A Common Weighted Performance Evaluation Process by Using Data Envelopment Analysis Models

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Abstract – **The finance literature searches for a link between production and performance, controlling for variables, such as sales, firm size, employee number, etc., that influence production packages. The performance indices are designed according to the resulting effects and determine whether the performance model is appropriate or not, and/or whether the performance of system is good or not. In this paper, a process, based on data envelopment analysis (DEA), is developed to evaluate and rank the relative importance of key performance indices (KPIs). The relative importance of each KPI is evaluated by performance loss measure, and each KPI is weighted according to the measure. Then, the relative performance of each unit is the ratio of weighted output to weighted input based on the common weights.**

Keywords – **data envelopment analysis (DEA), ranking, key performance index (KPI), common weights, efficiency.**

I. INTRODUCTION

Decision-making problems involve both quantitative and non-quantitative factors. The non-quantitative factors are not usually well defined or are subjectively determined by the decision-maker. Such factors cannot be included in the mathematical models while the quantitative factors are modeled as multiple objective linear programming (MOLP). The coefficients in MOLP may obtainable, well defined, or not sensitive to the final solution. An example of MOLP may be projects of government investment, in which the minimization objective functions (inputs) may be manpower, machines, construction costs, operation costs, other controllable costs and uncontrollable costs while the maximization objective functions (outputs) may be revenues, rate of population growth, and growth of economic improvement.

In real world problems, there exist peer groups of decision-making units (DMUs), such as, corporations, hospitals, and cities, etc., which use multiple resources to generate multiple products. For example, hospitals may use labor inputs of physicians, nurses, and technicians, and capital inputs of medical equipments and beds to produce service of inpatient and outpatient care, and researches. Many studies focus on evaluating the allover performance of DMUs based on their resources consumed and products generated. It is expected that multiple inputs and outputs could be transformed into one performance measure, such as the ratio of aggregated outputs to aggregated inputs. This provides the performance of DMUs to be evaluated and ranked by the corresponding measure. The significance of various performance indices (inputs and outputs) affect such kind of performance measure of DMUs, so the weights for various indices are needed to determine in order to obtain the measure.

The performance indices are designed according to the resulting effects and determine whether the performance model is appropriate or not. Buyukozan [1] proposes a measure, namely the e-Marketplace success index (e-MSI) to quantify the performance of e-Marketplace. As the performance indices are collected and selected by some managerial information and experience. The significance of performance indices are set to determine whether the performance evaluation system is good or not. When the key performance indices (KPIs) are identified by the expert opinions or other managerial information, the relative performance of each DMU is hinged on the weights of the KPIs.

There are some ways to determine the prioritization (weights) of KPIs. The analytic hierarchy process (AHP), developed by Saaty [2] is designed to solve complex multi-criteria decision problems. AHP requires the decision maker to provide judgments about the relative importance of each criterion and then specify a preference for each DMU using each criterion. The Delphi method was conceived as a group technique whose aim was to obtain the most reliable consensus of opinion of a group of experts by means of a series of intensive questionnaires with controlled opinion feedback [3]. It is a method of structuring communication in a group of people who can provide valuable contributions in order to resolve a complex multi-criteria problem [4]. So, we could adopt expert opinions through Delphi method to specific the weights. Moreover, we could also use statistical method, such as principal component analysis (PCA) to determine the weights [5]. The above methods all provide the relative weight correspond to each KPI.

Data Envelopment Analysis (DEA) is a robust and valuable methodology for the frontier estimation [6]. Based on mathematical programming techniques, it is particularly suited to estimating multiple input and output production correspondence. In the last two decades, DEA has become a popular method for analyzing the efficiency of various organization units [7] which differ both in the quantities of inputs they consume and in the outputs they produce, and does not require any subjective or economic parameters (weights, prices, etc.). Many studies have been concerned with the efficiency of production. It is clear that DEA is now playing a wider role in operational research/management science arena. In particular, DEA approaches have assumed important status within the toolkits of investigators concerned with multiple criteria decision-making [8, 9].

