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Measuring Productivity Changes of Hospitals in Tehran: The Fuzzy Malmquist Productivity Index

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Abstract

Background and Objectives: The purpose of this paper is to suggest a novel method to measure the productivity changes of hospitals over time in the presence of linguistic variables along with fuzzy data.

Methods: Applying the popular and applicable approaches including data envelopment analysis (DEA), Malmquist productivity index (MPI) and possibilistic programming, the fuzzy Malmquist productivity index (FMPI) is proposed.

Results: In this study, the proposed fuzzy MPI is implemented for measuring productivity changes of 10 hospitals in Tehran. Notably, the input variables include the number of beds, the number of doctors, equipment & infrastructures and hospital location. Also, the output variables include the number of inpatient days, the number of outpatient, and overall patient satisfaction. According to the obtained results, the productivity of 5 hospitals has increased in 2014 in comparison to 2013.

Conclusions: The obtained results have shown the capability of the proposed index to calculate the changes in productivity of hospitals in the presence of ambiguity in data.

Keywords: Hospital Productivity, Malmquist Productivity Index, Data Envelopment Analysis, Fuzzy Mathematical Programming, Fuzzy Data.

1. Introduction

Assessing the performance and productivity of health care systems and treatment centers such as hospitals is of great important and almost mandatory. Data envelopment analysis (DEA) is one of the effective and popular methods that widely used in health care.¹⁻³ DEA is a powerful mathematical programming approach that can be applied for performance measurement, and ranking of homogenous decision making units (DMUs).⁴⁻⁸ Moreover, DEA approach, unlike other multiple criteria decision making (MCDM) techniques, also has the capability of benchmarking for inefficient DMUs.

One of the important issues in the performance evaluating of hospitals in real-world cases and applications is to identify the advance as well as regress of each hospital over time periods. In this regard, it is essential to know whether the hospital has a degree or type of functional change, including progression, regression, or stagnation over its previous period compared to other hospitals. Using DEA and Malmquist productivity index (MPI) enables us to identify, calculate, and evaluate the trends and types of hospital productivity changes.

It should be noted that some of the variables, such as overall patient satisfaction level, which should be considered in performance evaluating of hospitals, are linguistic variables. These linguistic variables can be converted to fuzzy variables. In this respect, it is imperative to say that the very important point that should be taken into account when calculating MPI is to consider the uncertainty and ambiguity in the data.

Classic DEA models cannot encompass the uncertainty of data. As a result, ignoring this point may mislead ones over the identification and classification of DMUs in terms of the process of productivity changes. In this study, the development of novel Malmquist productivity index with the ability to be implemented in the presence of fuzzy data is discussed. For this purpose, the possibilistic programming approach, which is one of the most useful and effective approaches in fuzzy mathematical programming, has been employed. It should be noted that the main research questions of the current study can be mentioned as follows: What is the trend of hospital productivity changes over time periods? How to convert linguistic variables into quantitative concepts in order to measure hospital performance?

The rest of this paper is organized as follows. The literature review, as well as literature gaps, will be introduced in section 2. Section 3 provides the background involving the MPI and fuzzy event via necessity measure. The novel fuzzy MPI approach based on possibilistic programming

will be proposed in section 4. Then, the proposed PMPI will be applied for measuring productivity changes of 10 hospitals in a real-life case study of hospitals in Tehran in section 5. Finally, the conclusions and some directions for future research will be given in section 6.

2. Literature Review

In this section, the literature of previous research from two viewpoints including the application of MPI in Iranian hospitals, and the application of uncertain DEA in health care will be reviewed. Then, the literature gaps, which this study aims to fill, are presented.

2.1. The Application of MPI in Iranian Hospitals

In the first viewpoint, all studies that applied MPI for measuring productivity changes of Iranian hospitals have been collected. Table (1) shows the characteristics of these studies as well as current research:

