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MEASURING THE RELATIVE EFFICIENCY OF IC DESIGN FIRMS: A DIRECTIONAL DISTANCE FUNCTIONS AND META-FRONTIER APPROACH

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Abstract

An alternative approach for evaluating the efficiency of integrated circuit (IC) design firms is presented in this paper. We took into account the differences between technology groups, containing one or more design firms, and input and output factors to prevent influences of scale (e.g., firm size). Specifically, we employed a directional distance function approach to data envelopment analysis in order to evaluate inefficiency scores and differences among groups based on input and output factors. We found the efficiency of Taiwan's IC design firms to be dependent not only on firm size but also on R&D expenditure and patent revenue. Our findings suggest that these factors significantly influenced the technical efficiency of Taiwan IC design. Furthermore, by focusing on technology gaps, we offer some suggestions for the different groups based on group-frontier and meta-frontier analyses. Finally, using the results of these analyses, we extended the global results of this study, presenting ways to further improve their efficiency.

Keywords: Directional distance function, IC design firm, Performance evaluations, Meta-frontier,Group-frontier.

1 INTRODUCTION

Integrated circuit (IC) design firms, also called “fabless companies”, play a key role in the overall IC industry because they produce highly “intelligent goods” in the value chain. The IC industry in Taiwan has a “Vertical Specialization” structure, ranging from IC design to IC testing, which is very different from businesses in other countries that use “Vertical Integration”. Based on this characteristic, it is not easy to evaluate the efficiency of an IC company in Taiwan from the design stage to the market stage because the different stages have diverse goals. As Taiwan’s IC design firms vary in terms of scale and scope, we cannot use only a single variable group (e.g., companies in the same country) to evaluate efficiency. Thus, it is necessary to analyze them in several groups to make the evaluation more accurate. Most previous studies have examined the efficiency of the different groups employing the data envelopment analysis (DEA) approach, which uses a single frontier to compare the efficiency among different groups. These studies assume that the different groups possess the same technology (Wu et al., 2006; Chiang et al., 2004). However, the IC design firms in the different groups have different available resources (e.g., investment capability), scale (e.g., size), scope, and characteristics (e.g., operation philosophies and managerial modes); thus, they have different technology sets.

Previous studies have employed a input or output model to analyze the operations of IC design firms (Wu et al., 2006). However, such models are not really suitable for analyzing IC design firms. A producer’s behavior should be able to focus on both maximum outputs and minimum inputs instead of one direction alone. Moreover, these studies have neglected the fixed inputs that may overstate a firm’s capacity for adjustment, thus producing misleading results. Furthermore, fixed inputs prevail in all sectors of the economy so their optimal value cannot be adjusted within the periods. To remedy this problem, we employed the directional distance function and a meta-frontier in this study.

The contributions of this research to IC design firm evaluation are twofold. First, we used the directional distance function to assess the operational efficiency of IC design firms in Taiwan. Using this function, we considered factors related to output slack, input slack, and fixed input constraints. Second, we used DEA with a meta-frontier to estimate the efficiency in the IC design industry, whereas previous studies have used conventional DEA and other methods (e.g., analytic network process (ANP)) that did not take into account the group concept.

The remainder of this paper is organized as follows. Section 2 presents our review of the literature about the IC Industry. Section 3 describes our methodology and explains the rationale behind it. Section 4 reports the empirical results from 87 IC design firms in 2008. Section 5 summarizes our findings and considers their theoretical and managerial implications. Finally, section 6 offers our conclusions and our suggestions for future research.

2 LITERATURE REVIEW

The integrated circuit (IC) design industry has four critical characteristics. First, its industrial cost structures are centralized in the middle. Second, gross profits are widely different between the firms. Third, this industry is highly knowledge-intensive. Fourth, there is a strong connection with the manufacturers. In addition, the industry sometimes has a winner-takes-all attitude, which means the higher gross profits may be concentrated on one or two large companies, which hold the patents to a wide range of techniques to avoid the diffusion of the necessary knowledge. The competition is fierce among the IC design firms dealing with the same application, while the competition is not so acute among the IC design firms dealing with different applications. Furthermore, a high-technology barrier exists for the various applications because IC design firms find it hard to break into new unfamiliar territories. IC design firms also need to have a good relationship with their downstream partners because they do not have factories.

