented by the results of sensitivity analysis conducted in Section 4.3. It is worth noting that the calculated weight of each sub-indicator has been obtained using the results presented in Tables 3 and 4. In order to illustrate this point further, the mathematical formula used to calculate the weight percentage of each sub-indicator can be presented as follows:

$$\frac{|\mu_{overal} - \mu_{ommited\ indicator}|}{\sum_{k=1}^{26} |(\mu_{overal} - \mu_{ommited\ indicator})|_k}$$

K = Number of sub-indicators

The ideas presented in this section have been inspired by and modeled based on the following articles.[81–83]

For instance, Figure 5 shows the weight of each sub-indicator in Qom province. The weight of each sub-indicator in other provinces can be found in Figure A1 in Appendix.

According to the following figures, sub-indicator a6 (i.e. ED occupancy) has a greater weight than other sub-indicators in all considered provinces. This could be due to the unprecedented increase in the number of patients with COVID-19. The weight of each sub-indicator on ED efficiency is determined in the following figures.

Improvement actions

According to the average efficiency of different provinces (Section 2–4), EDs in Qom province had the weakest performance. Indeed, this province was the first to be infected with COVID-19,[84] and the disease spread from this province to other parts of the country. Consequently, there was a lot of sensitivity and attention to ED performance and management of COVID-19 in this province. Based on the experts' opinions, we considered improvement measures only for Qom province. This is because, on the one hand, according to the results of the present study, emergency departments in

Qom province had the weakest performance, and on the other hand, this province was the first to be infected with COVID-19 in Iran. The performance of EDs in terms of each indicator and sub-indicator could be observed in the results of sensitivity analysis obtained for each province. According to the results of sensitivity analysis, EDs in Qom province have performed poorly in terms of safety (D) and COVID-19 (B) indicators. Besides, the EDs of this province have not performed well in terms of sub-indicators a4, b2, b3, a5, b7, a1, a6, b8, c1, b6, c2, d1, and d5. Therefore, they need solutions to improve their performance in relation to these indicators and sub-indicators. In this regard, one could suggest measures such as timely updating of information and software and quick identification of the needs of the staff and patients. It is also recommended to constantly update the official instructions and guidelines – according to emerging conditions – during the crisis.

SWOT analysis was used to provide appropriate strategies to boost the performance of EDs in Qom province. Considering the results in Section 4, we used sensitivity analysis and statistical tests to find the strengths and weaknesses of EDs in each respective province. In this regard, the weaknesses of Qom province are associated with safety and COVID-19 indicators. Sub-indicators a4, b2, b3, a5, b7, a1, a6, b8, c1, b6, c2, d1, and d5 are among the weaknesses of EDs in Qom province, and they have not performed well in relation to these sub-indicators. Conversely, sub-indicators b1, a2, a3, b4, b5, d2, d3, and d4 are the strengths of EDs in this province, and their elimination will impair the efficiency of these centers.

Having identified the strengths and weaknesses of EDs in Qom province, considering the severity of the circumstances caused by the COVID-19 pandemic and due to restrictions on face-to-face meetings, the interviews were held online in three consecutive sessions using Skype. we used the opinions of three experienced ED experts all of whom hold Doctor of Medicine degrees issued by the Medical Council of Iran and have at least 10 years of experience as the manager or deputy manager of various departments in the National Medical Emergency Organization to find out the related opportunities and threats to identify the related opportunities and threats, the researchers formed a committee and held collaborative online sessions of brainstorming with all the members. There was no conflict of interests in determining the existing threats and opportunities. This outcome was achieved due to the adapted decision-making process that is described as follows. When a committee member made a suggestion, all the other members expressed their agreement or disagreement and, based on years of experience in this field, they proceeded to provide valid reasons in order to persuade all the other members. Eventually, all the committee members reached a consensus and a unanimous decision was made and approved by all the committee members. In addition, we reviewed previous studies[75–77] and the strategic plan of EDs of Qom province. Appropriate strategies were subsequently formulated. With the assistance of this committee and through brainstorming, appropriate strategies were presented based on the SWOT framework. SO and ST strategies exploit the strengths to face and respond to threats and take advantage of the identified opportunities; on the other hand, WO and WT strategies are intended to overcome weaknesses according to the opportunities and threats (Table 6). To promote the efficiency of EDs in Qom province, we have proposed several strategies. SWOT analysis can also be employed to enhance the performance of EDs in other provinces.

