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Toward green production practices: empirical evidence from Thai manufacturers' technical efficiency

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Abstract

Purpose – The development of green manufacturing has become essential to achieve sustainable development and modernize the nation's manufacturing and production capacity without increasing nonrenewable resource consumption and pollution. This study investigates the effect of green industrial practices on technical efficiency for Thai manufacturers.

Design/methodology/approach – The study uses stochastic frontier analysis (SFA) to estimate the stochastic frontier production function (SFPF) and inefficiency effects model, as pioneered by Battese and Coelli (1995).

Findings – This study shows that, on average, Thai manufacturing firms have experienced declining returns-to-scale production and relatively low technical efficiency. However, it is estimated that Thai manufacturing firms with a green commitment obtained the highest technical efficiency, followed by those with green activity, green systems and green culture levels, compared to those without any commitment to green manufacturing practices. Finally, internationalization and skill development can significantly improve technical efficiency.

Practical implications – Green industry policy mixes will be vital for driving structural reforms toward a more environmentally friendly and sustainable economic system. Furthermore, circular economy processes can promote firms' production efficiency and resource use.

JEL Classification — D20, D24, L25, L60, Q59

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Originality/value – To the best of the authors' knowledge, this study is the first to investigate the effect of green industry practices on the technical efficiency of Thai manufacturing enterprises. This study also encompasses analyses of the roles of internationalization, innovation and skill development.

Keywords Technical efficiency, Manufacturing, Green production, Stochastic frontier analysis, Green industrial policy

Paper type Research paper

1. Introduction

Natural resource depletion and ecological degradation have negatively impacted sustainable global economic growth, thereby propelling a range of policies encouraging a balance between economic development, social progress, and environmental protection. Developing a green industry is critical for transitioning to a green economy based on production and consumption (Dornfeld, 2014). Manufacturing enterprises may participate in the transition to a green economy by implementing a range of green industry policies requiring adjustments in their production methods (Anzolin and Lebdioui, 2021).

The Thai government ratified the Johannesburg Declaration on Sustainable Development in 2002 and the Manila Declaration on Green Industry in Asia in 2009 (UNIDO, 2009; Ministry of Industry, 2013). In addition, the Ministry of Industry has supported industrial organizations to achieve their Green Industry Certificates since 2010 (Ministry of Industry, 2013). The five levels of Green Industry Certificates are as follows:

(1) 1st Level – Green Commitment: A firm can demonstrate its commitment by communicating its policies, goals, and action plan within the organization;

(2) 2nd Level – Green Activity: Involves implementation of the policy commitments from Level 1;

(3) 3rd Level – Green System: Entails systematic environmental management, including monitoring, assessment, and review for continuous improvement, as well as a notable environmental awards, certificates, and accreditation;

(4) 4th Level – Green Culture: The firm collaborates with employees at all organizational levels to adopt an environmentally friendly setting in all parts of its operations;

(5) 5th Level – Green Network: The firm demonstrates that it has incorporated its supply chain network, corporate partners and/or allies into its green industry umbrella.

Thailand has also prioritized climate action activities in response to COP 26. Being one of the top ten nations most affected by climate change, Thailand has pledged to reach carbon neutrality by 2050 and net-zero greenhouse gas emissions by 2065 (Ministry of Foreign Affairs, 2021).

Nevertheless, Thailand's green industry's adoption rate is relatively low, and especially so for SMEs (Noranarttakun and Pharino, 2020). As of May 2021, only 39,470 green industry certifications have been issued, accounting for 28.22% of the total registered factories. Approximately half of the certifications (14.91% of factories) were for green commitments only, with a further quarter (7.14% of factories) receiving green activity certification. Less than one percent of factories were certified with green culture or networks, with the remainder (5.77% of factories) receiving green system certification (Department of Industrial Works, 2021).

Even though the manufacturing sector's productivity growth is relatively high compared with other sectors due to its advanced labor-replacing technology, Thailand still has substantially lower productivity growth than developed countries and some developing economies (Chuntongvirat, 2020). Some recent empirical studies have established a positive association between green supply chain management and firm performance, as reviewed in Section 2. However, these empirical studies have yet to examine the impact of green manufacturing practices on technical efficiency, especially in the case of Thailand. Therefore, it is critical to examine whether Thai manufacturers adopting various levels of green production practices will enhance their technical efficiency. This study aims to fill the gap in the existing literature by examining the effect of green production practices on the technical efficiency of Thai manufacturers.

2. Literature review

Developing green industries is critical for transitioning to a green economy based on environmentally friendly production and consumption (Dornfeld, 2014). Several recent empirical studies have found a positive association between green supply chain management/green regulation and firm performance (Namagembe *et al.*, 2019; Abdallah and Al-Ghwayeen, 2019; Hasan and Ali, 2015; Luan *et al.*, 2016; Habib *et al.*, 2020; Cheng *et al.*, 2020; Jiang *et al.*, 2020; Li and Ouyang, 2020; Wang *et al.*, 2020). For instance, Luan *et al.* (2016) classified green activities into (1) ISO 14000, (2) green processes, (3) pollution prevention, and (4) green certifications and examined their associations with Taiwanese listed firms' performance in the electronic industry. Their results revealed that firms adopting green processes performed the best, followed by ISO 14000, pollution prevention, and green certifications. Other studies have analyzed green activities and technical efficiency but not for the manufacturing sector. For example, Alexopoulos *et al.* (2011) examined the association between environmental performance and technical efficiency for Greek-listed enterprises. They revealed that having an environmental system certificate (ISO) could increase the technical efficiency of Greek-listed firms. Similarly, Li *et al.* (2021) found a positive relationship between adopting agricultural green production technology (AGPT) and the technical efficiency of Chinese rice producers.

