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New network data envelopment analysis approaches: an application in measuring sustainable operation of combined cycle power plants

Gholam Reza Faramarzi [a], Mohsen Khodakarami [a], Amir Shabani [b], Reza Farzipoor Saen [c,*], Fatemeh Azad [a]

[a] Young Researchers and Elites Club, Karaj Branch, Islamic Azad University, Karaj, Alborz, Iran
[b] Young Researchers and Elites Club, Science and Research Branch, Islamic Azad University, Tehran, Iran
[c] Department of Industrial Management, Faculty of Management and Accounting, Karaj Branch, Islamic Azad University, P. O. Box: 31485-313, Karaj, Iran

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A B S T R A C T

Nowadays, organizations deal with numerous economic, environmental, and social problems. To have sustainable operations, they have begun to incorporate environmental and social concerns into conventional economic objectives. A combined cycle power plant (CCPP) is a good instance of an open system with multistage processes and interconnected activities. Efficiency evaluation of CCPPs is a complex task since there exist a variety of inputs (outputs) which enter into any stages of network. Additionally, there might be intermediate products which are consumed by the same power plants. We call such factors "loop" intermediate measures. To measure efficiency of CCPPs, network data envelopment analysis (NDEA) is used. This paper proposes new NDEA models to evaluate efficiency of CCPPs. The proposed models calculate the efficiency of power plants and their sub-sectors under both CRS (constant returns to scale) and VRS (variable returns to scale) assumptions. This paper provides a comprehensive analysis for returns to scale. We apply the new NDEA models to measure relative efficiency of CCPPs.

1. Introduction

Organizations as open systems interact with their environment. Nowadays, organizations deal with numerous economic, environmental, and social problems. To be sustainable, they have begun to incorporate environmental and social concerns into conventional economic objectives. Balancing economic, environmental, and social operations to realize sustainable development is a major objective of many responsible organizations (Shabani et al., 2014; Jabbour and Jabbour, 2009). However, sustainability evaluation of the open system is a complex task, and many approaches for measuring sustainability cannot deal with this multidimensional perspective (Gerdessen and Pascucci, 2013).

A combined cycle power plant (CCPP) is a good instance of an open system with multistage processes and interconnected activities. The process of generating electric power includes different activities such as generation, transmission, distribution, and retailing, which consumes large amounts of capital, labor, and financial resources (Vaninsky, 2006). Among these activities, the generation of electric power is at core of the production process. According to Yuzhi and Zhangna (2012), one of the features of electric power is that it is non-storable. Therefore, its production, transportation, sales, and consumption are done concurrently (Farzipoor Saen, 2010). Perishable nature of non-storable commodities forces decision makers to be efficient to prevent losses (Tavassoli et al., 2015). From another point of view, power plants are one of the major users of fossil fuels in the world and their environmental impact such as pollution and global warming are significant. In the meantime, power plants influence societies.

Farrell (1957) proposed a method to evaluate technical efficiency of decision making units (DMUs), and determined an efficient frontier to measure efficiency of each DMU. The classical data envelopment analysis (DEA) model deals with multiple inputs and single output. Based on Farrell (1957), CCR (Charnes, Cooper, and Rhodes) was developed to measure efficiency of DMUs with multiple inputs and multiple outputs (Charnes et al., 1978). Their approach is called DEA. Subsequently, BCC (Banker, Charnes, and Cooper) model was extended under VRS (variable returns to scale) assumption by Banker et al. (1984).

* Corresponding author. Tel.: +98 (26) 34418144 6; fax: +98 (26) 34418156.
E-mail addresses: grfaramarzi@yahoo.com (G.R. Faramarzi), m.khodakarami@chmail.ir (M. Khodakarami), shabani_dp@yahoo.com (A. Shabani), farzipour@yahoo.com (R. Farzipoor Saen), azad.fatemeh@chmail.ir (F. Azad).

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In conventional applications of DEA, a DMU is generally treated as a "black box" in which internal processes are not examined (Farzipoor Saen, 2009). In the conventional applications of DEA, initial inputs and final outputs are considered and production system is assumed as a whole unit. However, in some situations, the DMU may have network structure. To overcome this shortcoming, Färe and Grosskopf (1996) were the first researchers who proposed network data envelopment analysis (NDEA) approach. To evaluate efficiency of DMUs with network structure, the NDEA model can be used. Therefore, the NDEA is a proper approach to evaluate efficiency of electric power plants. It deals with efficiency of divisions as well as overall efficiency in a unified framework (Tone and Tsutsui, 2009).

