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A hybrid data envelopment analysis and game theory model for performance measurement in healthcare

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Abstract
Performance measurement plays an important role in the successful design and reform of regional healthcare management systems. In this study, we propose a hybrid data envelopment analysis (DEA) and game theory model for measuring the performance and productivity in the healthcare centers. The input and output variables associated with the efficiency of the healthcare centers are identified by reviewing the relevant literature, and then used in conjunction with the internal organizational data. The selected indicators and collected data are then weighted and prioritized with the help of experts in the field. A case study is presented to demonstrate the applicability and efficacy of the proposed model. The results reveal useful information and insights on the efficiency levels of the regional healthcare centers in the case study.

Keywords Efficiency · Data envelopment analysis · Game theory · Healthcare

1 Introduction

Maintaining and enhancing the efficiency and productivity of healthcare centers is clearly necessary, given their importance as organizational providers of public healthcare services and their key role in providing quality of services [1–4]. Achieving this goal requires sound decision making regarding the allocation of healthcare resources, which naturally requires an objective performance evaluation [5]. However, performance evaluation in a service industry such as healthcare could become challenging because of the difficulty of balancing service quality and resource usage [6]. The field of healthcare involves disease treatment and management and health maintenance using the services provided by medical, pharmaceutical, dentistry, laboratory, nursing and paramedical professionals [7]. However, achieving an optimal performance in this field often requires the use principled management techniques such as resource allocation models, methods that the traditional medical personnel may not be accustomed to. These methods enable an organization to adjust its trajectory in the course of change, accelerate its progress in the areas that best serve its mission, address future threats, and obtain the most benefit from emerging opportunities [8, 9].

In past studies, the performance of healthcare centers and systems have been evaluated by a wide range of methods including data envelopment analysis (DEA) [10–19]. Using DEA to evaluate healthcare centers, the relative efficiency of each DMU can be compared to the efficient units. Consequently, it is possible to benchmark the DMUs for the central administration, as well as determine the changes required for their

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effectiveness. Zhou et al. [13] used DEA and panel data analysis for modeling the capital inputs of community health and human resources to determine the scale and technical efficiency of community health resources. Lai et al. [14] integrated DEA and the theory of teams for designing a mechanism in public healthcare to allocate resources optimally. Toloo and Jalili [15] utilized a solution to implement a LU decomposition technique on the basic DEA models with an application to hospitals. Rouyendegh et al. [16] introduced a new model based on DEA and fuzzy multi-criteria decision making to enhance business performance in the healthcare industry. Foo et al. [17] used DEA for evaluating relative performance based on three efficiency components including congestion, scale and technical in the public healthcare sector. Ozcan and Khushalani [20] and Hadad et al. [18] studied the DEA healthcare system's efficiency in OECD countries based on several determinants including, environmental, population behavior, and socioeconomic and institutional arrangements. Weng et al. [19], DePuccio and Ozcan [21], and Highfill and Ozcan [22] used DEA to evaluate the performance of healthcare centers.

Game theory is the process of modeling the strategic interaction between two or more players in a situation containing set rules and outcomes. Indeed, the decisions of each player are based on the actual utility or outcome [23]. Game theory is mainly used in economics, political science and many other fields including healthcare: Blake and Carroll [24], Hampshire et al. [25], Roshanaei et al. [26], Li et al. [27], Gao et al. [28], Wu et al. [29], Sykes and Rychtář [30], and Dakun et al. [31]. Blake and Carroll [24] used game theory to provide a framework for understanding strategic decision making in medical practice and education, Hampshire et al. [25] used this theory to analyze health-related trust issues, and Roshanaei et al. [26] used it for collaborative operating room allocation with the aim of improving hospital efficiency and costs. Li et al. [27] used game theory to develop a strategic model for vaccination, and Gao et al. [28] used this theory to evaluate and choose the strategies for a telemedicine system. Wu et al. [29] employed game theory to examine the market dynamics of electronic health products, and Sykes and Rychtář [30] utilized it to predict the need of populations for vaccination and the strategic selection of related solutions. In a study carried out by Dakun et al. [31], game theory was used to provide an effective control model for a wireless body area network and its application in healthcare.

In previous studies, the performance of healthcare centers has been analyzed in terms of the relationship between cooperation and competition [13]. Competition in healthcare typically improves consumer welfare through lower prices and better service while cooperation and joint ventures among healthcare organizations typically results in better financial performance and cost savings. Since it is very difficult to use DEA in peer appraisal to reach a consensus on the allocation of resources for the DMUs, DEA-game theory can be used to improve the allocation. Indeed, the relationship between cooperation and competition is more understandable using game theory.

Although, previous studies have used DEA and GT models to assess various topics such as healthcare centers, few works have integrated these two models. The main purpose of this paper is to fill this gap by developing a mathematical model that combines DEA with game theory for the evaluation of the relative efficiency of healthcare centers in Yazd, Iran. The research attempts to answer the following questions: (a) what are the inputs and outputs associated with the performance of healthcare centers in Yazd? (b) What is the relative efficiency of each healthcare center in Yazd when evaluated by the data envelopment analysis-game theory (DEA-game) model? (c) What is the optimal quantity of resources needed in each healthcare center in Yazd?

The structure of this review paper is structured as follows. Section 2 presents the application of DEA and GT in the evaluation of the healthcare industry. Section 3 presents the research methodology used in this paper. Section 4 presents the results of the application. Section 5 provides a discussion of the results and Section 6 presents the conclusion and recommendations for future studies.

2 Applications of DEA and game theory in healthcare

Data Envelopment Analysis (DEA) is a linear programming method originally developed by Charnes et al. [32] to evaluate nonprofit and public-sector organizations. The ability of DEA to incorporate multiple inputs and outputs into a linear programming model makes it a perfect choice for measuring the relative efficiency of healthcare centers, where multiple outputs are produced by the consumption of several inputs. Another advantage of DEA is the ability to process inputs and outputs in their natural units instead of converting them into a single unit; a task that is subject to data loss [2]. Previously, Pilyavsky et al. [33] proposed a two-stage method for comparing the efficiency of hospitals in east and west Ukraine. In this work, DEA was used in the first stage to estimate the technical efficiency of hospitals. Ancarani et al. [34] presented a model for examining the relationship between the decision-making process of a hospital department and its technical efficiency. The proposed model used a two-stage approach, where in the first stage DEA was used to determine the technical efficiency of the departments belonging to a large hospital. In a research conducted by Valdmanis et al. [35], where they designed a disaster response program for Florida hospitals, DEA was used to measure the hospitalization capacity using an economic capability criterion that ensured that Pareto optimal conditions be maintained. In recent studies, Yang [5] proposed a new DEA method to measure health indicators and allocate health resources. Additionally, Sun and Luo [36] utilized DEA to measure the efficiency of the allocation of health resources in China, Çelik et al. [37] used this method to measure the efficiency of the healthcare sector in non-EU countries, and Wang et al. [38] used DEA to evaluate the efficiency and performance of Chinese state hospitals after a hospital reform program. Villamil et al. [39] combined DEA with data mining for the qualitative evaluation of health service providers in Colombia. Ali et al. [40] used a combination of DEA and the Tobit model to measure the efficiency and performance of hospitals in eastern Ethiopia.

