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Dynamic DEA models with network structure: An application for Iranian airlines

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ABSTRACT

Efficiency estimation of interdependent divisions within a company or assessing the interrelated processes in a production system provides insights for improving the operational performance. Recent developments in network data envelopment analysis (NDEA) models enable decision making units (DMUs) to be informed of inefficient processes within the system. The NDEA model assesses the processes of the system in a specific moment and ignores the dynamic effects within the production processes. Thus, without considering the temporal dimension of production processes, biased efficiency measurement will be obtained that provides misleading information to DMUs. For evaluating the performance of a DMU with interrelated processes during specified multiple periods, this paper proposes a relational dynamic NDEA (DNDEA) model which measures the efficiencies of the system and its internal processes over the time, simultaneously. To illustrate the capability of the proposed model, this study for the first time measures the efficiency of eight Iranian airlines in several periods connected to each other by carry over flows. The actual data is gathered in three periods from 2010 to 2012 and the results are compared with the dynamic DEA and network DEA models in the same time span.

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1. Introduction

Charnes et al. (1978) introduced data envelopment analysis (DEA) to measure the efficiency of DMUs with multiple inputs and multiple outputs. DEA considers the system as a black box, which ignores internal relations of processes. In the real world, DMU's structure may contain several connected processes. One of the most important approaches for evaluating the system with several processes is network DEA (NDEA) model, which takes into account the component processes and their internal relations via intermediate products in measuring efficiency. Fare and Grosskopf (2000) proposed network DEA models to evaluate the performance of organization and its component processes. Their model considered the processes as independent ones in the network, so no mathematical relationship does exist between the system and process efficiencies. To overcome the problem, Kao (2009) proposed relational network DEA model. This model takes into account the relationship of the processes, to measure the system and process efficiencies at the same time and obtained a relationship between system and process efficiencies. Independent models which calculate the process efficiencies independently, allow a factor (input/output/link) to have different multipliers in different places, but the relational model requires the same factor to have the same multiplier associated with it, regardless of the place it corresponds to. The network systems are classified in various structures such as two-stage, series, parallel and mixed (Kao and Hwang, 2010). Models used to measure the efficiency of network systems are classified in several types, such as independent models, distance measure model, slacks-based measure model, ratio-form model, game theoretic model and value-based model (Kao, 2014). Tone and Tsutsui (2009) measured the efficiency of network systems by a slack-based measure (SBM) DEA model which can decompose the system efficiency into processes efficiency. For evaluating the processes of the system, Fare and Grosskopf (1996) considered the production system consisting of independent processes and calculated the efficiency of processes, separately. In the real world, companies have long-term planning, so dynamic models are needed to consider inter-relationships between single periods, which are any kind of flows, to assess the performance of DMUs over time. The capital inputs that generate outputs in the future are suitable for explaining dynamic aspects of systems to measure the efficiency, appropriately. In the inter-temporal case, the capital inputs change

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along the optimal path of capacity expansion yielding a long-run production frontier (Sengupta, 1994). Sengupta (1994) developed an adjustment cost approach which modifies the standard model of production frontier to analyze risk aversion behavior of the DMUs on the dynamic production frontier, but the proposed system had one output. Fare et al. (1996) presented a discussion of dynamic structures with multiple outputs and introduced dynamic aspect of production on DEA model. They developed a sequence of network models that became the base for further studies on dynamic DEA.

Most of the studies in dynamic systems calculate overall efficiency and period-specific efficiencies, separately. Jaenicke (2000) used dynamic DEA (DDEA) analysis to model the dynamic production technology associated with relational crop production. In his study, soil capital was considered as intermediate output of model. The model measures efficiency of rotation made up from three kinds of crops. Tone and Tsutsui (2010) developed dynamic DEA model in slack-based measure framework that deals with inputs and outputs individually (such non-radial models). Kao (2013) presented a relational model for dynamic systems to calculate the radial measures of the overall and period efficiencies of multi-period production system where consecutive periods are connected by flows. Radial approaches assume proportional changes in inputs or outputs. Chen (2009) proposed a new approach named "ψ-efficiency measure" to incorporate the dynamic effect within the production network, systematically. This approach estimates the efficiencies of sub-DMUs (SDMUs), then the efficiency of the entire DMU. ψ is defined as input-oriented efficiency indices of SDMU that represents the minimal aggregate input requirement with respect to the aggregate final output in the periods (Chen, 2009). Chen (2012) proposed a dynamic multi-activity network DEA (DMNDEA) model to determine the performance of farrow-to-finish swine production in Taiwan. The production was consisting of two processes; the breed-to-farrow and wean-to-finish. Chen (2012) applied a distance function to construct DMNDEA model and calculated the overall and process efficiencies of pig farms. Distance function considers the distance of DMU's current condition from the ideal condition (frontier) for calculating the efficiency. Tone and Tsutsui (2014) proposed dynamic DEA models for network structures within the slack-based measure (SBM) to evaluate the performance of a company and applied the model to a dataset of US electric companies over multiple years. The SBM approach uses slack variables for calculating the efficiency scores and no relationship is defined between system and processes efficiency. In this paper, a radial dynamic DEA model with network structure is presented to observe dynamic changes of both subsystem and period efficiency. It is notable that the relational models obtain the relationship between system and processes inefficiency to configure the source of inefficiency in system, whereas the SBM-DNDEA model presented by Tone and Tsutsui (2014) is not capable to. The reason for developing DNDEA model is that in real problems the performance of DMU's internal divisions relies on several periods. For example in a supply chain consisting of supplier, producer and distributor, it's possible that at the end of the year production division has excess inventory in its warehouse. Thus, extra stock will be sent to distributor at the next year. The main contribution of this paper is combination of the relational DDEA model introduced by Kao (2013) and the relational NDEA model presented by Kao and Hwang (2010) to present the DNDEA model. The proposed dynamic network (DNDEA) model is applied to calculate the efficiency scores of Iranian airlines and the results of dynamic (DDEA) and network (NDEA) models are compared. The rest of this paper organized as follows: Section 2 presents the NDEA model. Section 3 outlines relational dynamic DEA model graphically and its mathematical formulations. In section 4, our model is proposed and the case of Iranian airline companies is presented in section 5. Section 6 shows the results of our proposed model and the contribution of this paper is discussed in the conclusions.

2. Network DEA models (NDEA)

The systems with$p$ processes are evaluated by network DEA models, which take in to account the component processes and their internal relations via intermediate products. Systems are classified in various structures as two-stage, series, parallel and mixed structures. In this section, the series model introduced by Kao and Hwang (2010) is presented. In series structure, all processes are consecutive and output of a process is input of subsequent process. A simplified form of series structure is shown in Fig. 1.