Chen and Chen (2007) measured the efficiency of semiconductor operations in Taiwan using balanced scorecards. They showed that the basic financial inputs and outputs are considered to be suitable factors for measuring the efficiency of the high-tech industry. Kozmetsky and Yue (1998) evaluated the performance of the global semiconductor operations from 1982 to 1994. Their findings revealed that efficiency can be determined by scale, implying that larger-scale companies sometimes are more efficient because they can adjust their resources the “right” way. As a result, the scale should probably be considered when evaluating the performances of IC design firms. Chen et al. (2004) investigated the largest computer and office equipment manufacturers on the Fortune 500 list to evaluate their efficiency. Using data envelopment analysis (DEA), they measured the relative efficiency of these companies, employing the Malmquist productivity index to evaluate the changes in company productivity. Apart from conventional factors (e.g., the number of employees), they also employed stockholder equity as an input and found that this variable has a significant impact on operational efficiency.

Thore et al. (1994) used DEA and production analysis to measure management efficiency and productivity in 44 US computer firms from 1981 to 1990. They observed the importance of providing efficient R&D expenditures, especially in major R&D investment decision-making units (e.g., Apple). In addition, Chen et al. (2006) used the number of US patents to analyze the semiconductor company values in Taiwan. They found that the number of US patents has a high correlation with the value of IC design firms, but the correlation is lower for packaging and testing companies. Based on these two empirical studies, R&D expenditures and patent authorizations have proven vital in knowledge-intensive industries.

After reviewing the previously published studies, we performed a variable selection and identified the following factors as inputs: fixed assets, inventories, investments, other assets, operational costs (e.g., sales cost), operational expenses (e.g., management cost), number of employees, amount of depreciation, R&D expenditures, and bad debt. The following factors were identified as outputs: Book Values Per Share (BVPS), sales revenue, patent authorization revenues, and net profits.

3 MODELING AND PROBLEM FORMULATION

The proposed approach can be modeled in four phases. In the first phase, clustering techniques are used to cluster and extract similar decision-making processes from the parameters needed in group frontiers to avoid large-scale, size-dominated decision-making unit in our results. Once the clustering process has been completed, the second phase applies the directional distance function to give each decision-making unit (DMU) in each group an inefficiency score. The third phase evaluates all observed inefficiency scores using directional distance function. The fourth phase calculates the differences between the inefficiency scores identified in the second and third phase.

Before modeling and formulation, let j ($j=1,...,N$), r ($r=1,...,N_z$), z ($z=1,...,C$) denote the indicies of IC deisgn firms, indicies of IC design firms and indicies of groups, respectively. Specificially, $X_{aj}^{(0)}$, $X_{bj}^{(0)}$, $X_{cj}^{(0)}$, $X_{dj}^{(0)}$, $Y_{ej}^{(0)}$, $Y_{fj}^{(0)}$ and $Y_{gj}^{(0)}$ represnet vector of $a-th$ ($a=1,..,n_a$) specific scale input variables, the $c-th$ ($c=1,..,n_c$)specific operational input variables, the $b-th$ ($b=1,..,n_b$) specific financial input variables, the $d-th$ ($d=1,..,n_d$) specific R&D expenditure input variables, the $e-th$ ($e=1,..,n_e$) specific market values output variables, the $f-th$ ($f=1,..,n_f$) specific operational variable outputs, and the $g-th$ ($g=1,..,n_g$) specific patent output variables of the $j-th$ IC design firm, respectively, and X_{ar}^{z}, X_{br}^{z}, X_{cr}^{z}, X_{dr}^{z}, Y_{er}^{z} Y_{fr}^{z} and Y_{gr}^{z} represent vector of $a-th$ specific scale input variables, the $c-th$ specific operational input variables, the $b-th$ specific financial input variables, the $d-th$ specific R&D expenditure input variables, the $e-th$ specific market values output variables, the $f-th$ specific operational output variables, and the $g-th$ specific patent output variables of the $r-th$ IC design firm, respectively. As such, simplifying these steps could help to evaluate efficiency scores. Four steps are illustrated in this study.

