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Retraction

Retracted: Evaluation Model and Decision Analysis of Digital Firms Ranked in Forbes' Top Companies

Discrete Dynamics in Nature and Society

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This article has been retracted by Hindawi following an investigation undertaken by the publisher [1]. This investigation has uncovered evidence of one or more of the following indicators of systematic manipulation of the publication process:

(1) Discrepancies in scope
(2) Discrepancies in the description of the research reported
(3) Discrepancies between the availability of data and the research described
(4) Inappropriate citations
(5) Incoherent, meaningless and/or irrelevant content included in the article
(6) Manipulated or compromised peer review

The presence of these indicators undermines our confidence in the integrity of the article's content and we cannot, therefore, vouch for its reliability. Please note that this notice is intended solely to alert readers that the content of this article is unreliable. We have not investigated whether authors were aware of or involved in the systematic manipulation of the publication process.

Wiley and Hindawi regrets that the usual quality checks did not identify these issues before publication and have since put additional measures in place to safeguard research integrity.

We wish to credit our own Research Integrity and Research Publishing teams and anonymous and named external researchers and research integrity experts for contributing to this investigation.

The corresponding author, as the representative of all authors, has been given the opportunity to register their agreement or disagreement to this retraction. We have kept a record of any response received.

References

[1] F. C. Kao, T. N. Dinh, and A. T. T. Nguyen, "Evaluation Model and Decision Analysis of Digital Firms Ranked in Forbes' Top Companies," *Discrete Dynamics in Nature and Society*, vol. 2022, Article ID 2722914, 15 pages, 2022.

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Research Article

Evaluation Model and Decision Analysis of Digital Firms Ranked in Forbes' Top Companies

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This study evaluates the profitability and marketability efficiencies of digital firms ranked in Forbes' list of top companies by using a two-stage network data envelopment analysis (DEA) model with multiplicative efficiency aggregation under the second-order cone programming (SOCP) and examines the respective impacts of the 1995–2001 dot-com bubble and the 2007–2009 global financial crisis on the companies' efficiencies by applying impulse response function (IRF) analysis. The data of our 49 sampled companies are derived from the Compustat database. The covered period is 1999–2018. These results present the stable and increasing improvement of profitability and marketability efficiencies; in addition, two crisis events have no significant impact on the performance of digital firms. This research is supposed to offer a reasonable and objective evaluation model to measure the performance of digital firms, providing the managers and investors a reference for making their decision.

1. Introduction

The coming of digital technology, digital competition, and digital customer behavior have been leading to pressure on the digital transformation of traditional firms as well as the booming of new digital entrepreneurs [1]. Transformational digital firms consider digitalization as a corporate strategy, and they use digital technologies to change the business model, thus providing new revenue and value-producing opportunities [2]. Digital firms are companies that are fully or highly facilitated by digitalization immediately after inception [3].

When companies become more digital, the value of intangible assets which are not on the firms' balance sheets are on trends of overcoming the values' physical ones in firms' operation [4]; consequently, financial statements and current financial accounting models may have become less meaningful in capturing the main value drivers and investor decisions [5]. Besides, the use of financial ratios to assess the performance and efficiency of a firm has been criticized because of its drawbacks [6]. Because of these reasons, the application of classic criteria, such as return on equity (ROE) or return on asset (ROA), is out of date, particularly in the context of digital firms. Additionally, we have also observed that the academic studies on the performance measurement of digital firms are limited. Therefore, an alternative performance measurement to the financial ratios that can present the overall performance of a firm is worth discussing.

Data envelopment analysis (DEA) with the advantages of performance measurements, identification of areas requiring improvement, and describing the development possibilities have been applied and published in the fields of education, sports [7, 8], finance area with investment decision [9] to areas of high-tech industries [10], and others [11, 12]. This research employs two-stage network DEA models, which have been created to examine the internally complicated structures of decision-making units (DMUs) [13], to assess the performance of 49 digital firms belonging to the list of "2019 Forbes 100 Digital Companies from 1998 to 2018." The following three approaches are currently used to solve the network DEA model: multiplicative efficiency aggregation (MEA), multiplicative efficiency decomposition (MED), and additive efficiency decomposition (AED). Among them, MEA is the most advanced model, as it can handle the general two-stage network DEA model with or without additional inputs and/or additional outputs. MEA does not require the predetermined weight of the individual stages in the network model [14], but it is burdened by its sole problem of nonlinearity. Therefore, in line with the work of Chen and Zhu [15] and Chen and Zhu [16], we combine MEA and second-order cone programming (SOCP) to solve the general form of a two-stage network DEA model with nonlinearity problems. Considering the operations of digital firms and the evolution of the network DEA model, this study adopts MEA-SOCP [17] measuring both profitability efficiency (the ability of a firm to generate revenue/profits from input resources) and marketability efficiency (the ability to create shareholder value from earned revenues and profits) of the digital firms' performance. The application of this model has been limited to the performance measurement of banks [18, 19]; meanwhile, the other industries have mainly focused on operational efficiency models to decomposing productivity, profitability, or marketing only [20, 21]. This study is an attempt to contribute to the literature on measuring the overall performance of a digital company, thus offering a whole new meaningful picture to both managers and investors. Although previously published works measure the profitability and marketability efficiencies of high-tech industries or firms [22–24], to the best of our knowledge, this is the first work that explores these efficiency aspects in digital firms by combining MEA and SOCP.

In the first 10 years of the 21st century, the financial market experienced the 2001 dot-com bubble and the 2007–2009 global financial crisis. A review of the related literature has shown that some researchers have determined the characteristics that would allow firms to become more durable than other firms during a financial crisis [25, 26]. However, research regarding the resilience of firm performance during the financial crisis, particularly the postcrisis period, is lacking. The digital firms sampled in this research have survived the abovementioned two recessions. Such scenarios raise the question as to how the firms, particularly their operational efficiency and marketability efficiency, were able to respond to the crises, which supposedly have a wide and deep impact on their operations during those periods. This study applies the impulse response function (IRF) to examine how financial crises had contributed to digital firms' efficiencies.

This research involves two general objectives. First, we design a two-stage network DEA model to simultaneously measure the profitability and marketability efficiencies of world-ranking digital firms. The model is solved by integrating MEA into the SOCP technique. Second, we employ IRF to examine the resilience of firm performance to business changes caused by financial recessions.

In general, this article has two contributions: First, it is the first empirical application of the MEA-SOCP model in measuring digital companies' performance; this research consolidates the advantages of the current framework and methodology that related stakeholders could consider in their evaluation of digital firms. A robustness test is added to prove this. Second, it explores the impact of the financial crisis on the durability of digital firms' efficiencies and presents the implications to the digital firms as well as other industries' strategies to confront coming crises.

The rest of this article is as follows: Section 2 presents a review of relevant past studies. Section 3 introduces the research design. Section 4 presents and discusses the findings. Section 5 concludes the article.

2. Literature Review

2.1. Profitability Efficiency, Marketability Efficiency, and Application of the Two-Stage DEA. Seiford and Zhu [17] explored the production process by extending the concept of operational performance from the aspect of a firm's capability to generate profit and shift to marketability; their research is one of the first studies that applied the two-stage DEA to measure firm performance. The two individual stages (profitability and marketability efficiencies) of the top 55 US commercial banks are simultaneously investigated using three fundamental DEA models, namely CCR, BCC, and RTS. The subsequent research on this topic has developed in both financial [19] and nonfinancial firms [27, 28].