Let X_{ij}^p, Y_{rj}^p and Z_{lj}^p denote ith input ($i = 1,\ldots,m$), rth output($r = 1,\ldots,s$) and lth intermediate product ($l = 1,\ldots,t$) produced from process $p(1,\ldots,q)$ of the jth DMU ($j = 1,\ldots,n$), respectively. The input-oriented model for calculating the efficiency of DMU_O is as model 1:

Model (1):

$$E_k = \max \sum_{r=1}^{s} u_r Y_{ro} \tag{1}$$

$$s.t. \tag{2}$$

$$\sum_{i=1}^{m} v_i X_{io} = 1 \tag{3}$$

$$\sum_{r=1}^{s} u_r Y_{rj} - \sum_{i=1}^{m} v_i X_{ij} \le 0, \quad j = 1, \ldots, n \tag{4}$$

$$\left(\sum_{r\in O^{(P)}} u_r Y_{rj}^{(p)} + \sum_{l\in M^{(P)}} w_l Z_{lj}^{(p)}\right) - \left(\sum_{i\in I^{(P)}} v_i X_{ij}^{(p)} + \sum_{l\in M^{(P-1)}} w_l Z_{lj}^{(p-1)}\right) \le 0, \quad j = 1, \ldots, n; p = 1, \ldots, q \tag{5}$$

$$u_r, v_i, w_l \ge \varepsilon \quad r = 1, \ldots, s \ ; \ i = 1, \ldots, m \ ; \ l = 1, \ldots, t \tag{6}$$

Where,u_r,v_i and w_l denote the multipliers associated with the output r , input i and link l, respectively. ε is a small non-Archimedean number which is applied to prevent ignoring any factor from efficiency calculation (Charnes and Cooper, 1984). By obtaining optimal solutions of $u_r^*, v_i^*, w_l^{(k)*}$ in model (1), process efficiencies can be calculated as:

$$E_o^{(p)} = \sum_{r\in O^{(P)}} u_r Y_{rj}^{(p)} + \sum_{l\in M^{(P)}} w_l Z_{lj}^{(p)} \Bigg/ \sum_{i\in I^{(P)}} v_i X_{ij}^{(p)} + \sum_{l\in M^{(P-1)}} w_l Z_{lj}^{(p-1)} \tag{7}$$

3. Dynamic DEA models (DDEA)

The dynamic DEA model concerns the repetition of single-period structure over a long term period. It seems that the dynamic structure is a type of series one which has a special structure in each period. The dynamic system considered in Kao (2013) is

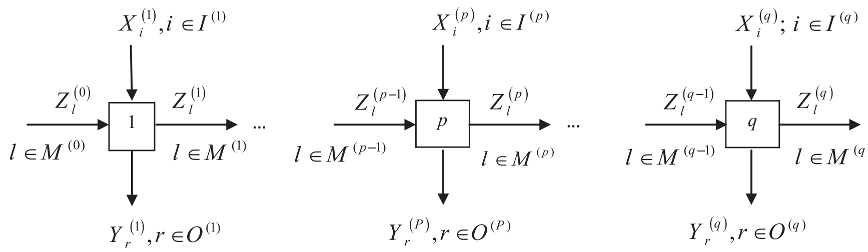

Fig. 1. A network with series structure.

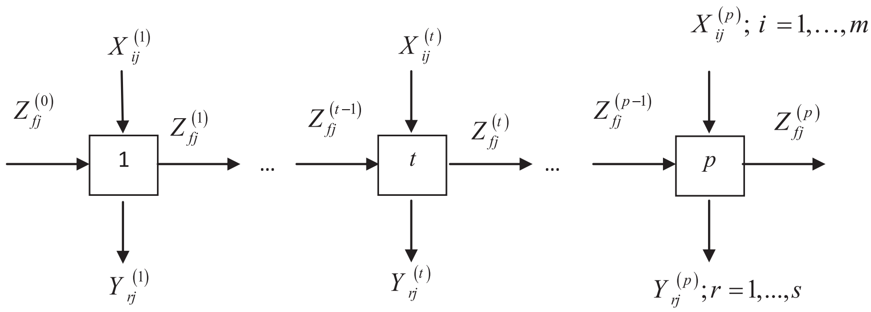

Fig. 2. Dynamic system with flows connecting two consecutive periods.

shown in Fig. 2.

Let $X_{ij}^{(t)}$, $Y_{rj}^{(t)}$ and $Z_{fj}^{(t)}$ denote ith input (i = 1,…,m), rth output(r = 1,…,s) and fth linking flow (f = 1,…,g) to next period of the jth DMU (j = 1,…,n) in period t, respectively. Denote $X_{ij} = \sum_{t=1}^{p} X_{ij}^{(t)}$ and $Y_{ij} = \sum_{t=1}^{p} Y_{ij}^{(t)}$ as total quantities of ith input and rth output, respectively, over all t periods. The relative efficiency of DMUo under the assumption of constant return to scale is calculated as following output-oriented model (Kao, 2013):

Model (2):

$$\frac{1}{E_o} = \min\left(\sum_{i=1}^{m} v_i X_{io} + \sum_{f=1}^{g} w_f Z_{fo}^{(0)}\right) \tag{8}$$

s.t:

$$\sum_{r=1}^{s} u_r Y_{ro} + \sum_{f=1}^{g} w_f Z_{fo}^{(p)} = 1 \tag{9}$$

$$\left(\sum_{i=1}^{m} v_i X_{ij} + \sum_{f=1}^{g} w_f Z_{fj}^{(0)}\right) - \left(\sum_{r=1}^{s} u_r Y_{rj} + \sum_{f=1}^{g} w_f Z_{fj}^{(p)}\right) \geq 0 \tag{10}$$

$$\left(\sum_{i=1}^{m} v_i X_{ij}^{(t)} + \sum_{f=1}^{g} w_f Z_{fj}^{(t-1)}\right) - \left(\sum_{r=1}^{s} u_r Y_{rj}^{(t)} + \sum_{f=1}^{g} w_f Z_{fj}^{(t)}\right) \geq 0 \tag{11}$$

$$u_r, v_i, w_f \geq \varepsilon, i = 1, \ldots, m; \quad r = 1, \ldots, s; j = 1, \ldots, n; \tag{12}$$

Where,u_r,v_i and w_f denote the multipliers associated with the output r, input i and carry over f, respectively. Model (2) is input-oriented model, which tries to minimize inputs with respect to fixed level of outputs. Also, the output-oriented form of NDEA model can be written as model (3):