3.1 Phase I (Fuzzy C-means)

Let $H_j=\{X_{aj}^{(0)},X_{bj}^{(0)},X_{cj}^{(0)},X_{dj}^{(0)},Y_{ej}^{(0)},Y_{fj}^{(0)},Y_{gj}^{(0)}\}\in R^{(n_a+n_b+n_c+n_d+n_e+n_f+n_g)\times N}$ .For the details about the fuzzy C-means, one can refer to the paper of Dunn(1973). After Fuzzy C-means manuiplation, thus, the IC design dataset could be divided into $z=\{1,...,C\}$ different scale and/or scope sub-group sets of IC design firms which can use input quantities $X_j^z=\{X_{aj}^z,X_{bj}^z,X_{cj}^z,X_{dj}^z\}$ to produce output quantities $Y_j^z=\{Y_{ej}^z,Y_{fj}^z,Y_{gj}^z\}$. Let η_z represent the decision-making units of subset z ; if $DMU_v\in\eta_z$, then $\mathbf{DMU_v}$ cannot be found in η_p , where $p\neq z$.

3.2 Phase II (Group Frontier)

After phase I, the directional distance function (Chung et al., 1997) is employed to increase the outputs and decrease the inputs directionally. Cluster z inefficiency is defined by the following equation:

$$D(X_{ar}^z,X_{br}^z,X_{cr}^z,X_{dr}^z,Y_{er}^z,Y_{fr}^z,Y_{gr}^z;\mathbf{g_z})=\theta_r^z=\sup\{\beta^z:(X_{ar}^z,$$
$$X_{br}^z-\beta^z g_{br}^z,X_{cr}^z-\beta^z g_{cr}^z,X_{dr}^z-\beta^z g_d^z,Y_{er}^z+\beta^z g_{er}^z,Y_{fr}^z+\beta^z g_{fr}^z,Y_{gr}^z+\beta^z g_{gr}^z)\in T^z\} \quad (1)$$

where the non-zero vector $g_z=(g_{br}^z,g_{cr}^z,g_{dr}^z,g_{er}^z,g_{fr}^z,g_{gr}^z)$ determines the "directions" in which outputs and inputs are scaled for each cluster z .The technology set is $T^z=\left\{(X_a^z,X_{b\sim d}^z,Y_{e\sim g}^z):X_a^z \textit{ and } X_{b\sim d}^z \textit{ can produce } Y_{e\sim g}^z\right\}$. The variable X_{ar}^z is a fixed input; thus, it does not have any scale to adjust. In addition, $D(\bullet)=\theta_r^z=\beta^z$, called the technical efficiency indicator, is between zero and infinity. Given that the IC design firms varied greatly in size, it is safe to assume that variable returns to scale (VRS) holds. The efficient DMU of cluster z corresponds to $\theta_r^z=0$. In other words, the larger the value of θ_r^z, the further the DMU is from the frontier of cluster z. Therefore, the $\mathbf{DMU_k}$ of cluster z inefficiency can be expressed as in Model 2.

$$
\begin{aligned}
&\theta_k^z = \max \beta_k^z \\
&\text{suject to.} \\
&\sum_{r=1}^{N_z} \lambda_r X_{ar}^z = X_{ak}^z, && a=1,..,n_a, \\
&\sum_{r=1}^{N_z} \lambda_r X_{br}^z + s_{bk}^z = (1-\beta_k^z) X_{bk}^z, && b=1,..,n_b, \\
&\sum_{r=1}^{N_z} \lambda_r X_{cr}^z + s_{ck}^z = (1-\beta_k^z) X_{ck}^z, && c=1,..,n_c, \\
&\sum_{r=1}^{N_z} \lambda_r X_{dr}^z + s_{dk}^z = (1-\beta_k^z) X_{dk}^z, && d=1,...,n_d, \\
&\sum_{r=1}^{N_z} \lambda_r Y_{er}^z - s_{ek}^z = (1+\beta_k^z) Y_{ek}^z, && e=1,..,n_e, \\
&\sum_{r=1}^{N_z} \lambda_r Y_{fr}^z - s_{fk}^z = (1+\beta_k^z) Y_{fk}^z, && f=1,..,n_f, \\
&\sum_{r=1}^{N_z} \lambda_r Y_{gr}^z - s_{gk}^z = (1+\beta_k^z) Y_{gk}^z, && g=1,..,n_g, \\
&\lambda_r \geq 0, && r=1,...,N_z, \\
&\sum_{r=1}^{N_z} \lambda_r = 1
\end{aligned}
\tag{2}
$$

where λ_r represent the vector for projecting $\mathbf{DMU_r}$ at the $z-th$ groups and $s_{br}^z, s_{cr}^z, s_{dr}^z, s_{er}^z, s_{fr}^z, s_{gr}^z$ represent slacks in $X_{cr}^{(z)}$, $X_{br}^{(z)}$, $X_{dr}^{(z)}$, $Y_{er}^{(z)}$ $Y_{fr}^{(z)}$, $Y_{gr}^{(z)}$ between the group frontier and $\mathbf{DMU_r}$ at the $z-th$ groups , respectively.