In addition to examining green production practices, the extant research literature identifies several other crucial factors anticipated to impact technical efficiency. For instance, foreign direct investment (FDI) is likely to generate spillover effects for the host country, consequently enhancing domestic firms' productivity (Arif-Ur-Rahman and Inaba, 2021). In addition, FDI is likely to provide its subsidiary firm or the foreign-acquired firm with access to new technologies and know-how. Hence, a foreign-acquired firm should benefit from a technology transfer that enhances its competitiveness and increases technical efficiency. Several empirical studies have examined the impact of FDI on technical efficiency (Wang and Wong, 2016; Yasin, 2021; Charoenrat and Harvie, 2017; Amornkitvikai and Harvie, 2011; Sur *et al.*, 2018; Ghali and Rezgui, 2011; Zhang *et al.*, 2014). However, the empirical results from those studies are inconclusive, with cross-country variations evident.

Exports also play an important role in promoting the technical efficiency of export-oriented firms via learning-by-exporting experience (Mok *et al.*, 2010; Mengistae and Pattillo, 2004). Export-oriented enterprises have to comply with global standards and foreign clients' high expectations for product quality and variety, requiring them to improve their technological capabilities and technical efficiency (Mok *et al.*, 2010). Exporting has also been positively associated with the enhanced technical efficiency of Thai manufacturing SMEs (Charoenrat and Harvie, 2014, 2017), as well as suggested that exports are significantly and positively associated with the technical efficiency of Indonesian (Yasin, 2021) and Vietnamese (Ngo *et al.*, 2019) manufacturing firms.

Foreign patents or licensing is also one of the internationalization modes by which firms seek to expand their revenue in foreign markets (Clark *et al.*, 1997). Domestic firms in the host country will likely obtain foreign technology transfers from their foreign patents or licenses. In addition, foreign technology transfer can shorten a firm's learning curve to achieve "leapfrog" in technology (Chan and Daim, 2011). Foreign technology transfer enables domestic firms to use higher-quality inputs, produce outputs more effectively, and strengthen their management practices and capabilities (Chan and Daim, 2011; Lee, 2005). Thus, it enables them to enhance their technical efficiency due to positive spillover effects (Zhou *et al.*, 2021). For example, Zhou *et al.* (2021) revealed that foreign technology significantly enhanced the technical efficiency of Chinese firms in high-tech manufacturing sectors.

Innovation is expected to improve resource efficiency, leading to sustainable competitive advantages among innovating firms (Morris, 2018). Innovation via research and development (R&D) will likely enhance firms' absorptive capacity, assimilate their knowledge, and catch up (Morris, 2018). Additionally, a patent grants exclusive rights to the organization that invented a new product, technique, method, or technical solution. An organization that can register its patent will likely surpass others in production, especially in high-tech industries. Several empirical studies have confirmed the positive impact of patents on technical efficiency (Kumar and Sharma, 2016; Pattnayak and Chadha, 2013; Zou *et al.*, 2020).

R&D activities are critical drivers of the development of science and technology and play a critical role in achieving the sustainability of national economic performance and corporate business (Khoshnevis and Teirlinck, 2018; Zhong *et al.*, 2011). Several empirical studies have examined the impact of R&D on technical efficiency (Khoshnevis and Teirlinck, 2018; Zhong *et al.*, 2011; Fahmy-Abdullah *et al.*, 2018, 2021; Singh *et al.*, 2019; Sabli *et al.*, 2019; Kim, 2003; Berghäll and Nisar, 2016). Surprisingly, the impact of R&D on technical efficiency has not been established clearly in the empirical literature.

Human capital accumulation is vital in stimulating economic development and long-term growth (Ben Jemaa Cherif, 2021). Becker (2009) stated that education and training are the most critical investments in human capital. Hence, upgrading human capital via employee training is seen as an essential step to increasing labor productivity (Morikawa, 2021). Numerous empirical studies have also confirmed the positive impact of training on technical efficiency (Asfaw, 2021; Fahmy-Abdullah *et al.*, 2018, 2021; Batra and Tan, 2003).

3. Methodology and data

3.1 Methodology

This study utilizes the inefficiency effects model in a stochastic frontier production function (SFPF) proposed by Battese and Coelli (1995) to examine the impact of green production methods and other important factors on technical efficiency. This study adopts the one-step maximum likelihood estimation approach, which simultaneously estimates the SFPF and inefficiency effect model using Frontier 4.1 software. The single-stage estimation procedure has been shown to produce more efficient estimates than those acquired through the two-stage estimation technique (Kumbhakar *et al.*, 1991; Reifschneider and Stevenson, 1991; Coelli, 1996).