Conclusions

This study evaluated the performance of 72 EDs in the central provinces of Iran in the context of the COVID-19 crisis. Then, the performance of these centers was evaluated and ranked using the DEA method. We considered four main indicators – each comprising several sub-indicators – that affected the performance of EDs. These indicators were proposed based on previous studies and expert opinions. The four main factors included KPIs, COVID-19, health, and safety. To the best of our knowledge, this is the first study in Iran to evaluate the performance of emergency centers during the COVID-19 pandemic using the DEA method. After determining the indicators and sub-indicators, we considered four DEA models and used noise analysis to select the best one for evaluation. According to the results, we identified efficient and inefficient centers. Provinces with the best and weakest EDs were determined. Then, to calculate the effect of each indicator and sub-indicator on the performance of EDs, we used sensitivity analysis and analyzed the obtained intuitive results by performing some statistical tests. Finally, considering expert opinions and previous studies, we conducted SWOT analysis for the most inefficient province, that is, Qom. Furthermore, appropriate strategies were introduced to ameliorate the performance of EDs in this province.

The result of sensitivity analysis suggests that the performance of the considered EDs is generally poor in regard to the COVID-19 indicator, but it is good in terms of KPIs. The results of sensitivity analysis of all indicators and sub-indicators were presented for each province. In addition, we drew on these findings to calculate the percentage (weight) each factor could influence efficiency. These weights were determined based on the percentage change in efficiency obtained after the elimination of each factor. Specifically, ED occupancy (a6) was associated with the highest weight in all considered provinces, which demonstrates the importance of this factor in the efficiency of EDs.

The proposed framework can be used to evaluate any section of EDs based on the above indicators and sub-indicators. It is also possible to adopt fuzzy DEA methods or neural network algorithms to assess EDs'

Table 6. SWOT matrix.

SWOT	Strengths	Weaknesses
	Experienced, committed, motivated, and highly potential human resources	Job dissatisfaction among some employees and physicians
	High number of patients and high bed occupancy rate	Shortage of welfare facilities
	Holding in-service training programs at the center and relying on internal capacities	Low bed occupancy rate and high average of hospitalization days
	Interaction, capability, interest, and follow-up on the part of the management in pursuit of improving services	Physicians' irregular appointment hours and patients' dissatisfaction
	Willingness of full-time physicians to be present at the ED	Imbalance of income and expenses due to economic difficulties [and other similar problems]
	Availability, long history, and reputation of the center	Lack of enough subspecialists in various [medical] fields
	Availability of separate isolation rooms	Poor (preventive) maintenance
	Attempting to reduce human errors	Problems in performing various construction operations due to hospital's worn-out structure and insecurity of patients and staff
		Rapid spread of COVID-19
		Lack of awareness about COVID-19 on the part of people and EDs
Opportunities	**SO strategies**	**WO strategies**
Existence of contractor companies for construction materials and hospital equipment	Recruiting physicians in different specialties	Standardization and replacement of worn-out and inefficient equipment
Ability to cooperate with nearby EDs	Exchange of physicians and specialists with other EDs	Renovation of old buildings
Organizing training programs on crisis management by the Ministry of Health	Improving communications between different sections of the ED to reduce errors	Planning to increase flexibility and improve the health system in the direction of crisis management
Convenient geographical location and local access	Developing an appropriate reporting system to speed up affairs	Determining and justifying all of the duties of employees at times of crisis
Existence of isolation rooms		Integration and coordination of the information system with different sections of the ED
Availability of personnel with different specializations and high skills in dealing with crises		Raising budget for human resources and equipment
Further improvement and monitoring of the emergency system		
Providing educational opportunities for patients with infectious diseases		
Threats	**ST strategies**	**WT strategies**
Insufficient knowledge about COVID-19	Employing the required specialists on a contractual basis	Optimal deployment of competent and helpful staff
High number of patients referring to the center	Developing and promoting scientific research	Educational planning to improve the scientific knowledge of medical staff
Lack of modern medical technological equipment due to inflation and general increase in prices at all levels	Sharing the obtained information with other centers and collaborating in this area	Planning and improving (preventive) maintenance
Shortage of human resources and problems in recruiting nurses and other health workers	Providing complete reports on the process of patients' recovery and treatment	Strengthening the telemedicine system
Lack of enough budget and timely payments		Using home health services
Complicated process of recruitment		
Continuous changes in the Health Transformation Plan and delays in enforcing its guidelines		
Increasing expectations of patients and their caregivers		
Lack of an efficient system for evaluating the performance of personnel in the country		
Government and insurance laws and restrictions		
Profound impact of COVID-19 on people's personal and social lives		

performance in future studies. Moreover, future studies may identify and focus on other factors such as resilience or Macro-Ergonomics indicators that affect the performance and quality of EDs.