3.3 Phase III (Meta-Frontier)

All the observed inefficiency directional distance functions under the scale variables that cannot be adjusted are defined by equation 3:

$$
\begin{aligned}
&D(X_{aj}^{(0)}, X_{bj}^{(0)}, X_{cj}^{(0)}, X_{dj}^{(0)}, Y_{ej}^{(0)}, Y_{fj}^{(0)}, Y_{gj}^{(0)}; \mathbf{g}) = \theta_j^{(0)} = \sup\{\beta : (X_{aj}^{(0)}, X_{bj}^{(0)} - \beta g_{bj}, \\
&X_{cj}^{(0)} - \beta g_{cj}, X_{dj}^{(0)} - \beta g_{dj}, Y_{ej}^{(0)} + \beta g_{ej}, Y_{fj}^{(0)} + \beta g_{fj}, Y_{gj}^{(0)} + \beta g_{gj}) \in T^{(0)}\}
\end{aligned}
\tag{3}
$$

where the non-zero vector $g=(g_{bj}, g_{cj}, g_{dj}, g_{ej}, g_{fj}, g_{gj})$ determines the “directions” in which outputs and inputs are scaled for all observations. The technology set is $T^{(0)}=\left\{(X_a^{(0)}, X_{b\sim d}^{(0)}, Y_{e\sim g}^{(0)}) : X_a^{(0)} \textit{ and } X_{b\sim d}^{(0)} \textit{ can produce } Y_{e\sim g}^{(0)}\right\}$ .The $\mathbf{DMU_k}$ of all the observed inefficiencies can be expressed as in Model 4:

$$
\begin{aligned}
&\theta_k^{(0)} = \max \beta_k \\
&\textbf{suject to.} \\
&\sum_{j=1}^{N} \lambda_j X_{aj}^{(0)} = X_{ak}^{(0)}, && a = 1,..,n_a, \\
&\sum_{j=1}^{N} \lambda_j X_{bj}^{(0)} + s_{bk}^{(0)} = (1-\beta_k) X_{bk}^{(0)}, && b = 1,..,n_b, \\
&\sum_{j=1}^{N} \lambda_j X_{cj}^{(0)} + s_{ck}^{(0)} = (1-\beta_k) X_{ck}^{(0)}, && c = 1,..,n_c, \\
&\sum_{j=1}^{N} \lambda_j X_{dj}^{(0)} + s_{dk}^{(0)} = (1-\beta_k) X_{dk}^{(0)}, && d = 1,..,n_d, \\
&\sum_{j=1}^{N} \lambda_j Y_{ej}^{(0)} - s_{ek}^{(0)} = (1+\beta_k) Y_{ek}^{(0)}, && e = 1,..,n_e, \\
&\sum_{j=1}^{N} \lambda_j Y_{fj}^{(0)} - s_{fk}^{(0)} = (1+\beta_k) Y_{dk}^{(0)}, && f = 1,..,n_f, \\
&\sum_{j=1}^{N} \lambda_j Y_{gj}^{(0)} - s_{gk}^{(0)} = (1+\beta_k) Y_{gk}^{(0)}, && g = 1,..,n_g, \\
&\lambda_j \geq 0, && j = 1,...,N, \\
&\sum_{j=1}^{N} \lambda_j = 1
\end{aligned} \tag{4}
$$

where λ_j represent the vector for projecting $\mathbf{DMU_j}$ and $s_{br}^{(0)}, s_{cr}^{(0)}, s_{dr}^{(0)}, s_{er}^{(0)}, s_{fr}^{(0)}, s_{gr}^{(0)}$ represent slacks in $X_{cj}^{(0)}$, $X_{bj}^{(0)}$, $X_{dj}^{(0)}$, $Y_{ej}^{(0)}$ $Y_{fj}^{(0)}$, $Y_{gj}^{(0)}$ between the meta frontier and $\mathbf{DMU_j}$, respectively. Let $\rho_b^{(0)}, \rho_c^{(0)}, \rho_d^{(0)}, \rho_e^{(0)}, \rho_f^{(0)}$, and $\rho_g^{(0)}$ represent the values are the sum of the radio and non-radio operational input variables, financial input variables, R&D expenditure input variables, market value output variables, operational output variables, patent output variables the values are the sum of the radio and non-radio divided by the all observation amount of variables, respectively.Similar to the phase II evaluation, $\theta_k^{(0)}$ measures the maximum percentage in which all outputs and inputs are potentially improved for $\mathbf{DMU_k}$ and can thus serve as a measure of technical inefficiency.

