Int. J. Adv. Eng. Pure Sci. 2025, 37(3): <252-262>
DOI: 10.7240/jeps.1583402

**RESEARCH ARTICLE** / ARAŞTIRMA MAKALESİ

# Dynamic Network DEA Approach for Evaluating Hospital Performance in the Healthcare Sector

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**Abstract**
This study simultaneously evaluates the performance of Training and Research Hospitals in Turkey for 2018 and 2019 at both the overall and sub-unit levels. Traditional Data Envelopment Analysis (DEA) models treat decision-making units as a single process, often neglecting internal structures. To overcome this limitation, the study employs the Dynamic Network Data Envelopment Analysis (DN-DEA) approach, which incorporates two interrelated sub-units: administrative services and medical care services. This enables independent evaluation of sub-units, without disregarding their mutual connections. The results show that hospitals efficient in both sub-units are classified as fully efficient. However, some hospitals not on the overall efficiency frontier demonstrated full efficiency in specific sub-units. For instance, H12 and H33 were efficient in administrative services, while hospitals such as H14, H17, H21, and H23 attained efficiency only in medical services. In 2018, the budget account balance was identified as the most critical input requiring reduction (72.7%) for inefficient hospitals, followed by the number of resident physicians (50.7%). In 2019, the budget balance remained the top priority for reduction (62.1%), while the insufficient reduction in resident physicians caused the required adjustment to rise to 52.3%. In light of these findings, it is recommended that hospital performance management consider not only overall efficiency scores but also sub-unit-level analyses. Furthermore, the study emphasizes that improvements in budget management and human resource planning may play a critical role in enhancing hospital efficiency.
**Keywords:** Hospital efficiency, Network DEA, Dynamic and Network DEA, Slack-based measure

## I. INTRODUCTION

A decrease in hospital efficiency is observed worldwide [1,2,3].Correct and efficient uses of resources that will be used in health services play a critical role in determining the limit of health policies of states. The third strategic planning of the Republic of Turkey Ministry of Health, covering the period of 2019-2023, drew attention to this situation and stated that the objectives of the ministry are the provision of accessible, effective, efficient and high quality health services [29]. The share of education and research hospitals, which are tertiary care providers, in current has increased health expenditures significantly over the years [28]. In this context, examining the effectiveness of training and research hospitals is important for decision makers and health care policies. Evaluating hospital efficiency is a process that optimizes resource use and allocation [3]. Hospitals are organizations that have their own unique inputs, outputs and are made up of sub-units that are interconnected. To be able to continue their activities requires their sub-units to be organized with networks that enable them to connect with each other. This organization creates a network/network structure. Traditional data development analysis (DEA) methods, which see the hospital as a structure consisting of a single process that collects all inputs and transforms them into outputs, have been widely applied in the efficiency measurements of such structures [26].

The DEA approach is advantageous since this technique does not require any functional relationship between inputs and outputs [4]. On the other hand, traditional DEA models see the organization as a black box and neglect its internal structure. Not neglecting the internal dynamics of the organization allows us to get more accurate results [27].

In this study, it was considered that the two sub-units of the hospitals, which are the decision-making unit (DMU), perform service production with their activities. These subunits are; management unit and medical care unit. The output element of one of the units continues its activities in connection with each other as the input of the other. This structure creates a network system. In line with this information, the purpose of this paper is to simultaneously

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**Submitted:** 12.11.2024, **Revised:** 03.06.2025, **Accepted:** 21.07.2025

measure the total activity levels and period-sub-unit activities of Turkey training and research hospitals for the years 2018 and 2019, and to determine the efficiency change between years. In this context, Network DEA, which is suitable for the efficiency measurement of network systems, was used. In addition, the Dynamic Network DEA (DN-DEA) model was preferred to include the elements transferred from one period to the other in the analysis and to investigate the time-dependent efficiency change.

