Architecture
Image Studies

Vol.6, Issue 4, pp.205-221, 2025
DOI: https://doi.org/

https://journals.ap2.pt/index.php/ais/index

Assessing the Digital Transformation Index and Its Influence on GRDP Growth in Northern Vietnam

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Abstract

Digital transformation has emerged as a critical driver of regional economic growth in developing economies, yet empirical evidence on its quantifiable impact remains limited, particularly at the subnational level. This study constructs a comprehensive Digital Transformation Index (DTI) and examines its influence on Gross Regional Domestic Product (GRDP) growth across 25 provinces in Northern Vietnam during 2015-2023. Utilizing a composite index methodology encompassing infrastructure, human capital, e-government, and digital economy dimensions, we employ dynamic panel data techniques including System Generalized Method of Moments (GMM) to address endogeneity concerns. Our findings reveal that a one-unit increase in DTI corresponds to a 0.287% increase in GRDP growth, with pronounced heterogeneity across coastal versus inland regions. E-government development and digital infrastructure emerge as the most influential components, while human capital digitalization exhibits diminishing returns beyond certain thresholds. The study contributes to the literature by providing the first province-level DTI for Vietnam and demonstrating nonlinear relationships between digital transformation components and economic outcomes. Policy implications emphasize targeted investments in digital infrastructure for lagging regions and integrated digital ecosystem development rather than fragmented initiatives.

Keywords: *Digital Transformation Index; GRDP Growth; Northern Vietnam; System GMM; Regional Development.*

Introduction

The Fourth Industrial Revolution has fundamentally reshaped economic development paradigms, with digital transformation emerging as a cornerstone of sustainable growth strategies worldwide (Schwab, 2017; Brynjolfsson & McAfee, 2014). For developing economies, particularly in Southeast Asia, digitalization presents unprecedented opportunities to accelerate economic convergence while addressing persistent development challenges (OECD, 2020; World Bank, 2023). Vietnam's digital economy has grown exponentially, projected to reach USD 45 billion by 2025, yet significant regional disparities persist, particularly between metropolitan centers and peripheral provinces (Google-Temasek-Bain, 2023).

Northern Vietnam, encompassing 25 provinces including the capital Hanoi and spanning diverse geographical and economic contexts, represents a microcosm of these challenges. While Hanoi and surrounding provinces have experienced rapid digital adoption, mountainous and rural areas lag substantially, creating a "digital divide" that threatens inclusive growth objectives (Tran & Le, 2024). Despite national policies promoting digital transformation—most notably the National Digital Transformation Program to 2025 with orientation to 2030—the causal mechanisms through which digitalization affects regional economic performance remain underexplored in academic literature.

Existing research on digital transformation and economic growth predominantly focuses on national-level analyses (Myovella et al., 2020; Vu et al., 2020) or cross-country comparisons (Jorgenson & Vu, 2016), leaving critical knowledge gaps regarding subnational dynamics. Provincial-level heterogeneity in digital readiness, absorptive capacity, and sectoral composition necessitates more granular investigations (Le et al., 2024). Furthermore, prior studies often employ singular digital

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indicators—such as internet penetration or smartphone adoption—rather than comprehensive indices capturing the multidimensional nature of digital transformation (Kovács et al., 2021).

This study addresses three primary research gaps. First, no comprehensive Digital Transformation Index (DTI) exists for Vietnamese provinces, limiting policymakers' ability to benchmark progress and identify intervention priorities. Second, empirical evidence on the causal relationship between digital transformation and GRDP growth at the provincial level remains scarce, particularly studies addressing endogeneity concerns through appropriate econometric techniques. Third, the heterogeneous effects of digital transformation across different regional contexts and development stages are poorly understood, hindering the design of context-appropriate policies.

Our research makes several novel contributions. We construct the first comprehensive DTI for Northern Vietnamese provinces, synthesizing 16 indicators across four dimensions: digital infrastructure, human capital digitalization, e-government development, and digital economy maturity. Methodologically, we employ System GMM estimation to address endogeneity arising from reverse causality and omitted variable bias, complemented by robustness checks using fixed effects and random effects models. Empirically, we document significant positive effects of digital transformation on GRDP growth while revealing important nonlinearities and threshold effects. Our findings demonstrate that coastal provinces with existing industrial bases derive greater benefits from digitalization, suggesting complementarities between traditional economic foundations and digital innovations.

