Direct Investments in Japan and Operational Efficiency of Semiconductor Companies from Taiwan[1]

A Semi-parametric Analysis

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1. Introduction

Given the central role of semiconductors in Japan's economic strategy, the Japanese government has endorsed unprecedented subsidies for new IC manufacturing facilities in recent years (METI, 2021). These subsidies encompass ¥476 billion for the new facility of Japan Advanced Semiconductor Manufacturing (JASM) in Kumamoto, with mass production slated to commence in the latter half of 2024, and an additional ¥732 billion for a second facility, with construction anticipated to start by the end of 2024. JASM was founded in December 2021 by the Taiwan Semiconductor Manufacturing Company (TSMC), the world's leading integrated circuit (IC) manufacturer, as a joint venture with Sony Semiconductor Solutions, Denso, and Toyota Motor. By early 2024, TSMC held a controlling share of 86.5%, and its total investment in JASM is projected to surpass US$20 billion for the two plants (TSMC, 2024).

From the perspective of Japanese stakeholders, these substantial subsidies and investments are intended to bolster the resilience of the IC supply chain and to catalyze a resurgence in semiconductor manufacturing in Japan. For semiconductor companies from Taiwan, including those following TSMC's lead into Japan, such investments offer an opportunity to diversify their production sites, thereby mitigating the risk of disruptions due to escalating geopolitical tensions in the post-COVID-19 era (Brundage, 2023; Gao, Ren, & Shih, 2023). A pertinent concern, however, is whether Taiwanese semiconductor companies can sustain their competitiveness when operating in Japan. This question arises from their reliance on the agglomeration economies within Taiwan's high-technology districts (Sher & Yang, 2005) and on the support from domestic government and institutions (Ouyang, 2006). Furthermore, Japan's semiconductor industry has been in continuous decline, with its global market share decreasing from 50.3% in 1988 to 10.0% in 2019, and it continues to follow a downward trend (Kamakura, 2022).

The implications of these new investments remain uncertain; however, historical records may provide insights into future developments. Despite the scarcity of large-scale investments until recently, several Taiwanese semiconductor companies have maintained a longstanding presence in Japan. For example, TSMC established its first subsidiary in 1997, and ASE, the world's largest supplier of IC packaging and testing services, entered Japan in 2003. In this study, we compile historical data on

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direct investments in Japan undertaken by Taiwanese companies in three sectors of the semiconductor industry: IC manufacturing, IC packaging and testing, and IC design. Utilizing data from the past two decades (2004–2023), we compare the operational efficiency of companies that have undertaken direct investments in Japan with those that have not.

For empirical analysis, this research implements a two-stage semi-parametric modeling. We first utilize Data Envelopment Analysis (DEA) to estimate inefficiency scores of semiconductor companies, and then apply truncated regression to assess how investing in Japan affects these bias-corrected scores. As will be detailed later, we find that, across all three sectors, companies that have invested in Japan demonstrate higher efficiency (lower inefficiency scores) compared to non-investors, implying a beneficial role of undertaking direct investments in Japan. Nevertheless, there is no evidence that investing companies gain additional efficiency from engaging in supply chain activities in Japan.

2. Empirical Model

The operational efficiency of a company indicates its ability to transform inputs into outputs. For each firm k ($k = 1, \ldots, K$), vector $x_k = (x_{k1}, \ldots, x_{kN})$ denotes N inputs ($n = 1, \ldots, N$), and vector $y_k = (y_{k1}, \ldots, y_{kM})$ denote M outputs ($m = 1, \ldots, M$). The production technology T, under which y can be produced from x, is characterized by its production-possibility set $P(x) \equiv \{y: (x, y) \in T\}$ or by its input-requirement set $R(y) \equiv \{x: (x, y) \in T\}$.

In the output-based approach employed in this study, the upper boundary of $P(x)$ defines the production-possibility frontier. The necessary expansion in outputs to move a data point (y_k, x_k) to the frontier reflects the level of inefficiency in k's production practices. In DEA, the radial measure of inefficiency (Debreu-Farrell measure), denoted by θ_k, is calculated by solving the following linear programming problem for each k:

$$\widehat{F_k^o}(y_k, x_k, y, x) = \max_{\theta, \varphi} \theta$$

$$\text{s.t. } \sum_{k=1}^{K} \varphi_k y_{km} \geq y_{km}\theta_m, \sum_{k=1}^{K} \varphi_k x_{kn} \leq x_{kn}, and\ \varphi_k \geq 0$$

