Data Envelopment Analysis Approach and Its Application in Information and Communication Technologies

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Abstract. Data Envelopment Analysis (DEA) is a relatively new "data oriented" non-parametric approach for evaluating the performance of complex entities called Decision Making Units (DMUs) which convert multiple inputs into multiple outputs. DEA as a linear programming procedure computes a comparative ratio of outputs to inputs for each DMU, which is reported as the relative efficiency score. In a relatively short period of time DEA has grown into a powerful, quantitative, analytical tool for measuring and evaluating efficiency and has been successfully applied in many contexts worldwide. The reasons why DEA is seeing so much use is that it requires minimal assumptions about how the factors of production relate to each other and assessment by DEA relates to 'best' or 'efficient' rather than average behavior. The purpose of this paper is to describe Data Envelopment Analysis as a new way for organizing and analyzing data and to present the applications of this methodology in information and communication technologies.

Keywords: Data Envelopment Analysis, Efficiency, Performance, Information and Communication Technology.

1 Introduction

The interest in measuring efficiency and productivity has two reasons, (Fried et al., 1993). First of all, they are success indicators, performance measures, by which production units are evaluated. Second, only by measuring efficiency and productivity, and separating their effects from the effects of the production environment can we explore hypotheses concerning the sources of efficiency or productivity differentials. Identification of sources is essential to the institution of public and private policies designed to improve performance.

Productivity efficiency has two components. The purely technical, or physical, component refers to the ability to avoid waste by producing as much output as input usage allows, or by using as little input as output production allows. Thus the analysis of technical efficiency can have an output augmenting orientation or an

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input-conserving orientation. The allocative, or price component refers to the ability to combine inputs and outputs in optimal proportions in light of prevailling prices.

Following work by Dantzig (Dantzig, 1951) and Farrell (Farrell, 1957), Charnes, Cooper, and Rhodes (Charnes et al., 1978) developed mathematical programming technique, Data Envelopment Analysis (DEA).

DEA is a relatively new non-parametric approach for evaluating the performance of a set of peer entities called Decision Making Units (DMUs) which convert multiple inputs into multiple outputs. The characterization of the unit of assessment as "decision making" implies that it has control over the process it employs to convert its resources into outcomes.

Thanassoulis (Thanassoulis, 2001) explain that in DEA the resources are typically referred to as "inputs" and the outcomes as "outputs". The identification of the inputs and the outputs in an assessment of DMUs is as difficult as it is crucial. The inputs should capture all resources which impact the outputs. The outputs should reflect all useful outcomes on which we wish to assess the DMUs. Further, any environmental factors which impact the transformation of resources into outcomes should also be reflected in the inputs or the outputs depending on the direction of that impact.

Data Envelopment Analysis is a method for measuring comparative or relative efficiency. We speak of relative efficiency because its measurement by DEA is with reference to some set of units we are comparing with each other. The efficiency score is usually expressed as either a number between 0-1 or 0-100%. A DMU with a score less than 100% is deemed inefficient relative to other units[1].

Since DEA was first introduced in 1978, researches in a number of fields have in a short period of time recognized that DEA is an excellent and easily used methodology for modeling operational processes for performance evaluations.

The rapid pace of dissemination of DEA as an acceptable method of efficiency analysis can be inferred from the fact that Seiford (Seiford, 1994) in his DEA bibliography lists no fewer than 472 published articles and accepted Ph.D. dissertations even as early as 1992. Tavares (Tavares, 2002) includes 3, 183 items from 2, 152 authors, and in a more recent research, Emrouznejad et al., (Emrouznejad et al., 2008) give a survey and analysis of the 30 years of scholarly literature in DEA up to the year 2007.

In our paper we describe the leading non-parametric method Data Envelopment Analysis and we present its application in information and communication technologies according to recently published studies in this area.

2 Theoretical background

Data Envelopment Analysis is a body of concepts and methodologies that have been incorporated in a collection of models with accompanying interpretive possibilities (Charnes et al., 1994).

[1] This score means that a linear combination of other DMUs from the sample could produce the same vector of outputs using a smaller vector of inputs.

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One of the most basic DEA models is the CCR model, which was initially proposed by Charnes et al. (Charnes et al., 1978).