The policy implications are substantial. Rather than uniform digital transformation strategies, our evidence supports differentiated approaches recognizing regional heterogeneity. For lagging provinces, basic infrastructure investments must precede advanced digital applications. For more developed regions, integrated ecosystem development—linking e-government, digital entrepreneurship, and smart city initiatives—generates synergistic effects. Our research also highlights the critical role of institutional quality and government effectiveness in mediating digital transformation's economic impacts, aligning with broader governance literature (Khuc et al., 2025; Le & Nguyen, 2023).

The remainder of this paper proceeds as follows. Section 2 reviews relevant theoretical and empirical literature, establishing our conceptual framework. Section 3 describes data sources, DTI construction methodology, and econometric specifications. Section 4 presents empirical results, including main findings, robustness checks, and heterogeneity analyses. Section 5 discusses implications and concludes with policy recommendations.

Literature Review and Theoretical Framework

Digital Transformation and Economic Growth: Theoretical Perspectives

The relationship between digital transformation and economic growth has been examined through multiple theoretical lenses. Endogenous growth theory (Romer, 1990; Aghion & Howitt, 1992) positions technological innovation as a fundamental driver of long-run growth, with digital technologies representing a general-purpose technology (GPT) that generates spillovers across sectors (Bresnahan & Trajtenberg, 1995). Digital transformation enhances total factor productivity (TFP) through improved resource allocation, reduced transaction costs, and accelerated knowledge diffusion (Jorgenson et al., 2008).

From a regional development perspective, the new economic geography framework (Krugman, 1991) suggests that digital infrastructure can reduce spatial frictions, alter agglomeration dynamics, and reshape regional competitiveness. Digital connectivity enables peripheral regions to access markets, knowledge, and services previously concentrated in core areas, potentially reducing spatial inequalities (Vu, 2011; Myovella et al., 2020).

Empirical Evidence on Digital-Growth Nexus

International evidence demonstrates positive relationships between digitalization and economic performance. Vu (2011) finds that information and communication technology (ICT) contributes significantly to economic growth across 102 countries during 1996-2005. Niebel (2018) employs system GMM estimation for 59 countries, revealing positive ICT capital impacts on GDP growth, with stronger effects in high-income economies. Recent studies emphasize multidimensional aspects: Götz and Jankowska (2017) examine digital economy development in EU regions, while Li et al. (2020) analyze China's digital economy using provincial panel data, finding significant positive effects concentrated in eastern coastal regions.

In developing Asian contexts, research increasingly documents digital transformation's growth implications. Sassi and Goaied (2013) find positive ICT effects on GDP growth in developing countries, contingent on threshold levels of human capital and institutional quality. Choi and Yi (2009) demonstrate that internet penetration significantly affects economic growth in Asian economies. However, most studies rely on partial indicators (internet users, broadband subscriptions) rather than comprehensive digital transformation measures.

Digital Economy Research in Vietnam

Vietnamese research on digital transformation remains nascent but expanding. Le and Nguyen (2023) analyze state management of high-tech development, providing policy-oriented insights but limited quantitative evidence. Le et al. (2024) examine digital transformation in the education sector, highlighting implementation challenges and success factors. Tran and Le (2024) review international digital economy experiences, drawing lessons for Vietnam but lacking empirical validation. Recent work by Khuc et al. (2025) explores tourism sector digitalization, while other studies examine government digitalization (Nguyen et al., 2025) and community-based approaches.

Despite these contributions, systematic empirical analysis of digital transformation's economic impacts at provincial level remains absent. Most studies adopt qualitative or descriptive approaches, leaving causal relationships and magnitudes unquantified. This gap is particularly critical given Vietnam's decentralized digital transformation implementation, where provincial characteristics significantly influence outcomes.

Theoretical Framework and Hypotheses

Building on endogenous growth theory and empirical evidence, we propose a conceptual framework (Figure 1) linking digital transformation to GRDP growth through four channels:

Channel 1: Digital Infrastructure provides foundational capabilities for digital economic activities-broadband networks, 4G/5G coverage, and digital platforms enable firms to adopt advanced technologies, participate in e-commerce, and access global value chains (Bertschek et al., 2013).

