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Measuring the relative efficiency of IC design firms using the directional distance function and a meta-frontier approach

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ABSTRACT

This paper presents an alternative approach for evaluating the efficiency of integrated circuit (IC) design firms. In doing so, it accounts for 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 influence 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 extend the global results of this study, presenting ways to further improve efficiency.

1. Introduction

The integrated circuit (IC) design industry,[2] also called the "fab-less industry," plays a key role in the overall semiconductor industry, through its production of highly "intelligent" properties (i.e., patents). Within the semiconductor industry, IC design industry acts as a knowledge-intensive business service division. The IC design industry in Taiwan includes four types of designers: the independent professional design house, the design department within an integrated device manufacturer (IDM), the IC design center in a system vendor, and the design unit of an overseas company. Due to the diverse nature of these design firms, it is difficult to evaluate industry efficiency in Taiwan, particularly because each designer upholds different goals. Moreover, the products produced by these firms also have diverse characteristics, making it difficult to measure the knowledge capabilities of any particular firm.

Regarding IC design industrial cost structures, research and development (R&D) expenditures sometimes account for approximately 9–15% of total costs, while manufacturing outsourcing accounts for approximately 50–90%. In addition, the industry sometimes has a winner-takes-all attitude, which means higher gross profits may be concentrated in one or two large companies that hold the patents to a wide range of techniques to avoid the diffusion of necessary knowledge. As such, competition is fierce among IC design firms dealing with the same application, and lax elsewhere. High technology barriers exist for various applications, and firms find it difficult 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. This allows them to reduce their manufacturing costs and focus all their attention on IC design.

Six of the thirty largest IC design firms in the world can be found in Taiwan. In 2006, Taiwan's IC design firms accounted for the second-largest market share (18%) in the world, coming just after the United States (72%), with a production value of nearly US $9.8 billion. In addition, some of Taiwan's leading firms have captured more than 50% of the world market share in specific application domains, including network chipsets (e.g., RealTek), optical storage chipsets (e.g., MediaTek), and consumer market chips (e.g., SunPlus), to name but a few. The ascendancy of these firms on the world market makes it crucial to evaluate their operational efficiency and better understand the feedback processes needed to improve operational performance.

As Taiwan's IC design firms vary in terms of size and scope, we cannot use only one variable group (e.g., variables representing different countries) to evaluate efficiency. Chen and Chen [7] assume that the groups within different countries had the same technology set. When the frontier was applied to each country, the performance of each individual decision-making unit (DMU) was compared against the best practices in the same country, but the efficiency results between two different

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[2] The integrated circuit (IC) design industry has four critical characteristics. First, its industrial cost structures are centralized in the middle (i.e., there are 14 value chain activities within the cost structure, including human resources, marketing research, product positioning, specification development, process R&D, computer-aided design, circuit design, patent-granting, mask making, manufacturing, IC packing and testing, brand, sales, and services). Second, gross profits vary widely between firms. Third, this industry is highly knowledge-intensive. Fourth, there is a strong relationship between IC design firms and manufacturers.

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countries are incomparable. In practice, it is rare for the estimated frontiers of two countries/regions to be similar enough to facilitate the use of a single frontier.[3] As such, it is necessary to analyze these firms in several groups to ensure and improve evaluation accuracy. Most previous studies [6,9,44] have examined the efficiency of various firm groups by employing different approaches that use a single frontier to compare group efficiency. These studies assume that the different groups possess the same technology.[4] However, IC design firms within different groups have different available resources (e.g., investment capability), size, scope, and characteristics (e.g., operation philosophies and managerial modes); thus, they have different technology sets.[5] As a result, we used grouping techniques (i.e., fuzzy c-mean) to cluster Taiwan's IC design firms, rendering the similarities of the groups of IC design firms in Taiwan easier to observe. In addition, we used a meta-frontier and group-frontier[6] to examine the efficiency between the different groups of IC design firms and the IC design industry. More precisely, we not only measured the inter-groups of IC design firms with similar scales and/or scopes, but also the intra-group relations between IC firms with different scales and/or scopes.

Furthermore, previous studies have employed an input or output model to analyze the operations of IC design firms [44]. However, these models are not really suitable for analyzing the efficiency of an IC design firm because an IC design firm should simultaneously maximize outputs and minimize inputs instead of focusing on only one action. While evaluating the efficiency of an IC design firm produces projections by only considering input- (output-) oriented perspective, the efficiency score is still affected by the output (input) factor. Moreover, these studies have neglected the (quasi) fixed inputs that may overstate a firm's capacity for adjustment, thus producing misleading results [44]. Fixed (or, quasi-fixed) inputs prevail in all sectors of the economy, so their optimal value cannot be adjusted within a given period. To remedy this problem, we employed the directional distance function in this study. The directional distance function is an analytical tool used for measuring the input and output-orientated technical efficiency of different firms. Furthermore, the directional distance function programming model is linear, and the direction in which performance is measured can be specified to accommodate different analytical purposes.