In this research, we propose a process based on the optimization technique, DEA, to evaluate the relative importance of KPIs and determine relative weight of each KPI. Then, the relative performance of all DMUs based on common weights is follows. The next section reviews papers related to select and rank KPIs. Section three introduces the analysis for using DEA to prioritize and weight the given KPIs. Section four uses a data set comprised 20 corporations of personal computer (PC) industry in Taiwan to illustrate this analysis. Conclusion and discussion are presented in section five.

II. LITERATURE REVIEW

Shashua & Goldschmidt [10] develop a formal analytical model to construct an index for evaluating the allover performance of a firm relatively in the same industry. The index also serves as an indicator of economic progress. Philbin & Renegar [11] indicate that an engineering performance index method can be used to provide performance measurement and feedback for an entire engineering department, individual engineers, individual performance categories, individual projects, and individual element task units.

The world becomes more complex as we enter the information age. We find that almost every important real-world problem involves more than one objective, and decision makers find it imperative to evaluate solution alternatives according to multiple criteria [12, 13]. We now need to extend the single performance index problems to the multiple indices problems. Glandon et al. [14] present that aggregate indices reflect dimensions of hospital financial performance and simplify the information in financial ratios for the decision-making aid. Their study reviews the development and use of hospital financial performance measures and lays the groundwork for research into deriving a multi-dimensional measure.

The KPIs are critical assessment. Chang & Yeh [5] use AHP, DEA, and PCA to build an evaluative model for selecting and ranking KPIs in Liquid Crystal Displayer (LCD) industry in Taiwan. Chin et al. [15] identify the criteria and factors for managing supplier quality (MSQ) through literature review and a mail survey of manufacturers in Hong Kong. Using the AHP, industry experts were invited to determine the relative weights of these criteria and factors. As the KPIs are identified by expert opinions, the prioritization or the relative weights of KPIs is an important issue in transforming multiple indices into an aggregate performance measure.

DEA is also a popular technique that enables multiple inputs and outputs are transformed into one performance measure. If the performance reduces due to remove a specific KPI, we could compare the quantity of performance differences among all KPIs and rank these values to determine the prioritization of the KPIs. The methodology of using DEA to prioritize PKIs is developed in the next section.

III. METHODOLOGY

DEA was introduced into the operations research by Charnes et al. [6], which extended the work of Farrell [16]. DEA is a methodology based on mathematical programming and used for assessing the relative efficiency of observed DMUs with the same multiple input and output. This study employs the nonparametric approach to evaluate the significance differences in KPIs based on the production frontier literature. DEA is adopted to project KPIs to performance frontier with minimal assumption on performance correspondence.

Suppose a set of n DMUs numbered j=1,…, n, is under evaluation. For DMU_j, it consumes x_{ij}, $i\in \boldsymbol{I}=\{1,\ldots, m\}$, resource to produce y_{rj}, $r\in \boldsymbol{O}=\{1,\ldots, s\}$, products. The Farrell [16] "efficiency measure" for a specific DMU, say DMU_T, based on all KPIs in $\boldsymbol{I}$ and $\boldsymbol{O}$, is obtained by using the following model:

$$\begin{aligned} F_T^* &= \min\ \theta_T \\ \text{s.t. } & \sum_{j=1}^{n} \lambda_j x_{ij} \geq \theta_T x_{iT}, \quad i = 1,\ldots,m; \\ & \sum_{j=1}^{n} \lambda_j y_{rj} \geq y_{rT}, \quad r = 1,\ldots,s; \\ & \lambda_j \geq 0,\ j = 1,\ldots,n. \end{aligned} \tag{1}$$