Table (1): The Application of MPI in Iranian Hospitals: A Review

| Year | Research | Inputs | Outputs | Uncertainty |
|------|--|---|---|-------------|
| 2010 | Hatam et al. ⁹ | <ol style="list-style-type: none"> 1. Number of Fixed Beds 2. Number of Nurses 3. Number of Physicians 4. Number of Other Personnels 5. Total Expenses | <ol style="list-style-type: none"> 1. Bed Occupancy Rate 2. Patient-Day Admissions 3. Occupied Bed-Days 4. Average Length of Stay 5. Rate of Bed Turn-Over | - |
| 2014 | Lotfi et al. ¹⁰ | <ol style="list-style-type: none"> 1. Number of Active Beds 2. Number of Nurses 3. Number of Physicians 4. Number of Other Personnels | <ol style="list-style-type: none"> 1. Bed Occupancy Rate 2. Number of Patients 3. Number of Operations | - |
| 2014 | Torabipour et al. ¹¹ | <ol style="list-style-type: none"> 1. Number of Occupied Beds 2. Number of Nurses 3. Number of Physicians | <ol style="list-style-type: none"> 1. Number of Outpatients and Inpatients 2. Average of Hospital Stay 3. Number of Major Operations | - |
| 2017 | Raei et al. ¹² | <ol style="list-style-type: none"> 1. Number of Beds 2. Number of Physicians 3. Number of Non-Physician Staff | <ol style="list-style-type: none"> 1. Number of Admissions 2. Number of Mortality in Patients | - |
| 2018 | Alinezhad & Mirmozaffari ¹³ | <ol style="list-style-type: none"> 1. Number of Beds 2. Numbers of Nurses and Secretaries 3. Number of Doctors | <ol style="list-style-type: none"> 1. Outpatient Treated 2. Inpatient Treated | - |
| 2019 | Our Work | <ol style="list-style-type: none"> 1. Number of Beds 2. Number of Doctors 3. Equipment & Infrastructures 4. Hospital Location | <ol style="list-style-type: none"> 1. Number of Inpatient Days 2. Number of Outpatient 3. Overall Patient Satisfaction | ✓ |

As can be seen in Table (1), all of the existing studies in the literature are neglected the uncertainty of data for measuring productivity changes of Iranian hospitals. However, in the current paper, the productivity changes of hospitals over time can be measured using linguistic variables and fuzzy data.

2.2. The Application of Uncertain DEA in Health Care

In the second viewpoint, all research that considered the uncertainty of data in performance measurement of hospitals have been gathered. Table (2) summarizes the main characteristics of the previous studies and compares them with the FMPI approach that proposed in this paper:

Table (2): The Application of Uncertain DEA in Health Care: A Review

| Year | Research | DEA Approach | | | | | | Form | | Uncertainty Method | | | | | |
|------|-------------------------------------|--------------|-----|-----|-----|------------|-----------------|------------------|-------------|--------------------|------|------|------|------|------|
| | | CCR | BCC | SBM | MPI | Congestion | Cost Efficiency | Cross Efficiency | Multipplier | Envelopment | SDEA | FDEA | RDEA | BDEA | IDEA |
| 2012 | Ebrahimnejad ¹⁴ | | | | | | ✓ | | ✓ | | ✓ | | | | |
| 2012 | Hatami-Marbini et al. ¹⁵ | | | | ✓ | | | ✓ | | | ✓ | | | | |
| 2012 | Khaki et al. ¹⁶ | ✓ | | | | | | ✓ | | | | ✓ | | | |
| 2013 | Costantino et al. ¹⁷ | | | | | | ✓ | ✓ | | | ✓ | | | | |
| 2013 | De Nicola et al. ¹⁸ | | ✓ | | | | | | ✓ | | | | | ✓ | |
| 2014 | Kalantary & Azar ¹⁹ | ✓ | | | | | | ✓ | | | | ✓ | | | |
| 2014 | Karadayi & Karsak ²⁰ | ✓ | | | | | | ✓ | | | ✓ | | | | |
| 2015 | Haji Sami et al. ²¹ | ✓ | | | | | | ✓ | | | | ✓ | | | |
| 2015 | Kheirollahi et al. ²² | | | | | ✓ | | | ✓ | | ✓ | | | | |
| 2015 | Mitropoulos et al. ²³ | ✓ | | | | | | | ✓ | | ✓ | | | | |
| 2016 | Rabbani et al. ²⁴ | ✓ | | | | | | ✓ | | | | ✓ | ✓ | ✓ | ✓ |
| 2017 | Arya & Yadav ²⁵ | ✓ | | | | | | ✓ | | | ✓ | | | | |
| 2017 | Karsak & Karadayi ²⁶ | ✓ | | | | | | ✓ | | | ✓ | | | | |
| 2017 | Kheirollahi et al. ²⁷ | | | | | ✓ | | | ✓ | | ✓ | | | | |
| 2018 | Wu & Wu ²⁸ | ✓ | | | | | | ✓ | | | | ✓ | | | |
| 2019 | Hatefi & Haeri ²⁹ | ✓ | | | | | | ✓ | ✓ | | ✓ | | | | |
| 2019 | Peykani et al. ³⁰ | ✓ | | | | | | ✓ | | | ✓ | | | | |
| 2019 | Our Work | | | | ✓ | | | | ✓ | | ✓ | | | | |