The above equation yields a CRS (constant returns to scale) specification. For the VRS (variable returns to scale) specification employed in this research, an additional convexity constraint is added to the process operating levels φ_k:

$$\sum_{k=1}^{K} \varphi_k = 1$$

Conditional on θ_k, k selects a combination of outputs and inputs (y_k, x_k) represented as $(y_k^*/\theta_k, x_k^*)$, where $(y_k^*/\theta_k, x_k^*)$ denotes a point on the production-possibility frontier. This implies that instead of achieving the maximal feasible output y_k^*, only $(100/\theta_k)$ percent of y_k^* is realized. Thereby, θ_k takes a minimum value of 1 in scenarios of perfect efficiency, where no expansion in outputs is necessary to attain the production-possibility frontier.

With the inefficiency score θ_k estimated, the next objective is to assess the impact of situational conditions, denoted by vector z_k, on k's efficiency of transforming inputs into outputs. In this research, the influence of z_k on θ_k is conceptualized as:

$$\ln(\theta_k) = z_k\beta + \varepsilon_k$$

Given that θ_k is constrained within the interval $[1, \infty]$, the error term ε_k is assumed to follow a truncated normal distribution, with left-truncation at $-z_k\beta$. The vector β, which encapsulates the effect of z_k on the efficiency of k, can be estimated using truncated regression.

The true value of θ_k is not observable, necessitating the use of its estimate $\hat{\theta}_k$ derived from DEA in estimating β. However, as noted by Simar and Wilson (2007), this approach is associated with two issues. Firstly, since estimates $\hat{\theta}_k$ are derived from a common sample, the errors in a regression of $\hat{\theta}_k$ on z_k are not statistically independent across K. Secondly, in typical DEA applications, numerous $\hat{\theta}_k$ would take a value of 1, despite that the probability of achieving perfect efficiency is close to zero.

In Simar and Wilson (2007), the first issue is addressed by estimating standard errors and confidence intervals for β using a parametric bootstrap procedure, where artificial pseudo-errors are drawn from a truncated normal distribution. The second issue can be addressed using two alternative algorithms. Algorithm #1 simply excludes data points where $\hat{\theta}_k$ equals 1 in the truncated regression. The more intricate algorithm #2 involves an additional bootstrap procedure that corrects the finite-sample bias in DEA's boundary estimation (that $\hat{\theta}_k$ is biased towards 1) to produce bias-corrected inefficiency scores $\hat{\theta}_k' > 1$ for all K. Then, the bias-corrected $\hat{\theta}_k'$ is used in truncated regression to estimate β.

Following Simar and Wilson (2007), this study implements a semi-parametric two-stage modeling. Inefficiency scores are first obtained by DEA, with IC manufacturing, IC packaging and testing, and IC design sectors estimated separately. Then, truncated regression is utilized in conjunction with bootstrapped confidence intervals and bias-corrected inefficiency estimates (algorithm #2) to examine the impact of investing in Japan on the operational efficiency of semiconductor companies from Taiwan.

3. Data and Variables

The sample analyzed in this research encompass all public companies in three sectors of the semiconductor industry: IC manufacturing, IC packaging and testing, and IC design. The majority of these companies are traded on either the Taiwan Stock Exchange (TWSE) or the Taipei Exchange (TPEx). The list of sample companies is obtained from the Taiwan Economic Journal (TEJ) database, which classifies all public companies in Taiwan based on their primary business activities. Over the observation period from 2004 to 2023, there are 16 companies in the IC manufacturing sector, 36 companies in the IC packaging and testing sector, and 153 companies in the IC design sector. Notably, at the inception of the observation period in 2004, TSMC emerged as the pioneer in producing 90nm chips utilizing its novel immersion lithography technology, which featured a water media scanner (in contrast to the traditional dry scanner). In hindsight, this innovation proved pivotal in solidifying TSMC's leadership in the global market.

The first step in DEA involves the quantification of input and output variables. Classical economic theory emphasizes the quantity of output under the assumption of homogeneity across all firms' products. In practical scenarios where products are heterogeneous, most empirical studies use revenue as the output variable, which converts output quantities into a comparable monetary metric. While DEA has the capability to encompass multiple output variables, Wilson (2018) demonstrates that when output variables exhibit high correlation, the dimensionality of output can be effectively reduced to a single measure with limited loss of information. Consistent with previous studies, this research focuses on *operating revenue* as the output variable.