In case of F_T^*=1, DMU_T is on the performance frontier and is called efficiency, while F_T^*<1, DMU_T is inside the performance frontier and is called inefficiency. In general, suppose $\boldsymbol{M}$ and $\boldsymbol{S}$ are subsets of index sets $\boldsymbol{I}$ and $\boldsymbol{O}$, respectively. In the "correct" version, we compute:

$$\begin{aligned} F_T^*(\boldsymbol{M},\boldsymbol{S}) &= \min\ \theta_T \\ \text{s.t. } & \sum_{j=1}^{n} \lambda_j x_{ij} \geq \theta_T x_{iT}, \quad i \in \boldsymbol{M}; \\ & \sum_{j=1}^{n} \lambda_j y_{rj} \geq y_{rT}, \quad r \in \boldsymbol{S}; \\ & \lambda_j \geq 0,\ j = 1,\ldots,n. \end{aligned} \tag{2}$$

For each DMU, which differs from model (1) in that our "efficiency measure" is constructed from KPIs in $\boldsymbol{M}$ and $\boldsymbol{S}$ only. An interesting result emerges from further inspection of the solutions to $F_T^*(\boldsymbol{M}, \boldsymbol{S})$ and F_T^*. Because of an optimal solution to $F_T^*(\boldsymbol{M}, \boldsymbol{S})$ is also a feasible solution to F_T^* in the analysis of corporation T. Hence, $F_T^* \geq F_T^*(\boldsymbol{M}, \boldsymbol{S})$ for all index subsets $\boldsymbol{M} \subseteq \boldsymbol{I}$ and $\boldsymbol{S} \subseteq \boldsymbol{O}$. We now introduce a formal definition of a performance loss.

Definition 1. For corporation T,

$$PL_T(\boldsymbol{M}, \boldsymbol{S}) = F_T^* - F_T^*(\boldsymbol{M}, \boldsymbol{S}), \quad (3)$$

is a measure of performance loss due to remove KPIs from $\boldsymbol{I}$ and $\boldsymbol{O}$ to $\boldsymbol{M}$ and $\boldsymbol{S}$. ■

PL_T is a measure of performance loss because is reveals whether the best practices of corporation T are differences between allover KPIs and a deletion of some KPIs. It is obviously the measure of performance loss has the following properties:

1) $1 \geq PL_T \geq 0$. Since, $1 \geq F_T^* \geq F_T^*(\boldsymbol{M}, \boldsymbol{S}) \geq 0$, the result follows straightforward.

2) For corporation T, if $F_T^*(\boldsymbol{M}, \boldsymbol{S}) = 1$, $PL_T = 0$.

A. Weighting Input Indices

For a specific input index k, we take $\boldsymbol{M}_k = \boldsymbol{I} \setminus \{k\}$ and compute $F_T^*(\boldsymbol{M}_k, \boldsymbol{O})$. Then, the measure $PL_T(\boldsymbol{M}_k, \boldsymbol{O})$ could be regarded as the performance loss while input k is absent in the index set. In other words, $PL_T(\boldsymbol{M}_k, \boldsymbol{O})$ measure could be regarded as the efficiency contribution to DMU_T while input k is added into index set $\boldsymbol{M}_k$.

If the performance loss for deleting input k is greater than the measure for deleting input j, we conclude that the influence of input k should be larger than the influence of input j on the performance of DMU_T. That is, input k is more importance than input j with respect to DMU_T if $PL_T(\boldsymbol{M}_k, \boldsymbol{O}) > PL_T(\boldsymbol{M}_j, \boldsymbol{O})$.

However, we are interested in the relative weights (importance) of KPIs for evaluating all DMUs or possibly for evaluating a subgroup of DMUs in the same industry. The rule to determine the relative weights of KPIs is developed as the following:

*Rule 1***.** The importance of input k is prior to the importance of input j with respect to all DMUs, if

$$\overline{PL}(\boldsymbol{M}_k, \boldsymbol{O}) > \overline{PL}(\boldsymbol{M}_j, \boldsymbol{O}). \quad (4)$$

Where $\overline{PL}(\boldsymbol{M}_k, \boldsymbol{O}) = \text{Mean}\,\{PL_T(\boldsymbol{M}_k, \boldsymbol{O}) \mid T = 1, \ldots, n\}$. ■

