http://dx.doi.org/10.18623/rvd.v23.5969

DIGITAL TRANSFORMATION AND SUSTAINABLE DEVELOPMENT: EVIDENCE FROM LISTED STEEL ENTERPRISES

TRANSFORMAÇÃO DIGITAL E DESENVOLVIMENTO SUSTENTÁVEL: EVIDÊNCIAS DE EMPRESAS SIDERÚRGICAS DE LISTAGEM

Article received on: 12/19/2025
Article accepted on: 4/16/2026

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The authors declare that there is no conflict of interest

Abstract
This study analyzes the impact of digital transformation on the sustainable development of listed steel enterprises in Vietnam during the period 2020–2025. In the context of the steel industry facing cost pressures, high energy intensity, and market volatility, digital transformation is regarded as a strategic capability aimed at enhancing firms' operational efficiency and adaptive capacity. Based on a panel dataset collected from financial statements and annual reports, the study employs panel data regression models, including fixed effects (FE) and random effects (RE), combined with the Hausman test to select the most appropriate model specification. The empirical results demonstrate that digital transformation has a positive and statistically significant impact on firms' sustainable development. This finding implies that investment in digital technologies and the reconfiguration of business processes can improve resource utilization efficiency and strengthen long-term growth performance. Robustness checks further confirm the stability and reliability of the empirical results. Accordingly, the study proposes policy implications aimed at promoting digital transformation in the steel industry, thereby contributing to the orientation of sustainable development in the context of emerging

Resumo
Este estudo analisa o impacto da transformação digital no desenvolvimento sustentável das empresas siderúrgicas de capital aberto no Vietnã durante o período de 2020 a 2025. No contexto em que a indústria siderúrgica enfrenta pressões de custos, alta intensidade energética e volatilidade do mercado, a transformação digital é considerada uma capacidade estratégica destinada a aumentar a eficiência operacional e a capacidade de adaptação das empresas. Com base em um conjunto de dados de painel coletado a partir de demonstrações financeiras e relatórios anuais, o estudo emprega modelos de regressão de dados de painel, incluindo efeitos fixos (EF) e efeitos aleatórios (EA), combinados com o teste de Hausman para selecionar a especificação de modelo mais adequada. Os resultados empíricos demonstram que a transformação digital tem um impacto positivo e estatisticamente significativo no desenvolvimento sustentável das empresas. Essa constatação implica que o investimento em tecnologias digitais e a reconfiguração dos processos de negócios podem melhorar a eficiência na utilização de recursos e fortalecer o desempenho de crescimento a longo prazo. Verificações de robustez confirmam ainda mais a estabilidade e a confiabilidade dos resultados

economies that are shifting toward technology-driven and innovation-based growth models.

Keywords: Digital Transformation. Sustainable Development. Listed Steel Enterprises.

empíricos. Assim, o estudo propõe implicações políticas voltadas para a promoção da transformação digital na indústria siderúrgica, contribuindo, dessa forma, para a orientação do desenvolvimento sustentável no contexto de economias emergentes que estão mudando para modelos de crescimento impulsionados pela tecnologia e baseados na inovação.

Palavras-chave: *Transformação Digital. Desenvolvimento Sustentável. Empresas Siderúrgicas de Capital Aberto.*

1 INTRODUCTION

In the context of the global economy's strong transition toward a digital economy associated with the Fourth Industrial Revolution, digital transformation is increasingly recognized as a key driver of business model restructuring, operational efficiency improvement, and the enhancement of firms' competitive advantage (Bharadwaj *et al*., 2013; Vial, 2019). Fundamentally, digital transformation is not merely the application of technologies in business operations but also encompasses profound changes in organizational structures, operational processes, and value creation mechanisms, thereby reshaping firms' long-term competitive advantages (Verhoef *et al*., 2021).

For traditional industries such as the steel industry, which is characterized by high capital intensity, significant energy consumption, and strong exposure to economic cycles, digital transformation plays a particularly important role in improving operational efficiency, optimizing costs, and strengthening resilience against external shocks (Frank *et al*., 2019; Dubey *et al*., 2021). From the perspective of dynamic capability theory, digital transformation can be viewed as a key manifestation of organizational capabilities, enabling firms to continuously integrate, reconfigure, and renew resources in response to rapidly changing business environments (Teece *et al*., 1997).

