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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

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