Equation (1) depicts the SFPF incorporating two error terms. First, the idiosyncratic error (v_i) captures the random variation of the frontier across firms, which is caused by the exclusion of relevant factors from independent variables (x_i), random shocks that are out of the firm's control, and estimation errors (Coelli *et al.*, 2005). The idiosyncratic error term is independently and identically distributed as N (0, σ_V^2). Second, the error term (u_i), which is a non-negative random variable, demonstrates the inefficiency effects compared to the stochastic production frontier. This error term (u_i) is considered to be distributed independently of the idiosyncratic error (v_i), and is assumed to be non-negative ($u_i \geq 0$).

$$\mathbf{Q_i} = \mathbf{x_i}\beta + (\mathbf{v_i} - \mathbf{u_i})\ i = 1, \ldots, N, \qquad (1)$$

where:

$\mathbf{Q_i}$ is a firm's production;

$\mathbf{x_i}$ is a vector of input variables of a firm;

β is a vector of the unknown parameters;

$\mathbf{v_i}$ are independently and identically distributed unobserved variables, as N (0, σ_V^2), and independent of the $\mathbf{u_i}$.

$\mathbf{u_i}$ are non-negative unobserved variables caused by the production's technical inefficiency and are assumed to be *iid*. as N (0, σ_V^2). In accordance with the model proposed by Battese and Coelli (1995), the appropriateness of the functional form of the SFPF may be assessed by conducting tests on Equations (2) and (3).

The Equation for the Cobb–Douglas SFPF is given as:

$$\boldsymbol{Ln(Q_i) = \beta_0 + \beta_1 \ln(L_i) + \beta_2 \ln(K_i) + V_i - U_i} \quad (2)$$

The Equation for the Translog SFPF is given as:

$$\boldsymbol{Ln(Q_i) = \beta_0 + \beta_1 \ln(L_i) + \beta_2 \ln(K_i) + \frac{1}{2}\beta_3 \ln(L_i^2) + \frac{1}{2}\beta_4 \ln(K_i^2) + \beta_5 \ln(L_i) * \ln(K_i) + V_i - U_i} \quad (3)$$

where:

$\boldsymbol{Q_i}$ = A firm's value-added

$\boldsymbol{L_i}$ = A firm's employees

$\boldsymbol{K_i}$ = A firm's net fixed assets

$\boldsymbol{V_i}$ = Random error ($\boldsymbol{V_i \sim N(0, \sigma_V^2)}$)

$\boldsymbol{U_i}$ = Non-negative random variable (or technical inefficiency) ($\boldsymbol{U_i \sim N(\mathrm{Z_i}\delta, \sigma_u^2)}$)

The technical efficiency effects ($\mathbf{u_i}$) in the stochastic frontier model can be specified in Equation (4) as follows:

$$\boldsymbol{U_i = Z_i\lambda + \epsilon_i} \quad (4)$$

The random variable $\boldsymbol{\epsilon_i}$ is defined as the truncation of a normal distribution with a mean of zero and a variance of $\boldsymbol{\sigma^2}$. The truncation point is set at -$\boldsymbol{Z_i\lambda}$, implying that $\boldsymbol{\epsilon_i}$ is greater than or equal to -$\boldsymbol{Z_i\lambda}$. Moreover, it can be observed that these assumptions align with the fact that $\boldsymbol{U_i}$ is a non-negative truncation of the N($\boldsymbol{Z_i\lambda, \sigma^2}$) distribution (Battese and Coelli, 1995). Following Equation (4), the inefficiency effect model using the one-step maximum likelihood estimation approach is given as

$$U_i = \sigma_0 + \sigma_1 Medium_i + \sigma_2 Large_i + \sigma_3 FDI_i + \sigma_4 BOI_i + \sigma_5 Export_i + \sigma_6 R\&D_i + \sigma_7 Training_i + \sigma_8 Patent_i + \sigma_9 Foreign\ OEM_i + \sigma_{10} Municipal_i + \sigma_{11} Firm\ age_i + \sigma_{12} Greeen\ commitment_i + \sigma_{13} Green\ activitiy_i + \sigma_{14} Green\ system_i + \sigma_{15} Green\ culture_i + \sigma_{16} Green\ network_i + \sigma_{17} Bangkok_i + \sigma_{18} Central_i + \sigma_{19} Northern_i + \sigma_{20} South_i + W_i \quad (5)$$

In addition, technical efficiency scores can be predicted by Equation (4) (Coelli *et al.*, 2005).

$$\mathrm{TE_i} = \frac{\mathbf{y_i}}{\mathbf{exp}\,(\mathbf{x}'\beta + \mathbf{v_i})} = \frac{\mathbf{exp}\,(\mathbf{x}'\beta + \mathbf{v_i} - \mathbf{u_i})}{\mathbf{exp}\,(\mathbf{x}'\beta + \mathbf{v_i})} = \mathbf{exp}(-\mathbf{u_i}) \tag{6}$$

According to Equation (6), the predicted technical efficiency ($\mathrm{TE_i}$) value is between zero and one. A firm achieves its maximum feasible output $\mathbf{Y_i}$ if and only if $\mathrm{TE_i} = 1$. $\mathrm{TE_i} < 1$ indicates the shortfall of observed output from the maximum feasible output (Coelli *et al.*, 2005).