Model (3):

$$E_o = \max\left(\sum_{r=1}^{s} u_r Y_{ro} + \sum_{f=1}^{g} w_f Z_{fo}^{(p)}\right) \tag{13}$$

s.t:

$$\sum_{i=1}^{m} v_i X_{io} + \sum_{f=1}^{g} w_f Z_{fo}^{(0)} = 1 \tag{14}$$

$$\left(\sum_{r=1}^{s} u_r Y_{rj} + \sum_{f=1}^{g} w_f Z_{fj}^{(p)}\right) - \left(\sum_{i=1}^{m} v_i X_{ij} + \sum_{f=1}^{g} w_f Z_{fj}^{(0)}\right) \leq 0 \tag{15}$$

$$\left(\sum_{r=1}^{s} u_r Y_{rj}^{(t)} + \sum_{f=1}^{g} w_f Z_{fj}^{(t)}\right) - \left(\sum_{i=1}^{m} v_i X_{ij}^{(t)} + \sum_{f=1}^{g} w_f Z_{fj}^{(t-1)}\right) \leq 0 \tag{16}$$

$$u_r,\ v_i,\ w_f \geq \varepsilon\ , i = 1, \ldots, m; \quad r = 1, \ldots, s; j = 1, \ldots, n; \tag{17}$$

After obtaining the optimal solution(u_r^*, v_i^*, w_f^*), system and period efficiencies of DMU k can be calculated as:

$$E_o^{sys} = \frac{\sum_{r=1}^{s} u_r^* Y_{ro} + \sum_{f=1}^{g} w_f^* Z_{fo}^{(p)}}{\sum_{i=1}^{m} v_i^* X_{io} + \sum_{f=1}^{g} w_f^* Z_{fo}^{(0)}} \tag{18}$$

$$E_o^{(t)} = \frac{\sum_{r=1}^{s} u_r^* Y_{ro}^{(t)} + \sum_{f=1}^{g} w_f^* Z_{fo}^{(t)}}{\sum_{i=1}^{m} v_i^* X_{io}^{(t)} + \sum_{f=1}^{g} w_f^* Z_{fo}^{(t-1)}} \tag{19}$$

4. Dynamic DEA with network structure (DNDEA)

In this paper, dynamic network DEA model is proposed to measure period efficiency by taking into account the relationships of processes in the network. In this section, the dynamic DEA with network structure is presented and formulated. As shown in Fig. 3, which is derived from Tone (2014), intermediate products link divisions together and carry-overs connect two consecutive periods.

For measuring relative efficiency of n DMUs ($j = 1,\ldots,n$) consisting of k divisions ($k = 1,\ldots,K$) over t periods($t = 1,\ldots,T$), let m_k and s_k be the number of inputs and outputs to division k and$i^k \in \{1,\ldots,m_k\}$, $r^k \in \{1,\ldots,s_k\}$, respectively. Denotel_k as the number of links leading from division k to next division and d_k as the number of carry-overs at division k, from period t to period $t + 1$ and $l^k \in \{1,\ldots,l_k\}$, $d^k \in \{1,\ldots,d_k\}$, respectively.

$x_{ij}^{(t,k)}(i = 1,\ldots,m_k,\ldots,m;\ j = 1,\ldots,n;\ t = 1,\ldots,T;\ k = 1,\ldots,K)$: is input ith of DMU_j for division k in period t.

$y_{rj}^{(t,k)} y_{rj}^{(t,k)}(r = 1,\ldots,s_k,\ldots,s;\ j = 1,\ldots,n;\ t = 1,\ldots,T;\ k = 1,\ldots,K)$: is output rth of DMU_j for division k in period t.

$c_{lj}^{(t,k)}(l = 1,\ldots,\ l_k,\ldots,L;\ j = 1,\ldots,n;\ t = 1,\ldots,T;\ k = 1,\ldots,K)$: is the linking intermediate lth of DMU_j from division k to subsequent division in period t.

$z_{dj}^{(t,k)}(d = 1,\ldots,\ d_k,\ldots,D;\ j = 1,\ldots,n;\ t = 1,\ldots,T-1;\ k = 1,\ldots,K)$: is the carry-over dth ofDMU_j, at division k from period t to next period.

The approach starts from the primal moving towards the dual. Denoting totals of$x_{io} = \sum_{t=1}^{T}\sum_{k=1}^{K} x_{io}^{(t,k)}$ and $y_{ro} = \sum_{t=1}^{T}\sum_{k=1}^{K} y_{ro}^{(t,k)}$, the efficiency of DMU$o$ under the assumption of constant returns to scale is calculated via the following CCR model:

Model (4):

$$E_o^{sys} = max \cdot \sum_{r=1}^{s} u_r y_{ro} + \sum_{k=1}^{K}\sum_{d=1}^{D} f_d \cdot z_{do}^{(T,k)} \tag{20}$$

$s.t$:

$$\sum_{i=1}^{m} v_i x_{io} + \sum_{k=1}^{K}\sum_{d=1}^{D} f_d . z_{do}^{(t_0,k)} = 1 \tag{21}$$

$$\sum_{r=1}^{s} u_r y_{rj} + \sum_{k=1}^{K}\sum_{d=1}^{D} f_d . z_{do}^{(T,k)} - \left(\sum_{i=1}^{m} v_i x_{ij} + \sum_{k=1}^{K}\sum_{d=1}^{D} f_d \cdot z_{do}^{(t_0,k)}\right) \le 0 \quad (j = 1,\ldots,n) \tag{22}$$

Division $k = 1$:

$$\sum_{r\in r^1} u_r \cdot y_{rj}^{(t,1)} + \sum_{l\in l^1} w_l \cdot c_{lj}^{(t,1)} + \sum_{d\in d^1} f_d \cdot z_{dj}^{(t,1)} - \left(\sum_{i\in i^1} v_i \cdot x_{ij}^{(t,1)} + \sum_{d\in d^1} f_d \cdot z_{dj}^{(t-1,1)}\right) \le 0 \quad (j = 1,\ldots,n\ ;\quad t = 1,\ldots,T) \tag{23}$$

Division$k = 2\ldots,K-1$:

$$\sum_{r\in r^k} u_r \cdot y_{rj}^{(t,k)} + \sum_{l\in l^k} w_l \cdot c_{lj}^{(t,k)} + \sum_{d\in d^k} f_d \cdot z_{dj}^{(t,k)} - \left(\sum_{i\in i^k} v_i \cdot x_{ij}^{(t,k)} + \sum_{l\in l^k} w_l \cdot c_{lj}^{(t,k-1)} + \sum_{d\in d^k} f_d . z_{dj}^{(t-1,k)}\right) \le 0 \quad (j = 1,\ldots,n\ ;\quad t = 1,\ldots,T) \tag{24}$$

Division$k = K$:

$$\sum_{r\in r^K} u_r \cdot y_{rj}^{(t,K)} + \sum_{d\in d^K} f_d \cdot z_{dj}^{(t,K)} - \left(\sum_{i\in i^K} v_i \cdot x_{ij}^{(t,K)} + \sum_{l\in l^K} w_l \cdot c_{lj}^{(t,K-1)} + \sum_{d\in d^K} f_d \cdot z_{dj}^{(t-1,K)}\right) \le 0 \quad (j = 1,\ldots,n\ ;\quad t = 1,\ldots,T) \tag{25}$$