There are various international studies that have applied the DN-DEA model in the field of healthcare services. Kawaguchi et al. [6] examined the impact of healthcare reforms in municipal hospitals in Japan, focusing on treatment and administrative units. Lobo et al. [15] evaluated the efficiency of federal university hospitals in Brazil in terms of healthcare services, education, and research. Khushalani and Özcan [25] analyzed adult general hospitals in the United States based on medical and quality-related outputs. Considering the existing literature, this study appears to be among the first to apply the DN-DEA model to evaluate the efficiency of healthcare services in Turkey.

According to the results of the DN-DEA model analysis, not only are fully efficient and relatively inefficient hospitals identified, but the sources of inefficiency within specific service sub-units are also revealed. The remainder of the paper is organized as follows; section two mentions dynamic and network examples from studies using the DEA model are presented and the conceptual structure of the model is explained, and sample selection and data used for hospital efficiency measurement are presented. Section three results and finally, section four provides concluding remarks.

## II. METHOD AND DATA

### 2.1. Concept Dynamic and Network DEA Model

Farrell conducted one of the pioneering studies focus on measuring the efficiency of homogeneous entities known as Decision Making Units (DMUs) [5]. DEA is characterized as a data-oriented, non-parametric methodology grounded in linear programming, and has been extensively utilized to evaluate the technical efficiency of relatively homogeneous groups of DMUs. DMUs refer to comparable units that utilize identical resources (inputs) to generate similar products (outputs). A DMU is regarded as efficient if it generates a higher level of output with a constant amount of input (output-oriented) or achieves a given output using fewer inputs (input-oriented). Efficient DMUs define the best practice frontier that encompasses all units under comparison. A DMU is considered efficient if it reaches the Pareto-Koopmans optimum, where no output can be increased (or input reduced) without worsening another output or input [6].

The first DEA models were the CCR Model, proposed by Charnes, Cooper and Rhodes (1978). The CCR model is based on a production possibility frontier and assumes constant returns to scales, which implies a proportional relationship between the increases in inputs and the resulting increases outputs [7]. Alternatively, BCC (Banker, Charnes & Cooper) model was developed to analyze pure technical and scale efficiencies of DMUs by considering variable returns to scale. This assumption allows for non-proportional chances between inputs and outputs, which is especially useful when comparing units that differ significantly in size or output scale [4].

Any distance from the boundary (score less than "1" or 100%) is due to ineffectiveness, that is, the difference between current values and predicted values. By developing traditional DEA models, it can be used for network structures consisting of many subsystems and revealing intermediate products that can be used as inputs in a new process.

Network DEA consists of a family of DEA models that establish linear constraints on the size of each sub-activity of the system under study. In this way, it is possible to take into account the input and output elements of more than one dimension, the connection variables, and to measure the effectiveness separately for each dimension. Fare and Grosskopf [8], provided the theoretical groundwork for N-DEA models. Then, measurement methods suitable for the network structure of the system of interest were developed Löthgren and Tambour [9], Golany, Hackman, and Passy [10], Yu and Lee [11] Fukuyama and Weber [12], Kao and Hwang [13], Yu and Fan [14].

The models applied in the literature for network systems have generally not dealt with projections in the non-Pareto efficient regions of the frontier and estimates involving Pareto-efficiency target related slackness lead to efficiency prediction errors. Non-radial models determine efficiency based on Pareto-optimal targets, and among these, the SBM approach is particularly noteworthy [15]. The SBM approach was adopted by Tone and Tsutsi for efficiency measurement of network systems [27]. In addition, some studies have performed efficiency measurements for both the current and successive periods, taking into account the shift in the production frontier. These studies have also incorporated time-dependent variations into DEA models, thereby contributing to the development of dynamic efficiency analysis frameworks [16,12,17,18].

While the same outputs are produced by using the same inputs in each period in DMUs, some of the outputs in different systems can be processed as inputs in the following period. These variables that provide the inter-period connection are called carry over variables and can be used in fixed, desired, undesired, free options [15].