Game theory is the theory of strategic interactions. In this theory, the game is a computational means for formulating a strategic interaction between multiple agents. This theory utilizes a set of notions including players, strategies, payoffs, and game rules in an attempt to mathematically model the behavior that governs a strategic situation (conflict of interest) [41]. Game theory has been used in many fields including healthcare. Chapman et al. [42] used game theory to examine the transmission of influenza and the choice of vaccination strategies.

2.1 The advantages of combining DEA and game theory

In terms of resource allocation, the relationship between the DMUs are cooperative and competing. The peer appraisal approach based on cross-efficiency can be an appropriate solution [43]. Competition in healthcare is intended to improve consumer welfare through lower prices and cooperation is designed to result in better financial performance. Using the DEA method to calculate cross-efficiency reduces the usefulness of cross-efficiency because it is not possible to achieve a unique optimal solution [44]. But using game theory in efficiency analysis in term of the cross-efficiency as a *payoff*, leads to the achievement of a Nash equilibrium point [45]. Therefore, combining DEA and game theory results in cross-efficiency, and thereby it is possible to provide a fair and unique allocation plan for all the DMUs that are simultaneously competing and cooperating.

The purpose of cooperative game theory is to analyze whether incentives for cooperation are present or to allocate the payoff (gain or cost) of a game. Many researchers have combined cooperative game theory with DEA to solve practical problems. In these models, DMUs are viewed as players and cross-efficiency scores are viewed as payoffs (potential gains or loss). Each DMU takes a non-cooperative game stance to maximize its (worst possible) payoff.

On the other hand, the DMUs compete to achieve the lowest cost and the highest efficiency. Additionally, they cooperate to reach a final allocation pattern. However, in large organizations that have a multitude of different DMUs, allocating resources equitably requires consideration of the decision-making criteria. In such situations, the application of each decision-making strategy can seem unfair to each individual DMU, and thus cause conflicts between them. Li et al. ([43], p. 198) argue “DEA, thus can act as a preferable expert method in endogenously making trade-offs among different entities, criteria, and decision rules.” Li et al. ([43], p. 198) further argue that from this trade-off perspective, DEA is a powerful decision support tool since “managers can consider peer appraisal from all DMUs’ perspectives and require each unit to repeatedly negotiate with the others to determine an equitable allocation scheme as an expert system.” The use of the DEA-game cross-efficiency approach, allows managers to consider interactions and negotiations between sets of cooperative and competing DMUs. Therefore, it can be an appropriate decision-making support for managers. However, only a few studies have used a combination of DEA and game theory in the field of healthcare. These include the study of Chang et al. [46], where they used the DEA-game approach to evaluate the performance of medical personnel in Taiwan, and the study conducted by Jahangoshai Rezaee et al. [47], where this approach was used to evaluate the efficiency of healthcare centers in Tehran.

3 Proposed model

It is essential to choose the appropriate objectives, since the main goal of the research is to improve the performance of the health centers. The required data were collected from the health statistical databases of the Yazd healthcare center office, which have been compiled based on the routine information forms of the organization. Healthcare centers are under the supervision of the central administration affiliated with the Ministry of Health and Medical Education. There is the possibility of management by the government in the context of resource allocation, including the population and medical staff. Better allocation of resources can increase the efficiency of the centers. These cases came about from discussions with healthcare-related managers. The central administration can change the population covered by the healthcare centers based on the results of DEA-game theory. After identifying the inputs and outputs involved in the performance of the healthcare centers, the scores for each DMU of the DEA model were calculated. The work then proceeded by constructing and solving one model for each functional area of the healthcare centers. The cross-efficiency of the DMUs was then calculated to determine the breakdown points in the game theory model. Finally, the DEA-game theory model was constructed and used to determine the superior strategies in each functional area of the studied healthcare centers. The Research Methodology stages are shown in Fig. 1.

3.1 Statistical population

In this study, the organization under study consists of 18 urban healthcare centers, two urban-rural centers, and two rural