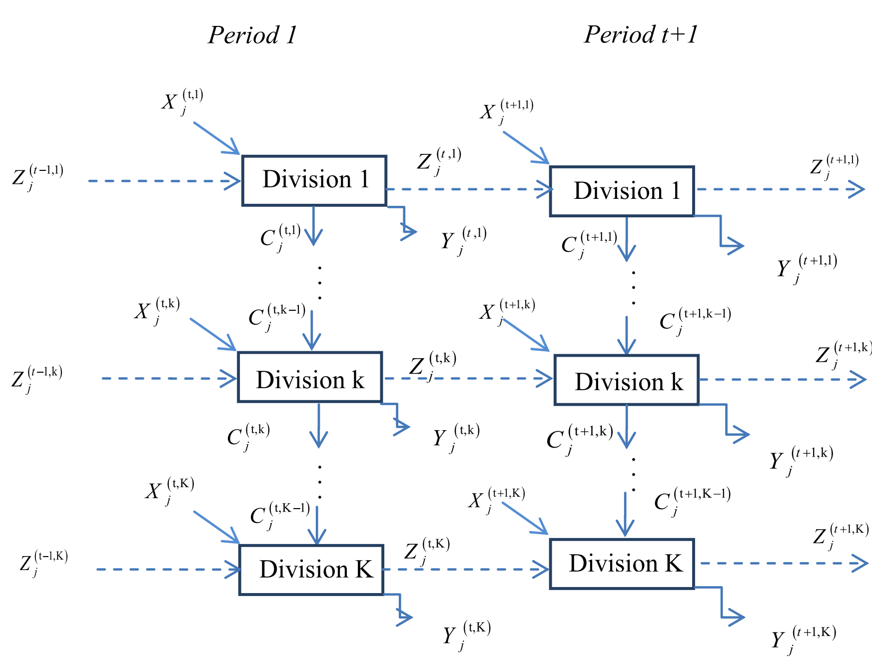

Fig. 3. A dynamic model with multi-stage structure.

$$v_i, u_r, w_l, f_d \geq \varepsilon \quad i = 1, ..., m; \quad r = 1, ..., s; \quad l = 1, ..., L; \quad d = 1, ..., D \tag{26}$$

Where w_l and f_d are the multiplier associated with the l th intermediate product and f th carry-over from one period to next, respectively. It is notable that $z_{do}^{(t_0,k)}$ and $z_{do}^{(T,k)}$ are$d$ th initial input flow which enters to division k from period t_0(as beginning period in timespan) and d th last output flow of division k in period$T$ for under study DMUo, respectively. The sum of constraints corresponding to the t periods of k processes is just the constraint corresponding to the system for every DMU. Therefore, the constraint corresponding to the system is redundant and can be removed. The objective is to find optimal solutions ofu_r^*, v_i^*, w_l^* and f_d^* that maximizes overall efficiency of the DMU being evaluated. This input-oriented model is radial and optimizes all inputs or outputs of a DMU in a constant proportion and one can extend the model to output-oriented form. The system and process efficiencies in each period are:

$$E_o^{sys} = \frac{\sum_{r=1}^{s} u_r^* y_{ro} + \sum_{k=1}^{K} \sum_{d=1}^{D} f_d^* \cdot z_{do}^{(T,k)}}{\sum_{i=1}^{m} v_i^* x_{io} + \sum_{k=1}^{K} \sum_{d=1}^{D} f_d^* \cdot z_{do}^{(t_0,k)}} = 1 - s_o^{sys*} \tag{27}$$

$$E_o^{(t,sys)} = \frac{\sum_{k=1}^{K} \sum_{r=1}^{s} u_r^* y_{ro}^{(t,k)} + \sum_{k=1}^{K} \sum_{d=1}^{D} f_d^* \cdot z_{do}^{(t,k)}}{\sum_{k=1}^{K} \sum_{i=1}^{m} v_i^* x_{io}^{(t,k)} + \sum_{k=1}^{K} \sum_{d=1}^{D} f_d^* \cdot z_{do}^{(t-1,k)}} \tag{28}$$

$$\begin{aligned} E_o^{(t,1)} &= \frac{\sum_{r \in r^1} u_r^* \cdot y_{ro}^{(t,1)} + \sum_{l \in l^1} w_l^* \cdot c_{lo}^{(t,1)} + \sum_{d \in d^1} f_d^* \cdot z_{do}^{(t,1)}}{\sum_{i \in i^1} v_i^* \cdot x_{io}^{(t,1)} + \sum_{d \in d^1} f_d^* \cdot z_{do}^{(t-1,1)}} \\ &= 1 - \left(s_o^{(t,1)*} \Big/ \left(\sum_{i \in i^1} v_i^* \cdot x_{io}^{(t,1)} + \sum_{d \in d^1} f_d^* \cdot z_{do}^{(t-1,1)} \right) \right) \\ &= 1 - \hat{s}_o^{(t,1)*} \end{aligned} \tag{29}$$

$$\begin{aligned} E_o^{(t,k)} &= \frac{\sum_{r \in r^k} u_r^* \cdot y_{ro}^{(t,k)} + \sum_{l \in l^k} w_l^* \cdot c_{lo}^{(t,k)} + \sum_{d \in d^k} f_d^* \cdot z_{do}^{(t,k)}}{\sum_{i \in i^k} v_i^* \cdot x_{io}^{(t,k)} + \sum_{l \in l^k} w_l^* \cdot c_{lo}^{(t,k-1)} + \sum_{d \in d^k} f_d^* \cdot z_{do}^{(t-1,k)}} \\ &= 1 - \left(s_o^{(t,k)*} \Big/ \left(\sum_{i \in i^k} v_i^* \cdot x_{io}^{(t,k)} + \sum_{l \in l^k} w_l^* \cdot c_{lo}^{(t,k-1)} + \sum_{d \in d^k} f_d^* \cdot z_{do}^{(t-1,k)} \right) \right) = 1 - \hat{s}_o^{(t,k)*}, k = 2, ..., K-1 \end{aligned} \tag{30}$$

$$\begin{aligned} E_o^{(t,K)} &= \frac{\sum_{r \in r^K} u_r^* \cdot y_{ro}^{(t,K)} + \sum_{d \in d^K} f_d^* \cdot z_{do}^{(t,K)}}{\sum_{i \in i^K} v_i^* \cdot x_{io}^{(t,K)} + \sum_{l \in l^K} w_l^* \cdot c_{lo}^{(t,K-1)} + \sum_{d \in d^K} f_d^* \cdot z_{do}^{(t-1,K)}} \\ &= 1 - \left(s_o^{(t,K)*} \Big/ \left(\sum_{i \in i^K} v_i^* \cdot x_{io}^{(t,K)} + \sum_{l \in l^K} w_l^* \cdot c_{lo}^{(t,K-1)} + \sum_{d \in d^K} f_d^* \cdot z_{do}^{(t-1,K)} \right) \right) = 1 - \hat{s}_o^{(t,K)*} \end{aligned} \tag{31}$$