3.4 Phase IV (Technology Gap)

After phase II and phase III, two values are determined to represent the inefficiency scores of each IC design firm. The difference between the two values is referred to as the technology gap, as shown in the following equation:

$$\psi_j = \theta_j^{(0)} - \theta_r^z \text{ and } \exists \mathbf{DMU_r} \in \eta_z \text{, such that } \mathbf{DMU_r = DMU_j} \tag{5}$$

4 EMPIRICAL ANALYSIS

Understanding the empirical studies about the analysis method applied in this study is important. The steps of our approache can be divided into six sub-steps. The first sub-step describes the dataset pre-processing. The second sub-step illustrates the group segments, since the scale and scope are quite different in Taiwan's IC design industry. We adopted McGrath's concepts (2001) in order to separate the firms into groups according to the four strategic types. In the third sub-step, the inefficiency of four groups was calculated using the directional distance function, thus determining the inefficiency of each DMU under a given fixed assets value, which cannot be adjusted (sub-step 4). Afterwards, all the observed inefficiency scores were determined by the directional distance function and meta analysis (sub-step 5). Finally, the difference between phase II and phase III inefficiencies, called the technical gap, was calculated by subtracting the group inefficiency scores from all the observed inefficiency scores (sub-step 6). The value of this technical gap provided us with information about the four groups. Calculations for the different groups and all the observed inefficiencies depend on their clustering result, whether or not the analysis of the groups and the observations occur in the same period.

4.1 Data and Input-Output Variables

The dataset obtained from the Taiwan Economics Journals (TEJ) database for 2008 contained observations related to 87 Taiwan IC design firms. These 87 design firms make up 99% of the market share in the Taiwan's IC design industry, and therefore they are influential and representative. As mentioned in Section 2, 10 input variables and four output variables were chosen. Except for the fixed asset, these input variables can be adjusted in the group frontier and meta-frontier analyses. To reduce the number of variables, the dataset was analyzed, leading to the elimination of two variables—operational expense and net profits—since the operational cost would include operational expenses and the sales revenue would include net profits. After reducing the number of variables, nine input variables and three output variables were processed. Their correlations were then calculated and the variable x_{c5} was excluded.

4.2 Clustering Analysis

As scale and scope are different across IC design industry, the firms were clustered for evaluation to prevent the bigger IC design firms from dominating the performance in the group frontier analysis. According to McGrath (2001), companies employ four levels of strategy, which can be used to group high-tech firms: strategic vision, product platform, product line, and individual products. Using McGrath's classification (2001), we used fuzzy c-means to cluster the 87 firms in four groups according to the similarity of their scale and scope. Table 1 shows the result of clustering analysis, thus illustrating the different scales of Taiwan's IC design firms. The four groups of IC design firms can be classified in terms of the mean of their variables: Group One $\succ$ Group Four $\succ$ Group Three $\succ$ Group Two. The IC design firm in Group One can be considered as a strategic vision company. The IC design firms in Group Four can be considered as product platform companies because they have embedded operational revenues and pre-emptive patents. These firms have larger scales, but do not have larger scopes. The IC design firms in Group Three can be considered as product line companies. The firms in Group Two can be considered as individual product companies that have neither scale nor scope. They are usually considered to be followers since they have no power to designate their market position.

Group	Company	Sites
Group1	6	1
Group2	5,8,10,13,14,15,16,17,18,9,20,21,22,23,25,26,27,28,29,30,31,32,33,34,36,37,38,40,42,43,44,45,46,47,48,49,51,52,53,54,55,56,58,60,61,62,63,64,65,66,67,68,69,70,71,72,73,74,76,78,79,80,81,82.84.85.86	67
Group3	1,3,4,7,9,12,24,35,39,41,50,57,59,75,77,83	16
Group4	2,11,87	3

Table 1. Results of Clustering Analysis

4.3 Group Frontier Analysis

We also investigated whether or not there were significant differences in the inefficiencies across the four groups. To compare the efficient frontiers of the four groups, the directional distance function was run separately for each group. The group frontier analysis of each group was obtained, as shown in Table 2. We ignored Groups One and Four because their factors and systems are efficient. As seen in Table 2, the first priority of Groups Two and Three is to improve their investment efficiency on the input side and expand their patent authorization revenue on the output side.