It should be noted that in the research conducted by Hatami-Marbini et al.¹⁵, the α -level based approach is applied for dealing with linguistic variables and fuzzy data, while in the current research, the possibilistic programming approach will be applied for proposing FMPI.

3. Background

In this section, the modeling and formulations of Malmquist productivity index based on DEA approach as well as the mathematical formulation of necessity measure to calculate the chances of occurrence of fuzzy events will be discussed.

3.1. Malmquist Productivity Index

Färe & Grosskopf³¹ were the pioneer researchers that combined MPI and DEA method to calculate the productivity changes. They have proposed this indicator by taking into account two periods of time and calculating technological changes and efficiency changes over these two periods.

Suppose that there are n homogenous decision making units DMU_j ($j = 1, \dots, n$) that convert m input x_{ij} ($i = 1, \dots, m$) into s outputs y_{rj} ($r = 1, \dots, s$) and DMU_0 is an under evaluation DMU. By applying the envelopment form of input-oriented CCR⁵ model, $\Omega_0^t(x_0^t, y_0^t)$, $\Omega_0^{t+1}(x_0^{t+1}, y_0^{t+1})$, $\Omega_0^t(x_0^{t+1}, y_0^{t+1})$, and $\Omega_0^{t+1}(x_0^t, y_0^t)$ are estimated from Models (1), (2), (3), and (4), respectively.

$$\Omega_0^t(x_0^t, y_0^t) = \text{Min } \theta \quad (1-1)$$

$$\text{S.t.} \quad \sum_{j=1}^n \lambda_j x_{ij}^t \leq \theta x_{i0}^t, \quad \forall i \quad (1-2)$$

$$\sum_{j=1}^n \lambda_j y_{rj}^t \geq y_{r0}^t, \quad \forall r \quad (1-3)$$

$$\lambda_j \geq 0, \quad \forall j \quad (1-4)$$

$$\Omega_0^{t+1}(x_0^{t+1}, y_0^{t+1}) = \text{Min } \theta \quad (2-1)$$

$$\text{S.t.} \quad \sum_{j=1}^n \lambda_j x_{ij}^{t+1} \leq \theta x_{i0}^{t+1}, \quad \forall i \quad (2-2)$$

$$\sum_{j=1}^n \lambda_j y_{rj}^{t+1} \geq y_{r0}^{t+1}, \quad \forall r \quad (2-3)$$

$$\lambda_j \geq 0, \quad \forall j \quad (2-4)$$

$$\Omega_0^t(x_0^{t+1}, y_0^{t+1}) = \text{Min } \theta \quad (3-1)$$

$$\text{S.t. } \sum_{j=1}^n \lambda_j x_{ij}^t \leq \theta x_{i0}^{t+1}, \quad \forall i \quad (3-2)$$

$$\sum_{j=1}^n \lambda_j y_{rj}^t \geq y_{r0}^{t+1}, \quad \forall r \quad (3-3)$$

$$\lambda_j \geq 0, \quad \forall j \quad (3-4)$$

$$\Omega_0^{t+1}(x_0^t, y_0^t) = \text{Min } \theta \quad (4-1)$$

$$\text{S.t. } \sum_{j=1}^n \lambda_j x_{ij}^{t+1} \leq \theta x_{i0}^t, \quad \forall i \quad (4-2)$$

$$\sum_{j=1}^n \lambda_j y_{rj}^{t+1} \geq y_{r0}^t, \quad \forall r \quad (4-3)$$

$$\lambda_j \geq 0, \quad \forall j \quad (4-4)$$

Finally, the Malmquist productivity index is calculated using Equation (5):

$$\text{MPI}_0 = \sqrt{\frac{\Omega_0^t(x_0^{t+1}, y_0^{t+1}) * \Omega_0^{t+1}(x_0^{t+1}, y_0^{t+1})}{\Omega_0^t(x_0^t, y_0^t) * \Omega_0^{t+1}(x_0^t, y_0^t)}} \quad (5)$$

It needs to be explained that based on the value of the MPI, which can be more or equal to or less than one, the productivity change of the DMU under consideration is interpreted as follows:

- $\text{MPI}_0 > 1$, the productivity increases and the progress is observed
- $\text{MPI}_0 < 1$, the productivity decreases and the regress is observed
- $\text{MPI}_0 = 1$, there is no change in productivity at time $t + 1$ in comparison to t .