Wheres_o^{sys*}, $s_o^{(t,1)*}$, $s_o^{(t,k)*}$ and$s_o^{(t,K)*}$ are the slack variables associated with the system constraints (17), (18), (19) and (20), respectively. Since the sum of constraints corresponding to the t periods of k processes is equal to the system constraint, we have$s_o^{sys*} = \sum_{t=1}^{T} \sum_{k=1}^{K} s_o^{(t,k)*}$. It shows that the inefficiency of processes causes inefficiency of the system. $s_o^{(t,k)*}$ is the difference between aggregated outputs and aggregated inputs of DMUo in the model. For obtaining a relationship between system and processes efficiency, it's easy to obtain the relationship between system and processes inefficiency, which are described with slack variables. By applying the system inefficiencys_o^{sys*}, division 1 inefficiency$\hat{s}_o^{(t,1)*}$, division k inefficiency $\hat{s}_o^{(t,k)*}(k = 2, ..., K-1)$ and division K inefficiency$\hat{s}_o^{(t,K)*}$ obtained from equations 27–31, we have:

$$s_o^{(t,1)*} = \left(\sum_{i \in i^1} v_i^* \cdot x_{io}^{(t,1)} + \sum_{d \in d^1} f_d^* \cdot z_{do}^{(t-1,1)} \right) \hat{s}_o^{(t,1)*} = \hat{w}^{(t,1)} \hat{s}_o^{(t,1)*} \tag{32}$$

$$\begin{aligned} s_o^{(t,k)*} &= \left(\sum_{i \in i^k} v_i^* \cdot x_{io}^{(t,k)} + \sum_{l \in l^k} w_l^* \cdot c_{lo}^{(t,k-1)} + \sum_{d \in d^k} f_d^* \cdot z_{do}^{(t-1,k)} \right) \hat{s}_o^{(t,k)*} \\ &= \hat{w}^{(t,k)} \hat{s}_o^{(t,k)*}, \quad k = 2, ..., K-1 \end{aligned} \tag{33}$$

$$\begin{aligned} s_o^{(t,K)*} &= \left(\sum_{i \in i^K} v_i^* \cdot x_{io}^{(t,K)} + \sum_{l \in l^K} w_l^* \cdot c_{lo}^{(t,K-1)} + \sum_{d \in d^K} f_d^* \cdot z_{do}^{(t-1,K)} \right) \hat{s}_o^{(t,K)*} \\ &= \hat{w}^{(t,K)} \hat{s}_o^{(t,K)*} \end{aligned} \tag{34}$$

$$s_o^{sys*} = \sum_{t=1}^{T}\sum_{k=1}^{K} s_o^{(t,k)*} = \sum_{t=1}^{T}\left(\widehat{w}^{(t,1)}\widehat{s}_o^{(t,1)*} + \sum_{k=2}^{K-1}\left(\widehat{w}^{(t,k)}\widehat{s}_o^{(t,k)*}\right) + \widehat{w}^{(t,K)}\widehat{s}_o^{(t,K)*}\right) \tag{35}$$

The dual form of the proposed model does not ask for weights for the divisions as the one proposed by Tone and Tsutsui (2014). The constraints (33) and (34) correspond to the system inputs and final outputs. The constraint (35) corresponds to the link between two consecutive stages. This constraint indicates that the output of the stage, which produces it, must be lower than or equal to the input of the same stage that consumes it. The constraint (36) corresponds to the carry-over between two consecutive periods and show the output of the period that produces it be lower than or equal to the input of the same period that consumes it.

$$\begin{aligned} E_o^{sys} &= 1 - s_o^{sys*} \\ E_o^{sys} &= 1 - \sum_{t=1}^{T}\left(\widehat{w}^{(t,1)}\left(1 - E_o^{(t,1)}\right) + \sum_{k=2}^{K-1}\left(\widehat{w}^{(t,k)}\left(1 - E_o^{(t,k)}\right)\right) + \widehat{w}^{(t,K)}\left(1 - E_o^{(t,K)}\right)\right) \\ E_o^{sys} &= 1 - \sum_{t=1}^{T}\left(\widehat{w}^{(t,1)} + \sum_{k=2}^{K-1}\widehat{w}^{(t,k)} + \widehat{w}^{(t,K)}\right) + \sum_{t=1}^{T}\left(\widehat{w}^{(t,1)}E_o^{(t,1)} + \widehat{w}^{(t,k)}\sum_{k=2}^{K-1}E_o^{(t,k)} + \widehat{w}^{(t,K)}E_o^{(t,K)}\right) \end{aligned} \tag{36}$$

Equations (32) (33) and (34) are derived from Equations (29) (30) and (31), respectively and show the relationship between slack variables of processes ($s_o^{(t,k)*}$) and their inefficiencies ($\widehat{s}_o^{(t,k)*}$). Equation (35) shows that the overall inefficiency is equal to summation of weighted inefficiency of processes. So the relationship between system and processes efficiency over T periods of time can be proposed by:

To formulate the envelopment-form of DNDEA model which is the dual of model (2), the term $\sum_{i\in i^k} v_i\cdot x_{ij}^{(t,k)}$ and $\sum_{r\in r^k} u_r\cdot y_{rj}^{(t,k)}$ will be replaced by $\sum_{i=1}^{m} v_i\cdot x_{ij}^{(t,k)}$ and$\sum_{r=1}^{s} u_r\cdot y_{rj}^{(t,k)}$, respectively, where and$y_{rj}^{(t,k)}, r\notin r^k$, have a value of zero and the redundant constraint will be removed. So, the envelopment model can be formulated as follows:

Model (5):

$$Min\ \ \theta - \varepsilon\left(\sum_{i=1}^{m} s_i^- + \sum_{r=1}^{s} s_r^+ + \sum_{l=1}^{L}\sum_{k=1}^{K} s_{lk} + \sum_{d=1}^{D}\sum_{k=1}^{K} s_{dk}\right) \tag{37}$$