3.2 Data

The 2017 Thai Industrial Census was employed to estimate the SFPF and inefficiency effects of 118,639 Thai manufacturers. The 2017 Thai Industrial Census is the most updated data source and is collected by the National Statistical Office (NSO) every ten years. Unlike the 2007 Industrial Census, questions regarding the levels of green industrial certification that Thai manufacturers can receive are addressed in the 2017 Industrial Census. Nevertheless, this study could only utilize data for 31,167 firms due to missing data when calculating the output (value-added) and input (capital and labor) variables and other factors affecting technical inefficiencies, as shown in Equations (2) and (3). The definition of the variables and data descriptive statistics are contained in Tables A1 and A2 [1]. The Pearson Correlation Matrix provides the correlations between each pair of variables in this study, as shown in Table A3 [1]. Low values of the Pearson Correlation are observed for each pair of variables. Furthermore, the mean variance inflation factor (VIF) value was 1.36, which is less than 10, as displayed in Table A4 [1]. These results indicate that multicollinearity was not present in this study. The details for all Thai sub-manufacturing industries 1 to 9 are listed in Table A5 [1].

4. Robustness tests

Four null hypotheses are examined to assess the validity of the SFPF and the inefficiency effects model (Amornkitvikai and Harvie, 2011; Coelli *et al.*, 2005; Charoenrat *et al.*, 2013; Tran *et al.*, 2008; Kim, 2003). A likelihood-ratio test (LR test) is used to test these hypotheses as follows:

$$\lambda = -2\{\log[L(H_0)] - \log[L(H_1)]\} \tag{7}$$

where $\log[L(H_0)]$ and $\log[L(H_1)]$ are obtained from the maximized values of the log-likelihood function under the null hypothesis (H_0) and the alternative hypothesis (H_1), respectively. Following Equation (3), the null hypothesis ($H_0 : \beta_3 = \beta_4 = \beta_5 = 0$) is tested to examine the validation of the Cobb–Douglas production function, as revealed in Table A6 [1].

The null hypothesis ($H_0 : \beta_3 = \beta_4 = \beta_5 = 0$) is statistically rejected at the 1% significance level for Thai manufacturers, encompassing all sub-manufacturing industries. Hence, the Translog production function is the adequate functional form in this study, compared to the Cobb Douglass production function. From Table A6 [1], given the specification of the Translog production function, the second null hypothesis ($H_0 : \gamma = \sigma_0 = \sigma_1 = \sigma_2 \ldots = \sigma_{18} = \sigma_{19} = \sigma_{20} = 0$), defines the lack of a technical inefficiency effects model indicated by equation (5), is statistically rejected. This indicates that the model of inefficiency effects applies to this investigation. In addition, the third null hypothesis ($H_0 : \gamma = 0$) is statistically rejected at the 1% significance level, implying that the inefficiency effects model cannot be reduced to a typical mean response function. Finally, the last null hypothesis ($H_0 : \sigma_1 = \sigma_2 = \sigma_3 \ldots = \sigma_{18} = \sigma_{19} = \sigma_{20} = 0$), which specifies that at the 1% significance level, the hypothesis that inefficiency effects are not linearly explained by all independent factors is statistically rejected for manufacturing firms as a whole, encompassing all sub-manufacturing sectors. From Table 1, the estimated (γ) is 0.7532, which is moderately high for the Thai manufacturing sector. This demonstrates that the variance in the composite error term is primarily attributable to inefficient components.

5. Empirical results

For the inefficiency effects model indicated in Tables 1 and 2, a negative sign of the estimated coefficient of an independent variable indicates its positive impact on technical efficiency. This study has found that the production of Thai manufacturers, including all sub-manufacturing sectors, illustrates decreasing returns to scale (DRS) due to the estimated returns to scale being less than one, as shown in Tables 1 and 2 This result shows that the production process of Thai manufacturers becomes less efficient as their output increases, which can occur when a firm becomes too large to be effectively managed as a single unit. In addition, the mean value of Thai manufacturing firms' technical efficiency is 0.67 (67%). Due to the positive estimation of output elasticity for labor in the Translog production function, Thai manufacturing enterprises rely heavily on labor-intensive production instead of capital-intensive production.

This result implies that Thai manufacturers employ more labor than capital during production. This evidence is consistent with the previous findings of Charoenrat and Harvie (2014) and Charoenrat and Harvie (2017) for the case of Thai manufacturing SMEs.

For the inefficiency effects model, this study found that firms that engage in green manufacturing play a vital role in enhancing their technical efficiency, including those in all sub-manufacturing sectors. This result shows that green manufacturing techniques will likely reduce costs associated with input materials, waste disposal and discharge, energy consumption, and fines or penalties related to environmental disasters (Afum *et al.*, 2020). More specifically, Thai manufacturing firms with green commitment (the first green level) have the highest technical efficiency due to the highest negative coefficient, followed by those with green activity (the second green level), those with green systems (the third green level), and those with green culture certifications (the fourth green level) compared to those without any involvement in green manufacturing practices. In addition, all manufacturers with a green network (the fifth green level), including industries 1,2,3,5, and 6, are not associated with technical efficiency. The green network is statistically and positively correlated with technical efficiency for industrial companies in sectors 4 and 7 only.