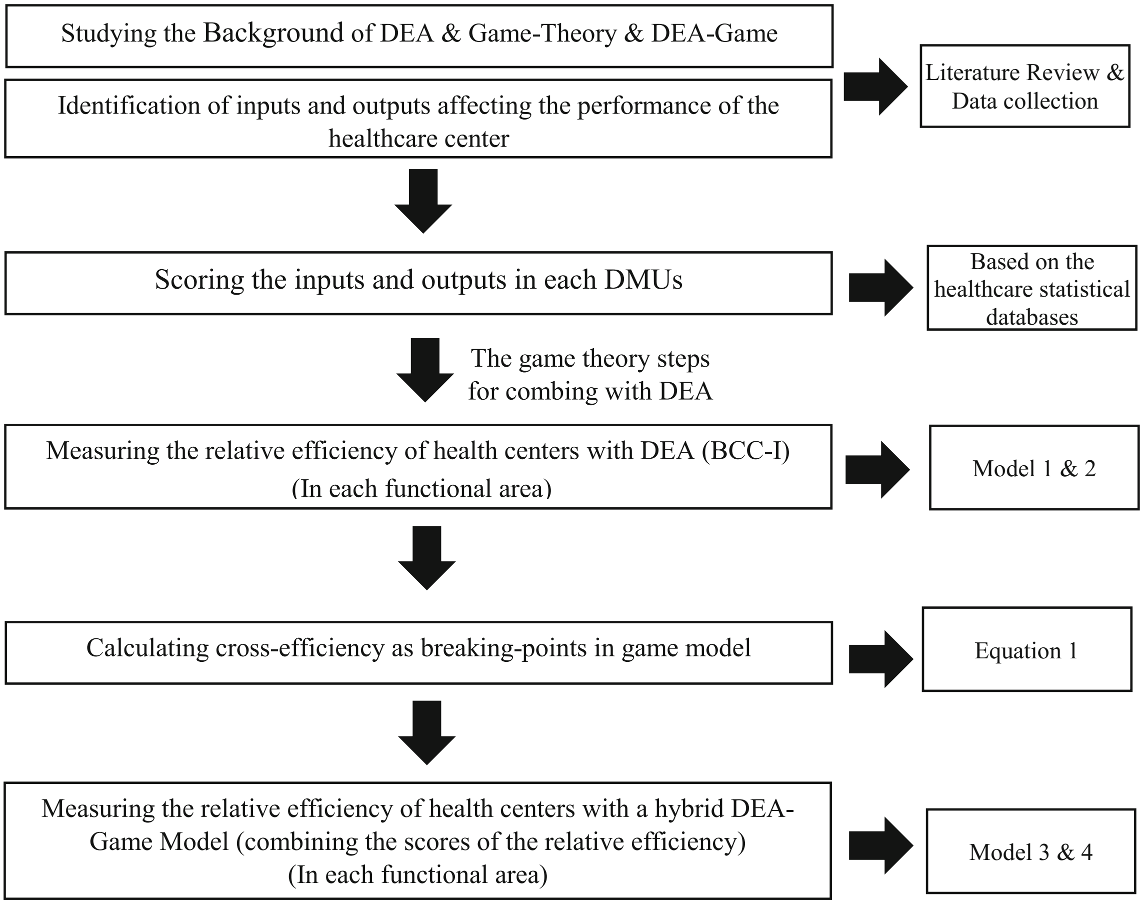

Fig. 1 Research stages

centers. Three of the urban centers are not large or active enough to be considered a full-fledged healthcare center and must be regarded as subsidiaries of the other centers. Since the research is not focused on rural centers and only rural-urban centers are included, the total number of centers included in this study is 17 (15 urban centers and two rural-urban centers).

3.2 Data collection and scoring

We determined the appropriate mathematical modeling methods, as well as identified the specific decision variables and model constraints. We also identified the appropriate decision criteria by reviewing the literature. The inputs and outputs that could be incorporated into the mathematical model were extracted from similar studies conducted in Iran, and by examining the contents of the information forms exchanged between the healthcare center of Yazd and its head office. Several meetings were then held with the senior experts of the Yazd healthcare center organization to identify and discuss the input and output variables, their association with the efficiency of healthcare centers, and the ones to be included in each sub-model (a separate DEA model was developed for each functional area of the healthcare centers). The choice of variables was made according to the availability of related information, their validity and reliability, and the impact of the variables on the efficiency. The outcome of steps was a rough conceptual model for the evaluation of the efficiency of healthcare centers in different categories.

Given the ratio of the number of healthcare centers (DMUs) to the total number of inputs and outputs in different models, many DMUs were expected to be found efficient by default. To prevent this, some inputs and outputs were combined to decrease their numbers, but without undermining the conceptual framework of the relevant functional areas. In the cases where such a combination was not possible (or when even after combination, the number of input and output variables was still higher than desired), the specific DMU was partitioned into several smaller functional areas. For example, the Family Health DMU (which involves many variables) was divided into four areas: children, women, pregnancy, and elderly, and the model was implemented for each area separately.

The above steps ensured the accuracy and validity of all the inputs and outputs for the selected population and allowed the functional system of the studied healthcare centers to be defined accordingly. Table 1 shows the inputs and outputs obtained from the data collection process and how they are combined before efficiency evaluation. After identifying the input and output variables for each healthcare center, a database

Table 1 Input and output variables

Unit	Input (personnel)	Input (target population)	Output
Family health (children[a])	Family health personnel and physicians (I1)	Number of children[a] (I2)	Number of times infant care provided (O1)
Family health (women[b])	Family health personnel and midwives (I1)	Number of women[b] (I2)	Number of times family planning services and other cares provided for non-pregnant women (O1)
Family health (pregnancy)	Family health personnel and midwives (I1)	Number of children[a] (I2)	Number of times pre- and post-pregnancy care provided (O1)
Family health (elderly)	Family health personnel (I1)	Number of elderly people (I2)	Number of elderly training sessions held (O1)
School health	Family health and disease control personnel and physicians (I1)	Number of covered students[c] (I2)	Number of students[c] surveyed (O1)
Disease prevention and control	Family health and disease control personnel and physicians (I1)	Size of the covered population (I2)	Number of vaccines administered (O1), cholera stool samples taken (O2), thalassemia patients monitored, and diabetes and hypertension patients screened (O3)
Medical care	Number of physicians(I1)	Size of the covered population (I2)	Number of patients visited (O1)

[a] Children up to one year of age

[b] Women aged 10–49 years

[c] Students enrolled in 1st, 7th, and 10th grades

consisting of data items related to their efficiency was constructed. For this purpose, the data needed to score indices were collected by referring to the healthcare statistical database and the senior experts of each unit of the healthcare centers. In other words, we have used the secondary data of the Provincial database from each unit of the healthcare centers. Table 2 shows an example of data items collected from the health unit of the schools. It is worth noting that the goal of the health unit of the schools is to provide, maintain and enhance the physical and mental health of the students.

3.3 DEA model

In the first phase of mathematical modeling (and after collecting the required data and identifying the input and output variables), an input-oriented DEA model with variable returns-to-scale (BCC-I) was developed. The generic multiplicative and envelopment BCC-I models for a given DMU_0, $0 \in \{1, ..., n\}$ are in the form of Models (1) and (2).

$$\begin{aligned} &\text{Max } Z_0 = \sum_{r=1}^{s} u_r y_{r0} + w \\ &s.t. \\ &\sum_{i=1}^{m} v_i x_{i0} = 1 \\ &\sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} + w \le 0; (j = 1, 2, \cdots, n) \\ &u_r, v_j \ge 0; w : Free \end{aligned} \tag{1}$$

If θ is the variable corresponding to the first constraint of the initial problem and λ_j is the variable corresponding to other constraints, then the following envelopment model can be obtained. Appendix Table 8 provides further details and shows that each DMUj ($j = 1, 2, \cdots, n$) uses inputs x_{ij} ($i = 1, 2, \cdots, m$) to generate outputs y_{rj} ($r = 1, 2, \cdots, s$). "w" represents the returns-to-scale.

$$\begin{aligned} &\text{Min } y_0 = \theta \\ &s.t. \\ &\sum_{j=1}^{n} \lambda_j y_{rj} \ge y_{r0} \quad ; \quad (r = 1, 2, \cdots, s) \\ &\sum_{j=1}^{n} \lambda_j x_{ij} \le \theta x_{i0} \quad ; \quad (i = 1, 2, \cdots, m) \\ &\sum_{j=1}^{n} \lambda_j = 1 \\ &\lambda_j \ge 0 \, ; \, \theta : Free \qquad (j = 1, 2, \cdots, n) \end{aligned} \tag{2}$$

The above model was solved using the DEA-Solver software. DEA-Solver is an engine for solving DEA models which was developed based on the Cooper et al. [48] textbook. The platform for this software is Microsoft Excel 97/2000 or later. DEA-Solver applies the following notation for describing DEA models.

$$< \text{Model} \quad \text{Name} > - < \text{I or 0} > - < \text{C or V or GRS} >$$

where I or 0 corresponds to "Input"- or "Output"-orientation and C, V or GRS to "Constant", "Variable" or "General" returns to scale. It should be reiterated that, one independent