$s.t$:

$$\sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{j=1}^{n} \lambda_j^{(t,k)}\cdot x_{ij}^{(t,k)} + s_i^- = \theta x_{io} \quad i = 1,2,\dots,m \tag{38}$$

$$\sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{j=1}^{n} \lambda_j^{(t,k)}\cdot y_{rj}^{(t,k)} - s_r^+ = y_{ro} \quad r = 1,2,\dots,s \tag{39}$$

$$\sum_{t=1}^{T}\sum_{j=1}^{n} \lambda_j^{(t,k)}\cdot c_{lj}^{(t,k)} - \sum_{t=1}^{T}\sum_{j=1}^{n} \lambda_j^{(t,k+1)}\cdot c_{lj}^{(t,k)} - s_{lk} = 0 \quad k = 1,2,\dots,K-1 \quad l\in l^k \tag{40}$$

$$\sum_{t=1}^{T}\sum_{j=1}^{n} \lambda_j^{(t,k)}\cdot\left(z_{dj}^{(t,k)} - z_{dj}^{(t-1,k)}\right) + z_{do}^{(T,1)} - s_{dk} = \theta z_{do}^{(1,1)} \quad k = 1,2,\dots,K \quad d\in d^k \tag{41}$$

$$\lambda_j^{(k,t)}, s_i^-, s_r^+, s_{lk}, s_{dk} \ge 0, \theta free, \quad j = 1,2,\dots,n; \quad k = 1,2,\dots,K; \quad t = 1,2,\dots,T \tag{42}$$

5. Case study: Iranian airlines

Iran Civil Aviation Organization (CAO) is established in 1946 and is responsible for applying rules to air transport industry, control airport's performance and safe flights. This governmental organization became a member of the International Civil Aviation Organization (ICAO) in 1949. “Iranian Airways” was the first domestic airline, which started to work in 1946. Persian Airways was another private airline that was established in 1954 for transporting cargo to Europe. Different factors such as Iran's geographical situation, people's welfare and requirements of having relationship with other countries caused the government to establish a national airline. Thus, in 1962 “Iranian Airways” and “Persian Airways” were merged and “Iranian national airline” was established that was known as “Iran Air”, internationally. Developments in technology and societies caused civil air transport to develop and allow private airlines to start their work. Now, 16 local airlines are active in Iran, such as Ata, Aseman, Taban, Iran air tour, Kaspian, Naft Iran, Mahan, Kish, which are responsible to carry passenger and transport cargo.

The framework to analyze the performance of transportation industry has been proposed in the literature. Sengupta (1999) proposed a dynamic efficiency model involving inter-temporal cost minimization in the framework of a DEA model and utilized the model to assess seven international airlines during 1988–1994. Three types of efficiency, e.g., technical efficiency, allocative efficiency and scale efficiency are measured over time. Zhu (2011) presented a two-stage network to consider the internal structure of airline companies and used centralized model to calculate overall and stage efficiency. In the first stage, resources such as fuel cost, benefit and other factors are used to maintain the load factor and fleet size, which generate revenue in the second stage. Centralized model was used to study the performance of 21 airlines during 2007 and 2008. Transportation services are non-storable, for example the seat-miles and airplane must be consumed by passenger concurrently, and otherwise they are wasted (Yu and Lin, 2008). These intertwined activities construct a two-stage structure composed of production and consumption processes (Tavassoli et al., 2014). Due to non-storable characteristic of transit systems, Yu and Lin (2008) presented a multi-activity network that represents production and consumption technologies in a unified framework and used a network DEA model to measure the technical efficiency (ratio of production to input factors), service effectiveness (ratio of consumption to production) and technical effectiveness (ratio of consumption to input factors) of 20 railways, simultaneously. Yu (2012) presented a two-process air route operation including production and consumption flows to analyze service efficiency (SE), production efficiency (PE) and operational efficiency (OE). DEA models ignore non-zero slacks associated with inputs and outputs. So the inefficiency source in inputs and outputs cannot be identified. Yu (2012) proposed enhanced-Russell measure (ERM-NDEA) model to overcome the problem. This model averages the input and the output efficiency separately and then combines these two efficiencies in a ratio form and reflects the nonzero slacks by allowing some inputs and outputs to be zero. The author assessed transport services of 15 domestic Taiwanese airlines to find input excesses without altering outputs of the production process, which cause production inefficiency and output shortfalls without changing intermediate inputs. Lozano and Gutierrez (2014) proposed a two-stage network of airline's operation, which is consisting of production process and sales process. Production process uses fuel cost, wages and operating costs to produce available seat kilometers and available ton kilometers. The available seat kilometers and available ton kilometers are input for sales process to produce revenue passenger kilometers and revenue ton kilometers. The study applied a slack-based network DEA to analyze the efficiency of European airlines. Lu et al. (2012) proposed a two-stage production process by using inputs such as the number of employees, fuel consumed, seating capacity and maintain expense to produce revenue passenger miles and non-passenger revenue. They calculated production efficiency and marketing efficiency and suggested that managers should focus first on improving inefficient allocation of resources in production and then their marketing efficiency. Tavassoli et al. (2014) used a slacks-based network DEA approach to measure technical efficiency and service effectiveness of Iranian airlines. They presented a network structure composed of production and consumption sections, which are separated to passenger and cargo processes. However, the studies on Iranian airlines' efficiency are very few.

5.1. Structure of airline activities

According to Zhu (2011), Yu (2012), Lozano (2014) and Lu et al. (2012), for assessing the performance of airlines, the airline structure is separated into two stages connected in series, which are named “Production” and “Consumption”. In each stage, for evaluating the performance of airlines, suitable inputs and outputs are selected from previous studies (Adler and Golany, 2001; Zhu, 2011; Lu et al., 2012; Tavassoli et al., 2014; Lozano and Gutierrez, 2014). The model presented in this study considers the dynamic aspect of activities in an organization. Thus, in our case study, a new flow is introduced to present the connection between single periods in a time span. Fig. 4 shows the dynamic two-stage structure of airlines.

5.2. Indicators and data

In the current analysis, financial factors are not included because the data was not available. Fig. 2 exhibits the structure of Iranian airlines consisting of two stages, production and consumption.

- Inputs: the number of employees (X)
- Intermediate products: available seat-kilometer (C_1), available ton-kilometer (C_2), and number of scheduled flights (C_3)
- Carry over flow among periods: the number of fleet's seat (Z)
- Outputs: passenger-kilometer performed (Y_1) and passenger ton-kilometer perfumed (Y_2)

The definitions of the selected factors are as follows:

The number of employees: number of the people working in the airline such as pilot, flight attendant, engineering and etc.

Available seat-kilometer: sum of the products obtained by multiplying the number of passenger seats available for sale on each flight stage by the stage distance.

Available ton-kilometer: sum of the products obtained by multiplying the number of tons available for the carriage of revenue load on each flight stage by the stage distance.

Scheduled flights: flights scheduled and perfumed according to a published timetable.

Fleet seat: the number of seats offered by the fleet.

Passenger-kilometer perfumed: sum of products obtained by multiplying the number of revenue passengers carried on each flight stage by the stage distance.

Ton-kilometer perfumed: multiplication of carried weight (ton) in every origin and destination of flight by the distance between the same origin and destination.

