



A new network data envelopment analysis models to measure the efficiency of natural gas supply chain

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Abstract

Natural-gas supply chain network (NGSCN) includes production, transmission, and distribution stages, numerous types of exogenous and undesirable inputs, intermediate products, and outputs. These lead to a complicated structure for NGSCN. Measurement of efficiency of NGSCN is essential and important. In this paper, network data envelopment analysis model is developed to measure the efficiency of the natural-gas supply chain in Iran. The main properties of the proposed model, i.e., feasibility and bound of the objective function, are discussed through several theorems. The proposed model is used to measure the efficiency of a gas supply chain and the associated efficiency of all elements in the chain during a 5-year planning horizon incorporating real monthly operational data. The results illustrate the total efficiency score of the NGSCN and the efficiency and inefficiency of the production, transmission, and distribution stages. The proposed model of this study can be customized and applied in other energy supply chains such as water, oil, electricity, and wind.

Keywords Measuring efficiency · Natural gas supply chain efficiency · Gas production–transmission–distribution efficiency · Network data envelopment analysis

1 Introduction

Natural gas supply chain network is one of the most important infrastructures which is responsible for the production, transmission, and distribution of gas to the domestic, industrial, and commercial sectors and power plants in Iran. In the

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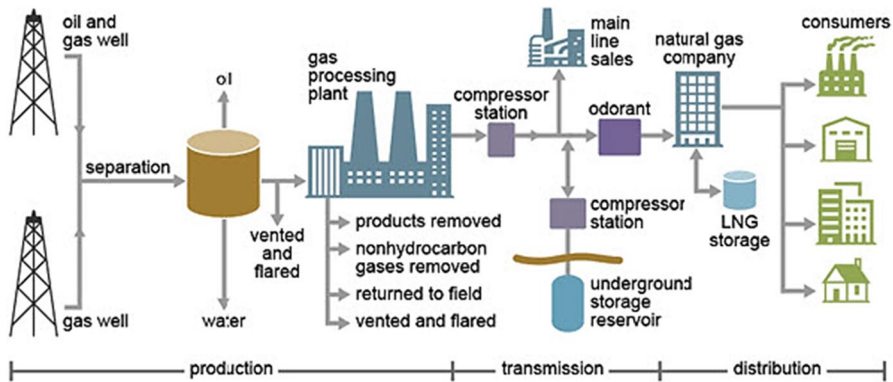


Fig. 1 Schematic view of a sample natural gas supply chain. Adapted from US Energy Information Administration (https://www.eia.gov/energyexplained/index.cfm?page=natural_gas_delivery)

production process, there are complex processing units which have been designed to clean raw natural gas by separation impurities and non-methane hydrocarbons to produce pipeline quality dry natural gas. Natural gas processing plants purify raw natural gas by removing common contaminants such as water, carbon dioxide, and hydrogen sulfide. Some of the substances have economic value and are further processed and some of them are undesirable. The movement of natural gas from producing regions to consumption regions requires a transmission system. The transmission system for natural gas consists of a complex network of pipelines, designed to transport natural gas from its origin, to demand areas of natural gas. Transmission pipelines with large-diameter distribution pipe carry natural gas across province boundaries. Distribution is the final step in delivering natural gas to customers. The most of users such as households and businesses receive natural gas from their local distribution company through small-diameter distribution pipe.

The complicated relations between production, transmission and distribution companies and several types of inputs and outputs (desirable and undesirable) of natural-gas supply chain form a complicated network structure. Thus the capability of assessing the overall efficiency of natural gas supply chain in presence of internal relations, undesirable outputs, and extra input and also determining the efficient and inefficient processes and sub-processes can be useful for improving the efficacy of natural-gas industry.

In this paper, a network structure is proposed to model the natural-gas supply chain network. Figure 1 shows the schematic view of the natural-gas supply chain.

In the proposed model, each decision making unit (DMU) has been formed on the basis of three serially connected sub-DMUs (i.e., production stage, transmission stage, and distribution stage). Extra inputs in the second stage, final products of the first stage, and undesirable outputs of the first stage have also been considered. The production stage includes eight parallel components as refinery companies. So, the efficiency of production stage can be decomposed into the efficiency of refinery companies. Ten transmission zones are considered in the transmission stage. These

transmission zones are connected to each other and make a complicated network structure.

The proposed structure is modeled on the basis of real process in the natural-gas supply chain network of Iran. The main purpose of this study is to calculate the relative efficiency of all three stages including production, transmission, and distribution stages as well as the efficiency of components and sub-processes in the natural-gas supply chain network during a 5-year planning horizon incorporating real monthly operational data.

The main contribution of this paper can be summarized as follows. A linear mathematical programming network data envelopment analysis (NDEA) model is proposed to measure the efficiency of the natural-gas supply chain network. The proposed NDEA model can easily be implemented and solved using Operations Research (OR) software to achieve global optimum efficiency scores. The generality of the proposed NDEA model, i.e., feasibility and bound of the objective function, is proved. A real case study of a natural-gas supply chain including production, transmission, and distribution stages is analyzed using the proposed NDEA model. The total efficiency score of the natural-gas supply chain is decomposed into efficiency scores of production, transmission, and distribution stages using the proposed NDEA model.

The next sections of the paper are organized as follows. In Sect. 2, the network structure is introduced and a network DEA model is developed. The main properties of the proposed network DEA model including feasibility situation and bound of the objective function are discussed. In Sect. 3, the real case study of Iranian natural gas network is introduced and then the proposed network DEA model is applied on a real case study to demonstrate the efficacy of the production, transmission and distribution stages and all components. In Sect. 4, the conclusions and future research directions are presented.

2 Literature review

One of the main techniques for efficiency measurement is data envelopment analysis (DEA). DEA is a technique on the basis of the linear mathematical programming in order to measure the performance of similar DMUs with several inputs and outputs (Charnes et al. 1978). NDEA is a type of DEA model in which internal relations of sub-DMUs are considered and modeled. In this paper, NDEA is used to measure the efficiency of the natural-gas supply chain. The natural-gas supply chain includes complicated relations between production, transmission and distribution stages. Thus in this section, a brief review of past research works on DEA is discussed. The main focus of literature review is on some recent research works in the field of the network structure in DEA models, and some practical issues of DEA models especially in the petroleum industry.

The standard DEA models were developed to measure the efficiency of a DMU without considering its internal structure, while in real cases internal processes and sub-processes should be considered. The network DEA, on the other hand, refers to multi-stage processes, which internal structures play a key role in the efficiency

assessment (Chen and Zhu 2004; Kao and Hwang 2008; Liang et al. 2008, 2011; Chen et al. 2009a, b; Cook et al. 2010).

2.1 Network DEA models with series/parallel structure

The simplest form of internal structure is series systems. The series structure refers to some of the processes connected serially (Kao 2009a). Another basic structure for extending network systems is the parallel structure with independent components. Kao (2009b) proposed a relational model to measure the efficiency of parallel systems when the total efficiency of the system is equal to the weighted average of the efficiency of its components. Kao and Lin (2011, 2012) extend the parallel relational model for qualitative and fuzzy parameters, respectively.

Seiford and Zhu (1999) measured the performance of commercial banks using a two-stage DEA model. Ebrahimnejad et al. (2014) measured the efficiency of bank industry in a three-stage system considering two independent parallel stages linking to a third final stage in series. Lewis and Sexton (2004) used a two-stage DEA model to measure the performance of the Major Baseball League. Chen et al. (2009a) applied a DEA-based distance measure model to measure the efficiency two-stage process and to find the projection of the intermediate products. Kao and Hwang (2008) proposed a model to measure the efficiency of 24 non-life insurance companies. The overall efficiency was the product of the two serially connected sub-processes. Kao and Hwang (2008) proposed two different models to optimize the maximum achievable efficiency of each sub-process. Liu (2011) developed a model on the basis of the Big-M method to combine the models proposed by Kao and Hwang (2008). Chen et al. (2009) proved that under constant returns to scale, the proposed model by Kao and Hwang (2008) is equivalent to the model proposed by Liu (2011). Liu and Wang (2009) applied the proposed model by Kao and Hwang (2008) to measure the production and profitability performance of printed circuit board manufacturing firms. Cao and Yang (2011) used the proposed model by Kao and Hwang (2008) to measure the marketability and profitability of internet companies.