Kuo and Yang [29] adopted slack-based measures to assess the profitability and marketability efficiencies of Taiwan's integrated circuit design companies. They employ the Simar–Wilson method and a truncated regression to define how intellectual capital affects firm efficiency. Their empirical results have provided inefficient companies with the knowledge on how they can manage their intellectual capital, human capital, and customer parameters as a means of improving their efficiency and success.

Hung and Wang [23] provided an alternative comparison between the performance of high-tech electronic and the performance of old and established nonelectronic manufacturing industries in Taiwan. A two-stage production process is utilized to improve the characterization of firm operating performance by using the two stages of profitability and marketability efficiencies.

Wang et al [22] integrated the R&D, productivity, and market value perspectives to estimate the short-term profitability and marketability efficiencies of Taiwan's high-technology firms from 2003 to 2007. These authors extend the two-stage DEA model of Chen and Zhu [30], which is limited in terms of measuring the framework of multiple-division organizations and different divisions. The new model can simultaneously estimate the profitability efficiency of both production and R&D divisions.

Assani et al [24] applied a two-stage DEA model to measure the case of 30 Chinese provinces' value chain in terms of its profitability and marketability. The empirical results identify the sources of inefficiency within the evaluated system as well as the necessary actions that can be made to improve the performance of the evaluated system.

However, the above studies have used a two-stage DEA approach that cannot address the potential conflicts between the two stages arising from intermediate measures [31]. In the other words, the intermediate measures have not been considered in the step of changing inputs to outputs, leading to information loss among DMU managers, as the model cannot specifically determine which part of the process is inefficient [32]. Therefore, the two-stage network DEA model is proposed to comprehend the internal structure; however, calculating precisely and consistently the stages and the overall efficiencies or calculating the optimality of the intermediates remains the major challenge of this two-stage DEA model [33].

Following the development line of the two-stage network DEA models to satisfy the abovementioned requirements, efficiency decomposition [34] and efficiency aggregation approaches [15] should therefore be considered. Recent studies have acknowledged the superiority of the efficiency aggregation approach, especially its viability of use with the mature SOCP technique, to solve highly nonlinear problems [15, 35]. Thus, measuring operation efficiency in the form of profitability and marketability efficiencies by employing the MEA approach is a timely contribution to the empirical application.

The profitability and marketability efficiencies present the levels of achieving the firms' goals, namely creating revenues, and profits and improving shareholder value [1, 36]. This supposes that the firm with high-efficiency scores presents a more durable and sustainable performance. This logic is true in any industry. Therefore, this current research employs these two stages in measuring the performance of digital firms. Apart from the performance measurements such as ratios or "black box" DEA, this study applies two-stage network DEA because of its improvement. The advantages of this method would be explained further in Section 3.

2.2. Recessions in the Financial Market and Firm Efficiency. A popular discussion is on establishing the link between the organization's performance and its operational environment [37, 38]. In the first 20 years of the 21st century, the normal operating environment of businesses around the world had been impacted by two recessions. The first recession began 13 months after the tech bubble burst and lasted 8 months from March 2001, while the second one is the Great Recession of 2008. Consequently, many empirical studies have been conducted to measure how these financial crises had affected firm performance.

Gonenc and Aybar [39] analyzed the impact of concentrated ownership and business group affiliation on the performance of exchange-listed nonfinancial firms in Turkey by focusing on the 12-month time window within the period of the February 2001 financial crisis. Their findings claim that balance sheet exposure significantly affected firm performance during the crisis, and the firms with higher concentrated ownership had lower stock market performance before and during the financial crisis. Akhigbe et al [40] examined the effect of ownership form on financial performance, with particular focus on the performance of bank holding companies before and during the 2008 financial crisis. The results offer important information to the commercial banking industry as the difference in firm performance before and during the crisis is not due to agency problems but caused by capital markets and managerial labor markets and specialization.

By using a sample of all firms listed in the S&P300 from 2008 to 2009, Aldamen et al [41] argued that governance has a role in increasing firm performance and value when firms undergo exogenous financial pressure, such as the financial crisis in 2008. Claessens et al [42] isolated and compared how the financial crisis of 2008 had led to changes in the business cycle, international trade, and external financing conditions. The focus of their research is the performances and profits of 7,722 nonfinancial firms in 42 countries for the sampling period of 2007–2009. Peric and Vitezic [43] investigated the surviving companies in the manufacturing and hospitality industries of Croatia, and the observation period is the economic recession between 2008 and 2013. They employed the two-step dynamic panel technique to examine how the global crisis had impacted firm growth. They found that the growth rates of large- and medium-sized firms are higher than that of small-sized firms in both industries. Ryu et al [44] divided the listed firms in Korea into precrisis and postcrisis period groups. A regression model is established to prove how the financial crisis in 2008 or the financial market condition at that time could change and how international strategic alliances would impact the firms' return on equity (ROE) and return on asset (ROA).

Several pointers can be deduced from the previously published research on the relationship between the financial crisis and firm performance. First, the indicator of firm performance can be measured by one or two variables, such as financial performance ratio (ROA and ROE) or stock prices. However, we suppose that these variables are insufficient to present the firm performance concept. Second, most of the research periods are in the short term and cover 2 or 3 years before and during the crisis, but the long-term period can better depict the change in firm performance. Lastly, the financial crisis factor in the abovementioned studies plays an environmental or supporting role in testing the impact of variables on firm performance rather than showing the deferred effect of the financial crisis on performance.

Consequently, besides employing the two-stage network DEA model and collecting 20-year data to solve the first and second problems, we use IRF to track the reaction of a system's variables via impulses of a system's shocks to overcome the third problem [45]. IRF has several merits that are believed to be appropriate for assessing the impact of changes on business performance [46]. To the best of our knowledge, our work is the first one to apply IRF as a means of observing the changes in firm performance after the two global financial crisis events, thus enhancing the understanding of the role of stable financial market conditions on the performance and growth of firms.

3. Methodology

3.1. Research Framework. The evaluation of the operating performance of a firm is not limited to the original production process. This research aims to decompose performance into two stages. The first one named profitability efficiency presents the ability to generate revenue/profits

Table 1: Classification of the digital firm industry.