In this study, Dynamic Network Slack Based Measure (DN-SBM) model, which was proposed by Tone and Tsutsi (2014), to analyze dynamic efficiency in systems with a network structure [18]. While the model deals with the interconnection variables of each DMU and the individual activities of its connected sub-DMUs, it connects the successive periods of DMUs through transferring variables and allows us to see the time-dependent change dynamically on the horizontal. We can measure the total activities of the DMUs for the relevant period and the their sub-activities, which are sub-DMUs. We can also see the changes in total activities and sub-DMU activities during the studied period. Based on the model's findings, in the case of a DMU to be efficient, the efficiency score of all its sub-DMUs must be 1.0. If at least one sub-DMU has a value of less than 1.0, the efficiency of DMU decreases. In addition, the slack based model gives the projection values of the inefficient DMU and sub-DMUs that can be made on the inputs/outputs to reach the effective limit.

In the study, DN-SBM was preferred as input-oriented. Public hospitals serve with the aim of using the resources in the most effective and optimum way by considering the public interest. For this reason, a model was used to prevent waste of resources and reduce inputs. Since the resources and workforce sizes of the hospitals also vary, the variable return to scale model was preferred. Modelling was done using Python 3.8 programming for efficiency measurement with DN-DEA.

### 2.2. Data

In our study, the effectiveness of Turkey's training and research hospitals for the years 2018-2019 was examined. The data used for analysis were obtained through official procedures relevant from units within the Republic of Turkey Ministry of Health. Specifically, information regarding the number of on personnel was accessed from Ministry's General Directorate of Administrative Services, while financial data were accessed from the department of Financial Affairs. For DN-DEA, the hospitals within the scope of the study as DMU are 91 training and research hospitals. 59 of these hospitals are general hospitals and 32 of them are special branch training and research hospitals. In the DN-DEA application, the decision-making unit should be chosen in a homogeneous structure to avoid incomplete and misleading comments. Special branch training and research (cardiovascular hospitals, eye hospitals, gynecology hospitals, etc.) were excluded from the analysis, since the machinery, equipment and health personnel used by them are specific to the hospital in the relevant branch, so comparing them with general hospitals in efficiency measurement will not yield reliable results. The sample was taken from 59 training and research hospitals.

The Dynamic Network model structure of the hospital organization is shown in Figure 1. In our model, hospitals represented as DMU are designed as an organization consisting of two sub-segments; the medical care division and the administration division. The administration division provides funds to the medical care unit to provide treatment services and is responsible for all necessary resources (beds, health personnel, non-health personnel, medical equipment, etc.). The medical care division is also responsible for all medical services. It also generates revenue for the administration division.

The inputs of the administrative division consist of the number of "Number of non-health personnel" and "total expenditures". Number of non-health personnel is composed of the number of administrative personnel and maintenance personnel. Administrative personnel represent management activities, while maintenance personnel are responsible for maintaining the hospital infrastructure [22,23].

The input "total expenditures" refers to non-labor operating expenses. These expenses include medical supplies, medications, energy (electricity, water, heating), cleaning, maintenance and repair, and other administrative costs. Such expenditures are essential for the sustainability of hospital operations and play a direct role in the healthcare service production process [19,26,24].

The output of the administrative division is the hospital's "total income". This includes payments received from the Social Security Institution and income generated from the hospital's own investments. The reason total income is used as an output is that it is evaluated against expenses to represent financial efficiency [23].