Khalili-Damghani and Taghavifard (2012) proposed a three-stage DEA model to calculate interval DEA efficiency scores of JIT practices, different levels of agility indices, and goals of supply chains under fuzzy situations. The proposed approach was applied in a real case study including 40 dairy supply chains. The efficiency score of each stage and the overall efficiency score of the supply chain were calculated and discussed for each DMU. Khalili-Damghani et al. (2012a, b) presented a fuzzy two-stage DEA model for performance assessment of providers of agility, capabilities of agility, and goals of the supply chain. Kao (2014a, b) proposed an ordinal two-stage DEA approach to assess the agility performance in dairy supply chains in Iran. They applied the proposed approach in a real case study wherein the capability and efficacy of the models were demonstrated. Khalili-Damghani et al. (2015) considered a three-stage process based on customer expectation, customer satisfaction, and customer loyalty to assess the performance of banking customer services in IRAN. To this end, they developed a hybrid procedure including Multi-Criteria Satisfaction Analysis (MUSA) and three-stage DEA.

Khalili-Damghani and Taghavifard (2013) developed a sensitivity and stability analysis approach for the two-stage DEA models in fuzzy environment. They represented a procedure to specify a radius of stability for each DMU. On the other hand, they developed a procedure to determine the range of variation in inputs and outputs of fuzzy two-stage DEA model by which the situation of a DMU was not changed in comparison with other DMUs. Tavana and Khalili-Damghani (2014) considered two-stage processes with uncertain inputs and outputs. In order to measure the efficiency scores of a DMU and its sub-DMU, they employed the Stackelberg (leader–follower) game. In the leader–follower assumption, they optimized the maximum achievable efficiency score of the leader stage. Then, the maximum achievable efficiency score of the follower stage was determined considering the maximum achievable efficiency score of the leader stage.

2.2 Extra inputs, intermediates and outputs in network DEA models

Series structures can be extended toward network structure by adding extra inputs, intermediate, and outputs. On the other hand, real network structures are formed based on several series and parallel structures while they cannot be decomposed into the pure series or parallel structure. Golany et al. (2006) proposed models to measure the efficiency of a two-stage system with shared inputs. Chiu et al. (2011) extended the pure two-stage system to a system with exogenous inputs in second sub-process. Kao and Hwang (2010) presented the model with shared inputs in the second sub-process. Khalili-Damghani and Shahmir (2015) developed a two-stage DEA model with undesirable outputs and exogenous inputs in electricity networks including production and distribution phases. Maghbouli et al. (2014) considered a two-stage DEA model with undesirable products. Maghbouli et al. (2014) developed two different cases of undesirable measure: either as final outputs or as intermediate measures. Tavana et al. (2016) proposed two-stage DEA model for calculating the overall efficiency of a multi-level supply chain in a way that the efficiency score of the whole process reflects the efficiency values of all the lower-level sub-chains. Khodakarami et al. (2015) developed a two-stage DEA model for evaluating supply chain such that suggestions for improvements and the objective function of efficiency are based on the input, output and intermediate measures simultaneously.

2.3 Complicated and customized network DEA models

Although the pure serial and parallel structures were developed and applied in different researches, these structures cannot model complicated real-life networks. So generalization of such structures is interesting. This will lead to complicated and customized network structures which can model internal sub-processes, multi-directional relations, and high interactive connections.

Kao (2009a) proposed NDEA model to measure the total efficiency of network and efficiencies of sub-process simultaneously. Kao (2009b) developed another NDEA model to identify the efficiency of the system and all stages at the same time where exogenous inputs and intermediate outputs were considered in the general

network. Kazemi Matin and Azizi (2015) developed a general model for assessing the efficiency of production systems, in which there are a variety of relationships between the production sub-processes. Boloori et al. (2016) proposed equivalent multiplier and envelopment DEA models for the efficiency of the new general network which inputs, outputs, and intermediates share between sub-process and also inputs, outputs, and intermediates could be simultaneous at all three positions.

Khalili-Damghani and Tavana (2013) proposed a new fuzzy network DEA model for measuring the performance of agility in supply chains. The proposed fuzzy NDEA model was linear and independent of the α -cut variables. The proposed model was used to measure the performance of agility in a real-life case study in the dairy industry. They calculated the overall efficiency score of the supply chain and the efficiency score of sub-processes and stages. The total efficiency score of the supply chain was decomposed into efficiency scores of sourcing, making, and delivery processes. Chodakowska and Nazarko (2018) proposed network DEA models to measure the efficiency of Couriers and Messengers. Badiezhadeh et al. (2018) proposed a network DEA model to measure the sustainability of supply chains. They used the proposed network DEA model to measure the performance of sustainable supply chain management (SSCM) in presence of Big Data considering optimistic and pessimistic efficiency. Iftikhar et al. (2018) proposed network DEA model under free disposability assumption for all undesirable outputs to measure energy and CO₂ emissions efficiency of major economies like China and US. Chao et al. (2018) proposed a dynamic network data envelopment analysis (DNDEA) to decompose the efficiency of the shipping service production for a container shipping company (CSC) into two processes. The efficiency of 13 major global CSCs was empirically evaluated. The scores for company efficiency and division efficiency of each CSC were measured.

3 Network DEA model for measuring the efficiency of natural gas supply chain

Conventional DEA model does not take into account the internal structure and sub-processes of the DMUs. So, the efficiency score of a DMU cannot be decomposed into efficiency scores of its sub-processes. In this section, network DEA model is proposed for the real case of natural gas supply chain network. The models are proposed in presence of undesirable outputs, intermediate final products, and additional inputs. The models are developed to measure the relative efficiency of the natural-gas supply chain including production, transmission, and distribution stages.

In the proposed NDEA model, the efficiency is calculated for a network with three serially connected sub-processes including production, transmission, and distribution stages. The extra inputs, intermediate final products, and undesirable outputs are also taken into accounts. Eight parallel components in the production stage as refinery companies are also considered. Complicated network interconnections among refineries and transmission zones are considered to model the real case of natural gas supply chain network. Formally, the main measurement tool in this paper is network DEA modeling which is used to measure the efficiency score of the

natural-gas supply chain and its associated stages including production, transmission, and distribution stages. The details of the proposed structure, modeling and the properties of the model are discussed in the following sections.

3.1 Proposed network DEA model

In real cases, networks are not restricted to contain just a series or parallel structure, so the general network process which depicted in Fig. 2 will be studied in this section. This network is quite associated with the real processes in the natural-gas supply chain. The network structure contains three stage series process which is composed of parallel components in first stage and complicated internal connections in second stage.

This structure for J decision making unit has L parallel components in the first stage and N mixed components in the second stage, where each $sub-DMU_{1-l}$ ($l = 1, \dots, L$) in the first stage converts I inputs x_{ij} ($i = 1, \dots, I$) to B undesirable outputs z'_{blj} ($b = 1, \dots, B$), A desirable outputs z''_{alj} ($a = 1, \dots, A$), and P intermediate measure $z_{p\ln j}$ ($p = 1, \dots, P$). The intermediate measures are transferred from $sub-DMU_{1-l}$ to $sub-DMU_{2-n}$. The sum of all inputs x_{ij} over l and outputs z'_{blj} , z''_{alj} over l and intermediate measures $z_{p\ln j}$ over l and n are equal to the inputs x_{ij} , outputs z'_{blj} , z''_{alj} , and intermediated measures z_{pj} of $sub-DMU_1$, respectively.