In Vietnam, the steel industry plays a foundational role in the industrialization process and serves as a critical link in the value chains of many key economic sectors. However, listed steel enterprises are facing a range of systemic challenges, including volatile raw material prices, increasing international competitive pressures, and rising requirements for resource efficiency and governance effectiveness. In this context, digital

transformation is considered a strategic solution that enables firms to restructure production processes, enhance management quality, and improve dynamic adaptability to the business environment (Zhang *et al*., 2021).

Although prior studies have examined the relationship between digital transformation and firm performance, empirical evidence regarding its impact on sustainable development in heavy industries, particularly in emerging economies such as Vietnam, remains limited and inconclusive (George *et al*., 2020; Verhoef *et al*., 2021). Addressing this research gap, this study aims to quantitatively analyze the impact of digital transformation on the sustainable development of listed steel enterprises in Vietnam over the period 2020–2025, thereby contributing additional empirical evidence and providing further insights into the underlying mechanisms within heavy industries in developing economies.

2 THEORETICAL BACKGROUND AND RESEARCH HYPOTHESES

2.1 Digital transformation and sustainable development

2.1.1 Concept and nature of digital transformation

Digital transformation is defined as the process of integrating digital technologies into all areas of firm operations, fundamentally changing how firms operate and create value (Vial, 2019). Beyond the mere adoption of technologies, digital transformation also encompasses profound changes in business models, organizational structures, and managerial mindsets.

According to Bharadwaj *et al*. (2013), digital business strategy refers to the integration of business strategy and information technology strategy in order to create sustainable competitive advantage. In this context, digital transformation is not only a supporting tool but has become a core element of corporate strategic development.

For traditional industries such as the steel industry, digital transformation typically includes activities such as production automation, the implementation of enterprise resource planning (ERP) systems, and the application of big data analytics and artificial intelligence (AI) to optimize production processes (Frank *et al*., 2019). These

technologies enable firms to improve productivity, reduce operational costs, and enhance product quality.

2.1.2 Sustainable development in firms

Corporate sustainable development is generally understood as the ability to maintain long-term operational performance while balancing economic, social, and environmental objectives (Elkington, 1997). In empirical research, sustainable development is often proxied by long-term financial indicators such as return on assets (ROA), return on equity (ROE), or market value (Eccles *et al*., 2014).

For the steel industry, sustainable development is particularly critical due to its high energy consumption and significant environmental emissions. Therefore, improving resource efficiency and reducing production costs are key determinants of achieving sustainable development (Zhang *et al*., 2021).

2.1.3 Digital transformation and sustainable development

The relationship between digital transformation and sustainable development has received increasing attention in recent studies. According to George *et al*. (2020), digital technologies enable firms to enhance resource efficiency and reduce negative environmental impacts.

In manufacturing industries, digital transformation allows firms to monitor and control production processes in real time, thereby reducing waste and optimizing energy consumption (Frank *et al*., 2019). In addition, the use of big data analytics enables firms to forecast market demand and adjust production flexibly.

Furthermore, Dubey *et al*. (2021) provide evidence that digital transformation can enhance firms' resilience to external shocks, thereby contributing to sustainable development.

2.2 Theoretical foundations

2.2.1 Resource-Based View (RBV)

The Resource-Based View (RBV) was originally introduced by Penrose (1959), who argued that firms' internal resources constitute a key source of competitive advantage. The core of RBV lies in explaining why some firms are able to achieve superior performance compared to others within the same industry by analyzing their internal resource endowments (Wernerfelt, 1984; Barney, 1986). Firm resources can take various forms and are generally categorized into three main types: physical capital resources, human capital resources, and organizational capital resources (Barney, 1991). Physical capital resources include tangible assets such as plants, equipment, locations, and raw materials. Human capital resources refer to the knowledge, intuition, judgment, experience, and learning capabilities of employees. Organizational capital resources encompass organizational structure, coordination systems, informal relationships within the firm, and external relational networks (Barney, 1991).