Regarding the selection of input variables, prior studies often emphasize labor and capital inputs delineated in the Cobb-Douglas production function. This study uses *personal expense* as the measure of labor input and *property, plant, and equipment* as the measure of physical capital input. For companies in the IC manufacturing and IC packaging and testing sectors, investment in new equipment is particularly vital to maintain their competitive market position. Further, given the knowledge-intensive nature of the semiconductor industry, *research and development expenditure* is added as the measure of intellectual capital input.

Data on input and output variables were obtained from the financial statements of sample companies archived in the TEJ database. The initial dataset comprises 2,918 observations from 204 companies. However, due to the presence of missing values, 161 observations were excluded from subsequent analyses. The final sample consists of 2,757 observations: 197 from 13 IC manufacturers, 486 from 34 companies in the IC packaging and testing sector, and 2,074 from 152 IC designers. **Table 1** presents the summary statistics of input and output variables, which have been transformed into their natural logarithms to reduce skewness.

Table 1. Summary statistics

	IC Manufacturing			IC Packaging & Testing			IC Design		
	Mean	S.D.	Median	Mean	S.D.	Median	Mean	S.D.	Median
Output									
Operating revenue	17.339	1.574	17.424	15.453	1.600	15.457	14.079	1.547	13.943
Input									
Personal expense	15.488	1.355	15.453	13.963	1.501	13.941	12.351	1.325	12.109
Property, plant & equipment	17.205	1.945	17.578	15.260	1.576	15.235	11.533	1.927	11.690
R&D expenditure	14.556	1.904	14.979	11.678	1.818	11.583	12.200	1.504	12.091
Condition									
Direct investment in Japan	By the end of 2023, 6 IC manufacturing companies, 4 IC packaging & testing companies, and 18 IC design companies have undertaken direct investments in Japan.								
Year	Year effects on bias-corrected efficiency scores are factored out in truncated regression.								

Unit in NTD thousand. Output and input variables are converted to their natural logarithms. Observations with missing values are excluded, leaving n = 197 from 13 companies in the IC manufacturing sector, n = 486 from 34 companies in the IC packaging & testing sector, and n = 2,074 from 152 companies in the IC design sector.

Data on direct investments in Japan were acquired by analyzing sample companies' long-term investments disclosed in their annual reports. The initial dataset includes a wide range of investments. Investments in bonds, mutual funds, and derivatives were excluded first, leaving only investments in corporate entities. Among these corporate entities, only those whose valuations are assessed using the equity method, rather than the cost method, were included for further analysis. This selection criterion is informed by Taiwan's accounting regulations, which require the use of equity method for investments of "strategic importance" – defined as corporate entities in which a company holds at least 20% of shares or exercises significant influence despite a lower shareholding. In contrast, the cost method applies only to investments motivated by financial interests. Further examination reveals that approximately 70% of corporate entities are sample companies' fully-owned subsidiaries in Japan.

For each sample company in a given year during the observation period, a binary variable labeled *direct investment in Japan* was constructed. This variable takes a value of 1 if the company has at least one corporate entity of strategic importance in Japan in the corresponding year, and 0 otherwise. By

the end of 2023, 6 IC manufacturers, 4 IC packaging and testing companies, and 18 IC designers have undertaken direct investments in Japan. In the second-stage analysis, the variable of direct investment is used as a predictor of estimated inefficiency scores. Also, year-specific dummy variables are included as predictors to account for the influence of temporal fluctuations over the 20-year observation period.

4. Results

This research applies the two-stage process advanced by Simar and Wilson (2007) by leveraging the computational routines developed by Badunenko and Tauchmann (2019). The results of this empirical analysis are delineated in **Table 2**, which shows that the coefficient of *direct investment in Japan* is negative across industry sectors. Unlike simple linear models, in truncated regression models the partial (marginal) effect of z on $\hat{\theta}$ and the p-value of this partial effect are not fixed but vary with z. To aid in interpretation, the average partial effect (APE) is also calculated. As illustrated in the table below, APE is negative and statistically significant for all sectors. This finding implies that a company's direct investment in Japan generally correlates with higher operational efficiency.

Table 2. The effect of direct investment in Japan on inefficiency scores (bias-corrected)

	IC Manufacturing		**IC Packaging & Testing**		**IC Design**	
	Coef.	APE	Coef.	APE	Coef.	APE
Direct investment in Japan	-0.026*	-0.026*	-0.085*	-0.050*	-0.079*	-0.065*
	(0.003)	(0.003)	(0.011)	(0.004)	(0.006)	(0.004)

* Significant at the 5% level. Standard errors in parentheses. Year effects are factored out.