Industry	Firm (code)
Broadcasting and cable	Altice (ATUS), Dish (DISH), and Disney (DIS)
Business and personal services	Automatic Data Processing (ADP), Booking Holdings Inc (BKNG), and DXC Technology Company (DXC)
Business products and supplies	Canon (CAJ)
Communications equipment	Nokia (NOK), Cisco (CSCO), and Corning (GLW)
Computer hardware	Fujitsu (FJTSY), Apple (AAPL), Dell (DELL), and HP Inc (HPQ)
Computer services	NetEase (NTES), Infosys (INFY), Accenture (ACN), Cognizant (CTSH), and International Business Machines (IBM)
Electronics	Kyocera (KYOCY)
Internet and catalog retail	Amazon (AMZN), eBay (EBAY), and Netflix (NFLX)
Recreational products	Nintendo (NTDOY)
Semiconductors	ASML Holding NV (ASML), Taiwan Semiconductor MFG (TSMC), Analog (ADI), Applied Materials Inc (AMAT), Intel Corporation (INTC), LAM Research Corp (LRCX), Micron (MU), Nvidia Corp (NVDA), Qualcomm (QCOM), and Texas Instruments Inc (TXN)
Software and programming	Adobe Inc (ADBE), Fiserv Inc (FISV), Microsoft Corp (MSFT), Oracle Corp (ORCL), and General Electric (GE)
Telecommunication services	Rogers Corp (RCI), China Telecom Corp Ltd (CHA), Orange (ORA), Deutsche Telekom (DTE), China Unicom Ltd (CHU), America Movil SA DE CV (AMXL), SK Telecom Co Ltd (SK), Vodafone (VOD), AT&T Inc (T), and Verizon Communications Inc (VZ)

from the input resources of costs and expenditures. Although transformational digital or digital firms are new business models, their end goals are generating revenues and profits and improving shareholder value [1, 36]. Therefore, we employ the second stage named marketability efficiency to measure its ability to create shareholder value from the earned revenue and profits. The linking between intangible assets and shareholder-added value or the shifting of shareholders seeking from tangible to intangible assets has been defined in various research [47, 48]. Additionally, intangible assets have been proved their role in an organization's sustainable competitive advantage and also their effect on the firms' significant transformation, particularly in digital firms [4, 49]. The theory and evidence indicate that the flows of revenues/earning information could explain the movement of stock price [50–52]. While intangible assets show the differences between a company's market value and book value that are not reflected on the balance sheets [29], the stock price is another added value showing the market value to the shareholders and investors. On the one hand, cash and short-term investment present the liquidity or the readily convertible capacity of a firm in the case of risk of changes (Short-term Investment Strategies to Manage Financial Risk, Global Liquidity Guide Series (2012), and Association for Financial Professionals) [53]; on the other, cash also presents the value creation from the shareholders' point of view [54] and persistent cash holdings predict low betas [55]. Because of these, this research employs intangibles, cash and short-term investment, and stock price measured at a close time as outputs of the marketability efficiency stage.

Generally, this research employs the following variables as inputs, intermediates, and outputs in the DEA model. The inputs are COGS (costs of goods sold), which refers to the cost of obtaining raw materials and producing finished goods that are sold to consumers [56, 57]; SGAX (selling, general, and administrative Expenses), playing as a form of operating expenses, refer to the necessary cost associated with the sales activities, including utilities of the sales department, and the general administration of the business [57, 58]. Intermediates are as follows: revenue is total net operating revenues, including revenues from all normal business activities, subtracting sales discounts, and allowances [56, 59, 60]; net incomes are total operating incomes, including incomes from all normal business activities, the rest after subtracting the cost of goods sold, and total operating costs from net operating sales [61]. Outputs include: intangibles assets, which can take the form of goodwill, franchise, patent right, right of trademark, usage of the land, etc [29, 60]; cash and STI (short-term investment) include cash and foreign currency on hand and equivalents, such as a deposit in the bank and foreign currency equivalent; short-term investment consists of any investments in debt and equity securities with maturity of 1 year or less [54]; closing price is the last price at which a stock is traded during a regular trading session [62, 63].

3.2. Data Collection and Validity Checking. The firm included in this research may be categorized in different industries and from various countries; however, they are playing role in leading and shaping the modern digital world (Table 1). The variables obtained in this research are mostly collected from the yearly financial statements of firms. Table 2 illustrates the descriptive statistics of chosen variables.

A total of 49 firms and a set of input, intermediate, and output variables were collected based on data availability of financial information for the 20 years covered from 1999 to 2008. The number is supposed to meet the sample size requirement [64]. The telecommunication services and semiconductor industries contribute the most firms to the list, with ten companies each, followed by the software and programming and computer services industries with five companies each.

Table 2: Description statistics of variables (unit: USD million).

Variables	Mean	Median	Min	Max	Std. Dev	Skewness	Kurtosis	K-S test (p value)
(I) COGS	15,906.96	6,145.41	1.30	15,2853.00	21,444.00	2.26	6.28	$p < 0.01$
(I) SGAX	7514.26	2,903.30	6.90	81,014.00	9,907.57	2.19	6.11	$p < 0.01$
(Int) Revenue	30,852.03	13,442.12	1.90	265,359.00	38,558.63	2.11	5.43	$p < 0.01$
(Int) Net income	3,089.26	1,336.05	−38,118.50	98,806.00	7,031.59	4.43	48.34	$p < 0.01$
(O) Intangibles	23,926.37	4,119.20	0.50	456,567.00	49,594.52	3.58	16.39	$p < 0.01$
(O) Cash and STI	8,183.14	3,786.98	10.00	133,768.00	14,650.83	4.31	22.85	$p < 0.01$
(O) Closing price	62.51	34.43	0.60	1,737.70	139.31	8.35	81.04	$p < 0.01$

Table 3: Correlation coefficients.

	(I) COGS	(I) SGAX	(Int) Revenue	(Int) Net income	(O) Intangibles	(O) Cash and STI	(O) Closing price
(I) COGS	1						
(I) SGAX	0.760* $p = 0.001$	1					
(Int) Revenue	0.945* $p = 0.001$	0.885* $p = 0.001$	1				
(Int) Net income	0.479* $p = 0.001$	0.469* $p = 0.001$	0.581* $p = 0.001$	1			
(O) Intangibles	0.537* $p = 0.001$	0.602* $p = 0.001$	0.639* $p = 0.001$	0.198* $p = 0.001$	1		
(O) Cash and STI	0.406* $p = 0.001$	0.554* $p = 0.001$	0.528* $p = 0.001$	0.470* $p = 0.001$	0.301* $p = 0.001$	1	
(O) Closing price	0.118* $p = 0.001$	0.155* $p = 0.001$	0.118* $p = 0.001$	0.087* $p = 0.007$	−0.058* $p = 0.007$	0.055* $p = 0.088$	1

Note: *, **, and *** are for 1%, 5%, and 10% confidence levels, respectively.

The Kolmogorov–Smirnov (K-S) test can be used to determine the significantly acceptable hypotheses of non-normally distributed variables. Thus, applying DEA to the collected data is suitable. Habibzadeh [65] also suggests the use of mean for normal distribution and median for non-normal distribution in descriptive statistics; thus, the median values of the variables are added. As shown in Table 3, most of the variables are significantly and positively correlated with the others, which means that isotonicity can also be proposed. The increase in the proportion of the inputs also increases the proportion of the outputs.

3.3. MEA in SOCP. The research framework presents that the digital firms' overall performance in this current work will be explored through two subdivisions. To obtain this, a two-stage network DEA model is employed.

Apart from parametric methods, DEA is a nonparametric method and it does not require a specific function form for the analysis model. In addition, DEA does not consider measurement units of variables and could simultaneously choose multiple inputs and outputs to transform complex and multiple performance indicators into a single summary measure of performance [66, 67]. This method explores the different dimensions of activity to analyze the efficiency of an individual unit in the whole sample through best performance, improved performance, or improvement targets [68–70].

