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Efficiency measurement for network systems: IT impact on firm performance

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ABSTRACT

A recent development in DEA (data envelopment analysis) examines the internal structure of a system so that more information regarding sources that cause inefficiency can be obtained. This paper discusses a network DEA model which distributes the system inefficiency to its component processes. The model is applied to assess the impact of information technology (IT) on firm performance in a banking industry. The results show that the impact of IT on firm performance operates indirectly through fund collection. The impact increases when the IT budget is shared with the profit generation process.

1. Introduction

One of the most useful methodologies for measuring the relative efficiency of a set of decision making units (DMUs) which utilize multiple inputs to produce multiple outputs is data envelopment analysis (DEA) developed by Charnes et al. [15]. This methodology has been applied to research related to decision support systems [32]; for example, facilitating the agent's intelligent behavior in agent-based merchandise management [50], selecting learning cases to improve the forecasting accuracy of neural networks [51], assessing the contribution of knowledge to business performance [1], measuring the efficiency in Internet companies [55], selecting enterprise resource planning (ERP) software [7], performing group evaluation of production units [59], and evaluating data warehouse operations [44]. Advances in DEA methodology will further aid research and applications in decision support systems.

In a production system, the input usually goes through several processes before it becomes the output. Traditional DEA models treat the system as a whole unit, disregarding the interactions of the processes in the system when calculating the efficiency. The first paper discussing this idea was prepared by Charnes et al. [13], which found that the army recruitment had two processes: the first created awareness through advertisement, and the second created contracts using other recruitment resources. Separating large operations into detailed processes helps identify sources of inefficiency and the real impact of factors. Many empirical studies have successfully applied this idea to real world problems. However, it has been frequently observed that, for some DMUs, the system is efficient while the component processes are not. For this reason, Färe and Grosskopf [27] proposed the idea of network DEA, taking the operation of component processes into consideration in calculating the efficiency of the system.

Several models for measuring the efficiency of network systems have been proposed [17,27,35,39,52,61,68]. They can be classified into three groups. The first is an independent approach which recognizes the existence of the processes in the system, yet the efficiencies of the system and all processes are calculated independently. The second is a connected approach, in that interactions between processes are taken into account in calculating the system efficiency. There are several variations on this approach; some are able to calculate the system efficiency and process efficiencies in the same mathematical program, while others need to rely on the conventional DEA model to calculate the process efficiencies separately. The third is a relational approach; its underlying concept is that some kind of mathematical relationship exists between the system efficiency and the component process efficiencies; for example, simple multiplications [37] and weighted average [18].

In this paper, we discuss a model which provides a unified mathematical relationship between the system efficiency and process efficiencies for all types of network structure. For illustration, the problem of assessing the impact of information technology on the performance of a firm as discussed in Wang et al. [65] and Chen and Zhu [21] is revisited. Moreover, a model for measuring the efficiency when certain resources are being shared is used to obtain a better assessment.

The rest of this paper is organized as follows. Section 2 introduces the idea of the relational approach using an example. Section 3 discusses how this approach is used to model series and parallel systems. The problem of assessing the impact of IT on bank performance is discussed in Section 4. Finally, some conclusion is given in Section 5 based on the discussion of the results.

2. The relational model

DEA is concerned with performance evaluation for a set of decision making units (DMUs) utilizing multiple inputs to produce multiple

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outputs. Let X_{ij} and Y_{rj} denote the ith input, $i=1,\ldots,m$, and rth output, $r=1,\ldots,s$, respectively, of the jth DMU, $j=1,\ldots,n$. The relative efficiency of DMU k under the assumption of constant returns to scale is calculated via the following CCR model [15]:

$$\begin{aligned} E_k = \max.\ & \sum_{r=1}^{s} u_r Y_{rk} \\ \text{s.t.}\ & \sum_{i=1}^{m} v_i X_{ik} = 1 \\ & \sum_{r=1}^{s} u_r Y_{rj} - \sum_{i=1}^{m} v_i X_{ij} \le 0, \quad j = 1,\ldots,n \\ & u_r, v_i \ge \varepsilon,\ r = 1,\ldots,s,\ i = 1,\ldots,m, \end{aligned} \tag{1}$$

where u_r and v_i are virtual multipliers and ε is a small non-Archimedean number [12,16] which is imposed to prevent any input/output factor from being ignored in calculating the efficiency. This model was extended by Banker et al. [3] to account for variable returns to scale. Other variations have also been developed for different problems [14].

Model (1) is generally referred to as the ratio-form DEA model because the constraint $\sum_{r=1}^{s} u_r Y_{rj} - \sum_{i=1}^{m} v_i X_{ij} \le 0$ has a ratio form of $\sum_{r=1}^{s} u_r Y_{rj} / \sum_{i=1}^{m} v_i X_{ij} \le 1$, which is just the efficiency of DMU k for $j=k$. This model is the dual of the following linear program:

$$\begin{aligned} E_k = \min.\ & \theta - \varepsilon\Big(\sum_{i=1}^{m} s_i^- + \sum_{r=1}^{s} s_r^+\Big) \\ \text{s.t.}\ & \sum_{j=1}^{n} \lambda_j X_{ij} + s_i^- = \theta X_{ik},\quad i = 1,\ldots,m \\ & \sum_{j=1}^{n} \lambda_j Y_{rj} - s_r^+ = Y_{rk}, \qquad r = 1,\ldots,s \\ & \lambda_j, s_i^-, s_r^+ \ge 0, \qquad j = 1,\ldots,n,\ i = 1,\ldots,m,\ r = 1,\ldots,s \\ & \theta \text{ unrestricted in sign.} \end{aligned} \tag{2}$$

Since the production possibility set is enveloped by $\sum_{j=1}^{n} \lambda_r X_{ij} \le X$, $\sum_{j=1}^{n} \lambda_j Y_{rj} \ge Y$, $\lambda_j \ge 0$, $j=1,\ldots,n$, this model is usually referred to as the envelopment-form DEA model. On optimality, $(\theta X_{ik} - s_i^-, Y_{rk} + s_r^+)$ is the target for the inefficient DMU to achieve efficiency.