3.2. Necessity Measure

Suppose that the triple $(\dagger, P(\dagger), Pos)$ be a possibility space where a universe set \dagger is a non-empty set, containing all possible events and $P(\dagger)$ is the power set of \dagger . Let $\tilde{\alpha}$ be a triangular fuzzy variable on the mentioned possibility space. The necessity of fuzzy events $\{\tilde{\alpha} \leq \beta\}$ and $\{\tilde{\alpha} \geq \beta\}$ are defined as Equations (6-1) and (6-2):

$$Nec\{\tilde{\alpha} \leq \beta\} = \begin{cases} 1, & \text{if } \alpha^{(3)} \leq \beta; \\ \frac{\beta - \alpha^{(2)}}{\alpha^{(3)} - \alpha^{(2)}}, & \text{if } \alpha^{(2)} \leq \beta \leq \alpha^{(3)}; \\ 0, & \text{if } \alpha^{(2)} \geq \beta. \end{cases} \quad (6-1)$$

$$Nec\{\tilde{\alpha} \geq \beta\} = \begin{cases} 1, & \text{if } \alpha^{(1)} \geq \beta; \\ \frac{\alpha^{(2)} - \beta}{\alpha^{(2)} - \alpha^{(1)}}, & \text{if } \alpha^{(1)} \leq \beta \leq \alpha^{(2)}; \\ 0, & \text{if } \alpha^{(2)} \leq \beta. \end{cases} \quad (6-2)$$

According to necessity measure, converting of fuzzy chance constraints into their equivalent crisp ones in a special confidence level (π) is conducted by Equations (7-1) and (7-2):

$$Nec\{\tilde{\alpha} \leq \beta\} \geq \pi \Leftrightarrow (1 - \pi) \alpha^{(2)} + \pi \alpha^{(3)} \leq \beta \quad (7-1)$$

$$Nec\{\tilde{\alpha} \geq \beta\} \geq \pi \Leftrightarrow \pi \alpha^{(1)} + (1 - \pi) \alpha^{(2)} \geq \beta \quad (7-2)$$

It should be noted that the possibilistic programming approach is an applicable method in fuzzy DEA for dealing with the uncertainty ensue from the absence or lack of knowledge about the exact value of model parameters in fuzzy mathematical programming.³²⁻³⁷

4. Fuzzy Malmquist Productivity Index

In this section, the fuzzy Malmquist productivity index (FMPI) is proposed by applying the necessity measure. Note that the inputs and outputs follow a triangular distribution $\tilde{x}(x^{(1)}, x^{(2)}, x^{(3)})$ and $\tilde{y}(y^{(1)}, y^{(2)}, y^{(3)})$ given that $x^{(1)} < x^{(2)} < x^{(3)}$ and $y^{(1)} < y^{(2)} < y^{(3)}$. Now by applying the Equations (7-1) and (7-2), Models (1) to (4) are rewritten to Models (8) to (11), respectively. Note that π is the confidence level for satisfying the fuzzy chance constraints.

$$\Psi_0^t(x_0^t, y_0^t, \pi) = \text{Min } \theta \quad (8-1)$$

$$\text{S.t.} \quad \sum_{j=1}^n \lambda_j \left((1 - \pi) x_{ij}^{t(2)} + (\pi) x_{ij}^{t(3)} \right) \leq \theta \left((\pi) x_{i0}^{t(1)} + (1 - \pi) x_{i0}^{t(2)} \right), \quad \forall i \quad (8-2)$$

$$\sum_{j=1}^n \lambda_j \left((\pi) y_{rj}^{t(1)} + (1 - \pi) y_{rj}^{t(2)} \right) \geq \left((1 - \pi) y_{r0}^{t(2)} + (\pi) y_{r0}^{t(3)} \right), \quad \forall r \quad (8-3)$$