Each $sub-DMU_{2-n}$ in the second stage uses P inputs $z_{p\ln j}$ ($p = 1, \dots, P$) and E extra inputs w''_{enj} ($e = 1, \dots, E$) to produce D desirable outputs w'_{dnj} ($d = 1, \dots, D$) that exit the system and F intermediated measures w_{fnj} ($f = 1, \dots, F$) that are transferred to next stage. The internal input $gt_{n'nj}$ is received from nearby $sub-DMU_{2-n'}$.

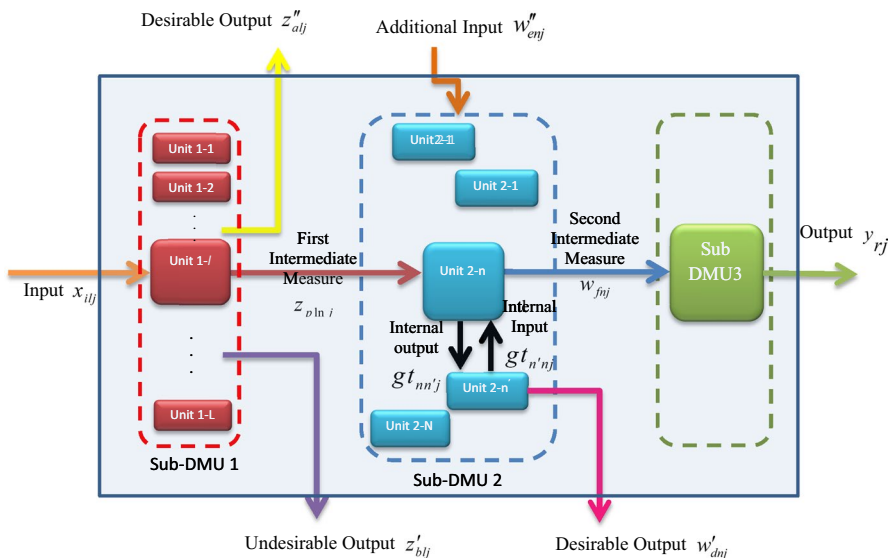


Fig. 2 Network model

The internal output $gt_{nm'j}$ is delivered to nearby $sub-DMU_{2-n'}$. These internal inputs/ outputs do not exit the sub- DMU_2 . The sub- DMU_3 produces R final outputs y_{rj} ($r = 1, \dots, R$) while consuming the intermediate measures w_{fj} ($f = 1, \dots, F$). The intermediate measures w_{fj} ($f = 1, \dots, F$) are equal to the sum of all second intermediate measures w_{fnj} over n . Table 1 represents the sets, indices, parameters, and decision variables used in proposed NDEA model.

Model (1) is proposed to calculate the total relative efficiency of the network structure depicted in Fig. 2.

$$\begin{aligned}
 \max e_o &= \frac{\sum_{r=1}^R u'_r y_{ro} + \sum_{d=1}^D \sum_{n=1}^N g'_{dn} w'_{dno} + \sum_{a=1}^A \sum_{l=1}^L k'_{al} z'_{alo}}{\sum_{i=1}^I \sum_{l=1}^L v'_{il} x_{ilo} + \sum_{b=1}^B \sum_{l=1}^L q'_{bl} z'_{blo} + \sum_{e=1}^E \sum_{n=1}^N h'_{en} w'_{eno}} \\
 s.t. & \\
 & \frac{\sum_{r=1}^R u'_r y_{rj} + \sum_{d=1}^D \sum_{n=1}^N g'_{dn} w'_{dnj} + \sum_{a=1}^A \sum_{l=1}^L k'_{al} z'_{alj}}{\sum_{i=1}^I \sum_{l=1}^L v'_{il} x_{ilj} + \sum_{b=1}^B \sum_{l=1}^L q'_{bl} z'_{blj} + \sum_{e=1}^E \sum_{n=1}^N h'_{en} w'_{enj}} \leq 1, \quad j = 1, \dots, J \\
 & \frac{\sum_{a=1}^A \sum_{l=1}^L k'_{al} z'_{alj} + \sum_{p=1}^P \sum_{l=1}^L \sum_{n=1}^N m'_{pln} z'_{plnj}}{\sum_{i=1}^I \sum_{l=1}^L v'_{il} x_{ilj} + \sum_{b=1}^B \sum_{l=1}^L q'_{bl} z'_{blj}} \leq 1, \quad j = 1, \dots, J \\
 & \frac{\sum_{f=1}^F \sum_{n=1}^N s'_{fn} w'_{fnj} + \sum_{d=1}^D \sum_{n=1}^N g'_{dn} w'_{dnj}}{\sum_{p=1}^P \sum_{l=1}^L \sum_{n=1}^N m'_{pln} z'_{plnj} + \sum_{e=1}^E \sum_{n=1}^N h'_{en} w'_{enj}} \leq 1, \quad j = 1, \dots, J \\
 & \frac{\sum_{r=1}^R u'_r y_{rj}}{\sum_{f=1}^F \sum_{n=1}^N s'_{fn} w'_{fnj}} \leq 1, \quad j = 1, \dots, J \\
 & \frac{\sum_{a=1}^A k'_{al} z'_{alj} + \sum_{p=1}^P \sum_{n=1}^N m'_{pln} z'_{plnj}}{\sum_{i=1}^I v'_{il} x_{ilj} + \sum_{b=1}^B q'_{bl} z'_{blj}} \leq 1, \quad j = 1, \dots, J; l = 1, \dots, L \\
 & \frac{\sum_{f=1}^F s'_{fn} w'_{fnj} + \sum_{d=1}^D g'_{dn} w'_{dnj} + \sum_{n'=1}^N c'_{n'n} g'_{n'n} t'_{n'n} j}{\sum_{p=1}^P \sum_{l=1}^L m'_{pln} z'_{plnj} + \sum_{e=1}^E h'_{en} w'_{enj} + \sum_{n'=1}^N c'_{n'n} g'_{n'n} t'_{n'n} j} \leq 1, \quad j = 1, \dots, J; n = 1, \dots, N \\
 & v'_{il}, k'_{al}, q'_{bl} \geq \epsilon, \quad i = 1, \dots, I; l = 1, \dots, L; a = 1, \dots, A; b = 1, \dots, B \\
 & s'_{fn}, h'_{en}, g'_{dn}, m'_{pln} \geq \epsilon, \quad f = 1, \dots, F; n = 1, \dots, N; e = 1, \dots, E; d = 1, \dots, D; p = 1, \dots, P; l = 1, \dots, L \\
 & u'_r \geq \epsilon, \quad r = 1, \dots, R \\
 & c'_{n'n}, c'_{n'n} \geq \epsilon, \quad n = 1, \dots, N; n' = 1, \dots, N
 \end{aligned} \tag{1}$$

Model (1) is an input-oriens fractional network DEA model considering the constant return to scale (CRS) assumption in multiplier form. Model (1) is nonlinear mathematical programming, so its global optimum solution is hard to find. Due to variable exchanges for the transformation of fractional mathematical programming (Bisschop 2012), Model (1) is changed into linear programming Model (2).