Declaration of conflicting interests

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Appendix

Table A1. Results of Shapiro-Wilk (S-W) test and Kolmogorov-Smirnov (K-S) test for Tehran province.

Omitted indicator	*p*-Value K-S	*p*-Value S-W	Omitted indicator	*p*-Value K-S	*p*-Value S-W	Omitted indicator	*p*-Value K-S	*p*-Value S-W
None	0.200	0.837	a5	0.200	0.712	b8	0.080	0.069
A	0.200	0.441	a6	0.160	0.154	c1	0.200	0.607
B	0.200	0.251	b1	0.146	0.324	c2	0.200	0.882
C	0.073	0.174	b2	0.200	0.587	d1	0.200	0.797
D	0.200	0.538	b3	0.200	0.938	d2	0.200	0.635
a1	0.200	1.000	b4	0.200	0.518	d3	0.200	0.398
a2	0.200	0.679	b5	0.200	0.789	d4	0.200	0.366
a3	0.200	0.492	b6	0.200	0.973	d5	0.200	0.214
a4	0.200	0.611	b7	0.200	0.565			

Table A2. Results of Shapiro-Wilk (S-W) test and Kolmogorov-Smirnov (K-S) test for Alborz province.

Omitted indicator	*p*-Value K-S	*p*-Value S-W	Omitted indicator	*p*-Value K-S	*p*-Value S-W	Omitted indicator	*p*-Value K-S	*p*-Value S-W
None	0.200	0.967	a5	0.200	0.703	b8	0.200	0.999
A	0.200	0.969	a6	0.200	0.857	c1	0.200	0.595
B	0.200	0.789	b1	0.200	0.975	c2	0.200	0.972
C	0.200	0.966	b2	0.200	0.797	d1	0.200	0.676
D	0.200	0.959	b3	0.200	0.561	d2	0.200	0.296
a1	0.200	0.412	b4	0.200	0.939	d3	0.200	0.848
a2	0.200	0.798	b5	0.200	0.675	d4	0.200	0.604
a3	0.200	0.844	b6	0.200	0.984	d5	0.200	0.936
a4	0.200	0.964	b7	0.200	0.727			

Table A3. Results of Shapiro-Wilk (S-W) test and Kolmogorov–Smirnov (K-S) test for Yazd province.

Omitted indicator	*p*-Value K-S	*p*-Value S-W	Omitted indicator	*p*-ValueK-S	*p*-Value S-W	Omitted indicator	*p*-Value K-S	*p*-Value S-W
None	0.200	0.914	a5	0.121	0.071	b8	0.112	0.059
A	0.200	0.096	a6	0.200	0.056	c1	0.064	0.033
B	0.200	0.150	b1	0.188	0.104	c2	0.200	0.187
C	0.102	0.100	b2	0.200	0.053	d1	0.079	0.041
D	0.200	0.223	b3	0.180	0.025	d2	0.200	0.036
a1	0.200	0.025	b4	0.200	0.065	d3	0.055	0.302
a2	0.200	0.061	b5	0.186	0.195	d4	0.200	0.124
a3	0.167	0.048	b6	0.149	0.088	d5	0.200	0.449
a4	0.200	0.074	b7	0.200	0.844			

Table A4. Results of Shapiro-Wilk (S-W) test and Kolmogorov–Smirnov (K-S) test for Isfahan province.