However, the "black box" or conventional DEA model only treats the system as a whole unit in measuring the performance; it is not fixed with the complicated operations with multiple processes. Therefore, the implications from this conventional DEA model cannot recognize which process in operation causes the inefficiency or what the sources of inefficiencies are [71, 72]. Two-stage DEA is an improved approach in comparison to the conventional one; however, it cannot address the potential conflicts between the two stages arising from intermediate measures, leading to information loss among DMU managers, and cannot specifically determine which part of the operation is inefficient [31, 32]

Since the prior work of Cooper [73], the network DEA model has been developing and solving these issues. Additionally, the network DEA advantage is raising the model discrimination because of its capacity of expanding the sample by subdivisions [74]. The two-stage network DEA model can be calculated by using three techniques including MED [34, 75], AED [76], and MEA [15, 16]. MED is usually used in a very specialized two-stage structure when constant returns to scale (CRS) is assumed. MED-based network DEA retains the property of the conventional DEA in the sense that input- and output-oriented models yield the same efficiency scores. Compared with the AED, MED does not require predetermined weights to combine individual stage efficiencies. However, if there are external inputs to the second stage, and/or some outputs leave the first stage and do not become inputs to the second stage, or if we assume variable returns to scale (VRS), MED has limited capability to address these extensions. Alternatively, multiplicative efficiency aggregation (MEA), which is highly nonlinear and is impossible to be transformed into a linear programming

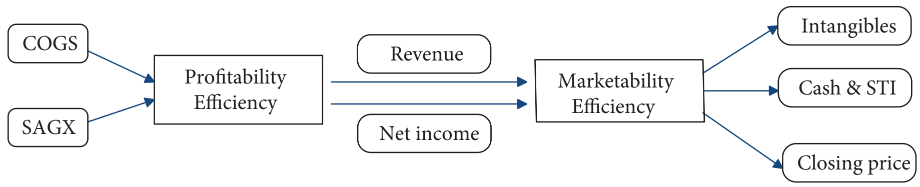


Figure 1: Research framework.

problem, defines the overall efficiency as a product of stage efficiency scores and can be easily applied to general two-stage network structures. In the other words, MEA can overcome the shortcomings of the AED and MED [77, 78].

Therefore, this study discovers that the MEA model for general two-stage networks corresponds to a cone structure in disguise and can be transformed into the form of second-order cone programming (SOCP). MEA in a two-stage network DEA can be effectively and efficiently solved, regardless of the network structures. This research enables us to solve both MEA using SOCP which is considered as effective as linear programming [79].

This study assesses the two-stage production process of digital companies by utilizing balanced panel data, and the two-stage network DEA is integrated into the SOCP technique to handle the multiyear data framework in considering the window effects of changes between the input, intermediate, and output items regarding efficiency. In this manner, profitability efficiency and marketability efficiency can be estimated. The related programming is described in the following paragraphs.

The two-stage production structure shown in Figure 1 assumes n digital companies in a two-stage during T terms. The first stage uses M inputs $O_{ij}^t\,(i = 1, \ldots, M;\ j = 1, \ldots, N;\ t = 1, \ldots, T)$ and D intermediates $P_{dj}^t\,(d = 1, \ldots, D;\ j = 1, \ldots, N;\ t = 1, \ldots, T)$ to measure the profitability efficiency at time t. These intermediates P_{dj}^t are utilized to produce S outputs $Q_{rj}^t\,(r = 1, \ldots, S;\ j = 1, \ldots, N;\ t = 1, \ldots, T)$ to evaluate marketability efficiency at time t. This study adopts MEA to compute the overall technical efficiency in a two-stage DEA structure based on the VRS. The overall efficiency of the observed digitalcompany$_o\,(o = 1, \ldots, n)$ is measured by using the following programming:

$$\begin{gathered}
\text{Max}\,\frac{\sum_{d=1}^{D} w_d^2 P_{do}^t + u_1}{\sum_{i=1}^{M} v_i O_{io}^t}\cdot\frac{\sum_{r=1}^{S}\mu_r Q_{ro}^t + u_2}{\sum_{d=1}^{D} w_d^2 P_{do}^t},\\
S.T.\\
\frac{\left(\sum_{d=1}^{D} w^d P_{dj}^t + u_1\right)}{\sum_{i=1}^{M} v_i O_{ij}^t \le 1},\\
(j = 1, \ldots, N; t = 1, \ldots, T),\\
\frac{\left(\sum_{r=1}^{S}\mu_r Q_{rj}^t + u_2\right)}{\sum_{d=1}^{D} w_d p_{dj}^t \le 1},\\
(j = 1, \ldots, N; t = 1, \ldots, T),\\
v_i, w_d, \mu_r \ge \varepsilon, \forall i, d, r, u_1, u_2 \text{ free in sign},
\end{gathered} \tag{1}$$

where v_i, w_d, and μ_r are assumingly positive weights, and u_1 and u_2 are free variables under the VRS assumption. ε is the small non-Archimedean. Here, w_d represents the weights of the links or intermediate measures between the two stages, and the values are assumed to be equal. The efficiencies of the first and second stages of specific digital companies under evaluation can be expressed as

$$\begin{gathered}
\frac{\sum_{d=1}^{D} w_d P_{do}^t + u_1}{\sum_{i=1}^{M} v_i O_{io}^t},\\
\frac{\sum_{r=1}^{S}\mu_r Q_{ro}^t + u_2}{\sum_{d=1}^{D} w_d P_{do}^t}.
\end{gathered} \tag{2}$$

(1) can be transformed into a SOCP problem to optimize the two-stage DEA. The related transfer techniques can be found in [15, 16]. The overall efficiency (OE_o^t) and the efficiencies of stage 1 (TE_{1o}^t) and stage 2 (TE_{2o}^t) for observed digital companies at time t can be expressed as

$$\begin{gathered}
TE_{1o}^t = \frac{\left(\sum_{d=1}^{D} w_d^* P_{do}^t + u_1^*\right)}{\sum_{i=1}^{M} v_i^* O_{io}^t},\\
TE_{2o}^t = \frac{\left(\sum_{r=1}^{S}\mu_r^* Q_{rro}^{*t} + u_2^*\right)}{\sum_{d=1}^{D} w_d^* z_{do}^t},\\
OE_o^t = TE_{1o}^t \times TE_{2o}^t.
\end{gathered} \tag{3}$$

The asterisks represent the optimal solution from (2).

3.4. IRF Analysis. Using ordinary least squares, we run (3), which has been adjusted for heteroscedasticity and autocorrelation.

$$\begin{aligned}
y_{t+k-1} &= \delta_{ok} + \delta_{ok}^* t + \sum_{r=1}^{R}\delta_{irk} y_{t-r} + \sum_{l=1}^{L}\delta_{2lk} d_{t-l}\\
&\quad + \sum_{l=1}^{k-1}\gamma_{2l} d_{t+k-1-l} + v_{tk}^*,
\end{aligned} \tag{4}$$

where δ_o and δ_o^* are used to control the firm- and year-fixed effects; $\sum_{r=1}^{R}\delta_{irk} y_{t-r}$ represents the lagged efficiency; $\sum_{l=1}^{L}\delta_{2lk} d_{t-l}$ represents the lagged shock events; $\sum_{l=1}^{k-1}\gamma_{2l} d_{t+k-1-l}$ is the sum of the events occurring during the kth year; r is the number of lags for y_t; l is the number of lags for d_t; and v_{tk}^* represents the residuals that can be extended as $v_{tk}^* = \sum_{m=1}^{K-1}\gamma_{3m} u_{t+k-1-m} + u_{t+k-1}$. See Koop and Pesaran [80] for the details of the IRF calculation.