Table 1 Sets, indices, parameters, and decision variables

Sets	Description	
j	Index of DMU	$j = 1, \dots, J$
i	Index of input of sub-DMU 1	$i = 1, \dots, I$
p	Index of output of sub-DMU 1; index of input of sub-DMU 2	$p = 1, \dots, P$
a	Index of the desirable outputs of sub-DMU 1	$a = 1, \dots, A$
b	Index of undesirable output of sub-DMU 1	$b = 1, \dots, B$
f	Index of output of sub-DMU 2; index of input of sub-DMU 3	$f = 1, \dots, F$
d	Index of desirable output of sub-DMU 2	$d = 1, \dots, D$
e	Index of additional input of sub-DMU 2	$e = 1, \dots, E$
r	Index of output of sub-DMU 3	$r = 1, \dots, R$
l	Index of units of sub-DMU 1	$l = 1, \dots, L$
n, n'	Index of units of sub-DMU 2	$n, n' = 1, \dots, N$
Parameters	Description	
x_{ij}	The value of i th input of l th unit within sub-DMU 1 of DMU j	
$z_{p\ln j}$	The value of p th output from l th unit within sub-DMU 1 to n th unit of sub-DMU 2 of DMU j	
z'_{aj}	The value of the a th desirable output of l th unit within sub-DMU 1 of DMU j	
z'_{bj}	The value of the b th undesirable output of l th unit within sub-DMU 1 of DMU j	
w_{fnj}	The value of the f th output of n th unit within sub-DMU 2 of DMU j	
w'_{dnj}	The value of the d th desirable output of n th unit within sub-DMU 2 of DMU j	
w''_{enj}	The value of the e th additional input of n th unit within sub-DMU 2 of DMU j	
y_{rj}	The value of the r th output of sub-DMU 3 of DMU j	
$gt_{nn'j}$	The value of internal input/output that is received from n th unit and delivered to n' th unit within sub-DMU2 of DMU j	
Decision variables	Description	
e_j	The efficiency of overall process of DMU j	
$e_j^{(1)}$	The efficiency of sub-DMU 1 of DMU j	
$e_j^{(2)}$	The efficiency of sub-DMU 2 of DMU j	
$e_j^{(3)}$	The efficiency of sub-DMU 3 of DMU j	
$e_j^{(1,l)}$	The efficiency of l th unit within sub-DMU 1 of DMU j	
$e_j^{(2,n)}$	The efficiency of n th unit within sub-DMU 2 of DMU j	
v_{il}, v'_{il}	The multiplier of the i th input of l th unit within sub-DMU 1	
$m_{p\ln}, m'_{p\ln}$	The multiplier of the p th output from l th unit within sub-DMU 1 to n th unit of sub-DMU 2	
k_{al}, k'_{al}	The multiplier of the a th desirable output of l th unit within sub-DMU 1	
q_{bl}, q'_{bl}	The multiplier of the b th undesirable output of l th unit within sub-DMU 1	
s_{fn}, s'_{fn}	The multiplier of the f th output of n th unit within sub-DMU 2; the multiplier of the f th input of sub-DMU 3	
g_{dn}, g'_{dn}	The multiplier of the d th desirable output of n th unit within sub-DMU 2	
h_{en}, h'_{en}	The multiplier of the e th additional input of n th unit within sub-DMU 2	
$c_{nn'}, c'_{nn'}$	The multiplier of internal input/output within sub-DMU 2	
u_r, u'_r	The multiplier of the r th output of sub-DMU 3	

$$\begin{aligned}
 \max e_o &= \sum_{r=1}^R u_r y_{ro} + \sum_{d=1}^D \sum_{n=1}^N g_{dn} W'_{dno} + \sum_{a=1}^A \sum_{l=1}^L k_{al} z''_{alo} \\
 \text{s.t.} \\
 &\sum_{r=1}^R u_r y_{rj} + \sum_{d=1}^D \sum_{n=1}^N g_{dn} W'_{dnj} + \sum_{a=1}^A \sum_{l=1}^L k_{al} z''_{alj} - \sum_{i=1}^I \sum_{l=1}^L v_{il} x_{ilj} \\
 &- \sum_{b=1}^B \sum_{l=1}^L q_{bl} z'_{blj} - \sum_{e=1}^E \sum_{n=1}^N h_{en} W''_{enj} \leq 0, \quad j = 1, \dots, J \\
 &\sum_{a=1}^A \sum_{l=1}^L k_{al} z''_{alj} + \sum_{p=1}^P \sum_{l=1}^L \sum_{n=1}^N m_p \ln z_p \ln j - \sum_{i=1}^I \sum_{l=1}^L v_{il} x_{ilj} - \sum_{b=1}^B \sum_{l=1}^L q_{bl} z'_{blj} \leq 0, \quad j = 1, \dots, J \\
 &\sum_{f=1}^F \sum_{n=1}^N s_{fn} W_{fnj} + \sum_{d=1}^D \sum_{n=1}^N g_{dn} W'_{dnj} \\
 &- \sum_{p=1}^P \sum_{l=1}^L \sum_{n=1}^N m_p \ln z_p \ln j - \sum_{e=1}^E \sum_{n=1}^N h_{en} W''_{enj} \leq 0, \quad j = 1, \dots, J \\
 &\sum_{r=1}^R u_r y_{rj} - \sum_{f=1}^F \sum_{n=1}^N s_{fn} W_{fnj} \leq 0, \quad j = 1, \dots, J \\
 &\sum_{a=1}^A k_{al} z''_{alj} + \sum_{p=1}^P \sum_{n=1}^N m_p \ln z_p \ln j - \sum_{i=1}^I v_{il} x_{ilj} \\
 &- \sum_{b=1}^B q_{bl} z'_{blj} \leq 0, \quad j = 1, \dots, J; l = 1, \dots, L \tag{2} \\
 &\sum_{f=1}^F s_{fn} W_{fnj} + \sum_{d=1}^D g_{dn} W_{dnj} + \sum_{n'=1}^N c_{nn'} g_{t_{nn'} j} \\
 &- \sum_{p=1}^P \sum_{l=1}^L m_p \ln z_p \ln j - \sum_{e=1}^E h_{en} W''_{enj} - \sum_{n'=1}^N c_{n'n} g_{t_{n'n} j} \leq 0, \\
 &j = 1, \dots, J; n = 1, \dots, N \\
 &\sum_{i=1}^I \sum_{l=1}^L v_{il} x_{ilo} \\
 &+ \sum_{b=1}^B \sum_{l=1}^L q_{bl} z'_{blo} + \sum_{e=1}^E \sum_{n=1}^N h_{en} W''_{eno} = 1 \\
 &v_{il}, k_{al}, q_{bl} \geq \varepsilon, \\
 &i = 1, \dots, I; l = 1, \dots, L; a = 1, \dots, A; b = 1, \dots, B \\
 &s_{fn}, h_{en}, g_{dn}, m_{pln} \geq \varepsilon, \\
 &f = 1, \dots, F; n = 1, \dots, N; e = 1, \dots, E; d = 1, \dots, D; p = 1, \dots, P; l = 1, \dots, L \\
 &u_r \geq \varepsilon, \\
 &r = 1, \dots, R \\
 &c_{nn'}, c_{n'n} \geq \varepsilon, \\
 &n = 1, \dots, N; n' = 1, \dots, N
 \end{aligned}$$

The efficiency scores of the stages and components can be calculated using (3).

$$\begin{aligned}
 e_j^{(1)} &= \frac{\sum_{a=1}^A \sum_{l=1}^L k_{al}^* z_{alj}'' + \sum_{p=1}^P \sum_{l=1}^L \sum_{n=1}^N m_{pn}^* z_{p \ln j}}{\sum_{i=1}^I \sum_{l=1}^L v_{il}^* x_{ilj} + \sum_{b=1}^B \sum_{l=1}^L q_{bl}^* z_{blj}'}, \quad j = 1, \dots, J \\
 e_j^{(2)} &= \frac{\sum_{f=1}^F \sum_{n=1}^N s_{fn}^* w_{fnj} + \sum_{d=1}^D \sum_{n=1}^N g_{dn}^* w'_{dnj}}{\sum_{p=1}^P \sum_{l=1}^L \sum_{n=1}^N m_{pn}^* z_{p \ln j} + \sum_{e=1}^E \sum_{n=1}^N h_{en}^* w''_{enj}}, \quad j = 1, \dots, J \\
 e_j^{(3)} &= \frac{\sum_{r=1}^R u_r^* y_{rj}}{\sum_{f=1}^F \sum_{n=1}^N s_{fn}^* w_{fnj}}, \quad j = 1, \dots, J \\
 e_j^{(1,l)} &= \frac{\sum_{a=1}^A k_{al}^* z_{alj}'' + \sum_{p=1}^P \sum_{n=1}^N m_{pn}^* z_{p \ln j}}{\sum_{i=1}^I v_{il}^* x_{ilj} + \sum_{b=1}^B q_{bl}^* z_{blj}'}, \quad j = 1, \dots, J; l = 1, \dots, L \\
 e_j^{(2,n)} &= \frac{\sum_{f=1}^F s_{fn}^* w_{fnj} + \sum_{d=1}^D g_{dn}^* w'_{dnj} + \sum_{n'=1}^N c_{nn'}^* g_{nn't}^{nm'j}}{\sum_{p=1}^P \sum_{l=1}^L m_{pn}^* z_{p \ln j} + \sum_{e=1}^E h_{en}^* w''_{enj} + \sum_{n'=1}^N c_{n'n}^* g_{n'n}^{t'nm'j}}, \quad j = 1, \dots, J; n = 1, \dots, N
 \end{aligned}
 \tag{3}$$