Group Frontier Analysis	Group 1 z =1	Group 2 z =2	Group 3 z =3	Group 4 z =4
Inefficiency	0.0000	0.0152	0.0061	0.0000
$\overline{s}_{b1}^{z}(\rho_{b1}^{(z)})$	0.00(0.0000)	0.00(0.0000)	0.00(0.0000)	0.00(0.0000)
$\overline{s}_{b2}^{z}(\rho_{b2}^{(z)})$	0.00(0.0000)	4.05(0.0005)	8.30(0.0013)	0.00(0.0000)
$\overline{s}_{c1}^{z}(\rho_{c1}^{(z)})$	0.00(0.0000)	16343.31(0.0012)	348923.35(0.0131)	0.00(0.0000)
$\overline{s}_{c2}^{z}(\rho_{c2}^{(z)})$	0.00(0.0000)	10610.76(0.0009)	76532.08(0.0060)	0.00(0.0000)
$\overline{s}_{c3}^{z}(\rho_{c3}^{(z)})$	0.00(0.0000)	5938.96(0.0005)	98297.19(0.0123)	0.00(0.0000)
$\overline{s}_{c4}^{z}(\rho_{c4}^{(z)})$	0.00(0.0000)	1009.10(0.0010)	6825.55(0.0066)	0.00(0.0000)
$\overline{s}_{d1}^{z}(\rho_{d1}^{(z)})$	0.00(0.0000)	6242.95(0.0007)	31308.56(0.0027)	0.00(0.0000)
$\overline{s}_{e1}^{z}(\rho_{e1}^{(z)})$	0.00(0.0000)	0.96(0.0010)	0.52(0.0015)	0.00(0.0000)
$\overline{s}_{f1}^{z}(\rho_{f1}^{(z)})$	0.00(0.0000)	0.00(0.0000)	0.00(0.0000)	0.00(0.0000)
$\overline{s}_{g1}^{z}(\rho_{g1}^{(z)})$	0.00(0.0000)	1409.67(0.0122)	10553.89(0.0233)	0.00(0.0000)
Efficient DMU	1/1	55/67	14/16	3/3

Table 2. Group Frontier Analysis Inefficiencies
Note: Each cell in the table contains the following information: $\overline{s}_{b1}^{z} \sim \overline{s}_{g1}^{z}$, where the right section represents the ($s_{b1}^{z} \sim s_{g1}^{z}$)average slack values; the numbers in parentheses represent the value of the sum of radio and non-radio slacks divided by the current amount of variables.

4.4 Meta-Frontier Analysis

After conducting meta-frontiers analysis, we found that 58 DMUs reached the meta-frontiers. This result contradicts the results of the group frontier analysis. Of these 58 DMUs, 9, 10, 12, 33, 43, 51, 57, 59, 65, 69, 74, 77, 79, 80 and 86 were found to be efficient with group frontier analysis, but were inefficient with meta-frontier analysis. Table 3 looks at the meta-frontier analysis inefficiencies from a Group perspective. This table shows that Group Two needs to pay attention to the number of employees, while Group Three needs to consider inventory on the input side. In contrast, Clusters Two and Three need to exert more effort towards their patent revenues. In addition, the Taiwan IC design industry lacks slack in operational cost and operation revenue, implying that this industry has good relationships with its downstream partners.