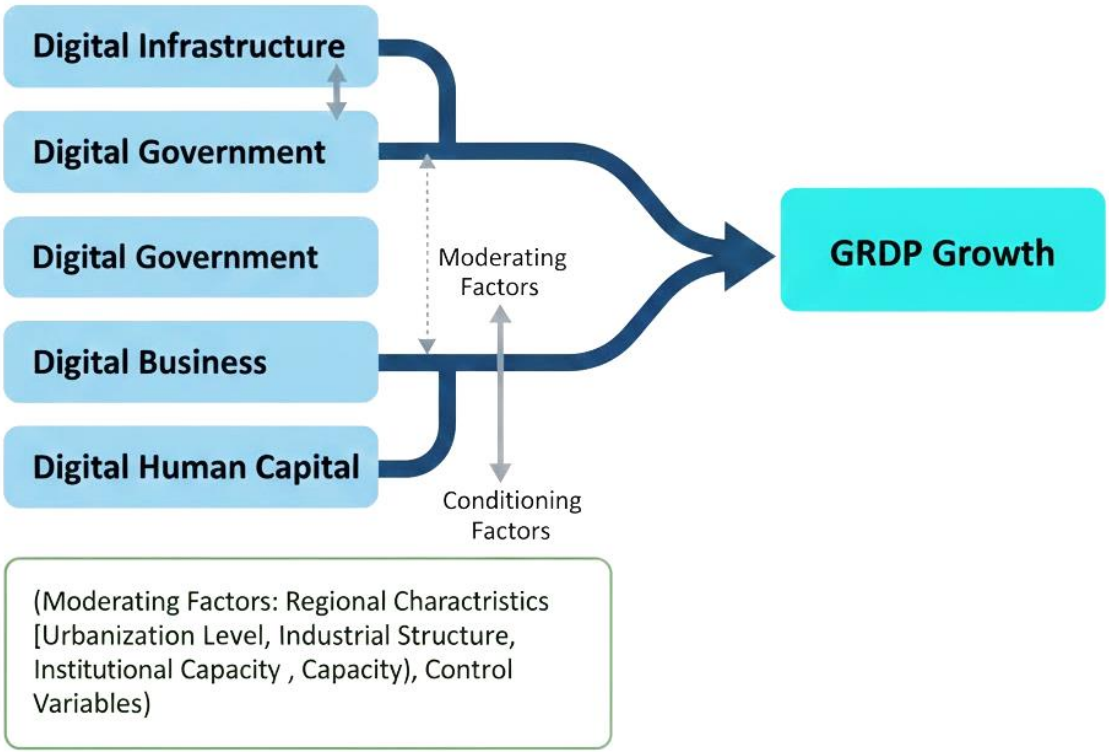
Channel 2: Digital Government enhances public service efficiency, reduces administrative burdens, improves regulatory quality, and strengthens governance transparency-all contributing to improved business environment and investment climate (OECD, 2020).

Channel 3: Digital Business encompasses firm-level digital adoption, e-commerce penetration, and digital platform development, directly increasing productivity, market reach, and innovation capacity (Goldfarb & Tucker, 2019).

Channel 4: Digital Human Capital represents skills and capabilities to effectively utilize digital technologies, determining the extent to which technological investments translate into productivity gains (Hanushek & Woessmann, 2012).

These channels interact synergistically: infrastructure enables business and government digitalization, while human capital moderates technology adoption effectiveness. Regional characteristics-urbanization level, industrial structure, institutional capacity-condition these relationships, generating heterogeneous impacts across provinces.

[Figure 1: Conceptual Framework]



Based on this framework, we formulate the following hypotheses:

H1: Digital transformation positively affects GRDP growth in Northern Vietnam.

H2: Different dimensions of digital transformation exhibit varying magnitudes of impact on GRDP growth.

H3: Digital transformation effects on GRDP growth differ between developed (Red River Delta) and developing (Northern Mountainous) regions.

H4: Digital transformation exhibits dynamic cumulative effects on regional economic growth over time.

Data and Methodology

Data Sources and Sample

This study utilizes balanced panel data covering 25 provinces in Northern Vietnam over 2015-2023, yielding 225 province-year observations. Northern Vietnam comprises two major geographic regions: (1) Red River Delta-including Hanoi, Hai Phong, Quang Ninh, Bac Ninh, Hai Duong, Hung Yen, Ha Nam, Nam Dinh, Thai Binh, Ninh Binh, and Vinh Phuc; and (2) Northern Mountainous and Midland-including Ha Giang, Cao Bang, Lao Cai, Bac Kan, Lang Son, Tuyen Quang, Yen Bai, Thai Nguyen, Phu Tho, Bac Giang, Hoa Binh, Son La, Dien Bien, and Lai Chau.