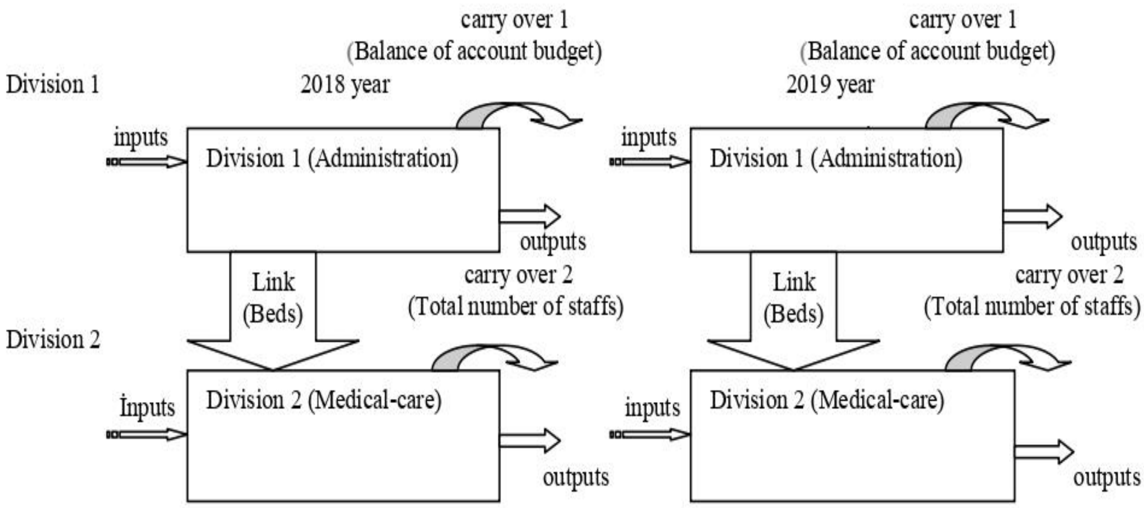


**Figure 1.** Structure of the Dynamic and network DEA model for hospital efficiency measurement

The number of beds was designated as a link variable from Division 1 to Division 2 (see Table 1). The management unit responsible for the financing and service continuity of hospital beds. The management unit supplies beds to the medical service unit, and the medical unit is responsible for providing medical services.

We defined the number of beds as a non-optional "fixed" connection state. The reason for this is that changes in the number of beds are rarely initiated by the medical unit in coordination with management; therefore, this was treated as a fixed connection situation [6].

The inputs of the medical care division include the number of doctors, medical residents (assistant physicians), general practitioners, nurses, and other healthcare staff. These inputs are considered important indicator of a hospital's capacity for patient admission and overall service delivery.

These staffing levels are typically measured in full-time equivalents, providing a comparable metric across different hospitals [22,30,31,32].

The outputs of the medical division are the total number of inpatients, outpatients, and intensive care beds. The number of inpatients is used to assess internal service production and resource utilization.

Outpatient visit indicate the extent and accessibility of ambulatory care services. In addition, the number of intensive care beds reflects the hospital's capacity to manage emergency cases [19,20,21,22].

The inputs, outputs, link variables, and carry-over variables used in the DN-DEA model for the management and medical care divisions of hospitals are presented in Table 1.

**Table 1.** Description of variables of DN-DEA model to hospitals Turkey, 2018-2019

| Division | | Variable | Observation | Units |
|---|---|---|---|---|
| Administration(Division 1) | Input | Number of non-health personnel | Total number of administrative officers, maintenance officers, workers | Person |
| | Input | Total expenditures | Personnel expenditures are not included in the total expenses. | Million TL |
| | Output | Total income | All incomes that the hospital receives from Social Security Enstitution and arise from its investments | Milion TL |
| Link(Div1→Div2) | | Number of beds | Total number of used active beds annually (including intensive care beds) | Unite |
| Carry over 1 | | Balance of account budget | It is the output of management division transferred from one year to the next. | Milion TL |
| Medical care(Division 2) | Input | Number of doctors | It is the number of specialist doctors working full-time in the hospital. | Person |
| | Input | Number of medical residents (assistant physician) | Number of doctors settled in hospitals to receive training after medical specialty exam, While medical residents continue their education, they also provide healthcare in the hospital. | Person |
| | Input | Number of general practitioners | Total number of newly graduated students who have not been trained in any specialty. | Person |
| | Input | Number of nurses | Considering the total workforce this variable has quantitatively important place in the care workforce. | Person |
| | Input | Number of other healthcare staff | These variable, in addition to doctors and nurses, it represents other health workers such as dentists, pharmacists and midwives in hospitals. | Person |
| | Output | Total number of inpatients | Annual total number of inpatients, reflects the intensity of medical care services. | Person |
| | Output | Number of outpatients | Total number of annual outpatient polyclinic visits | Person |
| | Output | Number of intensive care beds | It is the variable that indicates the hospital's capacity to provide care for emergency patients. | Unite |
| Carry over 2 | | Total number of staff | This variable transferred from the medical services division from one year to the next. | Person |

Two carry-over variables were defined that act as a connection from period 1 to period 2. The first is the Balance of account budget, which connects the inter-period activities of the management unit. Since the main task of the management is to ensure the income-expenditure balance, we have adopted this carry-over variable as an undesirable carry-over. Period 1 to period 2 is considered as input, and its redundancy is considered inefficiency [6].