Table 4: Efficiency scores of the digital firms.

Industry	Company	Profitability efficiency	Marketability efficiency	Overall efficiency
Broadcasting and cable	Altice	1.000	0.088	0.088
	Dish	1.000	0.055	0.055
	Disney	1.000	0.017	0.017
Business and personal services	ADP	0.873	0.102	0.089
	BKNG	1.000	0.887	0.887
	DXC	0.728	0.095	0.069
	Canon	1.000	0.019	0.019
Communications equipment	Cisco	1.000	0.021	0.021
	Corning	0.860	0.065	0.056
	Nokia	1.000	0.009	0.009
Computer hardware	Apple	0.964	0.031	0.030
	Dell	1.000	0.006	0.006
	Fujitsu	1.000	0.011	0.011
	HP	0.995	0.005	0.005
Computer services	Accenture	0.893	0.034	0.031
	Cognizant	1.000	0.137	0.137
	IBM	0.841	0.023	0.019
	Infosys	0.842	0.088	0.074
	NetEase	1.000	0.049	0.049
Electronics	Kyocera	0.874	0.082	0.072
Internet and catalog retail	Amazon	0.903	0.058	0.053
	eBay	1.000	0.208	0.208
	Netflix	0.940	0.027	0.026
Recreational products	Nintendo	1.000	0.006	0.006
Semiconductors	AMAT	0.930	0.050	0.046
	Analog	1.000	0.427	0.427
	ASML	1.000	0.161	0.161
	Intel	1.000	0.017	0.017
	Lam	0.893	0.255	0.228
	Micron	1.000	0.038	0.038
	NVidia	0.938	0.152	0.143
	Qualcomm	1.000	0.106	0.106
	Texas	1.000	0.067	0.067
	TSMC	1.000	0.043	0.043
Software and programming	GE	1.000	0.004	0.004
	Adobe	1.000	0.782	0.782
	Fiserv	1.000	0.110	0.110
	Microsoft	1.000	0.034	0.034
	Oracle	1.000	0.646	0.646
Telecommunication services	AMXL	0.896	0.017	0.016
	AT&T	1.000	0.009	0.009
	CHA	0.974	0.026	0.025
	CHU	1.000	0.010	0.010
	Deutsche	1.000	0.004	0.004
	Orange	0.985	0.024	0.023
	Rogers	0.991	0.256	0.254
	SK	1.000	0.029	0.029
	Verizon	1.000	0.009	0.009
	Vodafone	1.000	1.000	1.000

4. Results and Discussion

4.1. Efficiency Analysis. Table 4 shows the average profitability, marketability, and overall efficiency from 1999 to 2018 of the 49 digital firms. The concretization of the firm evaluation process is established using the two consecutive stages by converting the production investment costs to revenues and income, followed by the creation of additional value under the normal operating performance intangible assets [60]. The market price can also help to show the expectation of firms regarding growth and sustainability, especially alongside financial markets. Besides, the amount of cash and short-term investments on the balance sheets are the sources of information for stakeholders regarding capital efficiency, future investments, and financing opportunities [81].

Among these firms, Vodafone can be considered the benchmark in the evaluation of firm performance. In terms of profitability efficiency, 31 firms can reach the maximum

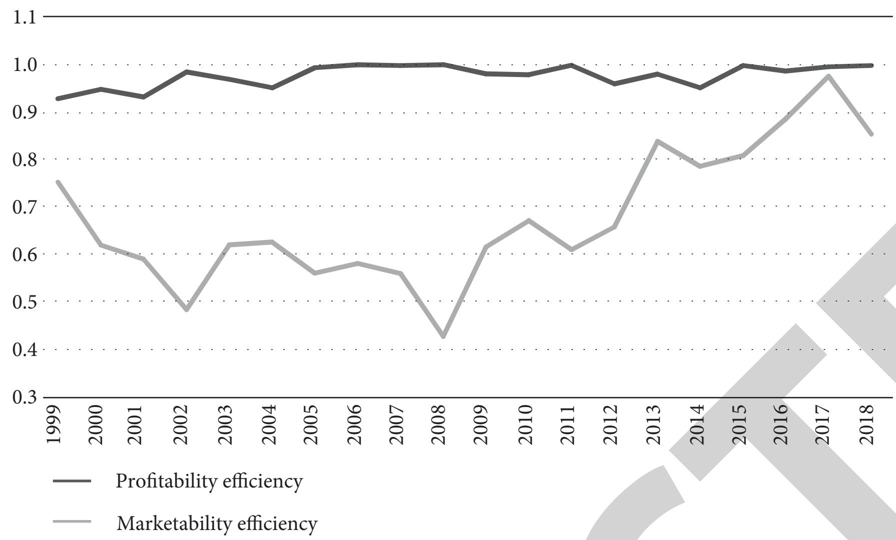


Figure 2: Trends of firm performance.

value of 1 as the score efficiency, and the minimum value belongs to DXC. These results indicate that the firms have equally comparative efficiency in terms of their main operating performance and almost no room for improvement can be expected. Therefore, marketability efficiency becomes the necessary and important criterion to evaluate the top global firms. Except for Vodafone, the average inefficiency scores of the sampled firms range from 11.3% to 99.4%, suggesting considerable improvement concerning upgrading their efficiency. We suppose the main reason can be attributed to the downward trend of market prices and the huge amount of cash in these firms' accounts. These aspects partly reflect the low expectation of stakeholders of these firms.

Although the average profitability efficiency scores are generally stable during the 20 years, the marketability efficiency scores fluctuate and then are at the lowest in 2002 and 2008, and they gradually increase in the final sampling years (Figure 2). The gap between the two stages narrows in the last 10 years, which may be explained by the change in investor expectations regarding the growth of digital firms in the context of the digital economic boom. Based on the profitability efficiency scores, we find that broadcasting and cable, recreational products, and software and programming are the leading industries in the age of digitalization. However, only software and programming followed by business and personal services and semiconductors have relatively good performances on the market stage. To the other countries (Figures 3 and 4), the US with the grey color seems to dominate the digitalization age with 31 firms across all industries, followed by Japan (four firms), China (two firms), and the Netherlands (two firms). The performances of the US firms in the grey color in terms of profitability and marketability are also higher compared with the other countries' companies on average.

4.2. Robustness Test. Galagedera and Silvapulle [82] tested the robustness between CRS and VRS assumptions, Avkiran [83] tested the robustness between the traditional black box and network DEA models. Avkiran and McCrystal [84] and Kaffash et al [85] examined the sensitivity of sample size for the network DEA model. In addition to these, this article provides the robustness test of performance changes by conducting two models: standard DEA (two-stage DEA) and the MED and then compares the results with current the MEA-SOCP; all models are under the assumptions of VRS.

Table 5 presents the discrimination of estimates. We find significant differences in efficiency scores between MEA-SOCP and standard DEA and between MEA-SOCP and MED models. It could be seen that the range of estimates from the standard DEA and the MED are narrower than the MEA-SOCP. The number of efficient DMUs from MEA-SOCP is lower than the MED, and there are no efficient DMUs from the standard DEA model. This demonstrates that the current DEA model can better discriminate the efficient and inefficient firms rather than others. These results come from the ability to solve the loss of information from the intermediate variable of network DEA and the problem of nonlinearity of SOCP.