Omitted indicator	*p*-Value K-S	*p*-Value S-W	Omitted indicator	*p*-Value K-S	*p*-Value S-W	Omitted indicator	*p*-Value K-S	*p*-Value S-W
None	0.200	0.998	a5	0.200	0.364	b8	0.200	0.098
A	0.200	0.100	a6	0.200	0.150	c1	0.200	0.197
B	0.200	0.252	b1	0.200	0.116	c2	0.200	0.254
C	0.200	0.149	b2	0.124	0.151	d1	0.200	0.502
D	0.200	0.088	b3	0.200	0.533	d2	0.200	0.271
a1	0.200	0.612	b4	0.200	0.305	d3	0.092	0.038
a2	0.200	0.203	b5	0.200	0.560	d4	0.200	0.141
a3	0.157	0.089	b6	0.200	0.109	d5	0.200	0.137
a4	0.200	0.108	b7	0.200	0.536			

Table A5. Results of Shapiro-Wilk (S-W) test and Kolmogorov–Smirnov (K-S) test for Qazvin province.

Omitted indicator	*p*-Value K-S	*p*-Value S-W	Omitted indicator	*p*-Value K-S	*p*-Value S-W	Omitted indicator	*p*-Value K-S	*p*-Value S-W
None	0.200	0.755	a5	0.200	0.321	b8	0.007	0.022
A	0.129	0.044	a6	0.058	0.068	c1	0.185	0.079
B	0.057	0.070	b1	0.095	0.041	c2	0.151	0.236
C	0.200	0.102	b2	0.200	0.117	d1	0.035	0.062
D	0.110	0.087	b3	0.200	0.108	d2	0.082	0.027
a1	0.200	0.107	b4	0.025	0.076	d3	0.045	0.028
a2	0.041	0.012	b5	0.145	0.170	d4	0.110	0.060
a3	0.106	0.070	b6	0.056	0.072	d5	0.200	0.119
a4	0.070	0.038	b7	0.200	0.336			

Table A6. Results of Shapiro-Wilk (S-W) test and Kolmogorov–Smirnov (K-S) test for Qom province.

Omitted indicator	*p*-Value K-S	*p*-Value S-W	Omitted indicator	*p*-Value K-S	*p*-Value S-W	Omitted indicator	*p*-Value K-S	*p*-Value S-W
None	0.200	0.138	a5	0.200	0.338	b8	0.200	0.397
A	0.135	0.378	a6	0.200	0.660	c1	0.200	0.596
B	0.200	0.508	b1	0.148	0.354	c2	0.200	0.689
C	0.054	0.269	b2	0.083	0.239	d1	0.200	0.584
D	0.117	0.344	b3	0.200	0.837	d2	0.200	0.368
a1	0.200	0.802	b4	0.023	0.087	d3	0.200	0.818
a2	0.110	0.201	b5	0.154	0.460	d4	0.200	0.437
a3	0.200	0.440	b6	0.200	0.420	d5	0.200	0.476
a4	0.200	0.482	b7	0.200	0.884			

Table A7. Results of Shapiro-Wilk (S-W) test and Kolmogorov–Smirnov (K-S) test for Markazi province.

Omitted indicator	*p*-Value K-S	*p*-Value S-W	Omitted indicator	*p*-Value K-S	*p*-Value S-W	Omitted indicator	*p*-Value K-S	*p*-Value S-W
None	0.200	0.914	a5	0.200	0.823	b8	0.200	0.926
A	0.200	0.967	a6	0.200	0.737	c1	0.200	0.742
B	0.200	0.869	b1	0.200	0.837	c2	0.200	0.758
C	0.200	0.985	b2	0.200	0.726	d1	0.200	0.456
D	0.200	0.919	b3	0.200	0.989	d2	0.200	0.902
a1	0.200	0.993	b4	0.200	0.457	d3	0.200	0.461
a2	0.200	0.827	b5	0.200	0.706	d4	0.200	0.949
a3	0.200	0.905	b6	0.200	0.980	d5	0.200	0.450
a4	0.200	0.914	b7	0.200	0.671			

Table A8. Results of Shapiro-Wilk (S-W) test and Kolmogorov–Smirnov (K-S) test for Chaharmahal and Bakhtiari province.

Omitted indicator	*p*-Value K-S	*p*-Value S-W	Omitted indicator	*p*-Value K-S	*p*-Value S-W	Omitted indicator	*p*-Value K-S	*p*-Value S-W
None	–	1.000	a5	–	0.490	b8	–	0.843
A	–	0.000	a6	–	0.000	c1	–	0.702
B	–	0.510	b1	–	0.000	c2	–	0.878
C	–	0.567	b2	–	0.726	d1	–	0.780
D	–	0.000	b3	–	0.952	d2	–	0.298
a1	–	0.831	b4	–	0.000	d3	–	0.463
a2	–	0.000	b5	–	0.780	d4	–	0.637
a3	–	0.000	b6	–	0.363	d5	–	0.298
a4	–	0.637	b7	–	0.637			

Table A9. Results of Shapiro-Wilk (S-W) test and Kolmogorov–Smirnov (K-S) test for Semnan province.