The contributions of this research to IC design firm evaluation are threefold. First, we use the directional distance function to assess the operational efficiency of IC design firms in Taiwan. Using this function, we consider factors related to output slack, input slack and (quasi) fixed input constraints. Second, we use data envelopment analysis (DEA) concepts with a meta-frontier to estimate efficiency in the IC design industry, whereas previous studies have used conventional DEA and other methods (e.g., analytic network process (ANP) and analytical hierarchy process (AHP)) that did not take into account the group concept. Third, we adopt the technology gap[7] concept to measure the difference between IC design firms and the IC industry. With these perspectives, we provide directions to specific IC design firms (or groups) on how to adjust their resources to reach maximal efficiency.

The remainder of this paper is organized as follows. Section 2 presents our review of the literature on the IC industry's performance evaluations. Section 3 describes our methodology and explains the rationale behind it. Section 4 reports the empirical results from a study of 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

Business performance evaluation generally measures the effectiveness and efficiency of a business. Here, effectiveness means that business goals are reached to a certain degree, while efficiency means using less input while generating more output. In the past, income statements and financial reports were used to evaluate business performance. Johnson and Kaplan [27] argue that merely taking management accounting into consideration is insufficient for evaluating businesses; they believe that organizational types, business innovations and competing goals should also be considered. In other words, applying a system view might obtain more global information than a process view. Gamble [19] illustrated that performance evaluation should consider both financial and non-financial parameters. He felt that considering financial indices alone cannot help to manage a business, and thus it is also necessary to consider business values (e.g., invisible assets).

Efficiency is a ratio that measures input and output. It is generally based on whether the unit cost can produce the maximum value or whether the unit can be produced at a minimum cost. There are two types of efficiency: absolute and relative. The evaluation of absolute performance involves finding the maximum output at a given constant input. In contrast, the evaluation of relative performance measures the ratio of input and output among homogeneous decision-making units. In practice, measuring company performance can sometimes be accomplished using a financial ratio combined with parametric or non-parametric analyses. Financial ratio analysis has been used for performance evaluation (Caves [2], Megginson et al. [36]), but it can only measure one input and one output simultaneously. This analysis method also presents some challenges, such as a lack of accredited financial ratio models and the presence of subjective weight assignments.

Parametric analysis involves deciding in advance what the production and/or cost functions will be, since different performance functions will influence evaluation results. Non-parametric analysis, on the other hand, does not involve the use of *a priori* assumptions. Thus, it avoids not only subjective weight assignments, but also the selections of the production and/or cost functions.

To date, most studies on IC industrial efficiency have mainly focused on regression analysis [8,23,32], multivariable analysis [25], stochastic frontier production [15,29], gray relation analysis [24], DEA [5,11,13,40,43], balanced scorecards [7,21] and multi-criteria decision-making (MCDM) [25,26,39]. Among these analysis methods, DEA is considered to be the best approach for organizing and analyzing data, because it allows efficiency to evolve over time and requires no prior assumptions for the specification of the best-practice frontier.

Golany and Roll [20] believed that DEA has the following advantages for evaluating efficiency: (1) it is able to evaluate multiple inputs and multiple outputs, (2) it standardizes the magnitude of unit effect, (3) it assumes no pre-specified form of the production function and avoids parametric measures, (4) it assigns no subjective weights to the inputs and outputs, and (5) it is able to deal with ratio scale data and ordinal scale data simultaneously. Moreover, Charnes et al. [4] compared financial ratio analysis, regression analysis and DEA for evaluating the efficiency of 75 electrical factories in Texas (USA). As experts, they found that DEA was more accurate than the other analysis methods. Lewin and Minton [33] further added that DEA is highly appropriate for

[3] There are several possible reasons for differing regional or group technologies. First, firms in different countries/regions could be operating in a different regulatory environment or market environment. Second, it is possible that due to different physical/financial infrastructure, or the technology under which firms operate under different environments, countries or regions could be different. Thirdly, it is possible that some countries, or firms in some countries, cannot access globally available technology due to constraints on foreign exchange and/or due to stringent import restrictions (Rambaldi et al. [38]).

[4] Here, technology is defined as a representation of the state of knowledge with respect to the transformation of inputs into outputs.

[5] From a benchmarking perspective, if an inefficient IC design firm cannot achieve its group frontier or learn from other groups how to reach that group frontier, then the information obtained from this efficiency evaluation model is not beneficial for this specific IC design firm, because it cannot obtain such scale or ability to reach the group requirements.

[6] The meta-frontier technique is considered as the boundary of an unrestricted technology set. In contract, the group-frontier is the boundary of the efficiency for a group of IC design firms that have a restricted technology set (O'Donnell et al. [37]).

[7] The estimation of a meta-frontier, group-frontier, and the relative inefficiency levels with respect to both, allows for the construction of a measure of the technology gap between groups with provided efficiency effects.