4.3. The Impact of the Financial Crisis on the Digital Industry. Impulse responses are employed to examine the impacts of the 2001 and 2007–2009 crises on the efficiency scores. As shown in Table 6, the financial crises have no significant effect on profitability performance. In the other words, the normal operating activities of the firms had not been influenced by the investment activities of the financial markets. The dot-com bubble in 2001 can be attributed to the overinvestment of Internet startups without serious consideration of their real operating performance. However, in the context of digital firms, especially those companies listed high in the world ranking, this overinvestment is not a problem. The results suggest that the efficiency of cost management and the income/profit creation of firms are not influenced by the financial market.

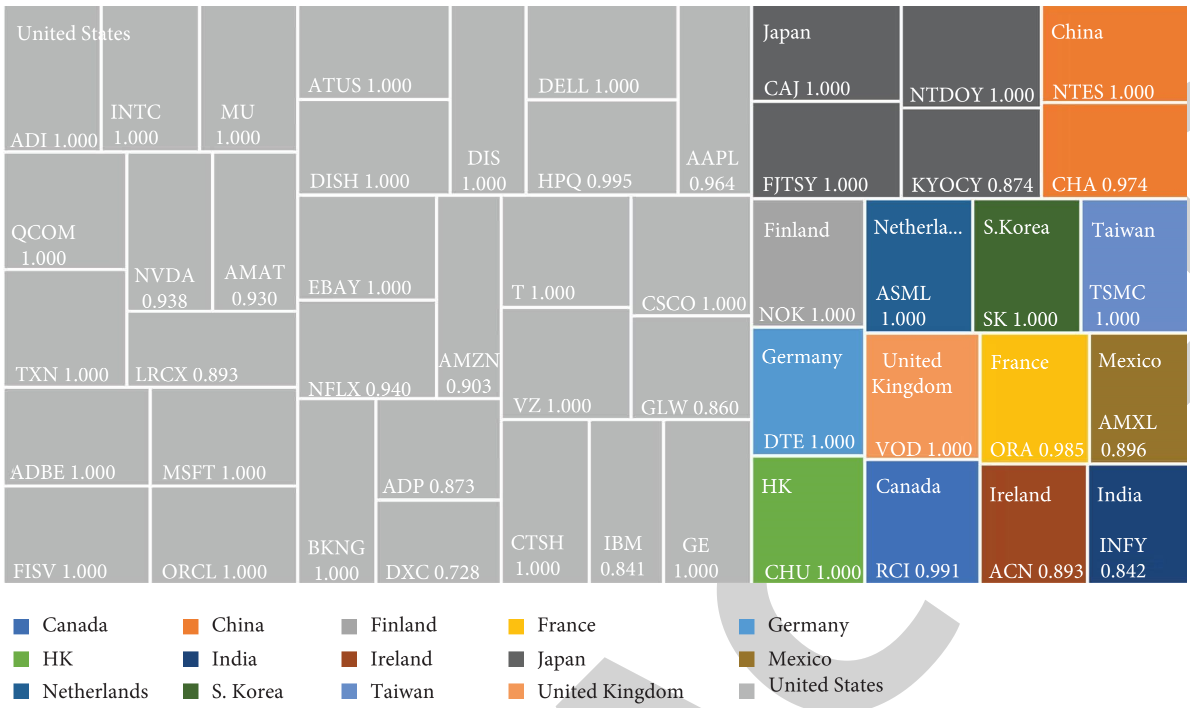


Figure 3: Tree map of profitability efficiency.

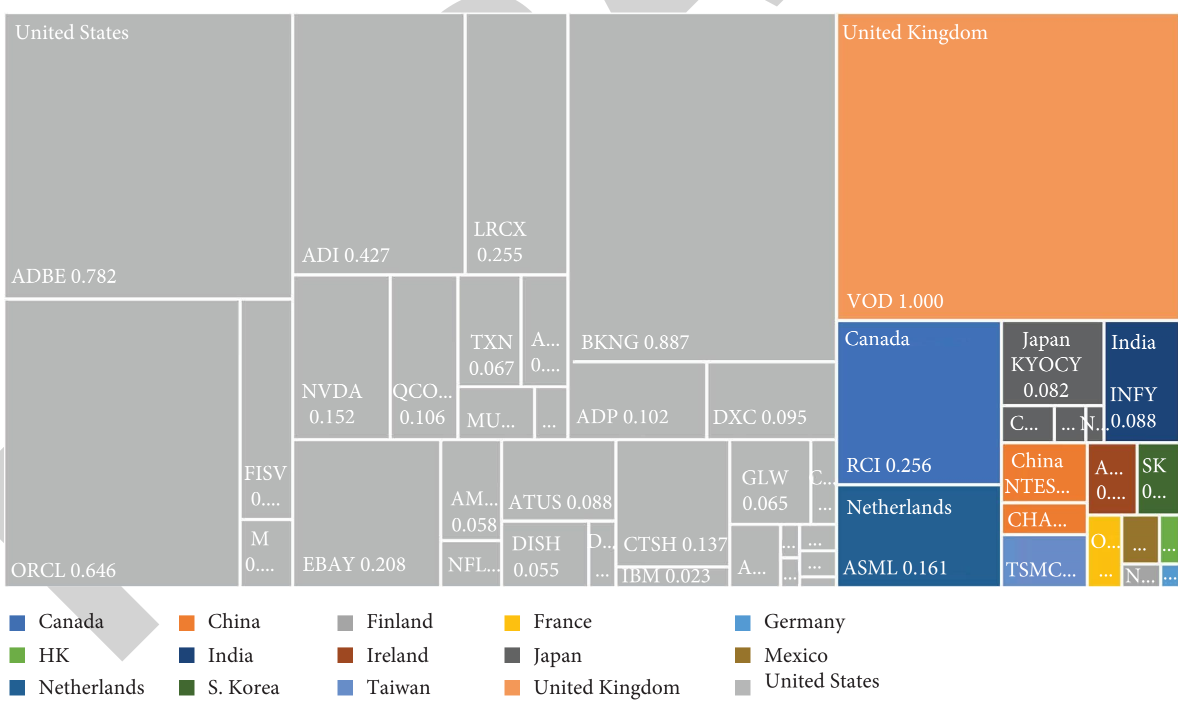


Figure 4: Tree map of marketability efficiency.

A universal agreement regarding the original cause of the financial crisis in 2007 is that it is a combination of a credit boom and the housing bubble [86]. The crisis' side effects have changed the business environment as evidenced by their financial constraints, and it has also changed the expectations of financial markets as evidenced by stock returns and prices. The empirical results show that the third year after the crisis in 2007 experienced a substantial increase in marketability efficiency before decreasing in the next three consecutive years. However, the significant influence of the crisis on profitability and marketability efficiencies cannot be estimated in the context of digital firms.