Omitted indicator	*p*-Value K-S	*p*-Value S-W	Omitted indicator	*p*-Value K-S	*p*-Value S-W	Omitted indicator	*p*-Value K-S	*p*-Value S-W
None	0.200	0.967	a5	0.200	0.984	b8	0.096	0.224
A	0.200	0.040	a6	0.042	0.065	c1	0.200	0.651
B	0.200	0.619	b1	0.200	0.155	c2	0.200	0.988
C	0.200	0.582	b2	0.200	0.335	d1	0.064	0.091
D	0.053	0.117	b3	0.200	0.589	d2	0.200	0.231
a1	0.200	0.549	b4	0.200	0.835	d3	0.200	0.545
a2	0.200	0.362	b5	0.128	0.146	d4	0.200	0.242
a3	0.113	0.071	b6	0.200	0.274	d5	0.200	0.854
a4	0.200	0.347	b7	0.200	0.678			

Table A10. Results of sensitivity analysis of sub-indicators for Tehran province.

Omitted indicator	$\mu_1 - \mu_2$	*p*-Value of paired *t*-test	Omitted indicator	$\mu_1 - \mu_2$	*p*-Value of paired *t*-test
b1	1.23	0.000	a6	−11.23	0.000
a2	1.38	0.000	b8	−2.53	0.000
a3	3.46	0.000	c1	−4.76	0.000
a4	−0.76	0.000	d5	−1.46	0.000
b4	2.23	0.000	b6	0.61	0.000
b2	−48.92	0.000	c2	−2.30	0.000
b5	1.076	0.000	d1	−5.15	0.000
b3	−4.84	0.000	d4	6.23	0.000
a5	−3.76	0.000	d2	−0.92	0.000
b7	−12.76	0.000	d3	−4.46	0.000
a1	−4.84	0.000			

Table A11. Results of sensitivity analysis of sub-indicators for Alborz province.

Omitted indicator	$\mu_1 - \mu_2$	p-Value of paired t-test	Omitted indicator	$\mu_1 - \mu_2$	p-Value of paired t-test
a1	−1.8	0.083	b6	−2.2	0.004
a2	6.8	0.004	b7	−7	0.003
a3	1.4	0.006	b8	−3.6	0.054
a4	−1.8	0.001	c1	−2.4	0.001
a5	3	0.004	c2	−0.4	0.001
a6	−5.8	0.001	d1	−6.2	0.004
b1	0.4	0.005	d2	−2	0.012
b2	−49.2	0.011	d3	−6.4	0.032
b3	−1.2	0.001	d4	3.4	0.019
b4	2	0.009	d5	0.2	0.000
b5	2.4	0.021			

Table A12. Results of sensitivity analysis of sub-indicators for Yazd province.

Omitted indicator	$\mu_1 - \mu_2$	p-Value of paired t-test	Omitted indicator	$\mu_1 - \mu_2$	p-Value of paired t-test
a1	−1.33	0.000	b6	0.22	0.000
a2	4.22	0.000	b7	−9.33	0.000
a3	5.67	0.000	b8	0.33	0.000
a4	−0.44	0.000	c1	−6.77	0.000
a5	−6.66	0.000	c2	−0.77	0.000
a6	−7.33	0.000	d1	−5.44	0.000
b1	2.11	0.000	d2	−3.77	0.000
b2	−42.22	0.000	d3	−5.22	0.000
b3	−6.33	0.000	d5	−2.55	0.000
b4	1	0.000	d4	3.66	0.000
b5	5.77	0.000			

Table A13. Results of sensitivity analysis of sub-indicators for Isfahan province.