The reliability of the above research finding depends heavily on the validity of inefficiency estimates. A straightforward validity check involves verifying whether the estimated scores align with common knowledge. **Table 3** lists the most efficient companies (lowest inefficiency scores) for the year 2023. TSMC is ranked foremost among all IC manufacturers, and United Microelectronics (UMC), the first IC manufacturer ever established in Taiwan, occupies the second spot. Regarding IC packaging and testing, ASE and Siliconware, the largest and third-largest service providers globally, are ranked first and second, respectively. In the IC design sector, Mediatek, the largest IC designer in Taiwan, is ranked fourth, whereas Novatek, the world's largest supplier of LCD driver ICs, holds the second position. These efficiency rankings are consistent with the commonly held perceptions regarding the relative operational performance of the sampled companies.

Table 3. Most efficient companies (with lowest inefficiency scores) in 2023

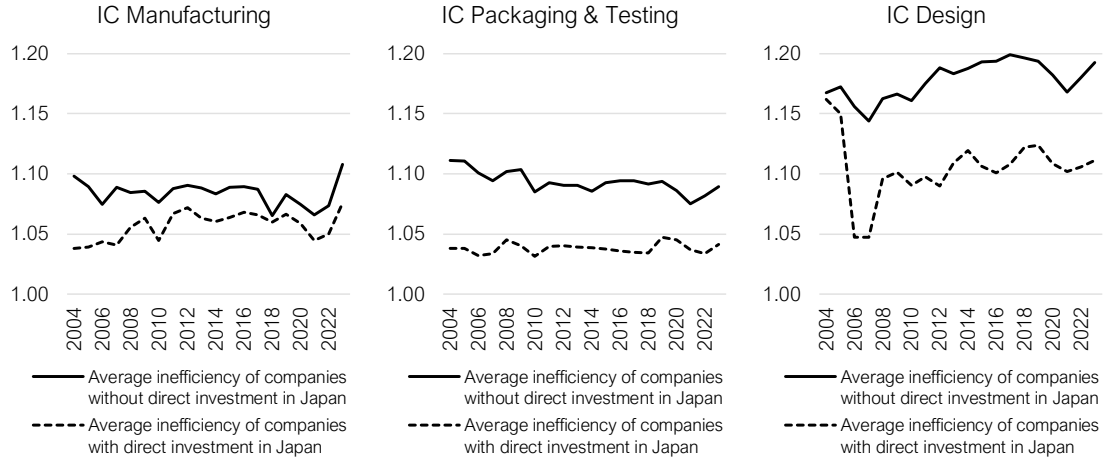
	Inefficiency scores (bias-corrected)
IC Manufacturing	
1. Taiwan Semiconductor Manufacturing	1.029
2. United Microelectronics	1.046
3. Vanguard International Semiconductor	1.082
4. Winbond Electronics	1.088
5. Nanya Technology	1.089
IC Packaging & Testing	
1. ASE	1.022
2. Siliconware Precision Industries	1.024
3. Powertech Technology	1.031
4. Orient Semiconductor Electronics	1.044
5. King Yuan Electronics	1.052
IC Design	
1. Airoha Technology	1.018
2. Novatek Microelectronics	1.029
3. Alchip Technologies	1.030
4. Mediatek	1.038
5. Global Unichip	1.048

Inefficiency scores are output-based radial distances under the VRS assumption.

A further consideration is whether the observed effect of direct investment might be a statistical artifact resulting from the complexity inherent in two-stage, non-linear modeling. Simple *t*-tests, which compare companies that have made direct investments in Japan with those that have not, might help address this concern. Test results reveal that the average inefficiency scores are significantly lower for investing companies compared to non-investing companies across the IC manufacturing sector (t = 7.283; p = .000), IC packaging and testing sector (t = 15.350; p = .000), and IC design sector (t = 14.069; p = .000).

Besides formal statistical tests, informal visual inspections may also be informative. **Figure 1** illustrates the temporal pattern of average inefficiency scores for both investing and non-investing companies. The efficiency differential between these two groups of observations appears consistent over the 20-year observation period.

Figure 1. Temporal pattern of average inefficiency scores (bias-corrected)



5. Additional Analysis

Before TSMC's recent investment in the Kumamoto plants, semiconductor companies from Taiwan had seldom made significant supply chain investments in Japan. However, considering that some companies have maintained a long-standing presence in Japan, it is plausible that they have previously engaged in supply chain activities there, albeit on a smaller scale. This raises the question: could these companies achieve even greater operational efficiency?