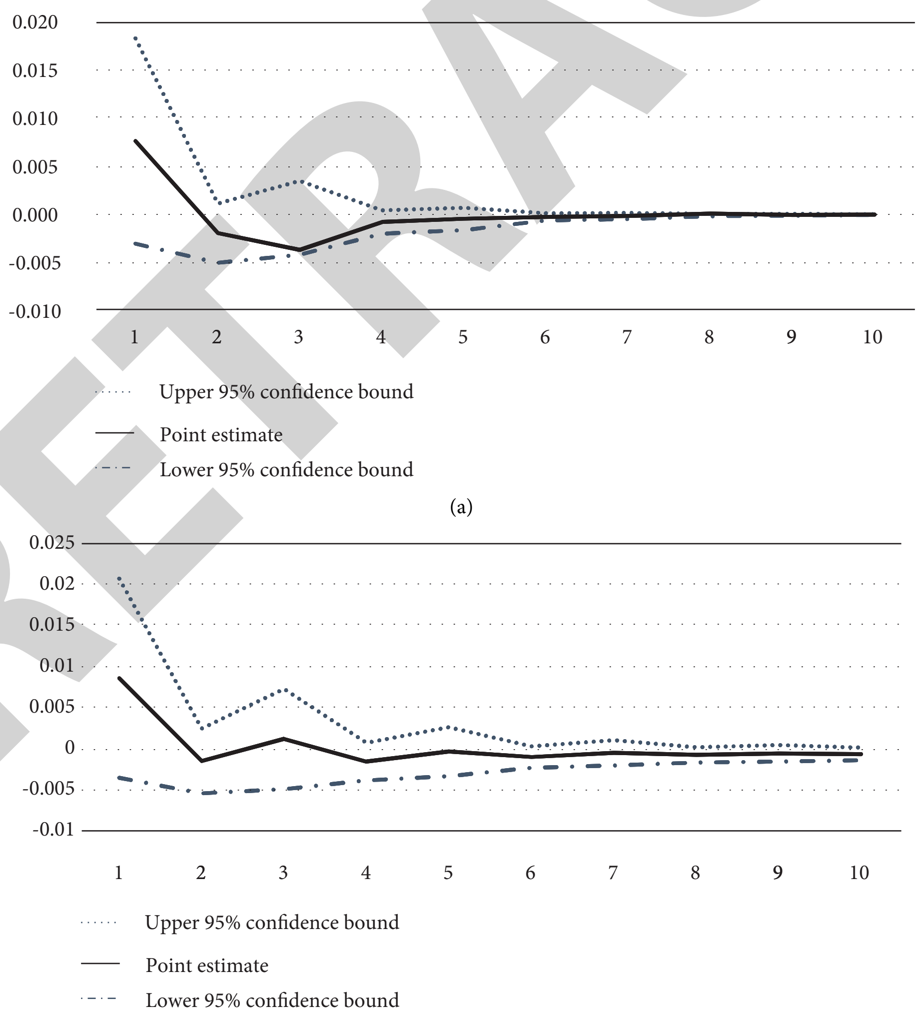
Table 5: Comparison of the discrimination across standard DEA, MED, and MEA.

	Standard DEA		MED		MEA-SOCP	
	Stage 1	Stage 2	Stage 1	Stage 2	Stage 1	Stage 2
Number of efficient DMUs	0	0	24	0	21	13
Average	0.349	0.085	0.504	0.034	0.583	0.219
Min	0.115	0.001	0.050	0.001	0.130	0.005
Max	0.956	0.633	1.000	0.506	1.000	1.000

Table 6: Impulse response estimate of the effect of financial crises on efficiency scores.

Year after the 2001 crisis	Stage 1	Stage 2	Year after the 2007 crisis	Stage 1	Stage 2
1	0.0076	0.0402	1	0.0086	0.0375
2	−0.002	0.0171	2	−0.0014	0.0068
3	−0.0037	0.0182	3	0.0013	0.0029**
4	−0.0008	0.0114	4	−0.0015	−0.0060**
5	−0.0005	0.0066	5	−0.0003	−0.0113**
6	−0.0003	0.0016	6	−0.0009	−0.0151***
7	−0.0002	−0.0019	7	−0.0004	−0.0175
8	0.0001	−0.0047	8	−0.0007	−0.0188
9	−0.0001	−0.0067	9	−0.0005	−0.0192
10	2.23E − 05	−0.0082	10	−0.0006	−0.0188

Note: *, **, and *** are for 1%, 5%, and 10% confidence levels, respectively.



(b)

Figure 5: Impulse response estimates of profitability efficiency by the financial crises in 2001 (a) and 2009 (b) with 95% confidence intervals.

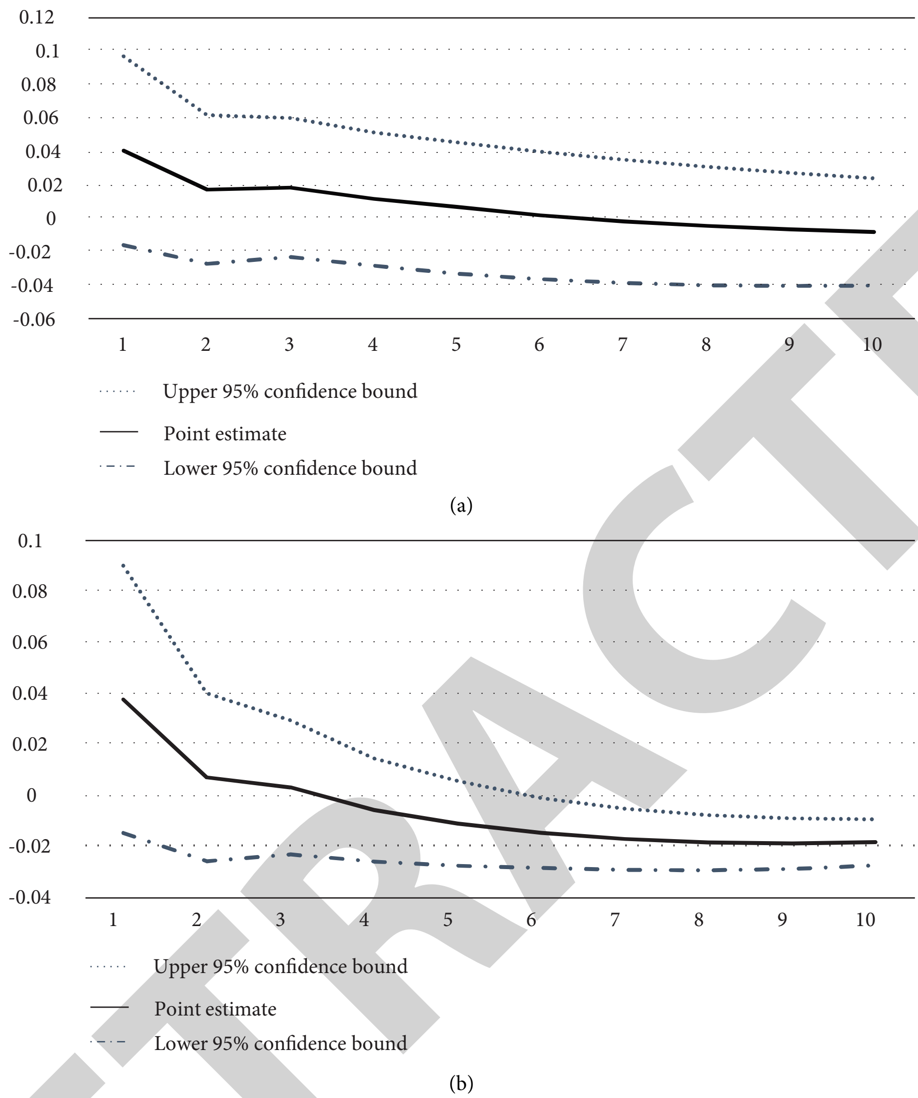


Figure 6: Impulse response estimates of marketability efficiency by the financial crises in 2001 (a) and 2009 (b) with 95% confidence intervals.