In this paper, the numbers of input and outputs variables are not at least three times more DMUs. The rule of at least three times more DMUs than the sum of inputs and outputs is necessary in conventional DEA model. Indeed, in conventional DEA model, if this issue is not considered, DEA is not able to distinguish among DMUs and the efficiency score of most of DMUs will be equal to one. However, in some models such as common weight DEA, cross efficiency DEA and NDEA models this rule is not necessary. In NDEA models, because of special structure of the model, the efficiency

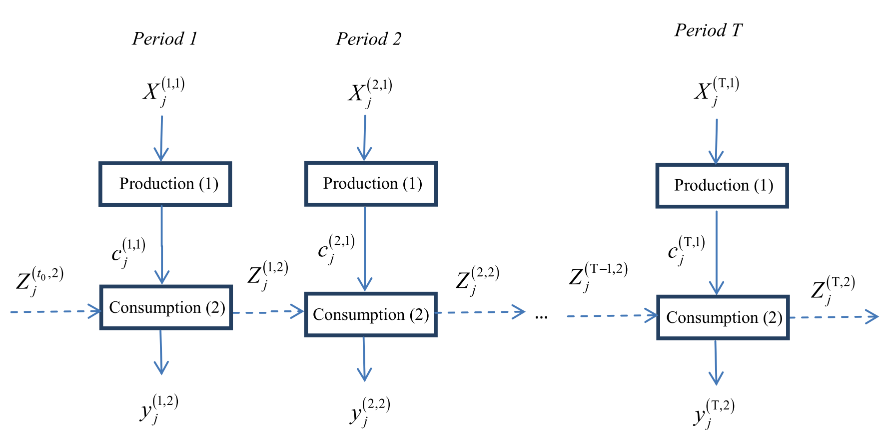

Fig. 4. Two-stage structure of Iranian airlines with flows connecting two consecutive periods.

Table 1
Data of the eight Iranian airlines in 2010–2012.

DMU	Number of employees	Available seat-km	Available ton-km	Number of scheduled flights	Passenger-km performed	Passenger ton-km performed	Number of fleet seat
Ata	434	1,029,362	115,802	8603	918,266	101,738	1470
Aseman	3192	2,583,457	222,795	38,979	23,343	193,573	3358
Iranairtour	809	1,285,423	113,176	10,795	1,022,305	92,674	1814
Taban	540	419,295	83,587	4355	376,632	70,272	874
Kaspian	276	381,259	34,810	2625	268,848	29,218	573
Kish	869	1,226,011	130,156	10,531	1,053,827	106,511	1673
Mahan	4712	3,632,645	514,161	21,315	3,009,943	272,293	10,617
Naftiran	549	531,229	56,432	9584	423,241	29,886	679

Table 2
Overall and period efficiencies.

DMU	Overall	Rank	System			Stage 1			Stage 2		
			2010	2011	2012	2010	2011	2012	2010	2011	2012
Ata	0.974	1	0.989	0.939	1	1	0.933	1	0.989	0.994	1
Aseman	0.339	8	0.410	0.381	0.340	0.373	0.342	0.303	0.960	0.961	0.946
Iranairtour	0.598	2	0.644	0.625	0.649	0.657	0.579	0.642	0.919	1	0.918
Taban	0.440	5	0.558	0.531	0.542	0.290	0.481	0.452	0.961	0.806	0.877
Kaspian	0.468	4	0.389	0.558	0.553	0.633	0.512	0.502	0.566	0.909	0.987
Kish	0.546	3	0.443	0.493	0.730	0.484	0.523	0.742	0.916	0.943	0.984
Mahan	0.357	7	0.517	0.512	0.652	0.262	0.225	0.344	0.883	0.958	0.936
Naftiran	0.366	6	0.285	0.391	0.531	0.268	0.393	0.551	0.865	0.882	0.896
Average	0.511		0.529	0.554	0.624	0.496	0.498	0.567	0.882	0.932	0.943

scores for most of the DMUs are different. As shown in the results of our paper, the efficiency scores of DMUs are different and the mentioned rule is not required for the proposed DNDEA model.

Table 1 shows the inputs, outputs, links and carry-overs of Iranian airlines for the years of 2010, 2011 and 2012. In this case study, since other airlines had not presented annual data, only eight airlines are considered to analyze. The actual data are gathered from Civil Aviation Organization (CAO) of Iran. The dataset are displayed in Table 1. It's notable that the data pertain to internal flights and international flights are ignored.

6. Results

The input-oriented CRS relational dynamic network DEA (DNDEA) model discussed in section 4 is applied to a dataset of Iranian airlines over three years. Table 2 depicts the obtained results from relational DNDEA model and has separated the system efficiency to two stages' scores over the years of 2010–2012. In this case study, stage 2 is more efficient than stage 1. The second column of Table 2 reports the overall efficiency of airlines. Ata has the highest rank in overall efficiency scores, 0.974 and Aseman has the lowest, 0.339. The average of overall efficiency of 8 airlines in the three-year period is 0.511, which shows mediocre performance. The columns 4, 5 and 6 show the system efficiency in three periods. The average score of system efficiency in 2010, 2011 and 2012 are 0.529, 0.554 and 0.624, respectively. Stage efficiency scores over three periods are presented in subsequent columns. There is only one DMU (Ata) which is efficient for the stage 1 during 2010 and 2012, and also for stage 2 during 2012. Furthermore, there is one DMU (Iran air tour) which is efficient for second stage in 2011. The system efficiency of relational models in series network is the product of stages efficiency. To consider this property, the mean of 8 DMUs is

Table 4
Overall efficiency scores of DNDEA and DDEA models.

DMU	Overall efficiency	
	DNDEA	DDEA
Ata	0.974	0.987
Aseman	0.339	0.421
Iranairtour	0.598	0.781
Taban	0.440	0.457
Kaspian	0.468	0.596
Kish	0.546	0.552
Mahan	0.357	0.531
Naftiran	0.366	0.491
Average	0.511	0.602

Table 3
Inefficiency variables.

DMU	$\widehat{s}_o^{(t,1)*}$			$\widehat{s}_o^{(t,2)*}$			$\widehat{w}^{(t,1)}$			$\widehat{w}^{(t,2)}$			$s_o^{sys*} = \sum_{t=1}^{T}(\widehat{w}^{(t,1)}\widehat{s}_o^{(t,1)*} + \widehat{w}^{(t,2)}\widehat{s}_o^{(t,2)*})$
	2010	2011	2012	2010	2011	2012	2010	2011	2012	2010	2011	2012	
Ata	0	0.067	0	0.011	0.006	0	0.268	0.301	0.369	0.329	0.347	0.435	0.026
Aseman	0.627	0.658	0.697	0.040	0.039	0.054	0.299	0.331	0.342	0.140	0.143	0.133	0.661
Iranairtour	0.343	0.421	0.358	0.081	0	0.082	0.290	0.352	0.315	0.233	0.247	0.273	0.402
Taban	0	0.780	0.795	0	0.329	0.240	0.261	0.207	0.213	0.579	0.236	0.205	0.560
Kaspian	0.367	0.488	0.498	0.434	0	0.009	0.263	0.330	0.361	0.212	0.203	0.227	0.532
Kish	0.516	0.477	0.258	0.084	0.057	0.016	0.381	0.317	0.302	0.184	0.166	0.224	0.454
Mahan	0.738	0.775	0.656	0.711	0.042	0.016	0.267	0.318	0.205	0.279	0.283	0.309	0.643
Naftiran	0.732	0.607	0.449	0.135	0.118	0.104	0.327	0.317	0.327	0.117	0.153	0.213	0.634