where $e_j^{(1)}, e_j^{(2)}, e_j^{(3)}$ are efficiency scores of the first, second, and third stages, respectively, $e_j^{(1,l)}$ is the efficiency score of l -th parallel component of the first stage, and $e_j^{(2,n)}$ is the efficiency score of n -th network component of the second stage.

4 Case study and results

The natural-gas supply chain consists of production, transmission, and distribution phases. It is one of the most important infrastructures in Iran. Its products are used in industries, power plants, commercial and household consumptions. Thus, performance measurement of this chain can be useful for improvement of the gas industry. This section illustrates the application of the proposed model for measuring overall efficiency of the natural-gas supply chain during a five-year period using monthly data. The natural-gas supply chain with monthly data is assumed as a DMU which consumes inputs in order to produce outputs. So, the Iranian natural gas supply chain is compared in 60 monthly periods starting from 2012 ending in 2016.

The natural-gas network consists of three major processes like production, transmission, and distribution. In the production process, gas refineries receive natural gas (sour gas) and fuel as inputs to produce treated gas (sweet gas). Several types of side products (Natural gas condensate, LPG, Ethan, Sulphur) as desirable outputs and acidic gas as undesirable output are also produced during this process. In the transmission phase, transmission zones receive treated gas from gas refineries or other sources such as imports from other nearby transmission zones, and imported gas as inputs to transport natural gas to some destinations such as distribution companies, exports, injection to underground gas storages (UGS), and neighboring

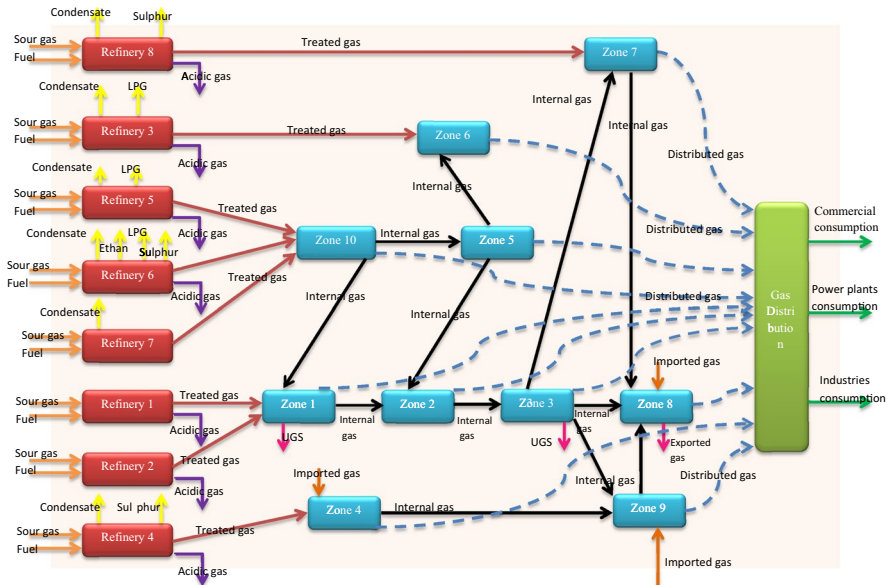


Fig. 3 Conceptual model of natural gas supply chain network

transmission zones as outputs. The third process of the natural-gas network is the distribution phase which distributes natural gas to major industries, power plants, commercial and household users.

The relations between production, transmission, and distribution processes, internal relations in every process, generation of desirable and desirable outputs, and additional inputs in each sub-process form a complicated network structure as depicted in Fig. 3.

4.1 Measurement and standard operating procedure

In this section, the standard operating procedure (SOP) of input, intermediate measures, and outputs of proposed DEA structure are described in order to provide sufficient detail to enable an operator to perform a measurement. National Iranian Gas Company (NIGC) acts on the basis of the gas measurement system which is established in the gas measurement master plan for the purpose of measuring all quantities of the natural-gas supply chain. Table 2 presents the definition, instrument, and standards of measuring inputs, outputs, and intermediate criteria for the case study of this research.

The Gas Act 1992 defines Gas measurement system (GMS) as follows. “Gas measurement system is a system for measuring the quantity of any gas whether by actual measurement or estimation”.

Table 2 Definition, instrument, and standards of measuring inputs, outputs, and intermediate criteria

Input/intermediate measure/output	Explanation	Measuring unit	Period of measuring	Oil and gas standard (national/international)	System of measurement	Instrument of measurement
Sour gas	A sour gas is a gas that specifically contains hydrogen sulfide in significant amounts and received from oil and gas wells	Million cubic meters	Monthly	AGA ^a IPS (IN) ^b IGS (IN) ^c	Operational	Ultrasonic/orifice
Fuel	The fuel that gas refinery consumes such as refinery fuel and flare fuel	Million cubic meters	Monthly	AGA IPS (IN) IGS (IN)	Operational	Ultrasonic/orifice
Treated gas	The sour gas must be treated to reduce impurities to acceptable levels that is commonly done with a treating process. So the treated gas is a gross sweet gas production in gas refinery	Million cubic meters	Monthly	AGA IPS (IN) IGS (IN)	Custody	Ultrasonic/orifice
Side products	Refineries can produce different shares of products which are materials derived from sour gas as it is processed in gas refineries such as natural gas condensate, LPG, Ethane and Sulphur	Million cubic meters, thousand tons	Monthly	AGA IPS (IN) IGS (IN)	Custody	
Acidic gas	The acid gas is a gas that contains significant amounts of acidic gases such as carbon dioxide (CO ₂) or hydrogen sulfide that flare in refineries	Thousand cubic meters	Monthly	AGA IPS (IN) IGS (IN)	Custody	Gas analyzer
Distributed gas	The amount of natural gas bringing from the point of production to the point of use along the transportation pipelines	Billion cubic meters	Monthly	AGA IPS (IN) IGS (IN)	Custody	Ultrasonic/orifice
Imported/exported gases	The net imports or exports of natural gas	Billion cubic meters	Monthly	AGA IPS (IN) IGS (IN)	Custody	Ultrasonic/orifice
Gas to UGS	The amount of gas injection to UGS	Billion cubic meters	Monthly	AGA IPS (IN) IGS (IN)	Operational	Ultrasonic/orifice

Table 2 (continued)

Input/intermediate measure/output	Explanation	Measuring unit	Period of measuring	Oil and gas standard (national/international)	System of measurement	Instrument of measurement
Internal gas	The amount of gas sent to nearby transmission zone or received from nearby transmission zone	Billion cubic meters	Monthly	AGA IPS (IN) IGS (IN)	Custody	Ultrasonic/orifice
Gas consumption	The amount of gas is sold to the major industries, power plants and commercial/household points	Billion cubic meters	Monthly	AGA IPS (IN) IGS (IN)	Custody	Ultrasonic/orifice

^aAmerican Gas Association Reports

^bIranian Petroleum Standards

^cIranian Gas Standards

Gas flows can be measured for operational purposes and/or for commercial purposes. As a general rule, a higher standard of accuracy is required for commercial measurement. Gas measurement equipment in NIGC is commercial. So new technologies of gas measurement are designed to decrease the uncertainty of the measurement error and provide reliable data for operational efficiency and custody transfer.