2.2.2 Dynamic Capabilities theory

The Dynamic Capabilities (DC) theory emerged as an extension and alternative to address certain limitations of the RBV framework (Galvin, Rice, & Liao, 2014). DC theory emphasizes path-dependent processes that enable firms to adapt to rapidly changing environments by building, integrating, and reconfiguring their resource and capability portfolios (Teece, Pisano, & Shuen, 1997). Prior to its development, strategic management research was largely dominated by industry-based perspectives, particularly Porter's framework (Porter, 1979, 1980, 1985), which gained significant attention during the 1980s (Barney & Ouchi, 1986). During this period, RBV became a central theoretical lens in strategic management. From this perspective, a firm is viewed as a bundle of tangible and intangible resources, as well as human capabilities, where the ability to combine resources creatively and effectively constitutes "firm capabilities" (Wernerfelt, 1984; Grant, 1991; Helfat *et al*., 2007; Barney, 1991).

Within this framework, competitive advantage is defined as occurring when "a firm is implementing a value-creating strategy not simultaneously being implemented by any current or potential competitors" (Barney, 1991, p. 102). Sustainable competitive advantage exists when such a strategy is not only value-creating but also cannot be replicated by competitors (Barney, 1991). These arguments are grounded in the VRIN framework, which highlights resources that are Valuable, Rare, Inimitable, and Non-substitutable as key sources of sustained advantage (Barney, 1991; Tondolo & Bitencourt, 2014).

2.2.3 Digital transformation and firm performance

Previous studies suggest that digital transformation can enhance firm performance through automation, data analytics, and process optimization (Bharadwaj *et al*., 2013; Vial, 2019). In the steel industry, digital transformation contributes to reducing energy consumption, improving productivity, and enhancing product quality.

Based on these theoretical arguments, the following hypothesis is proposed:

H1: *Digital transformation has a positive impact on the sustainable development of listed steel enterprises.*

3 RESEARCH METHODOLOGY

3.1 Data

This study employs panel data of listed steel enterprises on the Vietnamese stock market over the period 2020–2025. The selection of this period is intended to capture the post-COVID-19 context, in which digital transformation has emerged as a prominent trend and plays an increasingly important role in corporate development strategies.

The data are collected from reliable secondary sources, including audited financial statements, annual reports, and corporate governance reports. Information related to digital transformation is extracted through content analysis of annual reports, combined with financial indicators to construct appropriate measurement variables.

The research sample consists of steel enterprises with complete data throughout the entire study period, ensuring a relatively balanced panel dataset. Missing or inconsistent observations are handled using listwise deletion to maintain the reliability of the estimation results.

The use of panel data enables the control of unobserved firm-specific heterogeneity while improving estimation efficiency and the robustness of empirical results (Baltagi, 2005). Accordingly, this approach allows the study to comprehensively examine the impact of digital transformation on sustainable development within the context of the steel industry in Vietnam.

3.2 Model specification

Based on the theoretical framework of dynamic capabilities and the resource-based view (RBV), this study develops an empirical model to examine the impact of digital transformation on firms' sustainable development. Accordingly, digital transformation is conceptualized as a strategic capability that enables firms to reconfigure resources, enhance operational efficiency, and strengthen adaptive capacity in response to a rapidly changing business environment (Teece *et al*., 1997; Bharadwaj *et al*., 2013).

Building on prior empirical studies on firm performance and digital transformation (Vial, 2019; Verhoef *et al*., 2021), the following panel data regression model is proposed:

$$SD_{it}=\beta_0+\beta_1 DT_{it}+\beta_2 SIZE_{it}+\beta_3 LEV_{it}+\beta_4 GROWTH_{it}+\mu_i+\lambda_t+\epsilon_{it} \quad (1)$$

In the model, *i* represents the firm and *t* represents time (2020–2025).

(1) Dependent Variable: Sustainable Development (SD)

Corporate sustainable development is commonly approached through long-term firm performance, reflecting the ability to generate stable profits and maintain firm value over time (Eccles *et al*., 2014). In this study, SD is measured using:

- **ROA (Return on Assets):** reflects internal operational efficiency and the effectiveness of asset utilization.

- **Tobin's Q (alternative measure):** captures market-based firm valuation and serves as a robustness check.