Table 2 Healthcare center data

Healthcare center number	Healthcare center name	Environmental health personnel	Number of public places	Number of food preparation and distribution centers	Inspection of public places	Number of hygiene licenses reviewed for business permit applicants	Inspection of food preparation and distribution centers
1	Azadshahr	2.5	236	536	1083	101	2428
2	Imamshahr	3.5	260	649	870	93	2357
3	Akbari Safaiyeh	3.25	364	602	1144	138	2469
4	Akbarabad	1	153	298	372	47	1265
5	Rahmatabad	2	189	309	627	66	1191
6	Kheirabad	1.5	57	180	126	21	804
7	Zarch	1	50	228	186	26	879
8	Shahedie	1	133	182	285	19	805
9	Juy harhar	1.5	137	234	515	35	1268
10	Ghale asadan	1	46	279	177	35	911
11	Kasnavieh	1	77	224	286	24	1056
12	Maskan	2	179	510	1042	68	2853
13	Naimabad	1	109	245	225	57	1160
14	Panbekaran	1	30	275	193	26	1162
15	Nikupoor	1.5	71	349	266	22	1055
16	Hakimzadeh	3	318	456	1172	56	1880
17	Sheikhdad	1	73	208	235	16	1033

BCC-I model was developed and solved for each functional area of the healthcare centers.

3.4 Cross-efficiency calculation

Solving the game theory-based models requires a reliable method for the determination of the breakdown points. This study used the cross-efficiency of the DMUs for this purpose. The cross-efficiency of a healthcare center is the level of efficiency that is obtained by considering the available resources and the value (weight) of the inputs and outputs of the model for that center. The cross-efficiency in each of the seven models was calculated with respect to the functional areas of the healthcare centers. The following equation shows the method for calculating the cross-efficiency of the DMUs based on the method proposed by Doyle and Green [49]:

$$E_{kj} = \frac{\sum_{r=1}^{s} u_r^k y_{rj}}{\sum_{i=1}^{m} v_i^k x_{ij}}; k, j = 1, \ldots., n$$

The last stage of the research was to construct and then solve the combined DEA-game theory model. This mathematical model is founded upon a generic DEA structure of the BCC-I type but allows the breakdown points (cross-efficiency scores) to be used for integrating efficiency improvement policies through better use of resources. Therefore, a DEA-game theory model was developed and solved to evaluate the relative efficiency of healthcare centers in a set of functional areas. Model (3) illustrates the general form of the multiplicative-envelopment BCC-I model.

$$\begin{aligned}
& Max\left(\sum_{r=1}^{s}\mu_{r1}y_{r0}-\mu_0-\theta_0^1\right)\left(\alpha\sum_{r=1}^{s}\mu_{r1}y_{r0}-\alpha\mu_0-\theta_0^2\right) \\
& s.t. \\
& \sum_{r=1}^{s}\mu_{r1}y_{r0}-\mu_0\geq\theta_0^1 \\
& \left(\alpha\sum_{r=1}^{s}\mu_{r1}y_{r0}-\mu_0\right)\geq\theta_0^2 \\
& \sum_{r=1}^{s}\mu_{r1}y_{rj}-\alpha\mu_0-\sum_{i=1}^{m_1}v_i^1x_{ij}^1\leq 0 \\
& a\sum_{r=1}^{s}u_{r1}y_{rj}-\alpha\mu_0-\sum_{k=1}^{m_2}v_k^2X_k^2\leq 0, j=1,\ldots,n \\
& \sum_{i=1}^{m_1}v_i^1x_{i0}^1=1 \\
& \sum_{k=1}^{m_2}v_k^2x_{k0}^2=1 \\
& \mu_0\in R,\ \alpha.\mu_{r1},v_i^1,v_k^2>0,\ i=1,\ldots,m_1, j=1,\ldots,n, k=1,\ldots,m_2,\ r=1,\ldots,s
\end{aligned} \tag{3}$$

θ_0^1 here shows the efficiency breakdown point for DMU_0 calculated by the cross-efficiency. For each functional area, this score is computable. α_1 shows the ratio of the importance of the inputs, in the first functional area (see Appendix Table 8 for additional details). Regarding the seven functional areas for each DMU, it is necessary to separate φ_0 and α

for each DMU. Model (4) presents a complete formulation of the problem.

$$
\begin{aligned}
& Max\ Z = \left(\sum_{i}^{m}\mu_{i1}X_{i0}-\phi_0^1\right)\left(\alpha_1\sum_{k}^{m}\mu_{i2}X_{i0}-\phi_0^2\right)\left(\alpha_2\sum_{k}^{m}\mu_{i3}X_{i0}-\phi_0^3\right)\left(\alpha_3\sum_{k}^{m}\mu_{i4}X_{i0}-\phi_0^4\right) \\
& \left(\alpha_4\sum_{k}^{m}\mu_{i5}X_{i0}-\varphi_0^5\right)\left(\alpha_5\sum_{k}^{m}\mu_{i6}X_{i0}-\varphi_0^6\right)\left(\alpha_6\sum_{k}^{m}\mu_{i7}X_{i0}-\varphi_0^7\right) \\
& s.t. \\
& \sum_{i=1}^{m}\mu_{i1}X_{i0}\le\varphi_0^1 (\text{Constraint 4.1}) \\
& a_1\sum_{i=1}^{m}\mu_{i1}X_{i0}+\mu_{01}\le\varphi_0^2 (\text{Constraint 4.2}) \\
& a_2\sum_{i=1}^{m}\mu_{i1}X_{i0}+\mu_{01}\le\varphi_0^3 (\text{Constraint 4.3}) \\
& a_3\sum_{i=1}^{m}\mu_{i1}X_{i0}+\mu_{01}\le\varphi_0^4 (\text{Constraint 4.4}) \\
& a_4\sum_{i=1}^{m}\mu_{i1}X_{i0}+\mu_{01}\le\varphi_0^5 (\text{Constraint 4.5}) \\
& a_5\sum_{i=1}^{m}\mu_{i1}X_{i0}+\mu_{01}\le\varphi_0^6 (\text{Constraint 4.6}) \\
& a_6\sum_{i=1}^{m}\mu_{i1}X_{i0}+\mu_{01}\le\varphi_0^7 (\text{Constraint 4.7}) \\
& \sum_{r=1}^{S_1}u_r^1y_{rj}^1-\sum_{i=1}^{m}u_{i1}X_{ij}\le 0 (\text{Constraint 4.8}) \\
& \sum_{k=1}^{s_2}u_k^2y_{kj}^2-\alpha_1\sum_{i=1}^{m}u_{i1}X_{ij}\le 0 (\text{Constraint 4.9}) \\
& \sum_{l=1}^{s_3}u_k^3y_{kj}^3-\alpha_2\sum_{i=1}^{m}u_{i1}X_{ij}\le 0 (\text{Constraint 4.10}) \\
& \sum_{n=1}^{s_4}u_n^4y_{nj}^4-\alpha_3\sum_{i=1}^{m}u_{i1}X_{ij}\le (\text{Constraint 4.11}) \\
& \sum_{q=1}^{s_5}u_q^5y_{qj}^5-\alpha_4\sum_{1=1}^{m}u_{i1}X_{ij}\le 0 (\text{Constraint 4.12}) \\
& \sum_{p=1}^{s_6}u_p^6y_{pj}^6-\alpha_5\sum_{i=1}^{m}\mu i_1X_{ij}\le 0 (\text{Constraint 4.13}) \\
& \sum_{t=1}^{s_7}u\le_t^7y_{tj}^7-\alpha_6\sum_{i=1}^{m}u_{i1}X\le 0 (\text{Constraint 4.14}) \\
& \sum_{r=1}^{s_1}u_r^1y_{rj}^1=1 (\text{Constraint 4.15}) \\
& \sum_{k=1}^{s_2}u_k^2y_{kj}^2=1 (\text{Constraint 4.16}) \\
& \sum_{l=1}^{S3}u_l^3y_{lj}^3=1 (\text{Constraint 4.17}) \\
& \sum_{n=1}^{s_4}u_n^4y_{nj}^4=1 (\text{Constraint 4.18}) \\
& \sum_{q=1}^{s_5}u_q^5y_{qj}^5=1 (\text{Constraint 4.19}) \\
& \sum_{p=1}^{s_6}u_p^6y_{pj}^6=1 (\text{Constraint 4.20}) \\
& \sum_{t=1}^{s_7}u_t^7y_{tj}^7=1 (\text{Constraint 4.21}) \\
& \alpha_1,\alpha_1,\alpha_1,\alpha_1,\alpha_1,\alpha_1,>0 (\text{Constraint 4.22}) \\
& u_{i1}>0 (\text{Constraint 4.23}) \\
& u_r^i,u_k^2,u_l^3,u_n^4,u_q^5,u_p^6,u_t^7>0 (\text{Constraint 4.24})
\end{aligned} \tag{4}
$$