The gas measurement system is described briefly. A treated gas meter measures the volume of gas passing through it at actual conditions of temperature and pressure. This volume is recorded in units of actual cubic meters (ACM). It is necessary to convert the ACM volume to standard cubic meters (SCM). The conversion is done using flow computers which are connected to the chromatographs base on Boyle's Law:

$$V_{\text{standard}} = V_{\text{actual}} \times (P_{\text{actual}}/P_{\text{standard}}) \times (T_{\text{standard}}/T_{\text{actual}}) \times (Z_{\text{standard}}/Z_{\text{actual}})$$

where V, P, T, and Z are reserved for the volume, pressure, temperature, and compressibility factor of the gas, respectively.

The main equipment of NIGC gas measurement system is summarized as follows.

- A meter measures the amount of the gas being delivered.
- Temperature measurement device which measures the flowing gas temperature.
- Pressure measurement device which measures the flowing gas pressure.
- Gas analyzer which analyzes the chemical composition of the gas and calculates its properties, such as its calorific value and specific gravity.
- Conversion tool which performs the flow calculations known as flow computer or 'corrector'.
- Chromatographs which measures the energy quantity.

According to the equipment's capability for recording daily and monthly temperature, pressure and amount of gas data, through the memory of equipment, all data are read and mean of them are recorded on a monthly form. Meter owners in NIGC supply chain must ensure that measurement equipment complies with IGS-C-IN-105(0) standard and to be accurate within the margin of error specified in NIGC gas measurement master plan. So compliance with the standard assures that the mean of data which are collected monthly are considered to be certain with negligible errors. It can be said that uncertainty is considered to be negligible in the NIGC gas measurement master plan.

4.2 Results of network DEA model

The natural-gas supply chain is considered as a network with three series sub-process (i.e., the gas refinery, gas transmission, and gas distribution) which in the first stage there are eight parallel refineries and in the second stage, there are ten transmission zones. Each refinery produces treated gas and transmission zones receive treated gas from gas refineries or other sources such as imports and other nearby transmission zones, to transport treated gas to some destinations such as distribution

companies, exports, injection to UGS, and neighboring transportation zones. The conceptual model of the network structure, which is associated with the conceptual model represented in Fig. 2, is depicted in Fig. 3.

As mentioned earlier we have focused on 60 homogenous DMUs (i.e., monthly data for a 5 year planning period). Values of the inputs, intermediate measures, and outputs are collected from monthly reports of National Iranian Gas Company from 2012 to 2016. For the sake of brevity and anonymity details of data are not presented, although the descriptive statistics are presented in Tables 3, 4, 5 and 6.

Running the LINGO code developed for Model (2), the overall efficiency of the natural-gas supply chain is optimized. The efficiency of the three main stages, eight refineries, and ten transmission zones are also calculated for each period using Eq. (3). The descriptive statistics of efficiency scores are presented in Table 7.

The following findings are based on results presented in Online Appendix A, B, and C:

- The maximum achievable efficiency score for the natural-gas supply chain is 0.98 at DMU₁₁ wherein only the production stage is efficient. The first stage is efficient at DMU₁₀, DMU₁₅, and DMU₃₁.
- The mean efficiency scores of the natural-gas supply chain during all periods of planning at the production, transportation, and distribution stages are 97.75%, 86.40%, and 94.87%, respectively. There is no efficient DMU at the transmission stage. So the relative efficiency scores of the second stage compared to the first and third stages are low and the natural gas network should be improved in transmission process on the basis of benchmark studies in successful countries.
- The mean efficiency scores of ten transmission zones are 85.52%, 99.47%, 94.30%, 81.07%, 94.79%, 54.23%, 83.27%, 86.39%, 78.89% and 96.60%, respectively. The zone number 6, and zone number 2 have the lowest and highest efficiency scores, respectively.
- Figure 4 shows the frequency of DMUs with high-efficiency score at transmission zones. It can be concluded that zone 2 and zone 10 have the highest share in the performance of the transmission stage.
- The monthly efficiency scores during 5-years of the period of planning are presented in Fig. 5 for the entire network and all stages. It is clear that second stage 2 is the weakest stage during the last 60 months, as it had the lowest efficiency scores in comparison with the other stages and the entire network. This pitfall cannot be random. So, it should be discussed. Figure 6 shows the average efficiency scores of the entire network and the stages. Figure 6 also validates the weak average efficiency score of stage 2.
- Figure 7 shows the efficiency score of the production stage. It is clear that the average efficiency score of the production stage is high in comparison with the other two stages. The weak periods can be seen in red points during multiple periods of planning.
- Figure 8 shows the efficiency scores of stage 2. Stage 2 had the lowest efficiency score during the past periods. This was also obvious on the basis of the results of Figs. 5 and 6. It is obvious that in period 15 and period 38 the efficiency score of the second stage had a very high decrease.

Table 3 Value of parameters of refineries

Input/intermediate measure/output	Refinery	Parameter	Min	Max	Ave.	SD	
Sour gas	1	x_{11j}	112.22	845.90	578.46	182.29	
	2	x_{12j}	1.86	13.25	8.79	2.58	
	3	x_{13j}	266.18	499.13	398.96	66.34	
	4	x_{14j}	909.66	1689.66	1270.74	212.01	
	5	x_{15j}	1194.94	3636.24	2582.13	617.68	
	6	x_{16j}	5415.13	10,967.20	7478.24	1339.91	
	7	x_{17j}	917.34	2376.53	2108.18	293.50	
	8	x_{18j}	5.20	200.92	122.60	65.25	
Fuel	1	x_{21j}	2.42	9.01	6.97	1.72	
	2	x_{22j}	0.13	0.31	0.30	0.02	
	3	x_{23j}	0.00	3.34	1.91	1.38	
	4	x_{24j}	14.09	42.03	35.97	5.14	
	5	x_{25j}	11.28	27.14	20.08	4.54	
	6	x_{26j}	174.82	367.68	244.21	46.27	
	7	x_{27j}	3.16	10.21	6.72	1.48	
	8	x_{28j}	0.55	16.03	6.73	3.75	
Treated gas	1	z_{111j}	109.07	825.59	590.45	170.44	
	2	z_{121j}	1.55	12.77	8.45	2.56	
	3	z_{136j}	260.08	491.55	390.37	66.19	
	4	z_{144j}	873.70	1524.25	1181.00	193.35	
	5	z_{1510j}	1168.22	3571.20	2539.86	610.89	
	6	z_{1610j}	4298.80	9817.18	6218.58	1363.57	
	7	z_{1710j}	905.19	2338.29	2077.51	289.67	
	8	z_{187j}	4.10	169.66	110.54	59.36	
Condensate	3	z''_{13j}	0.02	0.33	0.04	0.04	
	4	z''_{14j}	0.01	0.02	0.01	0.01	
	5	z''_{15j}	0.07	0.17	0.13	0.02	
	6	z''_{16j}	1.19	2.51	1.75	0.28	
	7	z''_{17j}	0.08	0.20	0.15	0.02	
	8	z''_{18j}	0.00	0.21	0.03	0.03	
	Ethan	6	z''_{26j}	68.48	151.98	113.91	21.80
	LPG	3	z''_{33j}	1.72	20.02	2.84	2.28
5		z''_{35j}	0.10	6.13	1.92	1.51	
6		z''_{36j}	20.74	251.75	136.11	66.20	
Sulphur	4	z''_{44j}	35.64	61.59	51.70	6.88	
	6	z''_{46j}	17.52	42.26	28.53	4.83	
	8	z''_{48j}	0.00	0.07	0.02	0.02	

Table 3 (continued)