Omitted indicator	$\mu_1 - \mu_2$	p-Value of paired t-test	Omitted indicator	$\mu_1 - \mu_2$	p-Value of paired
a1	−2.8	0.000	b6	−2.73	0.000
a2	1.2	0.000	b7	−6.66	0.000
a3	4	0.000	b8	−4.33	0.000
a4	−0.86	0.000	c1	−8.2	0.000
a5	−2.13	0.000	c2	−1.66	0.000
a6	−5.27	0.000	d1	−7.46	0.000
b1	1.46	0.000	d2	0.86	0.000
b2	−61.26	0.000	d3	−3.8	0.000
b3	−2.4	0.000	d4	2.2	0.000
b4	1.26	0.000	d5	−0.2	0.000
b5	5.2	0.000			

Table A14. Results of sensitivity analysis of sub-indicators for Qazvin province.

Omitted indicator	$\mu_1 - \mu_2$	p-Value of paired t-test	Omitted indicator	$\mu_1 - \mu_2$	p-Value of paired t-test
a1	−0.77	0.000	b6	−3.55	0.000
a2	2.11	0.000	b7	−7.56	0.000
a3	3.88	0.000	b8	−3.33	0.000
a4	−0.44	0.000	c1	−5.56	0.000
a5	−4.22	0.000	c2	−0.33	0.000
a6	−5.33	0.000	d1	−5.77	0.000
b1	1.11	0.000	d2	−1.88	0.000
b2	−43.3	0.000	d3	−4.22	0.000
b3	−6.88	0.000	d4	7.55	0.000
b4	1	0.000	d5	−2.44	0.000
b5	8.89	0.000			

Table A15. Results of sensitivity analysis of sub-indicators for Qom province.

Omitted indicator	$\mu_1 - \mu_2$	p-Value of paired t-test	Omitted indicator	$\mu_1 - \mu_2$	p-Value of paired t-test
a1	−2.75	0.008	b6	−2	0.021
a2	5.5	0.005	b7	−10.75	0.032
a3	4.5	0.019	b8	−4.5	0.007
a4	−1.75	0.002	c1	−7.75	0.004
a5	−5.5	0.033	c2	−0.75	0.001
a6	−8	0.007	d1	−1	0.021
b1	0.1	0.004	d2	0.25	0.003
b2	−47.75	0.016	d3	0.5	0.026
b3	−4.75	0.026	d4	1	0.085
b4	1	0.002	d5	−2.75	0.010
b5	0.5	0.050			

Table A16. Results of sensitivity analysis of sub-indicators for Markazi province.

Omitted indicator	$\mu_1 - \mu_2$	p-Value of paired t-test	Omitted indicator	$\mu_1 - \mu_2$	p-Value of paired t-test
a1	−1.66	0.001	b6	−1	0.000
a2	3.11	0.000	b7	−6.11	0.000
a3	6.55	0.000	b8	−3.33	0.000
a4	−0.89	0.000	c1	−4.11	0.000
a5	−2.56	0.000	c2	−1.33	0.000
a6	−3.22	0.000	d1	−6.55	0.000
b1	0.33	0.000	d2	−4.44	0.000
b2	−47.89	0.000	d3	−3.33	0.000
b3	−5	0.000	d4	8.88	0.000
b4	1	0.000	d5	−1.78	0.000
b5	−1.33	0.000			

Table A17. Results of sensitivity analysis of sub-indicators for Chaharmahal and Bakhtiari province.

Omitted indicator	$\mu_1 - \mu_2$	p-Value of paired t-test	Omitted indicator	$\mu_1 - \mu_2$	p-Value of paired t-test
a1	−2.67	0.349	b6	4.67	0.821
a2	−1	0.667	b7	−14.33	0.433
a3	0.66	0.766	b8	0.33	0.277
a4	−0.33	0.000	c1	−9.33	0.386
a5	−1	0.830	c2	0	0.121
a6	−11.66	0.667	d1	−3.66	0.374
b1	1	0.667	d2	−1.67	0.099
b2	−47.67	0.667	d3	−2.67	0.437
b3	0.67	0.927	d4	11.33	0.821
b4	−0.33	0.879	d5	−3.33	0.260
b5	1.67	0.909			

Table A18. Results of sensitivity analysis of sub-indicators for Semnan province.