The other transferred variable is the total number of personnel transferred from the medical services unit between periods. We defined this variable as the desired transfer. The number of personnel is determined as a result of the work of the management and is a resource that cannot be easily changed. It is treated as an output from one period to the next, and its insufficiency leads to inefficiency [18].

## III. RESULTS

Table 2 shows descriptive statistics of input, output, connection and carry-over variables in the DN DEA model for 2018 and 2019 training and research hospitals in Turkey. The results of the model regarding the measurement of total efficiency, period efficiency and division efficiency of hospitals (Table 3, Figure 2) and possible projections for inefficient hospitals to reach the effective limit are given in the following sections (Figure 3).

As seen in Table 2 regarding the labor force inputs of training and research hospitals, an increase is observed in the number of doctors, nurses and other health personnel from 2018 to 2019.

When we look at the average annual income and expenditure balance of hospitals, 2019 showed an increase in expenses (238.70-285.23) compared to the previous year, while the average annual income increased from year to year (230.08-282.70). While the budget balance variable resulted in an average of 11.80 million TL in 2018 due to the change in expenditure and income, an average of 16.37 million TL deviation was observed in the budget balance in 2019.

On the other hand, the average number of inpatients, which is one of the output elements of hospitals, declines slightly from year to year. On the other hand, an increase was observed in the average number of outpatients from 2018 to 2019. This situation can be interpreted that the increase in the number of personnel, which is the input source of the hospital administrations, has a positive effect on the outpatients. The output of the number of intensive care beds is also used to measure the capacity of hospitals to respond to their emergency patients, and from Table 2 it is seen that hospitals preferred to increase the number of intensive care beds from 2018 to 2019 (95.12-100.53)

Table 3 presents the DMU total efficiency and division efficiency scores of Turkey's training and research hospitals for the years 2018 and 2019, as calculated by the DN model. Based on the analysis results derived from the DN model, it is observed that the average total efficiency scores of the hospitals increased in 2019 (0.8545-0.9412) compared to the previous year. The efficiency of the administration division (0.8505-0.9514) and the efficiency of the medical care division (0.8585-0.9311) also increased in 2019 compared to the previous year. The increase in the average efficiency score in 2019 in the administration division is remarkable (0.8505-0.9514).

Figure 2 shows the total effectiveness, administration division and medical care division efficiency results of 59 training and research hospitals according to the DN model analysis results.

In the efficiency analysis, hospitals of different sizes were evaluated by comparing them with the best ones in service production. Large-scale and complex hospitals, consisting of hospitals with one thousand beds or more, yield efficiency with maximum output production. On the other hand, small hospitals with a small number of beds are efficient because their input resource consumption is low. These differences are important for the selection of benchmarks for ineffective hospitals and the identification of their counterparts [26].

In Figure 2, 10 hospitals are at the effective margin (100%). Five of these hospitals have a bed capacity of less than one thousand (H5, H6, H42, H53, H57). Among the efficient hospitals, the remaining five operate with a bed capacity exceeding one thousand (H13, H15, H18, H44, H59).

In addition, H12 and H33 hospitals, whose total effectiveness scores are not “1” (They are not included in the 100% efficiency frontier shown in figure 2.) are fully efficient only in the administration division. On the other hand, hospitals such as H14, H17, H21, H23, H24, H25, H29, H31, H32, H35, H37, H38, H40, H45, H50, H52, H54 and H55 (although their total effectiveness scores are not “1”) are only in the efficiency frontier in the medical care division. In figure 3, the average values of the possible improvements in the input elements are given for the ineffective hospitals to reach the effective limit.