The objective function is to maximize the payoff of each DMU at its breakpoint. The first set of constraints (Constraints 4.1–4.77) represents that the efficiency of DMU_0 in each functional area is at least equal to breakpoint payoff of that DMU. The second set of constraints (Constraints 4.8–4.21) ensures that that the efficiency of a DMU in each functional area is smaller than one. Assuming the input-oriented hybrid model, Constraints 4.15–4.21 assumes that the input value is constant. If $t_1=\left(\sum_{r=1}^{s}u_r^1y_{r_0}^1\right)$ then $\mu_{i1}=t_1{}^*v_i$ shows the importance of the input "i" in each functional area. Therefore, $\alpha_1=\frac{t_2}{t_1}$ and θ_0, μ_i, α was calculated for seven functional areas (see Appendix Table 8 for additional details on the combined DEA-game theory model).

4 Results

The following sections provide the results of the DEA model for each of the seven functional areas of the studied healthcare centers. The analysis of only one of the seven functional areas (children) is explained here, since the tables related to the different areas have similar interpretations.

After collecting the research data, all the DEA models were solved using the DEA-solver software. Table 3 presents the relative efficiency scores of each healthcare center in the family health (children) functional area, their rank in this respect and the reference units. The results in Table 3 indicate that the Azadshahr, Akbari Safaiyeh, Rahmatabad, Ghale asadan, Kasnavieh, Naimabad, Panbekaran, Hakimzadeh, and Sheikhdad healthcare centers are located on the efficient frontier. Among other non-efficient healthcare centers, the best and worst efficiency scores belong to the Imamshahr and Shahedie centers, respectively. In addition, the Rahmatabad center was often identified as the reference unit for non-efficient units.

Table 3 also shows the ideal state of input variables for each efficient and inefficient healthcare center. The results show that among inefficient units, the Imamshahr healthcare center can become as efficient as a reference center, such as the Azadshahr center, by reducing its personnel size by 0.3 units or increasing the size of the covered population by 34 units. In addition, the worst center, i.e. Shahedieh can be made as efficient as its reference unit by reducing its personnel size by 3.61 units or increasing the size of the covered population by 213 units. It should be noted that here personnel size means the number of family health personnel and physicians.

Table 4 shows the ranking of the healthcare centers in terms of the change in inputs needed for the centers to reach the efficient frontier. Here, the first rank signifies the need for the greatest change in inputs and the last rank means the need

Table 3 Efficiency scores, rankings, reference units, and improvements needed in the inefficient healthcare centers to reach the efficient frontier for the family health (children) functional area

Healthcare center number	Healthcare center name	Efficiency score	Rank	Reference units	Ideal state of the input variable	Improvements needed to reach the efficient frontier	Improvements needed to reach the efficient frontier	
					I1[a]	I2[b]	I1	I2
1	Azadshahr	1	1	–	11.9	1644	0	0
2	Imamshahr	0.97	10	Azadshahr Rahmatabad	10.33	1197.68	0.3	33.68
3	Akbari Safaiyeh	1	1	–	11.85	1415	0	0
4	Akbarabad	0.83	12	Rahmatabad Sheikhdad	8.57	905.18	1.79	156.18
5	Rahmatabad	1	1	–	8.7	934	0	0
6	Kheirabad	0.66	16	Kasnavieh Hakimzadeh Sheikhdad	5.6	481.02	2.9	164.02
7	Zarch	0.68	15	Rahmatabad Ghale asadan Sheikhdad	7.03	649.15	3.37	210.15
8	Shahedie	0.64	17	Rahmatabad Ghale asadan Sheikhdad	6.38	587.35	3.61	212.35
9	Juy harhar	0.82	13	Azadshahr Rahmatabad	8.98	970.4	2.02	178.4
10	Ghale asadan	1	1	–	7	629	0	0
11	Kasnavieh	1	1	–	4.8	352	0	0
12	Maskan	0.77	14	Azadshahr Rahmatabad	9.2	1001.68	2.8	233.68
13	Naimabad	1	1	–	3	66	0	0
14	Panbekaran	1	1	–	2.5	80	0	0
15	Nikupoor	0.87	11	Kasnavieh Sheikhdad	4.9	374.32	0.73	48.32
16	Hakimzadeh	1	1	–	5.92	481	0	0
17	Sheikhdad	1	1	–	5.33	507	0	0

[a] Family health personnel and physicians

[b] Number of children younger than one year

for the smallest change in inputs for the respective inefficient unit to become efficient.