The results from this study are also consistent with the findings of Alexopoulos *et al.* (2011) and Li *et al.* (2021), who found a positive association between green activities and technical efficiency. This indicates that Thai manufacturers who receive at least the green commitment certification (the first green level) can use the green industry logo to promote and advertise their products (Ministry of Industry, 2013). In addition, adopting a more green-friendly technology also potentially and technologically assists efficiency and competitiveness. This result suggests that achieving a more eco-friendly economy is essential in improving Thailand's firm efficiency and competitiveness and addressing its middle-income trap. In addition, manufacturing firms obtaining at least the green system certification (the third green level) are equivalent to those receiving ISO 14001. They are eligible for tax incentives if investment projects are valued at more than 10 million baht. They can also transport waste from the facility (Ministry of Industry, 2013). Those who receive at least the green culture certification (the fourth green level) can use the "Thailand Trust Mark" logo on their products. This can help promote the reliability of their products in international markets.

Moreover, FDI positively contributes to higher technical efficiency levels for Thai manufacturing firms, including industries 2, 3, 6, and 7. The positive evidence between FDI and technical efficiency implies that FDI is expected to provide its subsidiary or foreign-acquired business with access to new technology and knowledge. Consequently, the acquired foreign business will gain from a technology transfer that enhances its competitiveness, resulting in better

Table 1.
Inefficiency effects model: All Thai manufacturing firms and industries 1 to 3

	All manufacturing firms		Industry (1)		Industry (2)		Industry (3)	
	Coefficient	Standard-error	Coefficient	Standard-error	Coefficient	Standard-error	Coefficient	Standard-error
Translog production								
Constant	10.3093***	(0.1419)	8.4268***	(0.3055)	10.6566***	(0.4004)	11.3268***	(0.4648)
Ln(L)	1.6537***	(0.0421)	2.2982***	(0.0925)	1.4046***	(0.1215)	1.1196***	(0.1464)
Ln(K)	−0.1794***	(0.0123)	−0.2156***	(0.0278)	−0.1123***	(0.0348)	−0.1586***	(0.0416)
$\frac{1}{2}Ln(L)^2$	0.0291***	(0.0053)	0.0127	(0.0111)	0.0256*	(0.0150)	0.0486***	(0.0226)
$\frac{1}{2}Ln(K)^2$	0.0290***	(0.0004)	0.0365***	(0.0010)	0.0230***	(0.0011)	0.0252***	(0.0013)
Ln(L)*Ln(K)	−0.0792***	(0.0029)	−0.1079***	(0.0063)	−0.0624***	(0.0079)	−0.0577***	(0.0099)
Inefficiency Effects model								
Constant	2.3930***	(0.0511)	1.4319***	(0.1215)	2.7910***	(0.1009)	3.2833***	(0.1086)
Firm size (ref: small)								
Medium	−0.3493***	(0.0715)	0.5232***	(0.1464)	−0.6045***	(0.1652)	−1.0066***	(0.2478)
Large	−1.0070***	(0.1516)	−0.4454	(0.3924)	−1.5720***	(0.3524)	−1.0635**	(0.5291)
FDI	−0.0106***	(0.0023)	−0.0080	(0.0088)	−0.0264***	(0.0081)	−0.0413***	(0.0070)
BOI	−1.3016***	(0.1401)	−0.9990***	(0.3468)	−0.7214	(0.5947)	−1.1750*	(0.6217)
Export	−1.8910***	(0.1214)	−1.9183***	(0.2804)	−1.5229***	(0.3285)	−1.4522***	(0.4621)
R&D	−0.6434***	(0.1170)	−1.0917***	(0.3494)	−0.0574	(0.3469)	−0.5545	(0.5100)
Training	−1.4788***	(0.0768)	−1.8658***	(0.2032)	−0.3388*	(0.1779)	−1.1685***	(0.2672)
Patent	0.2380	(0.2834)	0.2589	(0.6549)	−0.8564	(0.9266)	1.3778	(1.5337)
Foreign OEM	−0.6688***	(0.1940)	−0.4267	(0.5451)	−0.6104	(0.9874)	−3.2617***	(0.4229)
Municipal	−0.5287***	(0.1150)	−1.8521***	(0.3817)	0.0743	(0.3028)	0.3287	(0.4747)
Firm age	−0.0319***	(0.0020)	−0.0507***	(0.0043)	−0.0042	(0.0043)	−0.0249***	(0.0049)
Green industry (ref: no)								
Green Commitment	−2.7794***	(0.1747)	−2.1651***	(0.4403)	−1.5212	(0.9987)	−2.8515***	(1.0038)
Green Activity	−2.1276***	(0.1538)	−1.1475***	(0.3499)	−1.3724***	(0.6388)	−4.4555***	(0.6536)
Green System	−1.8858***	(0.1955)	−0.7959***	(0.3091)	−1.4230***	(0.6527)	−1.3830*	(0.7272)
Green Culture	−1.7469***	(0.3606)	−1.4270	(1.0058)	−0.0121	(0.9967)	−2.5594	(2.1834)
Green Network	−0.8213	(0.5039)	−1.4698	(1.0078)	1.2768	(1.0003)	0.5142	(0.9992)

(*continued*)

Table 1.