$$\lambda_j \geq 0, \quad \forall j \quad (8-4)$$

$$\Psi_0^{t+1}(x_0^{t+1}, y_0^{t+1}) = \text{Min } \theta \quad (9-1)$$

$$\text{S.t.} \quad \sum_{j=1}^n \lambda_j \left((1-\pi) x_{ij}^{t+1(2)} + (\pi) x_{ij}^{t+1(3)} \right) \leq \theta \left((\pi) x_{i0}^{t+1(1)} + (1-\pi) x_{i0}^{t+1(2)} \right), \quad \forall i \quad (9-2)$$

$$\sum_{j=1}^n \lambda_j \left((\pi) y_{rj}^{t+1(1)} + (1-\pi) y_{rj}^{t+1(2)} \right) \geq \left((1-\pi) y_{r0}^{t+1(2)} + (\pi) y_{r0}^{t+1(3)} \right), \quad \forall r \quad (9-3)$$

$$\lambda_j \geq 0, \quad \forall j \quad (9-4)$$

$$\Psi_0^t(x_0^{t+1}, y_0^{t+1}) = \text{Min } \theta \quad (10-1)$$

$$\text{S.t.} \quad \sum_{j=1}^n \lambda_j \left((1-\pi) x_{ij}^{t(2)} + (\pi) x_{ij}^{t(3)} \right) \leq \theta \left((\pi) x_{i0}^{t+1(1)} + (1-\pi) x_{i0}^{t+1(2)} \right), \quad \forall i \quad (10-2)$$

$$\sum_{j=1}^n \lambda_j \left((\pi) y_{rj}^{t(1)} + (1-\pi) y_{rj}^{t(2)} \right) \geq \left((1-\pi) y_{r0}^{t+1(2)} + (\pi) y_{r0}^{t+1(3)} \right), \quad \forall r \quad (10-3)$$

$$\lambda_j \geq 0, \quad \forall j \quad (10-4)$$

$$\Psi_0^{t+1}(x_0^t, y_0^t) = \text{Min } \theta \quad (11-1)$$

$$\text{S.t.} \quad \sum_{j=1}^n \lambda_j \left((1-\pi) x_{ij}^{t+1(2)} + (\pi) x_{ij}^{t+1(3)} \right) \leq \theta \left((\pi) x_{i0}^{t(1)} + (1-\pi) x_{i0}^{t(2)} \right), \quad \forall i \quad (11-2)$$

$$\sum_{j=1}^n \lambda_j \left((\pi) y_{rj}^{t+1(1)} + (1-\pi) y_{rj}^{t+1(2)} \right) \geq \left((1-\pi) y_{r0}^{t(2)} + (\pi) y_{r0}^{t(3)} \right), \quad \forall r \quad (11-3)$$

$$\lambda_j \geq 0, \quad \forall j \quad (11-4)$$

Finally, the fuzzy Malmquist productivity index for the desired confidence level is calculated using Equation (12):

$$\text{FMPI}_0(\pi) = \sqrt{\frac{\Psi_0^t(x_0^{t+1}, y_0^{t+1}, \pi) * \Psi_0^{t+1}(x_0^{t+1}, y_0^{t+1}, \pi)}{\Psi_0^t(x_0^t, y_0^t, \pi) * \Psi_0^{t+1}(x_0^t, y_0^t, \pi)}} \quad (12)$$

According to the value of the FMPI, which can be greater or equal to or less than one, the productivity change of the DMU under consideration for the desired confidence level is interpreted as follows:

- $\text{FMPI}_0(\delta) > 1$, the productivity increases and the progress is observed
- $\text{FMPI}_0(\delta) < 1$, the productivity decreases and the regress is observed
- $\text{FMPI}_0(\delta) = 1$, there is no change in productivity at time $t+1$ in comparison to t

5. Case study: Hospitals of Tehran

In this section, the applicability of FMPI that proposed in this research is implemented for measuring productivity changes of 10 hospitals in a real-life case study of Tehran. According to the experts' opinions, and literature review^{2,3}, the inputs and outputs are selected. The number of beds, the number of doctors, equipment & infrastructures and hospital location are considered as input variables. Also, the number of inpatient days, the number of outpatient, and overall patient satisfaction are selected as output variables. Data set of 10 hospitals for years 2013 and 2014 are presented in Tables (3) and (4), respectively:

Table (3): Hospitals Data for the Year 2013

| Hospitals | Inputs | | | | Outputs | | |
|-------------|----------------|-------------------|-----------------------------|-------------------|--------------------------|----------------------|------------------------------|
| | Number of Beds | Number of Doctors | Equipment & Infrastructures | Hospital Location | Number of Inpatient Days | Number of Outpatient | Overall Patient Satisfaction |
| Hospital 01 | 535 | 540 | VP | VP | 139248 | 114004 | VL |
| Hospital 02 | 187 | 126 | G | F | 31544 | 36984 | L |
| Hospital 03 | 218 | 140 | VG | VG | 61622 | 177572 | VH |
| Hospital 04 | 117 | 92 | F | P | 40594 | 35596 | H |
| Hospital 05 | 121 | 93 | G | F | 24607 | 69580 | M |
| Hospital 06 | 508 | 694 | P | F | 145773 | 150371 | M |
| Hospital 07 | 69 | 179 | F | G | 11563 | 202089 | VL |
| Hospital 08 | 340 | 164 | F | VP | 86034 | 96773 | M |
| Hospital 09 | 114 | 148 | G | G | 27713 | 162846 | L |
| Hospital 10 | 329 | 332 | VP | F | 96341 | 105928 | L |

Table (4): Hospitals Data for the Year 2014

| Hospitals | Inputs | | | | Outputs | | |
|-------------|----------------|-------------------|-----------------------------|-------------------|--------------------------|----------------------|------------------------------|
| | Number of Beds | Number of Doctors | Equipment & Infrastructures | Hospital Location | Number of Inpatient Days | Number of Outpatient | Overall Patient Satisfaction |
| Hospital 01 | 521 | 404 | P | VP | 121352 | 104235 | L |
| Hospital 02 | 188 | 109 | G | F | 38894 | 34544 | M |
| Hospital 03 | 215 | 139 | VG | VG | 62076 | 157754 | M |
| Hospital 04 | 118 | 83 | G | P | 40408 | 32893 | VH |
| Hospital 05 | 110 | 84 | F | F | 23890 | 63236 | M |
| Hospital 06 | 495 | 561 | P | F | 148280 | 147594 | H |
| Hospital 07 | 69 | 123 | G | G | 12960 | 189377 | M |
| Hospital 08 | 333 | 147 | F | VP | 83217 | 97272 | L |
| Hospital 09 | 96 | 120 | G | G | 22900 | 151538 | M |
| Hospital 10 | 320 | 151 | VP | F | 96971 | 94372 | L |

As previously discussed, patient satisfaction, equipment & infrastructures, and hospital location were measured with linguistic variables and the triangular fuzzy numbers (TFN) are presented in Table (5):

Table (5): The Linguistic Variables and Their Associated Triangular Fuzzy Numbers

| Linguistic Variable | Triangular Fuzzy Number |
|---------------------------------|-------------------------|
| Very Low (VL) / Very Poor (VP) | (0, 0, 0.25) |
| Low (L) / Poor (P) | (0, 0.25, 0.5) |
| Medium (M) / Fair (F) | (0.25, 0.5, 0.75) |
| High (H) / Good (G) | (0.5, 0.75, 1) |
| Very High (VH) / Very Good (VG) | (0.75, 1, 1) |

Now, Models (8) to (11), are solved for different confidence levels, including 0%, 25%, 50%, 75, and 100%. The obtained results of Models (8) to (11), are presented in Tables (6) to (9), respectively:

Table (6): The Results of $\Psi_0^r(x_0^r, y_0^r, \pi)$

| Hospitals | Confidence Levels | | | | |
|-------------|-------------------|---------|---------|---------|---------|
| | 0% | 25% | 50% | 75% | 100% |
| Hospital 01 | 1.00000 | 1.26858 | 3.34180 | 3.50251 | 3.82363 |
| Hospital 02 | 0.54471 | 0.54832 | 0.64787 | 1.05480 | 2.00000 |
| Hospital 03 | 1.00000 | 1.10817 | 1.27047 | 1.51202 | 1.77778 |
| Hospital 04 | 1.00000 | 1.77850 | 3.47881 | 3.98764 | 4.76519 |
| Hospital 05 | 0.81306 | 0.96641 | 1.25158 | 1.74312 | 3.00000 |
| Hospital 06 | 1.00000 | 1.89527 | 5.00000 | 6.14172 | 8.78816 |
| Hospital 07 | 1.00000 | 1.32748 | 1.75958 | 2.35918 | 3.25325 |
| Hospital 08 | 1.00000 | 1.37500 | 4.16667 | 6.19837 | 8.76265 |
| Hospital 09 | 0.97211 | 1.04523 | 1.23889 | 1.45192 | 1.70926 |
| Hospital 10 | 1.00000 | 3.39286 | 6.59152 | 7.10353 | 9.16615 |