Model (1) is used for calculating the efficiency of the DMU considered as a whole system. In many cases, a system is composed of several processes, where some outputs are the inputs of others. That is, in addition to the final output, there are intermediate products being produced and consumed within the system. There are also cases when the processes operate independently, without producing intermediate products for other processes to utilize. In these cases, it is possible that the conventional DEA model will evaluate the system as efficient even if none of its component processes is efficient. Cases have also been observed in which all the corresponding processes of one DMU are less efficient than those of another, yet the system has a higher overall efficiency score.

Consider a system that utilizes inputs X_1 and X_2 to produce outputs Y_1 and Y_2. The production can be separated into two processes with an intermediate product Z produced by the first process and utilized by the second, as depicted in Fig. 1. Table 1 shows the data of four DMUs, A, B, C, and D. The efficiencies of the system for converting X_1 and X_2 to Y_1 and Y_2, that of Process 1 for converting X_1 and X_2 to Z, and that

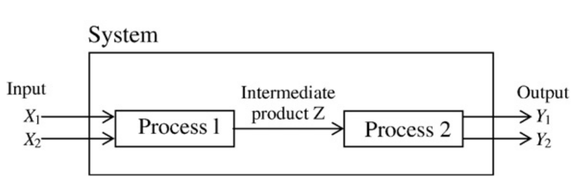

Fig. 1. Series system of two processes.

Table 1
Data and CCR efficiencies for the example.

DMU	Input		Intermediate product	Output		CCR efficiency		
	X_1	X_2	Z	Y_1	Y_2	Process 1	Process 2	System
A	1	2	1.6	2	3	1	0.4187	1
B	2	1	1.0	2	1	1	0.3	1
C	4	5	0.67	3	3	0.1595	1	0.5000
D	5	5	0.6	4	2	0.1385	1	0.6000

of Process 2 for converting Z to Y_1 and Y_2 can be calculated independently by applying the CCR Model (1). The last three columns of Table 1 show that A and B are efficient at the system level despite both of their Process 2 being inefficient. Furthermore, the process efficiencies of D are dominated by C, yet the system efficiency of D is greater than that of C. Although it is well known that, due to differences in the reference set, the CCR efficiency only identifies inefficient DMUs rather than providing a basis for ranking DMUs, these results still make evaluators feel uncomfortable. Therefore, the internal structure must be taken into account in order to obtain representative results.

Measuring the efficiency of network systems started with the innovative work of Färe and Grosskopf [25], whose basic idea was to take the production technology of individual processes into consideration when calculating the system efficiency. Via intermediate products and shared resources, all processes are connected together. The connected approach is flexible in modeling the production technology of the process, yet it is unable to show the mathematical relationship between system efficiency and the process efficiencies. Kao [35] proposed a relational approach to model network systems. The underlying assumption is that the virtual multiplier associated with the same factor should be the same no matter whether it is the output of one process or the input of another. In other words, the imputed price of a factor, as represented by the virtual multiplier, should be the same, no matter what role the factor plays. The rationale is that if this factor is treated as an output and is sold in the market, then an income equal to the price is earned. On the other hand, if the factor is used as an input and is bought from the market, then a cost equal to the price is incurred. Therefore, the same multiplier is used for the same factor. One consequence of this assumption is that, for a DMU, the sum of the constraints associated with the processes is exactly the constraint associated with the system, which reflects a desirable property of the network system that all intermediate products are produced and consumed within the system.

Since the network system does not have a general structure, we use an example to illustrate the relational model. Fig. 2 is the network system discussed in Lewis and Sexton [39]. Surprisingly, this simple network system is the most complicated one that has appeared in the literature. This system has five processes linked by intermediate products. Process 1 uses input X_1 to produce Intermediate Products Z_1^{13}, Z_2^{13}, and Z^{14}; Process 2 uses input X_2 to produce Intermediate Products Z_1^{24} and Z_2^{24}; Process 3 uses input X_3 and Intermediate Products Z_1^{13} and Z_2^{13}, produced by Process 1, to produce Intermediate Product Z^{35}; Process 4 uses Intermediate Products Z^{14}, produced by Process 1, and Intermediate Products Z_1^{24} and Z_2^{24}, produced by Process 2, to produce Intermediate Product Z^{45}; and Process 5 uses Intermediate Products Z^{35} and Z^{45}, produced by Processes 3 and 4, respectively, to produce the final output Y. The idea of Kao [35] is to represent a general network system by a series system where each stage of the latter has a parallel structure. Based on the series and parallel structures, the system efficiency is decomposed into a complicated relationship of process efficiencies. Notably, the series-parallel representation of a network system is not unique.

The relational approach in Kao [35] requires that the aggregated output be less than or equal to the aggregated input for all processes in addition to the usual requirement for the system. The key point is that the multipliers used in the aggregation are the same for the same