Based on Rule 1, the relative weight, v_k, of input k is assigned to equal to the measure $\overline{PL}(\boldsymbol{M}_k, \boldsymbol{O})$. Hence, we have:

$$v_k = \overline{PL}(\boldsymbol{M}_k, \boldsymbol{O}), \quad i = 1, \ldots, m. \quad (5)$$

B. Weighting Output Indices

For a specific output index k, we take $\boldsymbol{S}_k = \boldsymbol{O} \setminus \{k\}$ and compute $F_T^*(\boldsymbol{I}, \boldsymbol{S}_k)$. Then, the measure $PL_T(\boldsymbol{I}, \boldsymbol{S}_k)$ could be regarded as the performance loss while output k is removed from the index set. In other words, $PL_T(\boldsymbol{I}, \boldsymbol{S}_k)$ measure could be regarded as the efficiency contribution to DMU_T while input k is added into index set $\boldsymbol{S}_k$.

If the performance loss for deleting output k is greater than the measure for deleting output j, we conclude that the influence of output k should be larger than the influence of output j on the performance evaluation of DMU_T. That is, output k is more importance than output j if $PL_T(\boldsymbol{I}, \boldsymbol{S}_k) > PL_T(\boldsymbol{I}, \boldsymbol{S}_j)$.

*Rule 2***.** The importance of output k is prior to the importance of output j with respect to all DMUs, if

$$\overline{PL}(\boldsymbol{I}, \boldsymbol{S}_k) > \overline{PL}(\boldsymbol{I}, \boldsymbol{S}_j) \quad (6)$$

Where $\overline{PL}(\boldsymbol{I}, \boldsymbol{S}_k) = \text{Mean}\,\{PL_T(\boldsymbol{I}, \boldsymbol{S}_k) \mid T = 1, \ldots, n\}$. ■

Based on Rule 2, the relative weight, μ_k, of output k is assigned to equal the measure $\overline{PL}(\boldsymbol{I}, \boldsymbol{S}_k)$. Hence, we have:

$$\mu_k = \overline{PL}(\boldsymbol{I}, \boldsymbol{S}_k), \quad r = 1, \ldots, s. \quad (7)$$

C. Performance Evaluation in Common Weights

In order to discriminate the exact influence of each performance indices, we need to re-scale the data of indices that enable the weighted values of indices could reflect the index importance and affect the performance in a suitable quantity. The inputs and outputs of DMUs are re-scaled as follows:

$$\begin{cases} \hat{x}_{iT} = x_{iT} \Big/ \sum_{j=1}^{n} x_{ij}, & i = 1, \ldots, m, \quad T = 1, \ldots, n; \\ \hat{y}_{rT} = y_{rT} \Big/ \sum_{j=1}^{n} y_{rj}, & r = 1, \ldots, s, \quad T = 1, \ldots, n. \end{cases} \quad (8)$$

This re-scaling provides the total weighted influence of index k is greater than index j if weight of index k is greater than index j. Therefore, the relative performance of each DMU_T is given by:

$$\theta_T = \sum_{r=1}^{s} \mu_r \hat{y}_{rT} \Big/ \sum_{i=1}^{m} v_i \hat{x}_{iT}, \quad T = 1, \ldots, n. \quad (9)$$

IV. PERFORMANCE OF TAIWAN'S PC INDUSTRY

A data set comprises with 20 corporations (DMUs) of the PC peripherals and components industry (D1-D20) industry in 2005 [17] in Taiwan is listed in Table I. Suppose 4 input KPIs and 2 output KPIs have been identified according to the expert opinions. The input–output set is as follows:

Input: Assets (x_1), Shareholders' equity (x_2), Capital (x_3), and Employee number (x_4).

Output: Sales (y_1) and Profit (y_2).

We are interested in prioritizing the importance and setting the relative weights of the given KPIs for evaluating the relative performance of all DMUs. Our objectives include: (i) prioritizing KPIs with respect to a specific DMU, (ii) prioritizing KPIs with respect to the 20 DMUs in PC industry, (iii) evaluate the relative weights of each input/output indices, and (iv) evaluate the relative performance of all DMUs in common weights of KPIs.