Table (7): The Results of $\Psi_0^{r+1}(x_0^{r+1}, y_0^{r+1})$

| Hospitals | Confidence Levels | | | | |
|-------------|-------------------|---------|---------|---------|---------|
| | 0% | 25% | 50% | 75% | 100% |
| Hospital 01 | 1.00000 | 1.58723 | 2.05752 | 2.48914 | 2.94048 |
| Hospital 02 | 0.64369 | 0.68248 | 0.96353 | 1.35745 | 2.01584 |
| Hospital 03 | 1.00000 | 1.05896 | 1.14182 | 1.37310 | 1.76929 |
| Hospital 04 | 1.00000 | 1.77778 | 3.42857 | 4.46719 | 8.61539 |
| Hospital 05 | 0.87197 | 1.20283 | 1.67770 | 2.39276 | 3.69970 |
| Hospital 06 | 1.00000 | 1.91803 | 4.20000 | 6.66667 | 9.00000 |
| Hospital 07 | 1.00000 | 1.31049 | 1.71649 | 2.25333 | 2.97283 |
| Hospital 08 | 1.00000 | 1.60133 | 3.25814 | 5.30917 | 7.83810 |
| Hospital 09 | 0.95689 | 1.13296 | 1.47730 | 1.93554 | 2.54399 |
| Hospital 10 | 1.00000 | 1.78252 | 4.56103 | 6.42857 | 9.76159 |

Table (8): The Results of $\Psi_0^f(x_0^{t+1}, y_0^{t+1})$

| Hospitals | Confidence Levels | | | | |
|-------------|-------------------|---------|---------|---------|---------|
| | 0% | 25% | 50% | 75% | 100% |
| Hospital 01 | 1.00000 | 2.70074 | 3.32742 | 4.00373 | 6.14122 |
| Hospital 02 | 0.75166 | 0.78187 | 1.00000 | 1.65753 | 3.00000 |
| Hospital 03 | 1.00521 | 1.00846 | 1.02608 | 1.07032 | 1.33442 |
| Hospital 04 | 1.47791 | 2.18439 | 3.96705 | 7.26492 | 9.60000 |
| Hospital 05 | 0.86969 | 1.15598 | 1.69803 | 2.69236 | 4.00000 |
| Hospital 06 | 1.33333 | 2.71429 | 4.00000 | 8.91699 | 9.95362 |
| Hospital 07 | 1.95011 | 2.18033 | 2.45661 | 2.79428 | 3.21642 |
| Hospital 08 | 1.12140 | 2.43936 | 4.24690 | 7.34954 | 9.88855 |
| Hospital 09 | 1.30141 | 1.44756 | 1.63111 | 1.89458 | 2.17791 |
| Hospital 10 | 2.21305 | 3.11473 | 4.99572 | 5.99338 | 8.00000 |

Table (9): The Results of $\Psi_0^f(x_0^t, y_0^t)$

| Hospitals | Confidence Levels | | | | |
|-------------|-------------------|---------|---------|---------|---------|
| | 0% | 25% | 50% | 75% | 100% |
| Hospital 01 | 1.28572 | 1.37660 | 1.40235 | 1.47835 | 1.51620 |
| Hospital 02 | 0.52528 | 0.53791 | 0.64418 | 0.91302 | 1.47777 |
| Hospital 03 | 1.21323 | 1.27648 | 1.47131 | 1.79217 | 2.20035 |
| Hospital 04 | 1.07119 | 1.56545 | 3.01552 | 5.07692 | 7.46345 |
| Hospital 05 | 0.76159 | 0.86920 | 1.16928 | 1.60705 | 2.36536 |
| Hospital 06 | 0.99723 | 1.43255 | 3.01713 | 8.55556 | 9.87316 |
| Hospital 07 | 1.51907 | 1.83637 | 2.25245 | 2.82196 | 3.69098 |
| Hospital 08 | 1.98045 | 2.03435 | 3.44685 | 6.63254 | 8.84614 |
| Hospital 09 | 0.95625 | 0.99918 | 1.17144 | 1.49649 | 1.98633 |
| Hospital 10 | 1.12245 | 2.39742 | 5.00133 | 6.42857 | 8.00000 |