**Table 2.** Description variables of the dynamic network DEA model applied to hospitals Turkey, 2018-2019

| Year | Measure | Administration Division | | | A/C Link | Carry over A | Care Division | | | | | | | | Carry over C |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Non-health personnel (I) | Total expense (I) (million TL) | Total income (O) (million TL) | Number of beds | Balance of account budget (million TL) | Doctors (I) | Assistant physicians (I) | General practitioners (I) | Nurses (I) | Other health care staff (I) | Total number of inpts (O) (per 1000) | Total number of outpts (O) (per 1000) | Intensive care beds (O) | Total number of staff |
| 2018 | Mean | 931.86 | 238,70 | 230,08 | 721.27 | 11,80 | 286.36 | 136.36 | 32.92 | 609.08 | 456.10 | 40,42 | 1784,67 | 95.12 | 2442.31 |
| | Maximum | 1843.00 | 440,84 | 410,36 | 1660.00 | 59,49 | 556.00 | 467.00 | 161.00 | 1205.00 | 1096.00 | 83,75 | 3319,89 | 253.00 | 4082.00 |
| | Minimum | 344.00 | 88,49 | 88,59 | 260.00 | 0,10 | 73.00 | 0.00 | 1.00 | 209.00 | 173.00 | 16,44 | 349,17 | 27.00 | 1047.00 |
| | Sd. | 377.00 | 97,23 | 92,33 | 327.93 | 10,32 | 119.57 | 133.34 | 24.49 | 234.72 | 195.96 | 16,10 | 695,96 | 45.56 | 888.15 |
| 2019 | Mean | 970.90 | 285,23 | 282,70 | 730.63 | 16,37 | 290.39 | 150.90 | 37.61 | 617.20 | 467.03 | 40,27 | 1818,32 | 100.53 | 2526.03 |
| | Maximum | 2658.00 | 562,88 | 555,67 | 1660.00 | 138,66 | 573.00 | 532.00 | 200.00 | 1372.00 | 1132.00 | 89,87 | 3197,09 | 263.00 | 4373.00 |
| | Minimum | 332.00 | 52,05 | 106,19 | 260.00 | 1,30 | 73.00 | 0.00 | 1.00 | 216.00 | 177.00 | 1,68 | 33,70 | 27.00 | 1034.00 |
| | Sd. | 461.87 | 126,67 | 119,88 | 332.01 | 21,86 | 122.28 | 145.96 | 33.94 | 246.38 | 214.27 | 18,68 | 793,46 | 48.67 | 963.65 |

*Source*: Descriptive statistics of the data obtained from the Ministry of Health of the Republic of Turkey are calculated and presented.
I: input variable; O: output variable; inpts: inpatients; outpts: outpatients; A/C Link: the output of the administration division is the input for the care division; TL: Turkısh Lira.