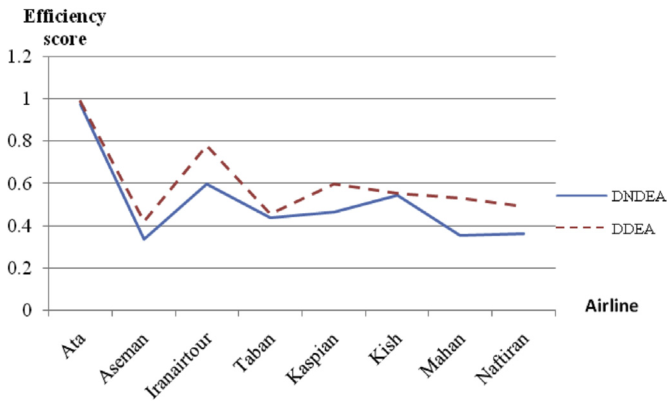

Fig. 5. Comparison of DNDEA and DDEA.

calculated in the last row of Table 2. For example, during 2010, the system efficiency average, 0.529, is the multiply of the two stage averages, 0.496 and 0.882. For obtaining the relationship between system and stage's efficiency scores, Table 3 shows the $\hat{s}_o^{(t,1)*}$, $\hat{s}_o^{(t,2)*}$, $\hat{w}^{(t,1)}$ and $\hat{w}^{(t,2)}$ measures. The last column of Table 3 represents s_o^{sys*} that is equal to $1 - E_o^{sys}$.

In order to clarify the advantage of relational DNDEA method over dynamic DEA (DDEA) model, the results of both models are compared in Table 4. As mentioned in section 3, DDEA model neglects the internal relations between subsystems. In this model the input/output factor is the sum of same inputs/outputs in all divisions and the carry-over is the same with DNDEA model. The efficiency scores obtained from DDEA model are higher than those of DNDEA model. It is possible that the efficient DMUs in DDEA be inefficient in DNDEA. For example, DMU1 has obtained the overall efficiency score of 0.987 by DDEA, but 0.974 by DNDEA. The difference is because of considering the network structure of DMU in DNDEA model, while DDEA model aggregates the subsystems into a single company which uses inputs to produce outputs. Fig. 5 compares the overall efficiencies between DDEA and DNDEA models. Network (DEA) model calculates the efficiency scores of system and subsystems in all periods, separately. Since this model neglects the relationship between periods, we can compare the obtained results from DNDEA model with those of NDEA model to find out the role of dynamic factor in measuring the performance of system in a timespan. Table 5 shows the system efficiency scores of NDEA model in three separate periods. Only Ata airline is efficient in 2012, other airlines have lower efficiencies. Table 5 shows the efficiency scores of DMUs calculated by three models of DDEA, NDEA and DNDEA during 2010, 2011 and 2012. It is obvious that the scores of DNDEA model are between DDEA and NDEA models. Scores of DNDEA model are higher than the scores of NDEA model. The efficiency scores calculated from the DNDEA model is larger than that calculated from the NDEA one. Because when you develop a NDEA model to DNDEA one, a new variable, which shows the dynamic aspect of processes is added. Indeed a constraint is added to the dual problem, which is minimization one. Thus, it's possible that the optimal solution gets better and the value of optimal solution in minimization problem becomes smaller. Since in optimality the solutions of both primal and dual problems are equal, the value of primal problem becomes greater. So we see that the efficiency scores calculated by DNDEA model are bigger than those calculated with NDEA model. Also, when a DDEA model is expanded to DNDEA one, some constraints are added to the primal model (each constraint in primal problem represents inputs and outputs of a division in system) and some variables are added to the dual model. So, it's probable that the solutions of dual model become greater and equally the solutions of primal model become smaller. Thus, the optimal solution obtained by DDEA doesn't get better in DNDEA model and we see that the solutions of DNDEA are lower than DDEA one.

7. Conclusion

Evaluation the performance of a system and its component processes over multiple periods requires a model that measures the efficiency of network considering its extension on a time span. In this paper, the relational DNDEA model is developed to incorporate the dynamic effect in network systems. This model has two advantages; first, considering the internal structure of DMU helps to detect the inefficient processes and improve them. Second, the temporal dimension of production processes is included. The relational model of this paper measures the efficiency of processes in connected time periods, properly and there is a mathematical relationship between processes over the time. Comparing the relational and SBM approaches, it's obvious that SBM approach uses slack variables for calculating the efficiency scores and there is no relationship between the efficiency scores of system and subsystems. This paper develops the two-stage form of the dynamic DEA model. The formulation of two-stage model can be extended to multi-stage networks. To illustrate the capability of the proposed model, the efficiencies of 8 airlines in Iran were measured over 2010 to 2012 with considering the interaction between time periods and divisions. The results obtained from the model help us to identify the divisions which cause the system to have lower efficiency. Decomposition the performance of a company to the component processes in a time span produces meaningful results. In the Iranian airlines, Ata airline has the highest rank between other airlines during 2010–2012 in both of two stages. The average of efficiency scores shows that the airlines have had the better performance in stage 2. Also, since the airlines have poor performance in stage 1, so, the final efficiency scores for airlines system are low.

Table 5
Different efficiency measures of Iranian airlines.

DMU	DNDEA			NDEA			DDEA		
	2010	2011	2012	2010	2011	2012	2010	2011	2012
Ata	0.989	0.939	1	0.990	0.936	1	1	0.977	1
Aseman	0.410	0.381	0.340	0.350	0.326	0.290	0.612	0.570	0.512
Iranairtour	0.644	0.625	0.649	0.593	0.502	0.586	0.797	1	0.796
Taban	0.558	0.531	0.542	0.533	0.508	0.483	0.572	0.647	0.694
Kaspian	0.389	0.558	0.553	0.325	0.479	0.501	0.583	0.877	0.741
Kish	0.443	0.493	0.730	0.443	0.493	0.730	0.448	0.499	0.739
Mahan	0.517	0.512	0.652	0.294	0.236	0.338	0.661	0.654	0.793
Naftiran	0.285	0.391	0.531	0.225	0.325	0.482	0.499	0.638	0.724
Average	0.529	0.554	0.624	0.469	0.475	0.551	0.646	0.733	0.750

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