For each DMU, we formed the virtual input and output by weights (v_i) and (u_r) (Cooper et al., 2002):

$$\text{Virtual input} = v_1 x_{1o} + \ldots + v_m x_{mo}$$

$$\text{Virtual output} = u_1 y_{1o} + \ldots + u_s y_{so}$$

Then we tried to determine the weight, using linear programming so as to maximize the ratio

$$\frac{\textit{virtual output}}{\textit{virtual input}}$$

The optimal weights may (and generally will) vary from one DMU to another DMU. Thus, the "weights" in DEA are derived from the data instead of being fixed in advance. Each DMU is assigned a best set of weights with values that may vary from one DMU to another.

Given the data we measure the efficiency of each DMU once and hence need n optimizations, one for each DMU_j to be evaluated. Let the DMU_j to be evaluated on any trial be designated as DMU_o where o ranges over $1, 2,\ldots,n$. We solve the following fractional programming problem to obtain values for the input "weights" (v_i) ($i=1,\ldots.,m$) and the output "weights" (u_r) ($r=1,\ldots.,s$) as variables.

$$(FP_o) \max \quad \Theta = \frac{u_1 y_{1o} + \ldots + u_s y_{so}}{v_1 x_{1o} + \ldots + v_m x_{mo}} \tag{1}$$

subject to

$$\frac{u_1 y_{1o} + \ldots + u_s y_{sj}}{v_1 x_{1j} + \ldots + v_m x_{mj}} \leq 1 (j = 1,\ldots, n) \tag{2}$$

$$v_1, v_2,\ldots\ldots, v_m \geq 0 \tag{3}$$

$$u_1, u_2,\ldots\ldots, u_s \geq 0 \tag{4}$$

The constraints mean that the ratio of "virtual output" vs. "virtual input" should not exceed 1 for every DMU. The objective is to obtain weights (v_i) and (u_r) that maximize the ratio of DMUo, the DMU being evaluated. By virtue of the constraints, the optimal objective value Θ^* is at most 1. Mathematically, the nonnegativity constraint (3) is not sufficient for the fractional terms in (2) to have a definite value.

We now replace the above fractional program (FP_o) by the following linear program (LP_o),

$$(LP_o) \max \quad \Theta = \mu_1 y_{1o} + \ldots + \mu_s y_{so} \tag{5}$$

subject to

$$v_1 x_{1o} + \ldots + v_m x_{mo} = 1 \tag{6}$$

$$\mu_1 y_{1j} + \ldots + \mu_s \mu_{sj} \leq v_1 x_{1j} + \ldots + v_m x_{mj} \tag{7}$$

$$j = 1,2,\ldots, n$$

$$v_1, v_2,\ldots\ldots, v_m \geq 0 \tag{8}$$

$$u_1, u_2,\ldots\ldots, u_s \geq 0 \tag{9}$$

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Theorem 1. *The fractional program (FP_o) is equivalent to (LP_o).*

Proof. Under the nonzero assumption of v and X>0, the denominator of the constraint of (FP_o) is positive for every j, and hence we obtain (7) by multiplying both sides of (2) by the denominator. Next, nothing that a fractional number is invariant under multiplication of both numerator and denominator by the same nonzero number, we set the denominator of (1) equal to 1, move it to a constraint, as is done in (6), and maximize the numerator, resulting in (LP_o). Let an optimal solution of (LP_o) be ($v=v^*$, $\mu=\mu^*$) and the optimal objective value Θ^*. The solution ($v=v^*$, $\mu=\mu^*$) is also optimal for (FP_o), since the above transformation is reversible under the assumptions above. (FP_o) and (LP_o) therefore have the same optimal objective value Θ^*.

Definition 1. (CCR- Efficiency)

1. DMUo is CCR-efficient if $\Theta^*=1$, and there exists at least one optimal (v^*, u^*), with $v^*>0$ and $u^*>0$.
2. Otherwise, DMU*o* is CCR-inefficient.