Input/intermediate measure/output	Refinery	Parameter	Min	Max	Ave.	SD
Acidic gas	1	z'_{11j}	1.38	20.36	10.87	4.23
	2	z'_{12j}	0.02	0.30	0.05	0.04
	3	z'_{13j}	0.00	0.49	0.06	0.11
	4	z'_{14j}	0.14	149.75	124.65	22.87
	5	z'_{15j}	0.04	64.23	44.24	12.60
	6	z'_{16j}	0.11	149.36	77.67	24.03
	8	z'_{18j}	0.01	15.19	8.50	4.97

Table 4 Value of parameters of transmission zones

Input/intermediate measure/output	Transmission zone	Parameter	Min	Max	Ave.	SD
Distributed gas	Zone 1	w_{11j}	0.87	1.37	1.19	0.10
	Zone 2	w_{12j}	1.25	2.56	1.84	0.38
	Zone 3	w_{13j}	1.85	4.80	3.15	0.81
	Zone 4	w_{14j}	0.94	1.74	1.29	0.24
	Zone 5	w_{15j}	0.61	0.96	0.80	0.09
	Zone 6	w_{16j}	0.44	1.03	0.70	0.12
	Zone 7	w_{17j}	0.77	1.84	1.35	0.29
	Zone 8	w_{18j}	0.78	2.20	1.36	0.40
	Zone 9	w_{19j}	0.83	1.77	1.21	0.26
	Zone 10	w_{110j}	0.40	0.99	0.76	0.11
Exported gas	Zone 8	w'_{18j}	0.49	0.94	0.76	0.11
Gas injection to UGS	Zone 1	w'_{21j}	0.09	0.77	0.33	0.17
	Zone 3	w'_{23j}	0.00	0.23	0.05	0.07
Imported gas	Zone 4	w''_{14j}	0.02	0.69	0.26	0.21
	Zone 8	w''_{18j}	0.01	0.32	0.03	0.04
	Zone 9	w''_{19j}	0.10	0.65	0.35	0.16

- Further investigation in stage 2, i.e., the weakest stage, is applicable using the proposed models of this study. As stage two is composed of ten transmission zones, the efficiency score of this stage can be decomposed into efficiency scores of each transmission zone in each period of planning. Figure 9 presents the average efficiency scores of each transmission zone during the past 60 periods of planning.
- It can be concluded from Fig. 9 that the transmission zone number 6 has the weakest efficiency score among the others. The managers can detect the weakest periods in the transmission zone number 6 using Fig. 10. Zone number 6 had the lowest efficiency score in periods 1 and 2. Although the more important issue is a seasonal behavior of efficiency scores detected in efficiency scores of zone

Table 5 Values of internal gas of transmission zones

Origin zone	Destination zone	Parameter	Min	Max	Ave.	SD
Zone 1	Zone 2	gt_{12j}	0.00	1.24	0.46	0.41
Zone 2	Zone 3	gt_{23j}	5.02	10.06	7.21	1.51
Zone 3	Zone 7	gt_{37j}	1.16	2.43	1.79	0.34
	Zone 8	gt_{38j}	0.79	1.80	1.30	0.24
	Zone 9	gt_{39j}	0.33	1.97	0.98	0.37
Zone 4	Zone 9	gt_{49j}	0.00	0.43	0.13	0.13
Zone 5	Zone 2	gt_{52j}	6.41	11.59	8.60	1.47
	Zone 6	gt_{56j}	0.00	0.32	0.16	0.08
Zone 7	Zone 8	gt_{78j}	0.30	0.77	0.54	0.13
Zone 9	Zone 8	gt_{98j}	0.00	0.80	0.26	0.19
Zone 10	Zone 1	gt_{101j}	0.09	1.36	0.63	0.38
	Zone 5	gt_{105j}	7.16	11.94	9.25	1.32

Table 6 Value of parameters of distribution stage

Users	Parameter	Min	Max	Ave.	Std. Dev.
Major industries	y_{1j}	3.56	13.82	7.27	3.50
Power plants	y_{2j}	0.56	7.02	3.68	1.60
Commercial and household	y_{3j}	1.35	2.99	2.56	0.30

number 6. This could be the direct result of the quality of inputs to zone number 6 during the past 60 periods.

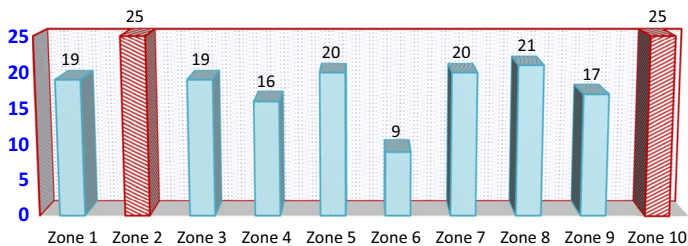
According to the above-mentioned analysis, the following policies are suggested in order to make a certain improvement on the natural-gas supply chain.

Policy #1. Analyzing the average efficiency score In this policy, we have calculated the average efficiency score of production, transmission and distribution stages during the past 60 planning periods. The average efficiency scores of production, transmission and, distribution stages are equal to 0.977, 0.864, and 0.949, respectively. It is clear that the production stage has the best average performance among the others. As the transmission stage has the lowest average efficiency score, this means that the managers should care about transmission stage if they have future improvement plans.

Policy #2. Analyzing the rage of the efficiency score In this policy, we have calculated the range of the efficiency score of production, transmission and distribution stages during the past 60 planning periods. The maximum and minimum efficiency scores were seen for each stage during past 60 periods reveal the interval efficiency scores equal to [0.906 1.00], [0.721 0.981], and [0.844 1.00] for production, transmission, and distribution stages, respectively. Calculating the range of each stage, i.e., 0.094, 0.26, and 0.156, shows that the production stage with the lowest range is

Table 7 Efficiency scores

Efficiency	Min	Max	Ave.	SD
Overall	0.889	0.985	0.954	0.023
Gas refinery	0.906	1.000	0.977	0.024
Gas transmission	0.721	0.981	0.864	0.053
Gas distribution	0.844	1.000	0.949	0.046
Gas refinery				
Refinery 1	0.295	1.000	0.670	0.136
Refinery 2	0.190	1.000	0.740	0.183
Refinery 3	0.894	1.000	0.970	0.025
Refinery 4	0.807	1.000	0.927	0.065
Refinery 5	0.835	1.000	0.955	0.033
Refinery 6	0.840	1.000	0.942	0.055
Refinery 7	0.946	1.000	0.995	0.009
Refinery 8	0.628	1.000	0.850	0.102
Gas distribution				
Zone 1	0.535	1.000	0.855	0.106
Zone 2	0.922	1.000	0.995	0.013
Zone 3	0.787	1.000	0.943	0.044
Zone 4	0.501	1.000	0.811	0.112
Zone 5	0.876	1.000	0.948	0.035
Zone 6	0.333	1.000	0.542	0.167
Zone 7	0.036	1.000	0.833	0.266
Zone 8	0.611	1.000	0.864	0.100
Zone 9	0.596	1.000	0.789	0.105
Zone 10	0.799	1.000	0.966	0.035

**Fig. 4** Frequency of high efficiency score of transmission stage and transmission zones

the most reliable stage among the other, while the transmission stage really presents very wide fluctuations. Again the transmission stage is the main candidate for future improvement plans in the natural-gas supply chain.