Omitted indicator	$\mu_1 - \mu_2$	p-Value of paired t-test	Omitted indicator	$\mu_1 - \mu_2$	p-Value of paired t-test
a1	–	0.503	b6	−5	0.145
a2	1	0.005	b7	−17.4	0.086
a3	4.6	0.045	b8	−4.2	0.471
a4	−3	0.000	c1	−4.8	0.008
a5	−6.2	0.041	c2	−0.2	0.022
a6	−13.2	0.002	d1	−6.6	0.034
b1	0.4	0.003	d2	−2	0.082
b2	−46.6	0.069	d3	−2.6	0.163
b3	−1.8	0.016	d4	10.2	0.187
b4	−0.2	0.003	d5	−3.2	0.014
b5	4	0.118			

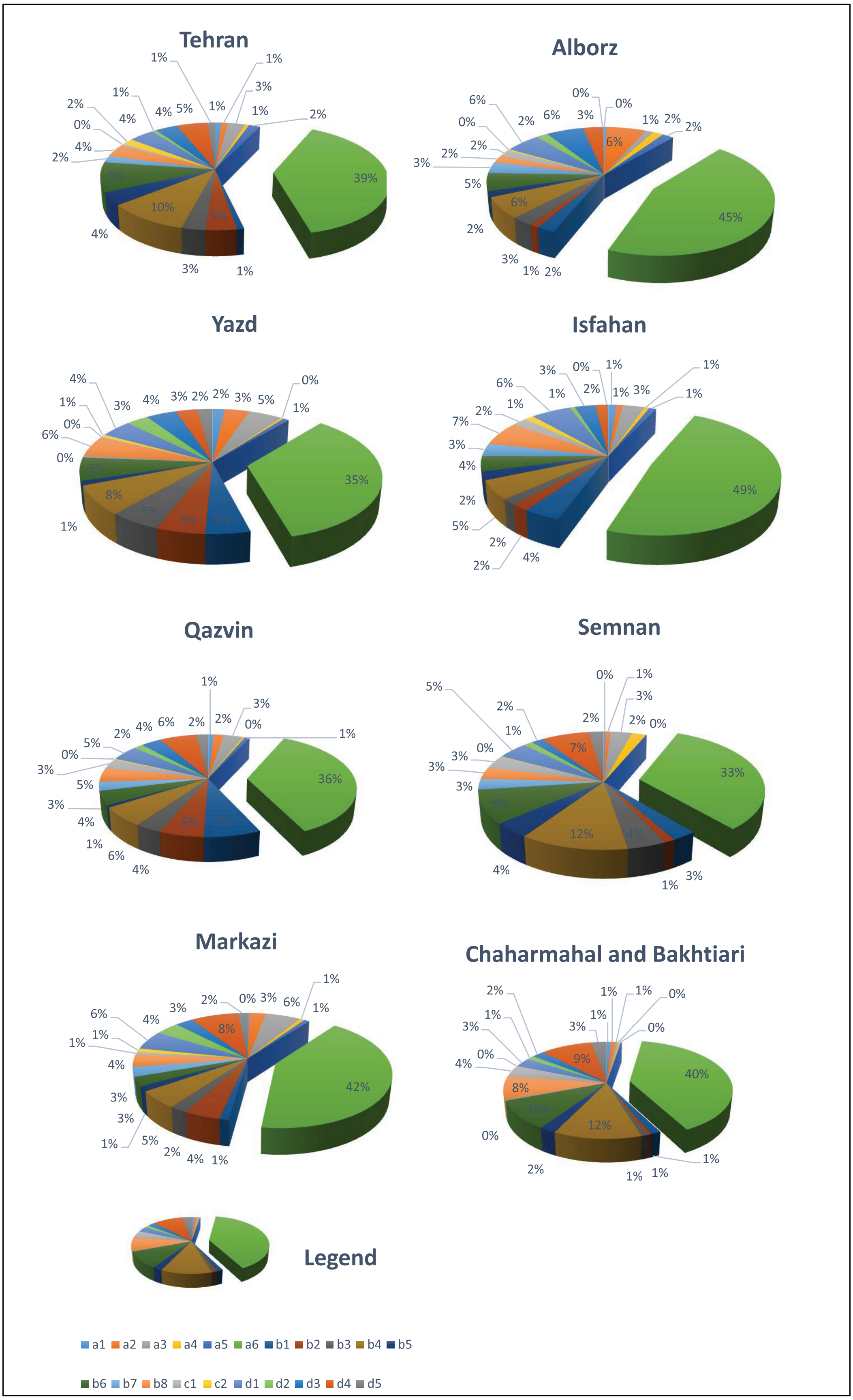

Figure A1. Weight of each sub-indicator in ED efficiency in each province.