Cooper et al., (Cooper et al., 2002) describe that the CCR model is built on the assumption of constant returns to scale of activities. That is, if an activity (x,y) is feasible, then, for every positive scalar t, the activity (tx, ty) is also feasible. Thus, the efficient production frontiers have constant returns-to-scale characteristics, as depicted Figure 1 (adapted from Cooper et al., 2002) for the single-input and single-output case. In what turned out to be major breakthrough, Banker et al., (Banker et al., 1984) extended the CCR model to accommodate technologies that exhibit variable returns to scale. The BCC model has its production frontiers spanned by the convex hull of the existing DMUs. The frontiers has piecewise linear and concave characteristics which, as shown in Figure 2 (adapted from Cooper et al., 2002) leads to variable returns-to-scale characterizations with (a) increasing returns-to-scale occurring in the first solid line segment followed by (b) decreasing returns-to-scale in the second segment and (c) constant returns-to-scale occurring at the point where the transition from the first to the second segment is made.

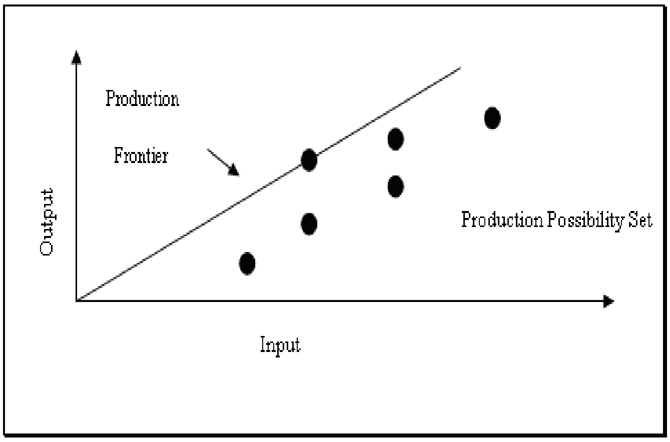

Fig.1. Production Frontier of the CCR Model

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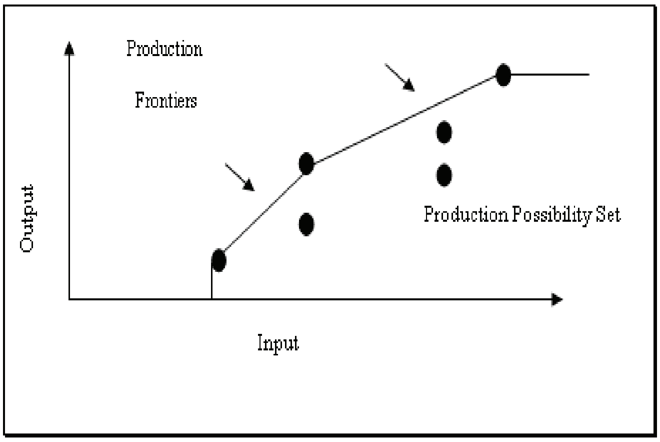

Fig.2. Production Frontiers of the BCC Model

In subsequent years, methodological contributions from a large number of researches accumulated into a significant volume of literature around the CCR-BCC models, and the generic approach of DEA emerged as a valid alternative to regression analysis for efficiency measurement (Ray, 2004).

DEA relative-efficiency solutions were of interest to operations analysts, management scientists, and industrial engineers largely because of three features of the method (Charnes et al., 1994):

1. characterization of each DMU by a single summary relative-efficiency score;
2. DMU-specific projections for improvements based on observable referent revealed best-practice DMUs; and
3. obviation by DEA of the alternative and indirect approach of specifying abstract statistical models and making inferences based on residual and parameter coefficient analysis.

Today's DEA practitioners and researchers possess various software packages[2] that provide a wide range of available models, features and capabilities, user interfaces, reporting options, model solution speeds, and acquisition costs.

3 Case study presentation

Data Envelopment Analysis is an increasingly popular management tool that has been successfully applied in: education (schools, universities), banking industry (banks, branches), health care (hospitals, doctors), courts, manufacturing, fast food

[2] A new and the most comprehensive DEA software: Performance Improvement management Software (PIMsoft) has been developed under supervision of: Prof Emmanuel Thanassoulis & Dr Ali Emrouznejad, for more details visit: www.DEAsoftware.co.uk

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restaurants, retail stores, information and communication technologies, benchmarking, management evaluation, etc.