When sample companies disclose their strategic investments in Japan, they also provide succinct statements about the activities undertaken by select corporate entities of greater significance. By searching in these statements for descriptions explicitly associated with supply chain activities, such as "production" (生産) or "manufacturing" (製造), this research further identifies those investing companies that have engaged in supply chain activities in Japan. As of the end of 2023, three IC manufacturing companies (TSMC, UMC, and Winbond) and two IC packaging and testing companies (ASE and King Yuan Electronics) belong to this category.

To conduct a formal test, two binary variables are constructed. The variable *direct investment in Japan without supply chain activities* is assigned a value of 1 if a company has at least one strategically important subsidiary in Japan but is not involved in supply chain activities in a given year, and 0 otherwise. Conversely, the variable *direct investment in Japan with supply chain activities* is assigned a value of 1 if a company has at least one strategically important subsidiary in Japan and is involved in supply chain activities in a given year, and 0 otherwise. These two variables serve as predictors (z_k) of inefficiency scores (θ_k).

Table 4 presents the results of this supplementary analysis, which adhere to the same two-stage modeling process. For both the IC manufacturing and IC packaging and testing sectors, the coefficients and APEs of both binary variables appear negative and statistically significant. This implies that companies undertaking direct investments in Japan, irrespective of their involvement in supply chain

activities there, exhibit greater efficiency compared to non-investors. However, according to likelihood ratio tests, the two variables do not exhibit significant differences in the magnitude of their effects. Hence, there is no evidence that companies could gain additional operational efficiency by engaging in supply chain activities in Japan. This latter finding should be interpreted with caution, as it is derived from a very small sample.

Table 4. Further analysis on the effect of direct investment in Japan

	IC Manufacturing		**IC Packaging & Testing**	
	Coef.	APE	Coef.	APE
Direct investment in Japan without supply chain activities	-0.026*	-0.025*	-0.097*	-0.055*
	(0.004)	(0.004)	(0.018)	(0.006)
Direct investment in Japan with supply chain activities	-0.029*	-0.028*	-0.077*	-0.048*
	(0.005)	(0.005)	(0.013)	(0.006)

* Significant at the 5% level. Standard errors in parentheses. Year effects are factored out.

Beyond supply chain operations, statements regarding activities also reveal additional endeavors by Taiwanese semiconductor companies in Japan. By the end of 2023, three IC manufacturers and six IC designers have reported engaging in research and development activities within Japan, whereas no companies in the IC packaging and testing sector have indicated such undertakings. On the other hand, two IC manufacturers, one IC packaging and testing company, and ten IC designers seem to be exclusively focused on customer-related activities, including client services, technical support, and customer relationship management. A summary of this information is provided in **Table 5**.

Table 5. Activities of Taiwan's semiconductor companies in Japan in 2023

	IC Manufacturing	**IC Packaging & Testing**	**IC Design**
No. of companies	10	22	111
No. of companies investing in Japan	6	4	18
No. of companies reporting supply chain activities in Japan	3	2	n/a
No. of companies reporting research & development activities in Japan	3	0	6
No. of companies focusing only on customer-related activities in Japan	2	1	10

Companies delisted before 2023 are not included.

6. Conclusion

Given Japan's commitment to reshoring the semiconductor supply chain and the substantial investments from Taiwan's semiconductor companies, led by TSMC, the question of whether these companies can maintain their competitiveness while operating in Japan warrants scholarly attention. Although the consequences of these new investments are yet to be fully understood, historical data may offer insights into future developments. Analyzing the direct investments in Japan undertaken by Taiwanese companies in the IC manufacturing, IC packaging and testing, and IC design sectors from 2004 to 2023, this research finds that companies investing in Japan exhibit higher operational efficiency compared to non-investors. Nevertheless, there is no evidence that investing companies gain additional efficiency from engaging in supply chain activities in Japan.

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Abstract:
This research examines direct investments in Japan by Taiwanese semiconductor companies over the past two decades (2004–2023) and their impact on operational efficiency. We first utilize Data Envelopment Analysis (DEA) to estimate inefficiency scores of semiconductor companies, and then apply truncated regression to assess how investing in Japan affects these bias-corrected scores. Our findings indicate that companies investing in Japan generally show higher operational efficiency than non-investors. However, we find no evidence that these investing companies gain extra efficiency from their supply chain activities in Japan.

Keywords:
semiconductor; foreign direct investment; operational efficiency; Taiwan