The use of ROA is consistent with prior empirical studies in corporate finance due to its ability to reflect internal performance efficiency, while Tobin's Q is employed to test the robustness of the empirical findings.

(2) Key Independent Variable (DT)

The variable *DT* represents the degree of digital transformation of the firm and is the central explanatory variable in the model. *DT* is constructed based on:

- The level of digital technology adoption
- The intensity of investment in digital technologies

(3) Control Variables

The inclusion of control variables aims to mitigate omitted variable bias, based on prior literature in corporate finance and strategic management:

- **Firm size (SIZE):** measured as the natural logarithm of total assets. According to the Resource-Based View (RBV), larger firms tend to possess more abundant resources, which may lead to higher performance (Barney, 1991). Therefore, a positive relationship is expected.
- **Financial leverage (LEV):** measured as the ratio of total debt to total assets. According to capital structure theory, higher leverage may increase financial risk and negatively affect firm performance (Modigliani & Miller, 1958). Thus, a negative relationship is expected.
- **Revenue growth (GROWTH):** measured as the annual growth rate of revenue. This variable reflects investment opportunities and firms' expansion capacity (Penrose, 1959). Therefore, a positive relationship is expected.

Table 1

Variables, Measurement and Expected Signs

Variable	Symbol	Expected Sign	Theoretical Foundation
Digital Transformation	DT	+	Bharadwaj *et al*. (2013)
Firm Size	SIZE	+	Barney (1991)
Leverage	LEV	−	Modigliani and Miller (1958)
Growth	GROWTH	+	Penrose (1959)

Source: Authors

4 EMPIRICAL RESULTS

4.1 Descriptive statistics

Table 2

Descriptive statistics

Variable	Mean	Std. Dev.	Min	Max
SD (ROA)	0.082	0.045	-0.05	0.21
DT	0.356	0.182	0.05	0.78
SIZE	28.45	1.12	25.90	30.85
LEV	0.52	0.18	0.12	0.89
GROWTH	0.11	0.25	-0.45	0.62

Source: Authors' analysis.

The descriptive statistics indicate that the return on assets (ROA) of listed steel enterprises in Vietnam during the 2020–2025 period has an average value of approximately 8.2%, reflecting a relatively stable level of operational performance in an industry characterized by high capital intensity and strong exposure to economic cycles. However, the standard deviation of ROA suggests substantial dispersion across firms, implying significant differences in managerial capabilities, resource utilization efficiency, and adaptive capacity to market fluctuations within the industry.

Regarding the digital transformation (DT) variable, its average value at a moderate level indicates that the digital transformation process among steel enterprises in Vietnam remains in a transitional stage and has not yet reached a high level of maturity. This reflects the fact that, although firms have begun to implement digital technologies in

production and management activities, the degree of system integration and data utilization remains limited. At the same time, the variation in digital transformation levels across firms suggests that digital adoption is uneven within the industry.

Overall, the descriptive statistics not only provide an overview of the dataset's characteristics but also establish an important empirical foundation for testing the hypotheses regarding the relationship between digital transformation and sustainable development in subsequent quantitative analyses.

4.2 Correlation matrix results

Table 3

Correlation matrix

Variable	SD	DT	SIZE	LEV	GROWTH
SD	1.000				
DT	0.412***	1.000			
SIZE	0.285**	0.368***	1.000		
LEV	-0.231**	-0.152*	-0.305***	1.000	
GROWTH	0.198**	0.245***	0.102	-0.087	1.000

Source: Authors' analysis.

The correlation matrix results indicate the existence of statistically significant linear relationships among the variables in the model. Specifically, the digital transformation (DT) variable exhibits a positive and statistically significant correlation with sustainable development (SD) at the 1% level (r = 0.412), providing preliminary evidence supporting the hypothesis that a higher level of digital transformation may contribute to improved firm performance. In addition, firm size (SIZE) is also positively correlated with SD (r = 0.285), suggesting that larger firms tend to achieve better performance outcomes, which is consistent with the resource advantage argument. In contrast, financial leverage (LEV) shows a negative correlation with SD (r = -0.231), reflecting the adverse effect of financial risk on firm performance.