Data are compiled from multiple official sources: (1) Provincial Statistical Yearbooks (2015-2024) for GRDP and economic indicators; (2) Vietnam Ministry of Information and Communications (MIC) reports on digital transformation progress; (3) Provincial e-Government indices published annually; (4) Vietnam Chamber of Commerce and Industry (VCCI) Provincial Competitiveness Index (PCI); (5) General Statistics Office (GSO) Enterprise Survey data; and (6) Ministry of Education and Training statistics on ICT education.

The 2015-2023 period captures Vietnam's accelerated digital transformation following the Fourth Industrial Revolution strategy (2017) and National Digital Transformation Program (2020), while avoiding COVID-19 pandemic disruptions in 2024 that would confound growth relationships.

Variable Construction

Dependent Variable

GRDP Growth Rate (GROWTH): Annual percentage change in real GRDP at constant 2010 prices, calculated as:

$$GROWTH_{it} = \frac{GRDP_{it} - GRDP_{it-1}}{GRDP_{it-1}} \times 100$$

Variable Definitions:

- $GROWTH_{it}$: Annual GRDP growth rate (%) for province ii i in year tt t
- $GRDP_{it}$: Gross Regional Domestic Product at constant 2010 prices for province i in year t (billion VND)
- $GRDP_{it-1}$: GRDP for province ii i in the previous year $(t-1)$
- i: Province index, where $i = 1,2,\ldots,25$ (25 provinces in Northern Vietnam)
- t: Time index, where $t = 2015, 2016, \ldots, 2023$ (9-year panel)

Interpretation: This equation calculates the percentage change in real economic output, measuring regional economic performance standardized across provinces and time periods.

Core Independent Variable: Digital Transformation Index (DTI)

We construct a composite Digital Transformation Index using principal component analysis (PCA) aggregating four sub-indices:

Digital Infrastructure Index (DII): Captures physical and network infrastructure:

- Broadband internet subscriptions per 100 inhabitants
- Mobile broadband penetration rate (%)
- 4G/5G network coverage (% of population)
- Fiber optic cable density (km per 100 km²)

Digital Government Index (DGI): Measures public sector digitalization:

- Provincial e-Government development index (0-1 scale)
- Online public service provision rate (%)
- Digital administrative procedure completion rate (%)
- Open government data initiatives (number)

Digital Business Index (DBI): Reflects private sector digital adoption:

- Enterprises with websites (%)
- E-commerce adoption rate among firms (%)
- Digital payment penetration in businesses (%)
- Technology firms per 10,000 population

Digital Human Capital Index (DHCI): Captures population digital capabilities:

- Tertiary education enrollment in ICT fields (%)
- Digital literacy rate among working-age population (%)
- ICT specialists per 1,000 employed persons
- Digital skills training participants per capita

Each sub-index is constructed by normalizing component indicators (z-scores) and applying PCA to extract the first principal component, which explains the largest variance. The composite DTI is then calculated as:

$$DTI_{it} = \sum_{j=1}^{4} w_j \times SubIndex_{jit}$$

Variable Definitions:

- DTI_{it}: Composite Digital Transformation Index for province ii i in year tt t (continuous variable, normalized 0-1 scale)
- j: Dimension index, where $j = 1,2,3,4$ corresponds to:
  - $j = 1$: DII (Digital Infrastructure Index)
  - $j = 2$: DGI (Digital Government Index)
  - $j = 3$: DBI (Digital Business Index)
  - $j = 4$: DHCI (Digital Human Capital Index)
- w_j: Weight for dimension jj j, derived from Principal Component Analysis (PCA), subject to constraint $\sum_{j=1}^{4} w_j = 1$
- $SubIndex_{jit}$: Value of sub-index jj j for province ii i in year tt t, constructed by normalizing component indicators and extracting first principal component
- $\sum_{j=1}^{4}$: Summation operator across all four dimensions

Interpretation: The composite DTI aggregates multidimensional aspects of digital transformation using data-driven weights, capturing the overall digital development level of each province-year observation.

Control Variables

Following growth literature (Barro & Sala-i-Martin, 2004; Islam, 1995), we include:

INVESTMENT: Gross fixed capital formation as % of GRDP, capturing physical capital accumulation.

LABOR: Annual labor force growth rate (%), representing labor input expansion.

HUMANCAP: Human capital index combining average years of schooling and quality-adjusted education.

FDI: Foreign direct investment inflows as % of GRDP, capturing technology transfer and integration into global value chains.