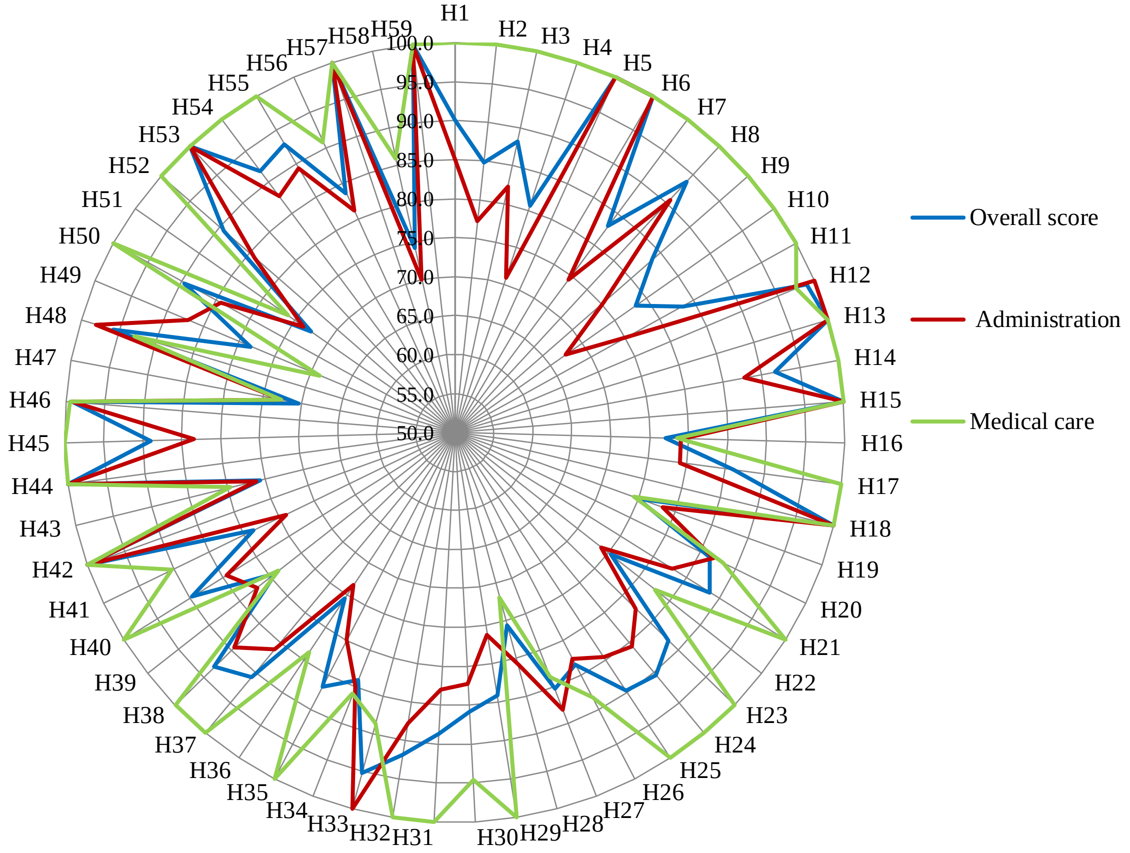


**Figure 2.** Efficiency scores of teaching-research hospitals dynamic network DEA, Turkey. 2018- 2019

In 2018, the most striking input that ineffective hospitals should reduce in order to reach the effective limit is the budget account balance (72.7%). In addition, it was observed that the number of assistant physicians should be reduced (50.7%). Similar results were seen in 2019. The budget account balance should have been reduced (62.1%). Compared to 2018, a more negative picture is observed in the number of assistant physicians in 2019. This ratio increased even more (52.3%) by not making the necessary reduction. The average improvement rates that can be made in other inputs of the hospitals to reach the effective limit are also seen in Figure 3 and interpreted in the same way.

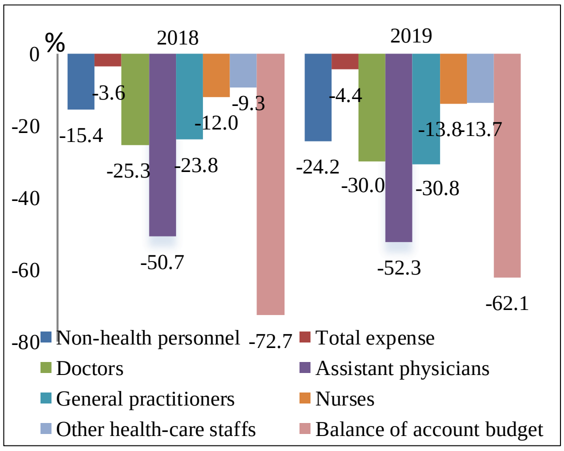


**Figure 3.**Variation need of input (I) and carry-over variable to reach best practice frontier. Turkey, 2018-2019

**Table 3.**Efficiency scores of hospitals Turkey, 2018-2019

| Dynamic-Network DEA model | | | |
|---|---|---|---|
| DMU | | 2018 | 2019 |
| Overall efficiency score | Average | 0,8545 | 0,9412 |
| | Sd. | 0,0956 | 0,0922 |
| | Minimum | 0,6743 | 0,6880 |
| | Maximum | 1 | 1 |
| Division 1 (Administration) | Average | 0,8505 | 0,9514 |
| | Sd. | 0,1184 | 0,1028 |
| | Minimum | 0,6623 | 0,5734 |
| | Maximum | 1 | 1 |
| Division 2 (Medical care) | Average | 0,8585 | 0,9311 |
| | Sd. | 0,1204 | 0,1086 |
| | Minimum | 0,6248 | 0,7140 |
| | Maximum | 1 | 1 |