In terms of the number of relevant personnel, the Shahedieh and Zarch centers need the greatest and the Imamshahr center needs the smallest change in personnel to become efficient. In terms of the covered population, the Maskan and Shahedieh centers need the greatest increase in the size of the covered population to reach the efficient frontier. The ranking of the studied healthcare centers in terms of their efficiency in the family health (children) functional area is illustrated in Fig. 2.

Table 4 also shows the importance of each input for each healthcare center to reach the efficient frontier. According to the mean importance values listed in Table 4, the size of the covered population (I2) plays the greatest role in the healthcare centers becoming more efficient. The same interpretation can be made separately for each healthcare center. For example, the input I2 plays the greatest role in improving the level of efficiency in the Azadshahr center.

Table 4 further shows the type of returns-to-scale of each healthcare center in the efficiency analysis for the family health (children) functional area. For example, Table 4 indicates that for the Sheikhdad center, changing the inputs I1 and I2 will lead to a relatively greater increase in output.

The combined DEA-game approach can model the interaction between healthcare centers to improve their technical efficiency. The results obtained by solving this model are the optimal efficiency of the centers that can adopt a combination of different functional strategies for their covered population. The results show that the centers can adopt a combination of different functional strategies for their covered populations, with the goal of obtaining optimal efficiency. The relative and combined efficiency scores of the healthcare centers, which were obtained from the combined Model (4), are presented in Table 5.

Table 4 Ranking of healthcare centers according to the change in input and output variables, individual importance weights, and returns-to-scale characteristics for the family health (children) functional area

Healthcare center number	Healthcare center name	Ranking according to change in input and output variables		Individual importance of inputs		Returns-to-scale characteristic
		I1	I1	I1	I2	
1	Azadshahr	9	9	0.03	991.9	Constant
2	Imamshahr	8	8	0.06	417.52	Increasing
3	Akbari Safaiyeh	9	9	0.08	0	Constant
4	Akbarabad	6	6	0.07	243.48	Increasing
5	Rahmatabad	9	9	0.1	158.59	Increasing
6	Kheirabad	3	5	0.08	98.9	Increasing
7	Zarch	2	3	0.06	153.9	Increasing
8	Shahedie	1	2	0.06	148.81	Increasing
9	Juy harhar	5	4	0.05	350.62	Increasing
10	Ghale asadan	9	9	0.1	177.02	Increasing
11	Kasnavieh	9	9	0.2	10.97	Increasing
12	Maskan	4	1	0.05	329.38	Increasing
13	Naimabad	9	9	0.33	0	Increasing
14	Panbekaran	9	9	0.3	19.1	Increasing
15	Nikupoor	7	7	0.13	81.34	Increasing
16	Hakimzadeh	9	9	0.13	118.62	Increasing
17	Sheikhdad	9	9	0.13	157.86	Increasing
Mean importance				0.115	203.414	–
Rank				2	1	–

5 Discussion

The results obtained by solving the DEA models show that the reference units can be used as models for the inefficient units and their supervisors to trigger performance improvement. In other words, the inefficient units can achieve better efficiency by trying to mimic the decisions of the reference units (or a combination of the reference units) to reach the same level of performance. Table 6 shows the mean percentage change and the importance of each input involving the efficiency of the healthcare centers.

According to Table 6, in the family health (children) functional area, the input I2 (the total number of children under 1 year of age) plays a more important role than the input 1I (family health personnel and physicians) in the inefficient units becoming

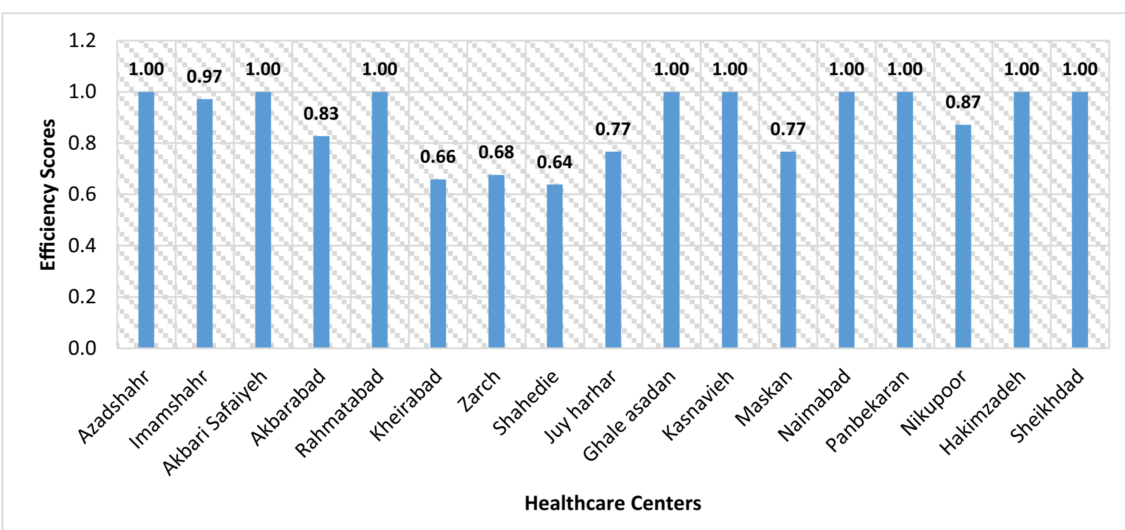

Fig. 2 Ranking of healthcare centers based on the efficiency in family health (children)

Table 5 Relative and combinatorial efficiency scores of healthcare centers obtained from the hybrid DEA-game theory model

Healthcare center number	Healthcare center name	Efficiency scores in the functional areas							
		Family health (children)	Family health (women)	Family health (pregnancy)	Family health (elderly)	School health	Disease prevention and control	Medical care	Combinatorial
1	Azadshahr	1	0.86	1	1	0.66	1	0.84	0.87
2	Imamshahr	0.89	0.89	1	0.5	0.76	0.78	0.65	0.71
3	Akbari Safaiyeh	1	1	1	1	1	1	1	1
4	Akbarabad	0.75	1	0.83	0.75	1	1	0.77	0.83
5	Rahmatabad	1	1	1	0.53	0.64	0.85	0.47	0.68
6	Kheirabad	0.58	0.67	0.6	0.36	0.54	0.83	0.4	0.59
7	Zarch	0.59	0.76	0.74	0.5	0.5	1	0.25	0.6
8	Shahedie	0.55	0.67	0.6	0.4	0.46	0.85	0.46	0.58
9	Juy harhar	0.7	0.8	0.73	0.75	0.71	0.81	1	0.74
10	Ghale asadan	1	0.87	0.81	0.5	0.8	0.88	1	0.8
11	Kasnavieh	1	0.85	1	0.76	1	1	1	0.91
12	Maskan	0.69	0.78	0.74	0.45	0.68	1	0.44	0.63
13	Naimabad	1	1	1	0.63	1	1	1	0.9
14	Panbekaran	1	1	1	1	1	1	1	1
15	Nikupoor	0.76	0.86	0.84	1	1	1	0.35	0.78
16	Hakimzadeh	1	1	0.77	1	0.89	1	1	0.92
17	Sheikhdad	1	1	1	0.6	0.73	1	1	0.85

efficient, and also needs a lower percentage of change to achieve this goal. Thus, better management of the healthcare personnel to make better use of their potentials can more effectively improve the efficiency of inefficient healthcare centers. Thus, the management of the healthcare personnel can be enhanced by a concerted effort on their part to improve the efficiency of inefficient healthcare centers. A similar condition is observed in other functional areas of family health (pregnancy, women, and elderly) and in the school health area. In the medical care and disease prevention and control areas, the input I2 is more important than