Inefficiency	**Group 1**	**Group 2**	**Group 3**	**Group 4**
	z **=1**	z **=2**	z **=3**	z **=4**
	0.0000	0.0245	0.0262	0.0000
$\overline{s}_{b1}^{(0)}$ ($\rho_{b1}^{(0)}$)	0.00(0.0000)	0.00(0.0000)	0.00(0.0000)	0.00(0.0000)
$\overline{s}_{b2}^{(0)}$ ($\rho_{b2}^{(0)}$)	0.00(0.0000)	7167.91(0.8221)	56.29(0.1363)	0.00(0.0000)
$\overline{s}_{c1}^{(0)}$ ($\rho_{c1}^{(0)}$)	0.00(0.0000)	38557.32(0.0029)	339470.39(0.2039)	0.00(0.0000)
$\overline{s}_{c2}^{(0)}$ ($\rho_{c2}^{(0)}$)	0.00 (0.0000)	47210.78(0.0041)	165753.59(0.2071)	0.00(0.0000)
$\overline{s}_{c3}^{(0)}$ ($\rho_{c3}^{(0)}$)	0.00(0.0000)	63799.37(0.0051)	77574.43(0.1553)	0.00(0.0000)
$\overline{s}_{c4}^{(0)}$ ($\rho_{c4}^{(0)}$)	0.00(0.0000)	1683.34(0.0016)	6248.75(0.0967)	0.00(0.0000)
$\overline{s}_{d1}^{(0)}$ ($\rho_{d1}^{(0)}$)	0.00(0.0000)	12702.46(0.0014)	49521.23(0.0682)	0.00(0.0000)
$\overline{s}_{e1}^{(0)}$ ($\rho_{e1}^{(0)}$)	0.00(0.0000)	1.98(0.0020)	4.13(0.1945)	0.00(0.0000)
$\overline{s}_{f1}^{(0)}$ ($\rho_{f1}^{(0)}$)	0.00(0.0000)	1285.15(0.0000)	0.00(0.0000)	0.00(0.0000)
$\overline{s}_{g1}^{(0)}$ ($\rho_{g1}^{(0)}$)	0.00(0.0000)	4828.09(0.0418)	22547.03(0.7949)	0.00(0.0000)
Efficient DMU	1/1	46/67	10/16	3/3

Table 3: Meta-frontier Analysis Inefficiencies from a Group perspective.
Note: Each cell in the table contains the following information: $\overline{s}_{b1}^{(0)} \sim \overline{s}_{g1}^{(0)}$, *where the upper section represents the (* $s_{b1}^{(0)} \sim s_{g1}^{(0)}$ *) average slack values; the numbers in parentheses represent the value of the sum of radio and non-radio slacks divided by the current amount of variables.*

4.5 Technology Gap Analysis

After the group frontier and meta-frontier analyses, two values were determined to represent the inefficiency scores of each IC design firm. The difference between these two values is referred to as the technology gap. Table 4 shows the technology gap of the individual factors for the four groups. Scale input variables were ignored because the group frontier and meta-frontier analyses do not have these values. Groups One and Four have a technology gap of zero. The IC design firms in Group Two were found to have more influence on the output variables than the firms in Group Three. Group Two has a larger technology gap in factor x_{b2} but Group Three has a larger technology gap in factor x_{c2}. The difference between the technology gaps of Groups Two and Three indicates that these two groups should employ different management policies for controlling their inputs. On the output side, both Groups Two and Three should increase their patent revenue to improve their efficiency.

	x_{b1}	x_{b2}	x_{c1}	x_{c2}	x_{c3}	x_{c4}	x_{d1}	y_{e1}	y_{f1}	y_{g1}
Group1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Group2	0.0000	0.8216	0.0017	0.0032	0.0046	0.0006	0.0007	0.0010	0.0000	0.0296
Group3	0.0000	0.1350	0.1908	0.2011	0.1430	0.0901	0.0655	0.1930	0.0000	0.7716
Group4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Overall	0.0000	0.2392	0.0481	0.0511	0.0369	0.0227	0.0166	0.0485	0.0000	0.2003

Table 4. Technology Gap of the individual factors for the four groups

5 DISCUSSION

Performance evaluation is used to measure the efficiency of a decision-making unit; it is not the "absolute" objective per se. Based on our empirical results, the group frontier and meta-frontier analyses obtained the efficiency of 87 IC design companies using the formula (1 minus the inefficiency scores). In Figure 1, the group frontier ranking, which is used to rank the group efficiency scores from high to low, is represented on the horizontal axis, while the meta-frontier ranking, which is used to rank the meta efficiency scores from high to low, is represented on the vertical axis. Both the horizontal and vertical axes have two values: one is set higher than the median, while the other is set lower than the median. The two axes separate the space into four ranking sectors: Maintaining (Zone 1), Impossible (Zone 2), Intra-Group Learning (Zone 3), and Inter-Group Learning (Zone 4).