TABLE I
DATA OF 20 PC PERIPHERALS CORPORATIONS

DMU	Input				Output	
	x_1^*	x_2^*	x_3^*	x_4	y_1^*	y_2^*
D1	1532.61	616.81	262.26	49833	2275.06	88.04
D2	401.44	201.72	78.21	15600	742.74	11.76
D3	422.56	210.63	136.51	18501	645.76	12.77
D4	364.73	155.47	71.34	7471	519.38	30.34
D5	336.56	185.92	67.19	8035	463.38	12.6
D6	181.96	53.72	41.5	15000	294.78	6.42
D7	79.4	15.2	25	1732	153.85	0.88
D8	104.23	38.09	29.83	6823	131.58	3.36
D9	130.59	69.76	46.53	7435	128.5	5.54
D10	111.03	41.62	22.11	8500	128.21	0.72
D11	62.03	19.8	20.5	549	125.43	1
D12	117.7	74.8	40.16	5314	120.16	7.84
D13	77.36	43.88	23.14	3600	118.09	6.98
D14	72.48	38.81	12.02	4298	116.95	10.24
D15	127.96	56.36	22.41	1940	115.49	12.95
D16	58.59	19.91	11.92	270	105.8	2.99
D17	159.49	109.11	28.37	13000	95.89	37.97
D18	31.2	15.95	11.13	500	87.37	2.87
D19	85.74	42.76	25.97	233	84.6	5.04
D20	30.15	2.07	1	140	83.12	0.79

[*] Unit: hundred million New Taiwan Dollars (NTDs).

All of the 20 corporations are evaluated by model (1) and (2). The computational results are presented in Table II. The original efficiency scores in the second column are evaluated by using model (1). The other values are the measure of performance loss, PL_T, of each KPI to DMU_T, which is the difference value between F_T^* and $F_T^*(\boldsymbol{M}, \boldsymbol{S})$ through deleting KPIs from $\boldsymbol{I}$ or $\boldsymbol{O}$.

We first consider D4 and D13 as the target DMUs to illustrate result of objective (i). The prioritization of KPI is obtained by ranking the PL values. Thus, we have the importance ranks as:

$x_1 > x_3 > x_2 = x_4$ and $y_2 > y_1$ for D4,

while

$x_1 > x_4 > x_3 > x_2$ and $y_1 > y_2$ for D13.

In case of prioritizing KPIs for the PC industry, the prioritization of KPI is obtained by ranking the mean *PL* values. Objective (ii) results that:

$x_1 > x_4 > x_3 > x_2$ and $y_1 > y_2$ with respect to all DMUs.

For objective (iii), the relative weights of indices are: v_1=0.2153, v_2=0.0006, v_3=0.006, v_4=0.0667, μ_1=0.1857, and μ_2=0.1664.

TABLE II
THE ORIGINAL SCORES AND PERFORMANCE LOSS OF EACH INDEX

DMU	Score (F_T^*)	*PL* of Inputs				*PL* of Outputs	
		x_1	x_2	x_3	x_4	y_1	y_2
D1	0.6339	0.2508	0	0.0266	0	0.1581	0.099
D2	0.6659	0.4974	0	0.005	0	0.4654	0
D3	0.5466	0.3877	0	0.0006	0	0.3487	0
D4	0.8365	0.1727	0	0.0084	0.1416	0.0575	0.324
D5	0.5216	0.2571	0	0.0299	0	0.2075	0.0262
D6	0.5847	0.2716	0.0026	0	0	0.2461	0.0018
D7	0.6998	0.4477	0.0065	0	0	0.5379	0
D8	0.4548	0.2237	0.0025	0	0	0.2037	0.0017
D9	0.3877	0.1796	0	0	0	0.1491	0.0363
D10	0.4155	0.3388	0	0.0012	0	0.3662	0
D11	0.7292	0.3444	0	0	0.0022	0.4837	0
D12	0.4835	0.2089	0	0	0	0.075	0.1187
D13	0.694	0.2772	0	0.0047	0	0.1502	0.1474
D14	0.9675	0.2253	0	0.0438	0	0.1892	0.386
D15	1	0	0	0	0.3436	0	0.6749
D16	1	0.0138	0	0	0.3112	0.0048	0.34
D17	1	0	0	0	0	0	0.7834
D18	1	0.2099	0	0	0	0.1068	0
D19	1	0	0	0	0.536	0	0.3884
D20	1	0	0	0	0	0	0
Mean	0.7311	0.2153	0.0006	0.0060	0.0667	0.1875	0.1664