Charnes et al. (Charnes et al., 1994) have compiled an extensive discussion of efficiency models across a variety of industries.

In this paper we focus on the application of DEA in information and communication technologies.

The application of DEA in ICT has received considerable attention in the recent literature (Anderson et al., 2008, Chen et al., 2006, Cinca et al., 2005, Emrouznejad et al., 2010, Goto, 2010, Jitsuzumi and Nakamura, 2003, Menéndez et al., 2009, Seol et al., 2011 and Shao and Lin, 2002).

For example, Anderson et al. (Anderson et al., 2008) present a framework to characterize, assess and forecast the wireless communication technologies. Wireless communications technologies have undergone rapid changes over the last 30 years from analog approaches to digital-based systems. These technologies have improved on many fronts including bandwidth, range, and power requirements. Development of new telecommunications technologies is critical. It requires many years of efforts. In order to be competitive, it is critical to establish a roadmap of future technologies. In their paper a DEA based methodology was used for predicting the state-of-the-art in future wireless communications technologies.

The increasing use of information technology (IT) has resulted in a need for evaluating the productivity impacts of IT. Chen et al. (Chen et al., 2006) developed a DEA non-linear programming model to evaluate the impact of IT on multiple stages along with information on how to distribute the IT-related resources so that the efficiency is maximized. In their paper is shown that this non-linear program can be treated as a parametric linear program. It is also shown that if there is only one intermediate measure, then the non-linear DEA model becomes a linear program.

Cinca et al., (Cinca et al., 2005) used a non-parametric approach - DEA to the estimation of production functions, in order to assess efficiency in dot com firms. These firms have two objectives: to make an impact in the Internet and to obtain revenues from their activities. For this reason, the outputs have been two: unique visitors—a web metric—and revenues. DEA efficiencies have been obtained under various input/output combinations. A ranking of dot com firms in terms of relative efficiency has been obtained. A method based on multivariate analysis has been proven to be successful at showing the strengths and weaknesses of individual dot com firms. It is shown that there is a relationship between the type of e-business (e-tailers, search/portal, content/communities), and the way in which efficiency is obtained. The paper suggests a new approach to the problem of deciding which inputs and outputs the model should contain.

Emrouznejad et al. (Emrouznejad et al., 2010) developed an alternative approach for measuring information and communication technology (ICT), applying Data Envelopment Analysis (DEA) using data from the International Telecommunications Union as a sample of 183 economies. They compared the ICT-Opportunity Index (ICT-OI) with their DEA-Opportunity Index (DEA-OI) and found a high correlation between the two. Their findings suggest that both indices are consistent in their measurement of digital opportunity, though differences still exist in different regions. Their new DEA-OI offers much more than the ICT-OI. Using their model, the target and peer groups for each country can be identified.

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Goto, (Goto, 2010), investigate the financial performance of the world telecommunications industry by DEA–DA (Data Envelopment Analysis–Discriminant Analysis). The proposed use of DEA–DA has a linkage with Altman's *Z* score that has long served as a methodological and conceptual basis in finance. Based upon the *Z* score of telecommunications companies, he ranks them for financial assessment. After evaluating their financial performance of the firms, this study pays attention to the financial performance of AT&T (American Telephone & Telegraph) and NTT (Nippon Telegraph and Telephone) after their divestiture. This study finds that AT&T outperformed NTT because AT&T changed itself to an IT (Information Technology) company that provides wireless communications services and other IT services, but NTT separated IT and wireless services into the other companies after the breakup.

Recent technological developments have transformed the cable television industry (CATV) from a simple re-transmitter of terrestrial broadcasting to a provider of a broader-band information infrastructure. With cable operators facing an undesirable market situation while operating a fiber optics network vital to the creation of an information-based society within Japan, the Japanese Government has introduced several supportive measures for the industry. Such governmental intervention should desirably be justified not only from a political viewpoint but also from an economic one; otherwise such measures may distort economic efficiency. Jitsuzumi and Nakamura (Jitsuzumi and Nakamura, 2003) used Data Envelopment Analysis to identify the deficiencies of an accounting-based intervention scheme and propose an alternative framework with no disincentive side effects.