Table 6 Mean change in inputs and their importance for the efficiency scores of the healthcare centers

Functional area	Input	Mean change (%)	Mean importance score
Family health (children)	Family health personnel and physicians (I1)	13.42	0.1160
	Number of children(I2)	11.83	203.4121
Family health (women)	Family health personnel and midwives (I1)	4.9	0.1214
	Number of women(I2)	4.67	2080.7389
Family health (pregnancy)	Family health personnel and midwives (I1)	2.53	0.1222
	Number of children(I2)	2.47	237.2680
Family health (elderly)	Family health personnel (I1)	40.35	0.1535
	Number of elderly people (I2)	30.7	1218.3261
school health	Family health and disease control personnel and physicians (I1)	6.24	0.1018
	Number of covered students (I2)	5.87	515.9503
Disease prevention and control functional	Family health and disease control personnel and physicians (I1)	1.42	0.1140
	Size of the covered population (I2)	1.42	6555.5579
Medical care	Number of physicians(I1)	24.09	0.6040
	Size of the covered population (I2)	24.7	6709.5249

the input I1, but the percentages of change required in I1 and I2 for reaching efficiency are approximately equal.

Another result of this study is the combined efficiency scores of the healthcare centers, which have been obtained from the combined DEA-game theory model. The advantage of this approach over DEA is its ability to combine relative efficiency scores across all functional areas to provide a final weighted score. The ranking of the healthcare centers in terms of their combined score from the combined DEA-game theory model in all functional areas is illustrated in Fig. 3.

According to the results of this study, the Yazd healthcare center office can improve the performance of inefficient centers by adjusting their coverage domains and adopting flexible work hours and zone-based assignments for the specialist staff. Since the size of the population covered by a healthcare center is one of the most important factors of its efficiency, the efficiency can be improved by adjusting the size of the population covered by an inefficient center. For example, the geographic proximity of the Naimabad, Akbarabad and Maskan centers provides an opportunity for increasing their collective efficiency by the reassignment of coverage in the respective areas. The current efficiency of these three centers and the extent of change needed to make them efficient indicates that this goal can be achieved by increasing the size of the population of students and women (up to 49 years old) covered by the Maskan healthcare center by about 680 and 1200, respectively. Naturally, achieving this objective requires an improved geographical zoning of the area covered by these three centers.

Some of the healthcare centers showed inconsistent efficiency scores in the subcategories of the family health function area. While these healthcare centers are efficient in some subcategories, they are inefficient in others. Some of the reasons for these inconsistencies are: the centers' failure to attract the targeted population to receive the specialized services, the lack of public trust towards some services, and the changing demographic characteristics of the population.

6 Conclusion and future research directions

The goal of this study is to design a system of performance evaluation for healthcare centers to facilitate the optimal allocation of resources, including specialized staff and equipment, to the centers according to their relative efficiency. The factors affecting the efficiency in each of these areas were identified after various stages of data collection, the appropriate literature review and meetings held with experts with sectoral and trans-sectoral knowledge in the field of health services and its functional areas. The result was the identification of inputs and outputs affecting the performance of each healthcare center, as shown in Table 1. After collecting the data related to input and output variables in each functional area, a DEA model calculated the relative efficiency of the healthcare centers. The relative efficiency scores, the reference units of each healthcare center, the degree of change needed in the inputs for the respective center to become efficient, and the type of envelopment model in terms of returns-to-scale was determined. A summary of the results is presented in Table 7.

It should be noted that some of the inputs of the performance evaluation model such as the size of the covered population are positive, and others such as the number of specialized personnel for each functional area are negative in nature. The required changes in the inputs affecting the efficiency of the healthcare

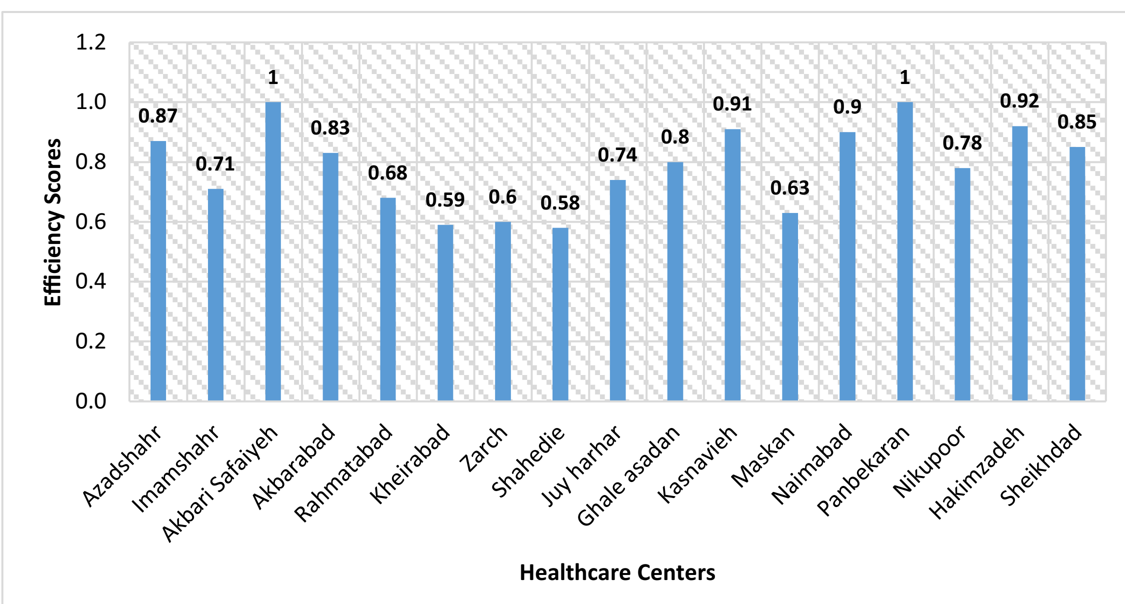

Fig. 3 Ranking of healthcare centers based on the combined efficiency scores in the proposed hybrid model