TABLE III
THE RANK AND RELATIVE PERFORMANCE

DMU	Score (F_T^*)	CCR rank[a]	Weighted input	Weighted output	Performance θ_T^*	New rank[b]	Difference of rank[c]
D18	1	1	0.0018	0.0043	2.4524	1	0
D17	1	1	0.0130	0.0269	2.0732	2	–1
D20	1	1	0.0015	0.0029	1.9141	3	–2
D16	1	1	0.0030	0.0049	1.6484	5	–4
D15	1	1	0.0071	0.0116	1.6380	6	–5
D19	1	1	0.0044	0.0056	1.2879	9	–8
D14	0.9675	7	0.0053	0.0099	1.8776	4	+3
D4	0.8365	8	0.0209	0.0342	1.6350	7	+1
D11	0.7292	9	0.0033	0.0042	1.2737	11	–2
D7	0.6998	10	0.0047	0.0050	1.0691	14	–4
D13	0.694	11	0.0053	0.0078	1.4812	8	+3
D2	0.6659	12	0.0260	0.0288	1.1090	12	0
D1	0.6339	13	0.0950	0.1214	1.2771	10	+3
D6	0.5847	14	0.0149	0.0125	0.8403	17	–3
D3	0.5466	15	0.0285	0.0267	0.9358	16	–1
D5	0.5216	16	0.0198	0.0213	1.0773	13	+3
D12	0.4835	17	0.0080	0.0084	1.0531	15	+2
D8	0.4548	18	0.0079	0.0059	0.7495	19	–1
D10	0.4155	19	0.0088	0.0041	0.4682	20	–1
D9	0.3877	20	0.0095	0.0072	0.7587	18	+2

[a] The CCR rank is based on original CCR scores.
[b] The new rank is based on our relative performance θ_T^*.
[c] The difference between CCR rank and new rank, where "+" indicates improvement and "–" indicates deterioration, respectively.

Further, the result of objective (iv) could be obtained from Eq. (9), and is presented in Table III. All DMUs are ranked according to the relative performance. There are slightly difference (–3~+3) between CCR rank and our new performance rank for most of DMUs. But, some DMUs have a strongly changed in rank. The most significant are that: D19 move from rank 1 to rank 9 and D15 move from rank 1 to rank 6. Table III has also shown that both D16 and D7 are deteriorated 4 ranks. By using our evaluation process of common weights, it results that the 7, 11 and 2 DMUs are improved, deteriorated, and unchanged their ranks, respectively.

V. CONCLUSION AND DISCUSSION

The DEA methodology possesses many valuable applications. Instead of pre-assigning weight to each KPI individually, free the weight lets us evaluate the DMUs in each oneself best practice condition. Our objective is to weight all KPIs based on their performance loss measures, then re-evaluate DMUs based on the given weights.

As the rank of KPIs is determined, corporation or industry can follow the information to improve their performance effectively. For example, assets decrement is prior to employee number decrement in order to improve the performance of D14, while profit augmented is prior to sales increment in performance improvement of D16. However, the PC industry should first decrease their assets and increase sales to improve the industry performance effectively and efficiently.

The common weighted evaluation process is more realized the real-world problems. It could rule out the unreasonable efficient DMUs from the efficiency set, and provide a full ranking evaluation for the decision problems. So, this process will enhance the fine quality of final decision.

The general multi-indices models are used to measure the efficiency of some difficult public service policies or non-profit issues, e.g., road construction, nuclear power plant sited, and location of an airport, etc.. Our process may provide a better aspect to the relative efficiency.

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