Figures 5 and 6 present the impulse response estimation at 95% confidence levels for the shocks in 2001 and 2007. As shown in Figures 5(a) and 5(b), the confidence intervals of the impulse estimation relative to the profitability stage are narrow along with the horizontal forecast, which implies a decreasing uncertainty of the financial shocks' impact on the firms' profitability efficiency. Conversely, the confidence intervals for the impulse estimation relative to the marketability stage are nearly unchanged (Figures 6(a) and 6(b)). Therefore, the two financial crises, especially the dot-com bubble in 2001, have a serious impact on marketability efficiency as opposed to profitability efficiency.

4.4. Discussion. According to the reviewed related literature, some researchers have identified the characteristics that allow firms to become more durable than others during financial crises [25, 26]. However, an investigation of the resilience of firm performance to the financial crisis, particularly in the postcrisis period, is lacking. In this study, we measure the operating performance of firms in the aggregated form of profitability and marketability efficiencies. This measurement is meaningful to both managers and investors, as it can widen the distinguishing power when evaluating and comparing firms (Figure 7). For example, firms that belong to the No. 3 quadrant can be regarded as the priority in the investment portfolio as opposed to those in the No. 4 and 1 quadrants. Moreover, the estimation of impulse responses of the efficiency scores in the long term has also proven the resilience of firm performance, especially profitability efficiency, to the financial recessions. This long-term view can be considered good evidence for investors who follow the value investment strategy. As the firms in the No. 3 quadrant exemplify good performance in both stages, the other companies are expected to improve their respective strategies to be able to move forward. For instance, the

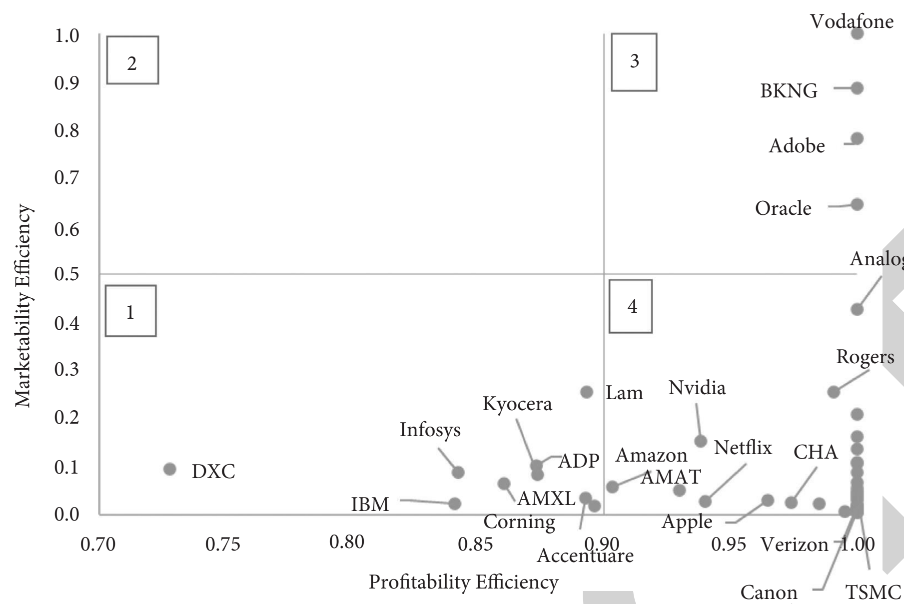


Figure 7: Quadrant of firm performance.

managers of firms in the No. 1 group can simultaneously improve both profitability and marketability efficiencies or upgrade in small steps at each stage.

Our work has employed the two-stage network DEA model to overcome all of the abovementioned drawbacks based on the model's advantages. However, certain limitations and suggestions should be considered in future research. For instance, although the sampled firms have been categorized as digital firms based on Forbes' ranked list, these companies are also specializing in different industries. This double categorization leads to two problems. First, our proposed model has ignored the firms' nonhomogeneous characteristics. In future research, the meta-frontier approach [87] that can be integrated with the current DEA model may be considered. Second, the empirical results have not fully identified the references of the firms. Future work may explore combining the current model with network-based ranking [88] to derive a much more in-depth implication regarding the firms.

5. Conclusion

This research designs a two-stage network DEA model to analyze the profitability and marketability efficiencies of firms. MEA and SOCP are integrated to measure the efficiency scores of digital firms from 1999 to 2008. Then, the durability of firm performance in the context of financial recessions is examined in the long-term horizontal period by employing the IRF technique. The findings of this study can be summarized as follows:

The stable profitability score during the 20 years and the small gaps between the inefficient and benchmark firms indicate that the sampled digital firms have equivalent productivity and profitability levels. Consequently, the second-stage marketability efficiency is used as a criterion to evaluate the firms. The average marketability efficiency of the firms has increased across the years. However, the relatively low scores of most of the firms reveal considerable room for improvement. Additionally, both managers and investors can refer to the quadrants of the two-stage efficiency scores when developing their management and stock investment strategies. Finally, the IRF technique is used to detect the two financial recessions. Both crisis events have no significant impact on the company performance, especially the profit-creating activities of these digital firms.

This study is the first one to measure the profitability and marketability efficiencies of digital firms by using the two-stage network DEA model. We suppose that this model offers a reasonable and objective evaluation model to measure the performance of digital firms, providing the managers and investors a reference for making their decision. For example, ROA and ROE are the traditional metrics for investors in choosing a stock portfolio; therefore, it is worth comparing these with our DEA model in further studies. Additionally, based on the empirical results, many companies have identical profitability and marketability efficiency score, so the ongoing studies are supposed to consider integrating this current DEA model with other techniques, like TOPSIS [89], for the differentiation among the fully efficient units.

Nevertheless, this study has one limitation, that is the current DEA model cannot deal with negative and missing data. Therefore, future research could refer to the work of Omrani and Emrouznejad [90] and Gardijan and Lukač [91]. In the future, under the condition that the data can be obtained, different network structures can be further developed for a more in-depth analysis, and the impact of the external environment on the performance can also be considered [92, 93].

Based on the prevailing view in which the operating activities of digital companies often differ from their revenue-generating activities, the method of designing new financial reports for modern digital firms as a means of capturing the main value drivers and investment decisions should be considered in the future when choosing the input and output DEA variables. Verhoef and Broekhuizen [1] suggest that accompanying traditional financial metrics to profitability aspects like revenues and incomes, the other variables such as the number of users or number of customers should be considered to present the digital metrics of digital firms. To the marketability aspect, the measurement of intangible assets could be enhanced by the concept of intellectual while these two are discussed and used interchangeably [49, 94, 95]. So, future works with data availability could consider these points to improve the evaluation model.

Data Availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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