## IV. CONCLUSION

In this study, we present the application of a novel method for evaluating hospital efficiency using Data Envelopment Analysis (DEA). Our study is the first study in which the Dynamic Network DEA approach has been applied for efficiency studies of hospitals serving in Turkey. Previous studies have been applied to hospitals in Japan, America, and Brazil [6],[15],[25]. In our study, hospitals were conceived as organizations consisting of two sub-units as management and medical care units. . The findings indicated an improvement in the overall average efficiency of the hospitals significantly in 2019 compared to 2018. The most noticeable improvement from year to year was seen in the average efficiency increase of the management unit.

The DN-DEA model applied in this study not only identifies the overall efficiency levels of hospitals but also reveals which specific sub-units are the sources of inefficiency. The results indicate that hospitals achieving efficiency across all sub-units are considered fully efficient; however, some hospitals that are not deemed efficient overall can still demonstrate full efficiency in certain sub-units. This highlights a key contribution of the model, as it allows hospital managers to focus not only on overall performance but also on unit-level improvements.

The findings of the study indicate that all input resources increased over the years and that the gap between actual and projected values slightly widened from 2018 to 2019. Although this may initially suggest a negative outlook, the observed improvement in average efficiency in 2019 is attributed to a shift in the production frontier.

The DN-DEA model applied in the study not only assesses hospitals' overall efficiency but also provides a detailed evaluation of performance at the sub-unit level. A key contribution of the model is that a hospital is not considered fully efficient unless all of its sub-units operate efficiently. This enables hospital managers to identify the specific service areas responsible for inefficiency and to set more targeted improvement priorities. Moreover, the model generates projections for input, link, and intermediate variables, offering decision support particularly for resource-constrained hospitals by indicating which parameters need improvement and to what extent. The DN-DEA approach accounts not only for current efficiency levels but also for the resources used, scale structures, and time-dependent changes among peer hospitals, thus providing more tailored and actionable planning insights. In this respect, the model offers healthcare managers and policymakers the opportunity to go beyond aggregate performance metrics and to focus on specific sub-units in developing evidence-based strategies.

Thanks to the methodological scope and multi-layered analytical capacity of the DN-DEA model, it becomes possible to evaluate both overall hospital efficiency and sub-unit performance simultaneously. However, future research can expand the scope of the model to generate additional insights. For instance, in the case of training and research hospitals — which are the focus of this study — a network-based model that incorporates the education and research dimensions could be constructed, allowing for the separate assessment of their impact on overall and sub-unit efficiency. In studies focusing on general public hospitals, sub-unit analysis can be further detailed by disaggregating medical services into surgical units (e.g., general surgery, orthopedics) and clinical departments (e.g., cardiology, dermatology), enabling a more granular measurement of efficiency.

Moreover, rather than focusing solely on internal hospital operations, future studies could explore broader system-level efficiency by constructing network structures that include interactions between hospitals, the Social Security Institution, pharmacies, and other healthcare providers. Additionally, since the DN-DEA model incorporates both the temporal dimension and inter-unit linkages within its structure, it internally accounts for inter-period changes, eliminating the need for separate calculation of the Malmquist index. Nevertheless, comparative studies between the results of the DN-DEA model and Malmquist-based efficiency analyses in future research may offer valuable methodological insights.

## ACKNOWLEDGMENT

This study is an expanded version of the paper presented actively at the "V. International Applied Statistics Congress (UYIK-2024)" held in Istanbul /Türkiye on May 21-23, 2024.

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