



# DEA and ranking with the network-based approach: a case of R&D performance

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## ABSTRACT

This study enhances the network-based approach, which is a novel method to increase discrimination in data envelopment analysis. The enhancements include removing the bias caused by a scale difference among organizations and highlighting the approach's ability to identify the strengths and weaknesses of each organization. The former makes the approach applicable to both the constant returns of scale (CRS) and the variable returns of scale (VRS) models. The network-based approach applies the centrality concept developed in social network analysis to discriminate efficient decision making organizations as determined by standard data envelopment analysis (DEA). More specifically, the results of data envelopment analysis are transformed into a directed and weighted network in which each node represents a decision making organization and the link between a pair of node represents the referencing relationship between the pair. The centrality value for each efficient organization provides the base for discrimination and ranking. This network-based approach suggests aggregating DEA results of different input/output combinations such that the merits of each organization under various situations can be considered. The final ranking of this approach favors organizations that have their strengths evenly spread and tends to screen out specialized efficient organizations. As a real world example, the approach is applied to evaluate and rank the R&D (research and development) performance of Taiwan's government-supported research institutes. The cross-organizations and within-organization strengths for each efficient research institute are identified after applying the approach. A two-stage R&D evaluation model separates the R&D process into the technology development and technology diffusion stage. The resulting performance map differentiates the research institutes into four categories—Achievers, Marketers, Innovators, and Underdogs.

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## 1. Introduction

Both academic and practical communities have found interesting applications for data envelopment analysis (DEA) ever since the pioneering works of Professor William W. Cooper and his co-workers [1,2]. Many of the applications adopting DEA emphasize the efficiency comparison of decision making units (DMUs) which transform a set of multiple efforts into another set of multiple results. In such a context, DEA usually provides a group of performance leaders that can be used as benchmarks for those who are outside the leading group. The leaders are of equal significance under the original DEA methodology. Some applications, however, expect unambiguous, preferably ranked, performance leaders. For example, when applying DEA to compare the

performance of R&D (research and development) organizations, one prefers a ranked list in order to correctly reward the R&D organizations and more importantly to allocate precious resources to organizations with better performance.

Many methods have been suggested to further discriminate DEA results [3–5]. Liu et al. [6] proposed a unique method that turns DEA results into a network and makes use of the tools developed in the social network discipline to further discriminate those DEA results. Three key concepts are embedded in this network-based approach. First, the result of DEA is transformed into a directed and weighted network in which each node represents a decision making organization and the link between a pair of nodes represents the referencing relationship between the pair. Second, information not used by conventional DEA is fully explored. By running DEA with many rather than just one specification, additional information can be extracted and used as the base for further discrimination. This study's DEA specification refers to an input/output combination. The idea of exploring efficiency information with multiple DEA specifications is not

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new. Previous researches [7–10] provided such examples. Third, conflicting results coming from the additional information is resolved through the ‘eigenvector centrality’ method commonly used in social network analysis, which has been an active research area among social scientists for several decades [11]. Eigenvector centrality indicates the ‘power’ of individual nodes in a social network. Bonacich [12] first proposed this measure.

The eigenvector centrality method is rooted in the benchmark concept. In essence, it is a much improved simple count method. The simple count ranks a DMU high if it is chosen as a reference target for many other DMUs, or in other words, endorsed by many peers. The eigenvector centrality brings in two additional conditions: endorsing weight and the importance of the endorsing peer. More precisely, eigenvector centrality highlights the nodes that are popular; yet the popularity of a node is defined not only by the number of peers that endorse it, but by the importance of the endorsing peers and their endorsement strengths.

This study makes improvements to the method proposed by Liu et al. [6] and applies the method to an R&D performance evaluation case. The improvement removes the bias caused by organization scale difference. Under the DEA context, small efficient organizations generally obtain higher lambda values than large efficient organizations. The original network-based approach applies lambda values as link weights between node pairs, thus giving preference to small organizations. We introduce a normalization scheme to eliminate this bias. The normalization scheme is similar to what is proposed in Zhu [13], who adjusts efficiency measures to organization size. In addition to the normalization improvement, we also suggest techniques to identify the relative strengths for each efficient organization.