	All manufacturing firms		Industry (1)		Industry (2)		Industry (3)	
	Coefficient	Standard-error	Coefficient	Standard-error	Coefficient	Standard-error	Coefficient	Standard-error
Region (ref: northeastern)								
Bangkok	−5.4910***	(0.1805)	−5.4069***	(0.3435)	−3.7182***	(0.2677)	−5.2797***	(0.3686)
Central	−4.6058***	(0.1161)	−3.4883***	(0.2245)	−3.5489***	(0.2322)	−3.9263***	(0.2031)
Northern	−0.6945***	(0.0540)	−0.4424***	(0.1020)	−0.6014***	(0.0822)	−1.1150***	(0.1551)
South	−1.7733***	(0.0784)	−1.1181***	(0.1283)	−1.0593***	(0.1846)	−2.8734***	(0.2483)
Sigma-squared	3.3571***	(0.0751)	3.5492***	(0.1667)	2.0921***	(0.0892)	2.6975***	(0.1179)
Gamma (γ)	0.7532***	(0.0067)	0.7253***	(0.0195)	0.6824***	(0.0149)	0.7369***	(0.0117)
Log-likelihood function	8.11674 E+11		1.22 E+10		9.35 E+10		2.22 E+10	
LR test	7994.49		965.37811		1719.43		1356.42	
The number of obs	31167		6,249		4,567		3,404	
Average technical efficiency (TE)	*0.56*		*0.53*		*0.44*		*0.49*	
Returns to scale	*0.49*		*0.62*		*0.58*		*0.43*	

Note(s): ***$p < 0.01$, **$p < 0.05$, and *$p < 0.1$; The negative sign of an estimated parameter in the inefficiency effects model indicates higher technical efficiency; ***$p < 0.01$, **$p < 0.05$, and *$p < 0.1$; Based on Equation (3), returns to scale is computed by adding the output's elasticity with respect to capital $\left(\frac{\partial \ln(Q_i)}{\partial n(K_i)} = \beta_2 + \beta_4 \ln(K_i) + \beta_5 \ln(L_i)\right)$ and the output's elasticity with respect to labor $\left(\frac{\partial \ln(Q_i)}{\partial n(L_i)} = \beta_1 + \beta_3 \ln(L_i) + \beta_5 \ln(K_i)\right)$ (Kim, 2003; Margono and Sharma, 2006)

Source(s): Authors' estimation

Table 2. Inefficiency effects model: Thai manufacturing firms in industries 4 to 7

	Industry (4)		Industry (5)		Industry (6)		Industry (7)	
	Coefficient	Standard-error	Coefficient	Standard-error	Coefficient	Standard-error	Coefficient	Standard-error
Translog production								
Constant	9.7035***	(0.3217)	12.4213***	(0.5986)	13.6714***	(0.3840)	10.5461***	(0.3902)
Ln(L)	1.8512***	(0.0978)	1.4281***	(0.1791)	1.0257***	(0.0912)	1.3743***	(0.1185)
Ln(K)	−0.1296***	(0.0279)	−0.3287***	(0.0405)	−0.3348***	(0.0368)	−0.0825	(0.0334)
$\frac{1}{2}Ln(L)^2$	0.0232**	(0.0109)	−0.0306*	(0.0160)	0.0077	(0.0120)	0.0604***	(0.0157)
$\frac{1}{2}Ln(K)^2$	0.0282***	(0.0008)	0.0257***	(0.0010)	0.0249***	(0.0012)	0.0235***	(0.0013)
Ln(L)*Ln(K)	−0.0885***	(0.0056)	−0.0321***	(0.0098)	−0.0300***	(0.0066)	−0.0748***	(0.0077)
Inefficiency Effects model								
Constant	2.2966***	(0.1233)	1.0190***	(0.1712)	0.7712**	(0.3170	2.4908***	(0.1571)
Firm size (ref: small)								
Medium	−0.2396*	(0.1474)	0.2921*	(0.1631)	−0.0126	(0.1500)	−0.1288	(0.1980)
Large	−0.7130***	(0.3387)	0.3410	(0.3027)	0.0787	(0.2516)	−0.2268	(0.3668)
FDI	−0.0042	(0.0048)	0.0039	(0.0035)	−0.0112***	(0.0045)	−0.0151**	(0.0069)
BOI	−1.1867***	(0.3762)	−0.7550***	(0.2706)	−0.8506**	(0.3609)	−1.2463	(0.9069)
Export	−2.2535***	(0.2331)	−0.3384	(0.2638)	−0.4181	(0.2603)	−1.2002***	(0.3349)
R&D	0.1712	(0.1771)	0.1265	(0.1646)	−0.8013***	(0.3205)	−0.4264	(0.3453)
Training	−2.3525***	(0.2058)	−0.3580***	(0.1408)	−1.0316***	(0.3003)	−0.5372***	(0.2038)
Patent	0.6107	(0.6885)	−2.3440*	(1.3678)	−1.8156	(1.1983)	−0.1262	(0.9965)
Foriegn OEM	−0.3761	(0.6601)	−0.1991	(0.8997)	−0.1610	(0.5719)	−1.2683	(0.9922)
Municipal	−0.8325***	(0.2833)	−0.0830	(0.2261)	0.0664	(0.1892)	−1.0913**	(0.5285)
Firm age	−0.0689***	(0.0049)	−0.0183***	(0.0054)	−0.0232***	(0.0077)	−0.0082	(0.0054)
Green industry (ref: no)								
Green Commitment	−2.8984***	(0.4206)	−1.7703**	(0.8821)	−1.8832***	(0.7657)	−1.8310***	(0.5930)
Green Activity	−3.3084***	(0.3422)	−1.0073	(0.9666)	0.1515	(0.3977)	−1.1695	(0.9868)
Green System	−1.8520***	(0.3572)	−2.4468**	(1.2162)	−1.7509**	(0.9170)	−1.4339	(0.9342)
Green Culture	−1.9656***	(0.6828)	1.6264*	(0.9650)	−1.1226	(1.0435)	−2.8216**	(1.2357)
Green Network	−1.8587***	(0.7063)	0.7687	(1.0020)	−0.2205	(1.0308)	−2.1216**	(1.0692)