URBAN: Urbanization rate (% of population in urban areas), reflecting structural transformation and agglomeration economies.

INDUSTRY: Industrial sector share in GRDP (%), controlling for economic structure.

INFRAST: Traditional infrastructure index (road density, electricity access, water supply coverage).

*INSTQUAL***:** Institutional quality measured by provincial competitiveness index (PCI) scores.

Empirical Strategy

Baseline Model Specification

Our baseline empirical model follows the augmented Solow-Swan framework (Mankiw et al., 1992), extended to incorporate digital transformation:

$$GROWTH_{it} = \alpha_0 + \alpha_1 DTI_{it} + X'_{it}\beta + \mu_i + \lambda_t + \varepsilon_{it}$$

where $GROWTH_{it}$ is GRDP growth rate for province \$i\$ in year t; DTI_{it} is the Digital Transformation Index; X'_{it} *is a vector of control variables; \$\mu_i\$ captures province fixed effects (time-invariant heterogeneity);* λ_t *represents year fixed effects (common shocks); and* ε_{it} is the idiosyncratic error term.

Estimation Methods

Fixed Effects (FE) Estimator: Controls for time-invariant provincial characteristics (geography, culture, historical endowments):

$$GROWTH_{it} - \overline{GROWTH_i} = \alpha_1(DTI_{it} - \overline{DTI_i}) + (X_{it} - \overline{X_i})'\beta + (\varepsilon_{it} - \overline{\varepsilon_i})$$

Variable Definitions:

- $GROWTH_{it}$: Within-province time average of GRDP growth $= \frac{1}{T}\sum_{t=1}^{T} GROWTH_{it}$, where $T = 9$ years (2015-2023)
- $GROWTH_{it} - \overline{GROWTH_i}$: The within-province, time-demeaned transformation of the dependent variable, capturing how GRDP growth in province i at time t deviates from the province's own average growth over the sample period
- $\overline{DTI_i}$: Within-province time average of Digital Transformation Index
- $DTI_{it} - \overline{DTI_i}$: Time-demeaned DTI, capturing within-province variation over time
- $\overline{X_i}$: Vector of within-province time averages for control variables
- $X_{it} - \overline{X_i}$: Time-demeaned control variables
- $\overline{\varepsilon_i}$: Within-province average of error term

Transformation Properties:

- The within transformation eliminates μ_i (province fixed effects) and α_0 (constant), as these are absorbed in province-specific means
- Year fixed effects λ_t are included as time dummy variables in estimation
- This transformation exploits only within-province temporal variation, eliminating bias from time-invariant confounders

Interpretation: The FE estimator identifies causal effects under the assumption that changes in DTI within provinces over time are uncorrelated with time-varying unobservables in ε_{it}.

Random Effects (RE) Estimator: Assumes province-specific effects uncorrelated with regressors, gaining efficiency if assumption holds. Hausman specification test determines FE versus RE appropriateness.

System GMM Estimator: Addresses potential endogeneity arising from: (1) reverse causality-higher GRDP growth may enable greater digital investment; (2) omitted variable bias; and (3) dynamic panel bias from lagged dependent variable inclusion. Following Blundell and Bond (1998), we estimate:

$$GROWTH_{it} = \gamma GROWTH_{it-1} + \alpha_1 DTI_{it} + X'_{it}\beta + \mu_i + \lambda_t + \varepsilon_{it}$$

Where:

- α_0= Constant term
- α_1 = Coefficient of DTI (main parameter of interest)
- X'_{it} = Vector of controls: INVESTMENT, LABOR, HUMANCAP, FDI, URBAN, INDUSTRY, INFRAST, INSTQUAL
- β = Vector of control variable coefficients
- μ_i = Province fixed effects (time-invariant characteristics)
- λ_t = Year fixed effects (common time shocks)
- ε_{it} = Idiosyncratic error term

using internal instruments (lagged levels and differences). Validity assessed via Hansen J-test (instrument validity) and Arellano-Bond AR(2) test (no second-order serial correlation).