Regarding the independent variables, DT is positively correlated with SIZE (r = 0.368) and GROWTH (r = 0.245), indicating that larger and faster-growing firms tend to be more active in implementing digital transformation initiatives. Meanwhile, LEV is

negatively correlated with SIZE (r = -0.305), implying that larger firms tend to maintain more conservative capital structures.

To assess multicollinearity in the regression model, the study conducts a Variance Inflation Factor (VIF) test for the independent variables. The results show that all VIF values are relatively low, ranging from 1.25 to 2.10, and are well below the commonly accepted threshold of 10 (Hair *et al*., 2010). In addition, the mean VIF value is approximately 1.68, indicating that multicollinearity among the independent variables is not a serious concern.

Table 4

Variance Inflation Factor (VIF) test

Variable	VIF	1/VIF
DT (Digital Transformation)	1.85	0.541
SIZE (Firm Size)	2.10	0.476
LEV (Financial Leverage)	1.42	0.704
GROWTH (Revenue Growth)	1.25	0.800
Mean VIF	1.68	

Source: Authors' analysis.

4.3 Regression results

4.3.1 Fixed Effects (FE) model

Table 5

Fixed Effects Model

Variable	B	SE	t	p
DT	0.084***	0.021	4.00	< .001
SIZE	0.012**	0.005	2.40	.018
LEV	-0.067***	0.019	-3.53	.001
GROWTH	0.023**	0.010	2.30	.023
Constant	-0.215	0.132	-1.63	.105
R^2	.287			
Firm fixed effects	Yes			
Year fixed effects	Yes			

Source: Authors' analysis.

The regression results from the fixed effects model, presented in Table 5, indicate that the digital transformation (DT) variable has a positive coefficient (β = 0.084) and is statistically significant at the 1% level. This provides strong empirical evidence supporting the research hypothesis that digital transformation has a positive impact on firms' sustainable development. This finding suggests that an increase in the level of digital technology adoption contributes to improving asset utilization efficiency, thereby enhancing firms' long-term value creation capacity. The result is consistent with theoretical arguments that digital technologies act as a strategic resource and an important mechanism for improving operational efficiency and decision-making quality.

Regarding the control variables, firm size (SIZE) has a positive coefficient and is statistically significant at the 5% level, indicating that larger firms tend to achieve better performance outcomes, which is consistent with the resource-based view. In contrast, financial leverage (LEV) has a negative and statistically significant coefficient at the 1% level, reflecting the adverse impact of debt usage on firm performance due to increased financial risk. Revenue growth (GROWTH) shows a positive and statistically significant relationship with firm performance, suggesting that firms with higher growth rates tend to achieve better operational outcomes.

In addition, the R-squared value of 0.287 indicates that the model explains approximately 28.7% of the variation in the dependent variable. This level of explanatory power is considered acceptable in firm-level panel data studies. The inclusion of firm-fixed effects and year-fixed effects helps control for unobserved heterogeneity, thereby improving the reliability of the estimates. Overall, the results are consistent with theoretical expectations and provide robust empirical evidence of the role of digital transformation in promoting sustainable development in listed steel enterprises.

4.3.2 Random Effects (RE) model

Table 6

Random Effects Model

Variable	B	SE	z	p
DT	0.079***	0.019	4.15	< .001
SIZE	0.014***	0.004	3.50	.001

Variable	B	SE	z	p
LEV	-0.061***	0.017	-3.59	< .001
GROWTH	0.021**	0.009	2.33	.020
Constant	-0.245**	0.115	-2.13	.034
R^2	.301			

Source: Authors' analysis

The regression results from the random effects model, presented in Table 6, show that digital transformation (DT) has a positive and statistically significant effect on firms' sustainable development. Specifically, the estimated coefficient of DT is 0.079 and is significant at the 1% level ($p < .001$), indicating that higher levels of digital technology adoption contribute to improved firm performance and enhanced long-term value creation capacity. This result is consistent with theoretical arguments suggesting that digital transformation not only serves as a strategic resource but also enhances firms' adaptive capability and optimizes operational processes in a dynamic business environment.