New applications for DEA continue to emerge in recent years. These include measuring the efficiency of strategic decision making processes [14], optimizing production planning problems [15], facilitating quality function deployment computations [16], and evaluating R&D activities. Previous studies applying DEA to R&D-related applications [17,18] and contexts include cross-country R&D efficiency comparison [19–21], university research performance measurement [22–25], efficiency evaluation of basic research in China [26,27], IC design companies’ performance measurement [28], and R&D project selection at Lucent Technologies [29,30]. Except for Linton et al. [30], all the above studies found a group of efficient research organizations, but do not rank them. We apply DEA with the network-based approach to evaluate and rank the performance of research institutes that participate in the governmental Technology Development Program in Taiwan. In addition, the strengths and weaknesses of each research institute are discovered in due course.

The network-based approach features two characteristics that are suitable for R&D performance evaluation [6]. First, the approach is likely to screen out specialized efficient DMUs, i.e. those units which are referenced by none or very few DMUs. Second, the approach favors efficient DMUs that have their strengths evenly spread. In evaluating the performance of R&D organizations, one is looking for organizations that do a good job in converting input resources such as funds, human resources, etc. into practical goals of the organizations such as license fees, industry services, etc. DEA can regard a DMU as being efficient even when it is particularly strong in one parameter yet very weak in the other parameters. For example, an R&D organization that is very good at managing human resources, but very weak in managing funds, can still be on the frontier in the analysis. This type of organization is not a desirable target to promote. The algorithm embedded in the network-based approach will weight low this type of organization.

Following this introduction, we describe the details of the network-based approach and its improvements in Section 2.

Section 3 follows with an empirical study of R&D performance applying the approach. Section 4 presents the empirical results. Section 5 concludes.

## 2. DEA and the network-based approach

DEA is an efficiency analysis method for decision making organizations. It is non-parametric and does not require beforehand the production functional form or the subjectively determined individual weights of inputs and outputs. This methodology defines a best practice frontier that can be used as a reference for efficiency improvement. Farrell [31] first used DEA estimators to measure technical efficiency for a set of observed organizations, but the idea did not gain wide acceptance until the appearance of the sentinel paper by Charnes et al. [1]. Cooper et al. [32], Zhu [33], and Avkiran [34] describe the methodology in detail.

DEA models usually give more than one efficient organization, especially when the total number of organizations under study is not much greater than the total number of inputs and outputs. The network-based approach provides a unique and powerful way to further distinguish efficient organizations. This approach also converts the efficiency calculation results under a DEA context to a directed and weighted network and then uses the eigenvector centrality concept developed in social network analysis to determine the significance of each organization.

The enhanced procedure of the network-based approach is described as follows. Step 3 introduces a normalization method which makes crucial improvement over the original procedure proposed by Liu et al. [6].

*Step 1.* Determine the scheme for transforming the DEA results into a network. For example, each organization under study is regarded as a network node. The reference to an efficient organization can be treated as an endorsement from an inefficient organization to that organization, and the corresponding lambda value is taken as the weight of the endorsement—that is, if organization  $j$  is an exemplar of organization  $k$  and the corresponding lambda value is  $\lambda_{jk}$ , then a directed link of weight  $\lambda_{jk}$  pointing from node  $k$  to node  $j$  can be created. This is an intuitive scheme to associate two organizations, but should not be the only method.

*Step 2.* Calculate the efficiencies of all organizations under the DEA context. The efficiency calculation is conducted on multiple DEA specifications; each specification  $t$  stands for one input/output combination. In other words, DEA is run on many input/output combinations; most likely all possible input/output combinations. This step allows the merits of each organization under various situations to be considered and thus provides the base for further discrimination. The linear programming problem for each DEA specification  $t$  can be represented as follows:

$$\begin{aligned} \text{Min } \theta_k^t \quad \text{s.t.} \quad & \sum_{j=1}^n \lambda_{jk}^t x_{ij}^t \leq \theta_k^t x_{ik}^t, \quad i = 1, \dots, m, \\ & \sum_{j=1}^n \lambda_{jk}^t y_{rj}^t \geq y_{rk}^t, \quad r = 1, \dots, s, \\ & \sum_{j=1}^n \lambda_{jk}^t = 1, \quad \theta_k^t, \lambda_{jk}^t \geq 0; \quad \forall i \text{ and } r, \end{aligned} \quad (1)$$

where  $n$  is the number of organizations;  $m$  and  $s$  are the respective number of inputs and outputs;  $x_{ij}^t$  and  $y_{rj}^t$  are the amount of the  $i$ th input consumed and amount of the

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