Table 7 Reference units (healthcare centers) for each functional area

Healthcare center number	Healthcare center name	Reference units						
		Family health (children)	Family health (women)	Family health (pregnancy)	Family health (elderly)	School health	Disease prevention and control	Medical care
1	Azadshahr	–	Akbari Safaiyeh-Akbarabad	–	–	Akbarabad- Nikupoor	–	Akbari Safaiyeh-Juy harhar
2	Imamshahr	Azadshahr-Rahmatabad	Akbari Safaiyeh-Akbarabad	–	Nikupoor- Hakimzadeh	Akbarabad- Nikupoor	Akbari Safaiyeh-Hakimzadeh	Akbari Safaiyeh-Juy harhar
3	Akbari Safaiyeh	–	–	–	–	–	–	–
4	Akbarabad	Rahmatabad-Sheikhdad	–	Naimabad-Sheikhdad	Akbari Safaiyeh-Hakimzadeh	–	–	Akbari Safaiyeh-Juy harhar
5	Rahmatabad	Rahmatabad	–	–	Nikupoor- Hakimzadeh	Akbarabad-Kasnavieh-Nikupoor	Azadshahr-Akbari Safaiyeh- Zarch-Naimabad- Hakimzadeh	Akbari Safaiyeh-Ghale asadan
6	Kheirabad	Kasnavieh-Hakimzadeh-Sheikhdad	Hakimzadeh-Sheikhdad	Naimabad-Sheikhdad	Nikupoor- Panbekaran	Kasnavieh- Nikupoor	Azadshahr- Zarch-Panbekaran- Nikupoor	Akbari Safaiyeh-Ghale asadan
7	Zarch	Rahmatabad-Ghale asadan-Sheikhdad	Hakimzadeh- Sheikhdad	Rahmatabad-Sheikhdad	Nikupoor- Hakimzadeh	Akbarabad-Kasnavieh-Nikupoor	–	Akbari Safaiyeh-Ghale asadan
8	Shahedie	Rahmatabad-Ghale asadan-Sheikhdad	Hakimzadeh- Sheikhdad	Rahmatabad-Sheikhdad	Nikupoor- Hakimzadeh	Kasnavieh- Nikupoor	Azadshahr- Zarch-Panbekaran	Akbari Safaiyeh-Ghale asadan
9	Juy harhar	Azadshahr-Rahmatabad	Akbari Safaiyeh-Akbarabad	Imamshahr-Rahmatabad	Akbari Safaiyeh-Hakimzadeh	Akbarabad- Nikupoor	Akbari Safaiyeh-Hakimzadeh	–
10	Ghale asadan	–	Rahmatabad- Hakimzadeh	Rahmatabad-Sheikhdad	Nikupoor- Hakimzadeh	Akbarabad-Kasnavieh-Nikupoor	Azadshahr-Akbari Safaiyeh- Naimabad-Hakimzadeh	–
11	Kasnavieh	–	Naimabad- Sheikhdad	Naimabad-Sheikhdad	Nikupoor- Hakimzadeh	–	Zarch- Panbekaran-Hakimzadeh	–
12	Maskan	Azadshahr-Rahmatabad	Akbarabad- Rahmatabad	Imamshahr-Rahmatabad	Nikupoor- Hakimzadeh	Akbarabad- Nikupoor	–	Akbari Safaiyeh-Juy harhar
13	Naimabad	–	–	–	Panbekaran	–	–	–
14	Panbekaran	–	–	–	–	–	–	–
15	Nikupoor	Kasnavieh-Sheikhdad	Rahmatabad- Naimabad-Sheikhdad	Naimabad-Sheikhdad	–	–	–	Akbari Safaiyeh-Juy harhar-Ghale asadan
16	Hakimzadeh	–	–	Rahmatabad-Sheikhdad	–	Akbarabad-Kasnavieh-Nikupoor	–	–
17	Sheikhdad	–	–	–	Nikupoor- Hakimzadeh	Akbarabad-Kasnavieh-Panbekaran	–	–

centers are presented in the tables of Section 4. The importance of each input for the efficiency of the healthcare centers was also calculated in Fig. 2. This figure indicates the amount of focus on the resources of the healthcare centers. One of the limitations of this research is that there are two categories of information forms (coded and non-coded) and we ignored the second category because of their ambiguity and large number. Moreover, we ignored the results in some of the units since they were insufficient due to the lack of personnel. Furthermore, some activities were performed in health centers which we were not able to evaluate and compare. Some suggestions for further research in this field involve using Dynamic-DEA to expand the domain of the research at the country level, using MADM and F-MADM to calculate the weights of the inputs and outputs, and considering the subjective opinions and the intuition of the decision makers to select a single efficient unit rather than ranking all the DMUs.

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Appendix 1

Table 8 Details of the combined DEA-game theory model

x_{i0}	The value of input i in the evaluated unit zero
$\varphi_0^1, \varphi_0^2, \varphi_0^3, \varphi_0^4, \varphi_0^5, \varphi_0^6, \varphi_0^7$	Cross-efficiency of the zero unit in the DEA model for different functional areas
$\mu_{i1}, \mu_{i2}, \mu_{i3}, \mu_{i4}, \mu_{i5}, \mu_{i6}, \mu_{i7}$	The importance of input i in the seven DEA models: $\mu_{i1} = \left(\sum u_r^1 y_{r0}^1\right) v_i$ $\mu_{i2} = \left(\sum u_r^2 y_{r0}^2\right) v_i$ $\mu_{i3} = \left(\sum u_r^3 y_{r0}^3\right) v_i$ $\mu_{i4} = \left(\sum u_r^4 y_{r0}^4\right) v_i$ $\mu_{i5} = \left(\sum u_r^5 y_{r0}^5\right) v_i$ $\mu_{i6} = \left(\sum u_r^6 y_{r0}^6\right) v_i$ $\mu_{i7} = \left(\sum u_r^7 y_{r0}^7\right) v_i$
$\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6$	The ratio of the importance of inputs and functional area: $\alpha_1 = t_2/t_1$ $\alpha_2 = t_3/t_1$ $\alpha_3 = t_4/t_1$ $\alpha_4 = t_5/t_1$ $\alpha_5 = t_6/t_1$ $\alpha_6 = t_7/t_1$
$u_r^1, u_r^2, u_r^3, u_r^4, u_r^5, u_r^6, u_r^7$	The importance of output r in the seven DEA models (problem variable)
$y_{rj}^1, y_{rj}^2, y_{rj}^3, y_{rj}^4, y_{rj}^5, y_{rj}^6, y_{rj}^7$	The value of output i in the unit jj in the seven DEA models (obtained from DEA-Solver)
x_{ij}	The value of input i in the unit j (in accordance with the data file of DEA-Solver)

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