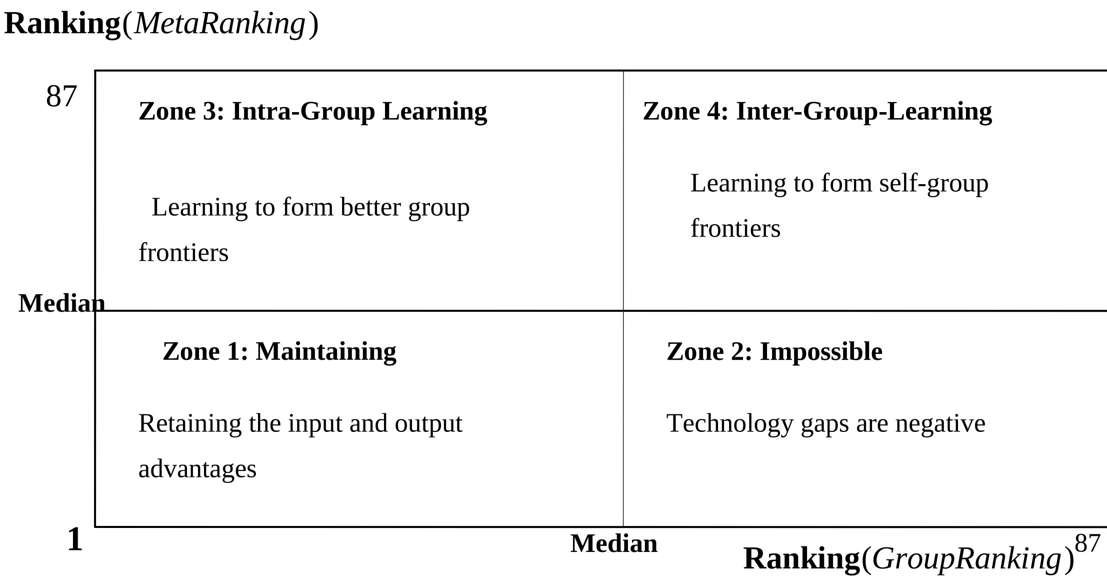

Figure 1: Efficiency Ranking Sectors

Combining the four ranking zones with the four McGrath groups leads to a four-by-four matrix with 16 sub-sectors. Based on the results of Table 1 and four zones concpets , we were able to construct an IC design firm's managerial decision matrix, as shown in Table 5. The DMU numbers for the four DMU zones and for the different McGrath groups are shown in each cell of Table 5.

	Maintaining (Z1)	Impossible (Z2)	Intra-Group Learning (Z3)	Inter-Group Learning (Z4)
Strategic Vision (G1)	6 **(1/1)**	N/A	N/A	N/A
Individual Product (G2)	8,13,14,15,16,17,18,20,23,25, 27,29,30,31,32,34,36,37,38,42, 44,45,46,47,48,49,52,53,54,55, 58,60,62,64,66,67,68,70,72,73, 78,81,82,84,85 **(45/67)**	N/A	43,79,74,86,69 ,51,80,10,33, 65 **(10/67)**	5,26,22,21,28,40, 76,56,19,63,61, 71 **(12/67)**
Product Lines (G3)	1,3,7,24,35,39,41,50,75,83 **(10/16)**	N/A	9,12,57,59,77 **(5/16)**	4 **(1/16)**
Product Platforms (G4)	2,11,87 **(3/3)**	N/A	N/A	N/A

Table 5. IC Design Firm's Managerial Decision Matrix

If a firm cannot reach "first to market," status, then it will be a follower. In contrast, the IC design industry is considered to be the "first in scale and/or scope", which has been proven by DMU 6. There are many start-up IC design firms that challenged the status quo and succeeded, similar to the "Maintaining-Individual product" zone. Companies in this particular zone know their advantages (inputs and/or output). Moreover, "incumbent curses" have also been observed, as in the case of DMU 4. These companies should learn from the companies in "Maintaining-Product Lines" zone. The number of employees, which is the most important input issue, has been shown to be a crucial factor . In addition, employee quality cannot be measured; the number of employees can only represent a variable quality, ranging from high to low. In the "Maintaining" zones, companies sometimes have many employees, unlike companies in the "Inter-Group Learning-Individual Product" zone. Firms in the "Intra-Group Learning" zone might want to consider horizontal integration or alliance when expanding their scale and developing/deploying their patents.

6 CONCLUSION

This study described a DEA application for evaluating IC design firms using technology grouping. A four-phase approach was proposed and applied to the Taiwan IC design industry, offering a number of suggestions for the different groups of IC design firms. Our results show that the different groups of IC design firms should use different management policies.

However, our analysis has certain limitations. First, according to the accrual accounting rule, the leading and lagging variables should incorporate dependent variables. Second, the issue of how many groups should be included was not adequately addressed. Researchers with different perspectives may disagree on whether or not the groups would result in four cases. This study showed that a group effect existed in homogeneous decision-making, as proven by our empirical evidence.

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