Most of previous studies on NDEA (e.g., Kao and Hwang, 2008; Liang et al., 2008; Chen et al., 2009) focus on pure serial processes in which the outputs of a stage are totally passed on to the next stage as inputs. In other word, neither input nor output enter or leave the network at intermediate stages, while in most of real life cases, there may be outputs from a given stage that leave network. Also, there might be external inputs that enter in any stage of the network. Some studies have been done to rectify this shortcoming (e.g., Tone and Tsutsui, 2009; Cook et al., 2010; Kao, 2014; Lozano, 2015). As Chen et al. (2013) addressed, the problem with the multiplier-based divisional efficiency under VRS is that it cannot be solved as a linear program. Cook et al. (2010) evaluated the efficiency of multistage processes with different types of inputs and outputs through a multiplier-based NDEA model. They defined open multistage process in which each stage has its own inputs and two types of outputs. One type of output is as an input to the next stage, and another type of output leaves the stage. However, their model works under constant return to scale (CRS) assumption. Furthermore, in multistage processes, there exist intermediate measures that are consumed by the same network. We call such a factor as "loop" intermediate measure. For CCPPs in electric power companies, for example, two gas power plants are arranged in parallel process whose generated electricity is transmitted to the network. Exhausted hot gas from two gas turbines is used to generate steam by passing it through heat recovery steam generators (HRSGs). The generated steam by HRSGs is jointly used to feed a steam turbine. In CCPPs, the generated electricity by gas or steam "re-enter" as an input for driving pumps, fans, and other equipment. Applying the NDEA models to determine performance of multistage processes we can receive further insights from the obtained results and accordingly we can make appropriate policy for performance improvement (Yu and Lin, 2008). In other words, employing the NDEA models determines not only inefficient DMUs, but also shows which inefficient stage of the network causes the inefficiency. As a result, to fill this research gap, and also to obtain returns to scale analysis of every stage of the network, this study proposes a new model based on multiplier divisional efficiency under VRS assumption.

Due to conflict objectives, decision making in manufacturing or service organizations may become very complex and uncertain (Wong et al., 2009; Azadi et al., 2015). To deal with such multiple criteria decision making (MCDM) problems, multi-objective programming methods including multiple objective linear programming (MOLP) models are introduced. Accordingly, this paper proposes new NDEA models based on MOLP concept to consider new inputs (outputs) which enter into (depart from) any stage of the network. This paper, first applies MOLP to propose a new linear NDEA model under CRS (constant returns to scale) assumption. Then, using this linear model, a new NDEA model under VRS (variable returns to scale) assumption is developed to measure the efficiency of both CCPPs and their sub-sectors. Furthermore, a comprehensive analysis for returns to scale of every stage can be achieved by this model. The present study has several distinctive innovations in the fields of Operations Research and sustainable development. The main contributions of this paper are as follows:

- Employing MOLP concept, a new linear NDEA model under CRS assumption is proposed to measure the efficiency of both CCPPs and their sub-sectors.
- Using this new linear model and based on multiplier divisional efficiency, a new NDEA model under VRS (variable returns to scale) assumption is developed.
- The proposed models are easy to implement and do not require complex and time consuming calculations.
- In our proposed models, weights of stages are unknown and their optimal values are determined.
- This paper provides a comprehensive analysis on returns to scale. Utilizing this analysis, one can set more reasonable benchmarks to help an inefficient DMU to become efficient.
- An extensive literature review of the most recent works on estimation of efficiency and sustainability of power plants is given.
- Applicability of proposed models is demonstrated through a case study. This paper for the first time estimates efficiency of network-structured power plants.

This paper is unfolded as follows. In Section 2 literature review is presented, and new NDEA models are developed in Section 3. A case study is presented in Section 4. Concluding remarks are discussed in Section 5.

2. Literature review

2.1. Employed techniques toward sustainability

World Commission on Environment and Development (WCED) defines sustainability as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". According to the United Nations definition, the main components of sustainability are social development, economic development, and environmental protection, which are "three interdependent and mutually reinforcing pillars".

Different methods have been employed to assess sustainability. Examples include analytic hierarchy process (AHP) (Chatzimouratidis and Pilavachi, 2009), fuzzy TOPSIS (Kannan et al., 2014), fuzzy AHP (Tasri and Susilawati, 2014; Deng et al., 2014). The problem with the aforementioned methods is that weights of criteria are often allocated in a subjective manner. This is a very challenging task for decision makers as the numbers of criteria are increased. DEA is a useful tool for allocating the weights to criteria objectively. A number of recent contributions of the DEA technique in measuring sustainability can be seen in Lee and Farzipoor Saen (2012), Zhu et al. (2014), and Khodakarami et al. (2014).

To recognize variables of efficiency and sustainability evaluation of power plants, here we review recent papers from 2010 to 2014. The outcome of the review is displayed in Table 1. As is seen, all inputs, outputs, and intermediate variables are categorized under the three dimensions of sustainability, including economic, environmental, and social pillars. Furthermore, for variables which overlap with each other, we classify them under the most common used term.

2.2. NDEA approach

The CCR model works under CRS assumption. Under CRS assumption an increase in inputs of a DMU causes the same