Finally, the results of fuzzy Malmquist productivity index are provided in Table (10) as follows:

Table (10): The Results of FMPI for Hospitals

| Hospitals | Confidence Levels | | | | |
|-------------|-------------------|---------|---------|---------|---------|
| | 0% | 25% | 50% | 75% | 100% |
| Hospital 01 | 0.88192 | 1.56675 | 1.20867 | 1.38733 | 1.76490 |
| Hospital 02 | 1.30038 | 1.34505 | 1.51944 | 1.52851 | 1.43044 |
| Hospital 03 | 0.91024 | 0.86888 | 0.79169 | 0.73644 | 0.77689 |
| Hospital 04 | 1.17460 | 1.18102 | 1.13866 | 1.26612 | 1.52498 |
| Hospital 05 | 1.10665 | 1.28658 | 1.39521 | 1.51649 | 1.44412 |
| Hospital 06 | 1.15630 | 1.38473 | 1.05529 | 1.06364 | 1.01610 |
| Hospital 07 | 1.13303 | 1.08264 | 1.03147 | 0.97250 | 0.89236 |
| Hospital 08 | 0.75249 | 1.18172 | 0.98156 | 0.97424 | 0.99995 |
| Hospital 09 | 1.15743 | 1.25314 | 1.28855 | 1.29912 | 1.27746 |
| Hospital 10 | 1.40415 | 0.82618 | 0.83137 | 0.91854 | 1.03197 |

As can be seen in Table (10), five hospitals including Hospital 02, Hospital 04, Hospital 05, Hospital 06, and Hospital 09 have progressed under all confidence levels. Also, with respect to the FMPI results, the productivity of Hospital 03 is decreased in 2014 in comparison to 2013.

Finally, according to the results of the implementation of the presented FMPI in the real-life case study, the main advantages of the current research can be summarized as follows: The proposed FMPI can measure the productivity changes of hospitals over time in a fuzzy environment. The presented FMPI is capable of being applied in the presence of linguistic variables. In this regard, it should be noted the discriminatory power of FMPI is more than classic MPI. Moreover, the proposed models are linear, and as a result, by employing the common optimization software packages, the global optimal solution can be easily achieved.

6. Conclusions and Future Research Directions

One of the main applications of data envelopment analysis is to be integrated with the Malmquist productivity index in order to calculate the process of changes in productivity of DMU over different time periods.³⁸ The goal of this paper is to provide the Malmquist productivity index in order to calculate the productivity changes of hospitals with the fuzzy data. To achieve this goal, the possibilistic programming approach is applied. Moreover, for solving and showing validation of the proposed FMPI, a real-life case study of hospitals in Tehran was used. For future studies, the network DEA approach could be employed for performance assessment of hospitals by considering internal structure and relations.^{39,40} Also, uncertain DEA models could be proposed based on robust optimization approach for performance measurement of hospitals under deep uncertainty.⁴¹⁻⁴⁵ Additionally, hybrid MCDM methods can be applied for performance assessment of hospitals.⁴⁶⁻⁴⁸

Abbreviations

MPI: Malmquist productivity index, **FMPI:** fuzzy Malmquist productivity index, **DEA:** data envelopment analysis, **DMU:** decision making unit, **CCR:** Charnes Cooper Rhodes, **BCC:** Banker Charnes Cooper, **SBM:** slack based measure, **SDEA:** stochastic data envelopment analysis, **FDEA:** fuzzy data envelopment analysis, **RDEA:** robust data envelopment analysis, **BDEA:** bootstrap data envelopment analysis, **SDEA:** interval data envelopment analysis, **MCDM:** multiple criteria decision making.

Competing Interests

The authors declare no competing interests.

Authors' Contributions

Pejman Peykani: Investigation, Conceptualization, Modelling, Data Preparation, Coding, Writing. **Fatemeh Sadat Seyed Esmaeili:** Conceptualization, Programming and Analyzing the Data, Writing. **Mohsen Rostamy-Malkhalifeh:** Supervision, Revision and Editing. **Farhad Hosseinzadeh Lotfi:** Supervision, Interpretation of the Results.

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