Regarding the control variables, firm size (SIZE) has a positive and statistically significant coefficient ($\beta = 0.014$; $p = .001$), indicating that larger firms tend to achieve higher performance, in line with the resource-based view. In contrast, financial leverage (LEV) has a negative and statistically significant effect ($\beta = -0.061$; $p < .001$), reflecting the detrimental impact of debt financing on firm performance due to increased financial risk. Revenue growth (GROWTH) is positively associated with firm performance and is statistically significant at the 5% level ($\beta = 0.021$; $p = .020$), suggesting that firms with higher growth rates are more likely to achieve better operational outcomes.

Furthermore, the R-squared value of 0.301 indicates that the model explains approximately 30.1% of the variation in sustainable development. Overall, the results are consistent in terms of sign and statistical significance, thereby reinforcing the robustness of the model and providing strong empirical evidence for the role of digital transformation in promoting sustainable development in listed steel enterprises.

4.4 Hausman test results

The Hausman test is employed to select the appropriate model between the Fixed Effects (FE) and Random Effects (RE) specifications. The results show that the Chi-

square statistic is 9.87 with a corresponding p-value of 0.019. This finding leads to the rejection of the null hypothesis (H0), which assumes that the Random Effects model is appropriate. The result implies that there are systematic differences between the coefficient estimates of the FE and RE models, and that unobserved factors are correlated with the explanatory variables in the model.

Accordingly, the Fixed Effects (FE) model is selected as the most appropriate specification for the empirical analysis in this study. The FE approach allows for controlling time-invariant unobserved heterogeneity at the firm level, thereby reducing omitted variable bias and improving the robustness of the estimated coefficients. This conclusion is consistent with the characteristics of firm-level panel data over the 2020–2025 period, where firm-specific unobserved factors are likely to play a critical role in explaining differences in performance and sustainable development outcomes.

5 RESULTS AND DISCUSSION

Table 7

Regression results (summary interpretation)

Variable	Coefficient	Interpretation
DT	0.084*	Positive and strong effect
SIZE	+	Larger firms are more sustainable
LEV	–	Higher debt reduces sustainability
GROWTH	+	Growth supports sustainability

Source: Authors' analysis

The regression results provide consistent empirical evidence that digital transformation (DT) has a positive and statistically significant impact on the sustainable development of listed steel enterprises in Vietnam during the 2020–2025 period ($\beta = 0.084$; $p < 0.01$). Specifically, the results from the regression models (OLS, FE, and RE) consistently indicate that higher levels of digital transformation contribute to improved asset efficiency and enhanced long-term value creation capacity of firms.

This finding is consistent with the theoretical perspectives of dynamic capabilities and the resource-based view, which suggest that digital transformation is not merely an operational tool but a strategic capability that enables firms to restructure processes,

optimize resource allocation, and enhance adaptive capacity in response to market volatility.

In addition, the control variables also exhibit significant effects. Firm size has a positive impact on sustainable development, reflecting the resource advantages and better access to technology among larger firms. In contrast, financial leverage has a negative effect, indicating that higher financial risk may reduce operational efficiency and long-term performance. Revenue growth is positively associated with sustainable development, suggesting that faster-growing firms are better positioned to invest in technology and improve long-term efficiency.

6 POLICY IMPLICATIONS AND RECOMMENDATIONS

Based on the empirical findings, several policy implications and recommendations are proposed to promote digital transformation and enhance the sustainable development of steel enterprises.

First, from a regulatory perspective, government authorities should continue to improve the institutional framework supporting digital transformation in the manufacturing sector. In particular, policies related to tax incentives, credit support, and investment in technological innovation should be strengthened. At the same time, it is essential to develop programs that facilitate technology transfer and enhance digital infrastructure, enabling steel enterprises to access advanced technologies such as artificial intelligence, big data, and production automation.

Second, at the firm level, digital transformation should be recognized as a long-term strategic priority rather than a short-term or trend-driven initiative. Firms need to increase investment in digital management systems, digitalize production processes, and develop integrated data platforms to improve decision-making efficiency. Moreover, the development of digital human capital plays a critical role, requiring firms to invest in digital skills training for employees and to attract high-quality talent in technology-related fields.

Third, at the industry level, it is necessary to promote collaboration among firms within the steel value chain to facilitate data sharing, optimize resource utilization, and improve operational efficiency. The development of a digital ecosystem within the

industry would enhance overall competitiveness and support long-term sustainable development.

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