The literature concerned with the relationship between performance and information and communications technology (ICT) is usually focused on the ICT investments. Menéndez et al. (Menéndez et al., 2009) show that it is the level of use of ICT within organizations, with preference as regards the expenses of ICT, which is responsible for the effect on performance. A general sample of 2255 Spanish companies has been used. Firms' performance is measured as technical efficiency, which is determined by a data envelopment analysis, in which special attention is paid to the problem of the outliers. Finally, the analysis of the level of use of ICT is focused on a key area of the organizations, the supply chain, which affects the technical efficiency of the firms analyzed. Results show that there is evidence of a positive effect of the use of ICT on technical efficiency. This effect is especially notable at intensive use levels in activities related to operations/manufacturing, purchasing or sales.

Seol et al., (Seol et al., 2011) in their research propose a systematic approach to identify new business areas grounded on the relative technological strength of firms. Patent information is useful as a measure of firms' technological resources and DEA is beneficial to obtain the weighted value of patents according to their quality. With this weighted quality of patents, a firm can evaluate their relative technological strength at the industry and product level according to potential business areas. To compute technological strength by products, this research applies text mining method to patent documents, a method which a researcher discovers knowledge with unstructured data with. This paper shows the usefulness of the newly proposed framework with a case study.

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Shao and Lin (Shao and Lin, 2002) present an approach to investigating the effects of IT on technical efficiency in a firm's production process through a two-stage analytical study with a firm-level data set. In the first stage, a nonparametric frontier method of data envelopment analysis is employed to measure technical efficiency scores for the firms. The second stage then utilizes the Tobit model to regress the efficiency scores upon the corresponding IT investments of the firms. Strong statistical evidence is presented to confirm that IT exerts a significant favorable impact on technical efficiency and in turn, gives rise to the productivity growth that was claimed by recent studies of IT economic value. Practical implications are then drawn from the empirical evidence.

The applications of DEA in the context of information and communication technologies are referenced in Table 1.

Table 1. The applications of DEA in information and communication technologies

Applications	Author (s) and year
Predicting the state-of-the-art in future wireless communications technologies	Anderson et al., 2008
Evaluation of information technology investment	Chen et al., 2006
Measuring efficiency in Internet companies	Cinca et al., 2005
Measuring information and communication technology (ICT)	Emrouznejad et al., 2010
Financial performance analysis of US and world telecommunications companies	Goto, 2010
Measuring efficiency in cable television network facilities	Jitsuzumi and Nakamura, 2003
Technical efficiency and use of ICT in Spanish companies	Menéndez et al., 2009
Identifying new business areas using patent information	Seol et al., 2011
Technical efficiency analysis of information technology investments	Shao and Lin, 2002

4 Conclusions

The ability to quantify efficiency and productivity provides management with a control mechanism with which to monitor the performance of production units under its control. For this purpose there is a rich variety of analytical techniques that can be used in making efficiency and productivity comparisons (Fried et al., 1993), but in our paper we focus on the most known non-parametric method, Data Envelopment Analysis.

Data Envelopment Analysis began as a new Management Science tool for technical-efficiency analyses of public sector and has become an alternative and a complement to traditional central-tendency analyses. Today DEA is an increasingly popular management tool that provides a new approach to traditional cost-benefit analyses, frontier estimation, policy making and learning from best practices.

DEA as a linear programming method for a frontier analysis of inputs and outputs assigns a score of 1 to a DMU only when comparisons with other relevant DMUs

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don’t provide evidence of inefficiency in the use of any input or output, and assigns an efficiency score less than 1 to inefficient units.

In this paper we give theoretical background of this mathematical method and also we present its application in information and communication technologies according to nine recently published studies in this area.

ICTs are acting as integrating and enabling technologies for the economy and they have a profound impact on our society and according to the knowledge that the application of ICT in agriculture is increasingly important our future research will be in this area. E-Agriculture involves the conceptualization, design, development, evaluation and application of innovative ways to use ICTs in the rural domain, with a primary focus on agriculture. The problem of prioritization of e-agriculture options can be solved with the help of multi-criteria decision making methods. For this purpose the multi-criteria model will be developed and DEA will be used to predict the efficiency of ICT investments in e-agriculture.

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