Policy #3. Analyzing the standard deviations of the efficiency score In this policy, we have calculated the standard deviations of the efficiency score of production, transmission and distribution stages during the past 60 planning periods. The standard

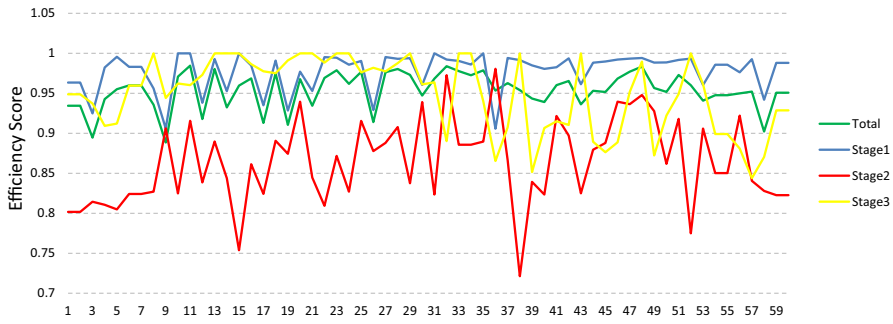


Fig. 5 Monthly efficiency scores of entire network, stage 1, stage 2 and stage 3

Fig. 6 Average efficiency scores of total supply chain and the stages

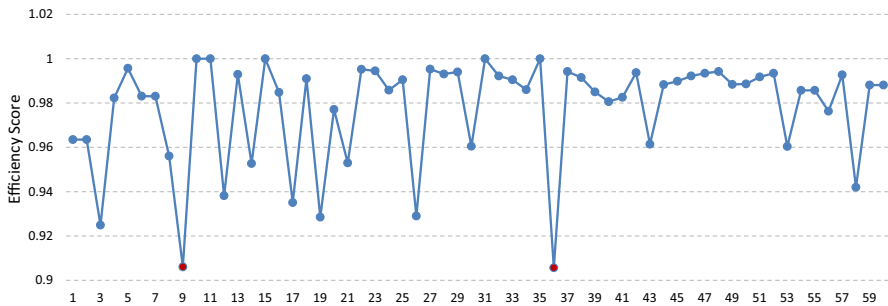
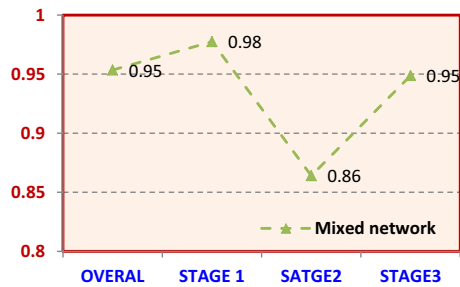


Fig. 7 Efficiency scores of stage 1

deviation of the efficiency score of production, transmission, and distribution stages is equal to 0.024, 0.053, and 0.046, respectively. Again, the transmission stage presents a high standard deviation of the efficiency scores in comparison with the other stages. Again the transmission stage is the main candidate for future improvement plans.

This should help the managers to recover the reasons of such decreases from the past performance of the natural gas supply chain. It is notable that using the proposed models of this research the managers are able to detect the exact points of

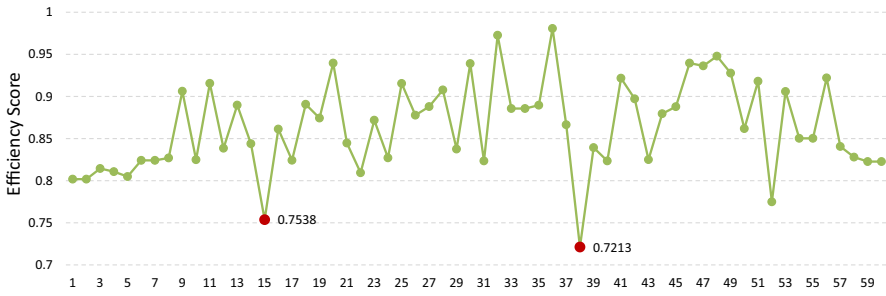


Fig. 8 Efficiency scores of stage 2

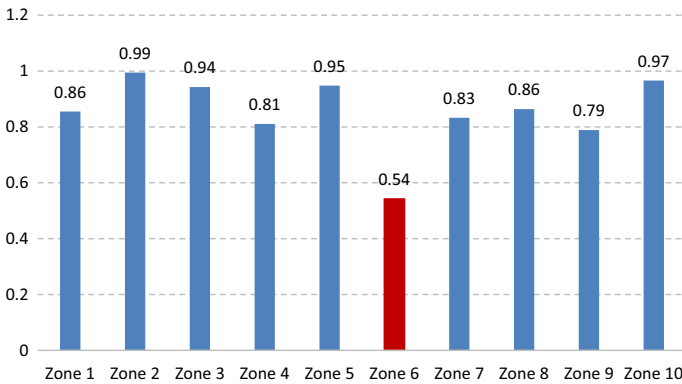


Fig. 9 Average efficiency scores of transmission zones in stage 2

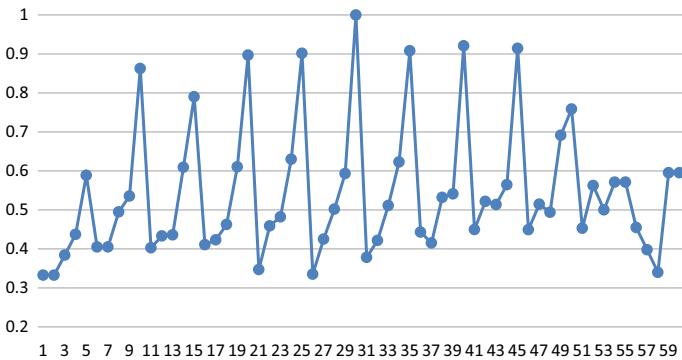


Fig. 10 Efficiency scores of transmission zones number 6 during planning periods

weakness in such a complicated network of the process during multiple periods of planning. On the other hand, using the proposed models of this study, the total efficiency score of the natural gas supply chain is measured during multiple periods

of planning. Then, the total efficiency score is decomposed to efficiency scores of production, transmission and distribution stages. The efficiency score of each stage can be calculated distinctively for multiple periods of planning. The weakness and strength of the total supply chain or stages can be detected and discussed.

5 Conclusions remarks and future research directions

Conventional DEA models cannot address internal processes of real systems with complicated structures. The natural gas supply chain network is more complex than to be modeled using classic series or parallel DEA structures. In this paper, a network DEA model was developed to measure the performance of the natural gas supply chain network. The technical efficiency of Iran natural gas supply chain network was calculated in a 5-year planning period using monthly data.

Three serially connected sub-processes as production, transmission, and distribution were considered. Exogenous and undesirable inputs and outputs, and intermediate final products were also considered. The first sub-process, i.e., production stage, was decomposed into eight parallel components as refinery companies. So, the efficiency of the production stage was decomposed into the efficiency of refineries. So, detail analysis of production stage was accessible. A general and complicated structure considering mixed relations among several stages was finally proposed. The efficiency scores were calculated for overall network, production, transportation, and distribution processes as well as eight refineries and ten transmission zones in a multiple-period of planning.

The contributions of this research can be summarized as follows.

- A customized network DEA model was developed to measure the relative efficiency of the natural-gas supply chain network through a multi-period planning horizon.
- The proposed model has been changed into a linear mathematical programming using suitable variable changes, so it can easily be implemented using Operations Research (OR) software. It can achieve exact and global optimum efficiency scores.
- As a general tool for measuring the efficiency score of real-world supply chains, the proposed network DEA model has been proved to be always feasible and bounded.
- A real case study including production, transmission, and distribution stages was analyzed using the proposed model.
- The overall efficiency score of the natural-gas supply chain was decomposed into efficiency scores of production, transmission, and distribution stage. The efficiency score of each production stage was decomposed into efficiency scores of 8 refineries in turn. Moreover, the efficiency score of each distribution stage was decomposed into efficiency score of 10 distribution zone in turn.

The results of case the study showed the efficacy and applicability of the proposed model in analyzing real-world problems. Following points are suggested for future researches.

- The model proposed in this research was developed on the basis of input-oriented multiplier form considering constant returns to scale assumption. Development of the model on the basis of output-oriented envelopment form under variable returns to scale assumption can be an interesting future research.
- Some inputs and outputs of this study can be measured through linguistic terms parameterized using fuzzy sets to represent the uncertainty in the data in future researches.
- Development of a procedure in order to improve inefficient DMUs and sub-DMUs towards efficient frontier can also be another future research direction.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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