(*continued*)

Table 2.

	Industry (4)		Industry (5)		Industry (6)		Industry (7)	
	Coefficient	Standard-error	Coefficient	Standard-error	Coefficient	Standard-error	Coefficient	Standard-error
Region (ref: Northeastern)								
Bangkok	−5.7056***	(0.3998)	−0.9534***	(0.2306)	−1.5727***	(0.4029)	−4.6916***	(0.3315)
Central	−4.7999***	(0.2750)	−1.2323***	(0.2217)	−1.6660***	(0.4036)	−3.3640***	(0.1969)
Northern	−0.1296	(0.1218)	−0.4505**	(0.2199)	0.2850	(0.2845)	−0.3744**	(0.1704)
South	−1.8303***	(0.1761)	−0.4563**	(0.2220)	−0.0226	(0.3216)	−0.5102**	(0.2386)
Sigma-squared	4.0755***	(0.2298)	1.3708***	(0.1084)	2.0471***	(0.3234)	2.6810***	(0.1132)
Gamma (γ)	0.8062***	(0.0153)	0.4353***	(0.0551)	0.6050***	(0.0661)	0.6940***	(0.0143)
Log-likelihood function	4.39 E+10		4.50 E+10		2.93 E+10		7.52 E+10	
LR test	1583.66		152.72		126.92		1014.1561	
The number of obs	6,202		3,935		3,035		3,775	
Average technical efficiency (TE)	0.57		0.66		0.67		0.42	
Returns to scale	0.49		0.77		0.51		0.55	

Note(s): ***$p < 0.01$, **$p < 0.05$, and *$p < 0.1$; The negative sign of an estimated parameter in the inefficiency effects model indicates higher technical efficiency; ***$p < 0.01$, **$p < 0.05$, and *$p < 0.1$; Based on Equation (3), returns to scale is computed by adding the output's elasticity with respect to capital $\left(\frac{\partial \ln(Q_i)}{\partial n(K_i)} = \beta_2 + \beta_4 \ln(K_i) + \beta_5 \ln(L_i)\right)$ and the output's elasticity with respect to labor $\left(\frac{\partial \ln(Q_i)}{\partial n(L_i)} = \beta_1 + \beta_3 \ln(L_i) + \beta_5 \ln(K_i)\right)$ (Kim, 2003; Margono and Sharma, 2006)
Source(s): Authors' estimation

technical efficiency. This result is similar to that of Sur *et al.* (2018) and Ghali and Rezgui (2011). Exports are significantly and positively associated with Thai manufacturers' technical efficiency, including those in industries 1, 2, 3, 4, and 7. Positive evidence between exports and technical efficiency suggests that exporting manufacturers tend to have greater technical efficiency than those that do not export due to economies of scale and scope. Moreover, export-oriented businesses are required to produce goods that meet international standards, including environmental standards, and the high expectations of foreign customers regarding product quality and variety, compelling them to improve their technological capabilities and, consequently, technical efficiency. This study's positive evidence is consistent with previous empirical evidence (Charoenrat and Harvie, 2014, 2017; Sur *et al.*, 2018; Ngo *et al.*, 2019; Yasin, 2021). Due to the spillover effects of adopting high technology from abroad, especially those in industry 3, foreign technology transfer (through foreign patent/licensing) is firmly and favorably associated with Thai manufacturing enterprises' technical efficiency. It also enables Thai manufacturing firms to utilize higher-quality inputs, produce outputs more efficiently, and enhance their management practices and capabilities. In addition, it can shorten the firms' learning curves and achieve their technology leapfrog. As a result, adopting foreign high technology enables them to increase their technical efficacy due to spillover effects. This evidence is similar to the findings of Zhou *et al.* (2021). Furthermore, innovation (via R&D) is found to help Thai manufacturers improve their technical efficiency, including those in industries 1 and 6. Innovation through research and development (R&D) will likely enhance lagging firms' absorptive capacity and knowledge assimilation, resulting in greater technical efficiency (Morris, 2018). This positive finding is similar to that of Berghäll and Nisar (2016) and Dilling-Hansen *et al.* (2003). Nevertheless, the patent is not a significant factor in promoting technical efficiency in this study.

More importantly, skills development (via employee training) significantly enhances Thai manufacturing firms' technical efficiency, including all sub-sectors. This can help workers improve their skills to perform several tasks and prepare for new technologies employed by their organizations (Batra and Tan, 2003). This favorable evidence implies that skills development contributes to the enhancement of human capital within an enterprise, resulting in increased technical efficiency due to the improvement of employees' knowledge, skills, and abilities. Additionally, worker training programs can enhance employees' motivation, familiarization with, and commitment to their organization's tasks. This positive finding in this study is consistent with that of previous findings by Batra and Tan (2003) and Fahmy-Abdullah *et al.* (2021).

Moreover, Thai manufacturing firms, including those in industries 1,3,4,5, and 6 that receive government assistance via the BOI, are more technically efficient than those without government assistance. This empirical result is again similar to previous studies (Charoenrat and Harvie, 2014, 2017; Tran *et al.*, 2008). This study also indicates that business size has a solid and favorable association with technical efficiency. Large firms, including those in industries 2, 3, and 4, will likely have the highest technical efficiency, followed by medium and small firms. This study also indicates that large manufacturers, such as those in industries 2, 3, and 4, will likely be the most efficient, followed by medium and small businesses. This research indicates that larger companies have greater technical efficiency due to economies of scale and scope (Charoenrat *et al.*, 2013). Similarly, older organizations, including those in industries 1, 3, 4, 5, and 6, will likely have greater technical efficiency due to their learning-by-doing process and increased management abilities acquired over their years of operation (Charoenrat *et al.*, 2013).

Finally, Thai manufacturing firms in Bangkok, including those in industries 1,2, 3, 5, and 7, have the highest technical efficiency, followed by central, south, northern, and northeastern regions. This evidence implies exacerbating the country's rural-urban income, unemployment, and infrastructure development divide (Charoenrat *et al.*, 2013). Moreover, this evidence is consistent with the empirical results of (Charoenrat *et al.*, 2013), Charoenrat and Harvie (2014), and Charoenrat and Harvie (2017) that location in urban regions and Bangkok is essential for boosting the technological effectiveness of Thai manufacturing companies.

6. Conclusions and policy implications

The findings from this study are vital as the manufacturing sector remains a crucial engine to Thailand's future economic growth and employment generation, and thus addressing its middle-income trap. A concerning finding from the present research is that of decreasing returns to scale (DRS) and low technical efficiency across sub-manufacturing sectors and enterprises. In other words, on average, Thai manufacturers' production process becomes less efficient as their output increases. Furthermore, the production of Thai manufacturers remains predominantly labor-intensive and relatively low-skill intensive. Policy implications from these findings are that workers in the manufacturing industry should have access to skill development programs. However, each sub-manufacturing sector should be targeted explicitly with distinct skill-upgrading activities.

The crucial finding from the present research is that green industry practices, mainly green commitment, green activity, green system, and green culture, can assist Thai manufacturing firms in improving their technical efficiency. That is, the production of manufactured goods through cost-effective processes that minimize adverse environmental impacts and conserve energy and natural resources, can also result in greater technical efficiency. Additionally, green industry practices contribute to sustainable manufacturing practices, and enhance worker, community, and product safety. However, the effectiveness of green activities and policies vary by industrial sector or activity. Consequently, a one-size-fits-all approach may not be appropriate and must be sector-specific.

Therefore, green industry policy mixes combining market-based instruments, institutional support, financial mechanisms, regulations, capacity building, subsidies, and other integrated government measures should be continuously implemented and adapted for Thai manufacturers (Altenburg and Assmann, 2017). The task of protecting the environment and promoting competitiveness, industrial growth, and job creation within a country is a complex one. Therefore, implementing policy mixes becomes crucial to fostering the development of the green sector in Thailand (Altenburg and Assmann, 2017). Environmental fiscal adjustments, including differential tax rates, help Thai clean-production manufacturers compete. To encourage Thai manufacturers to embrace clean production processes, the government should provide financial and institutional support. Clean technology can be transferred to all sub-manufacturing sectors.

Other findings from this research showed that FDI, exports, foreign technology, research and development, and BOI can also substantially improve the technical efficiency of Thai manufacturing. As FDIs also contribute new foreign technology and know-how to Thai manufacturers, emphasis should be placed on FDI promotion policies for Thai manufacturers. Policies which encourage Thai firms to export and invest more in R&D are required in order to promote sustainable manufacturing. Technical efficiency is essential for exporters to compete with global enterprises. Learning by exporting could additionally enhance technical efficiency for such organizations. Research and development policies can also help Thai manufacturers improve technical efficiency. Finally, the Board of Investment (BOI) should offer government incentives for Thai manufacturers to boost their technological efficiency. This should be undertaken with caution when embracing BOI investment incentives, as their success comes at a high cost, especially in terms of foregone income to the government [See Jongwanich and Kohpaiboon (2020)].

7. Limitation and future studies

Due to a lack of detailed data in the 2017 Thai Industrial Census, almost all independent variables used in this study are categorical (dummy), with the exception of FDI. Therefore, categorical variables may be more informative than dummy variables. In future studies, continuous variables should be included if appropriate data are available.

Note

1. Please see it in the Online Appendix.

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Online Appendix
Supplementary material for this article can be found online.

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