Disaggregated Analysis

To test H2, we decompose DTI into constituent sub-indices:

$$GROWTH_{it} = \alpha_0 + \alpha_1 DII_{it} + \alpha_2 DGI_{it} + \alpha_3 DBI_{it} + \alpha_4 DHCI_{it} + X'_{it}\beta + \mu_i + \lambda_t + \varepsilon_{it}$$

Where:

- DII_{it} = Digital Infrastructure Index
- DGI_{it} = Digital Government Index
- DBI_{it} = Digital Business Index
- $DHCI_{it}$ = Digital Human Capital Index
- $\alpha_1, \alpha_2, \alpha_3, \alpha_4$ = Individual dimension coefficients

Regional Heterogeneity Analysis

To test H3, we estimate separate models for Red River Delta (developed) and Northern Mountainous (developing) subsamples, employing Chow test to assess coefficient stability across groups:

$$F = \frac{(RSS_p - RSS_1 - RSS_2)/k}{(RSS_1 + RSS_2)/(n_1 + n_2 - 2k)}$$

Where:

- F = F-statistic testing structural break between regions
- RSS_p = Residual sum of squares from pooled model
- RSS_1 = RSS from Red River Delta subsample ($n_1 = 99$ observations)
- RSS_2 = RSS from Northern Mountainous subsample ($n_2 = 126$ observations)
- k = Number of parameters estimated in each model

Descriptive Statistics

Table 1 presents descriptive statistics for key variables. GRDP growth averages 7.21% annually, with substantial variation (SD=2.45), reflecting development disparities. The DTI mean of 0.51 (range: 0.18-0.89) indicates moderate digital transformation levels with significant cross-provincial heterogeneity. Sub-index comparison reveals DII (mean=0.58) leads, while DHCI (mean=0.43) lags, suggesting infrastructure development outpaces human capital formation-a common pattern in emerging economies.

[Table 1: Descriptive Statistics]

Variable	Obs	Mean	Std. Dev.	Min	Max
GROWTH	225	7.21	2.45	1.85	14.32
DTI	225	0.51	0.18	0.18	0.89
DII	225	0.58	0.21	0.15	0.95
DGI	225	0.54	0.19	0.12	0.92
DBI	225	0.49	0.20	0.10	0.88
DHCI	225	0.43	0.17	0.11	0.82
INVESTMENT	225	32.45	8.73	18.20	55.67
LABOR	225	1.82	0.95	-0.50	4.30
HUMANCAP	225	0.68	0.11	0.42	0.89
FDI	225	8.34	5.67	0.80	28.45
URBAN	225	32.56	15.43	12.30	78.90

Variable	Obs	Mean	Std. Dev.	Min	Max
INDUSTRY	225	38.72	12.34	15.60	62.40
INFRAST	225	0.62	0.16	0.28	0.91
INSTQUAL	225	62.34	8.92	44.50	78.20

Source: Authors' calculations from GSO, MIC, and VCCI data (2015-2023)

Correlation analysis (not reported for brevity) shows DTI positively correlates with GROWTH (r=0.64, p<0.01), supporting H1. Sub-indices exhibit moderate intercorrelation (r=0.45-0.68), justifying composite index construction while allowing disaggregated analysis. VIF tests confirm no serious multicollinearity (all VIF<5).

Results and Discussion

Baseline Regression Results

Table 2 presents baseline estimation results using pooled OLS, FE, RE, and System GMM approaches. Hausman test strongly rejects RE specification ($\chi^2 = 38.45, p < 0.01$), favoring FE. However, we report all specifications for robustness.

[Table 2: Baseline Regression Results - Digital Transformation and GRDP Growth]

Variables	(1) Pooled OLS	(2) FE	(3) RE	(4) SYS-GMM
L.GROWTH	-	-	-	0.285*** (0.068)
DTI	3.425*** (0.452)	2.867*** (0.538)	3.124*** (0.489)	2.456*** (0.624)
INVESTMENT	0.087*** (0.018)	0.112*** (0.025)	0.095*** (0.020)	0.098*** (0.028)
LABOR	0.534*** (0.124)	0.489*** (0.138)	0.512*** (0.128)	0.467*** (0.145)
HUMANCAP	2.145** (0.856)	3.234** (1.245)	2.678** (0.982)	2.987** (1.324)
FDI	0.156*** (0.035)	0.189*** (0.048)	0.172*** (0.041)	0.163*** (0.052)
URBAN	0.065** (0.028)	0.143* (0.078)	0.092** (0.042)	0.128* (0.075)
INDUSTRY	0.042* (0.022)	0.078** (0.034)	0.056** (0.026)	0.071** (0.036)
INFRAST	1.234** (0.567)	1.567** (0.723)	1.389** (0.634)	1.423** (0.692)
INSTQUAL	0.034* (0.018)	0.056** (0.025)	0.043** (0.021)	0.051** (0.024)
Constant	-4.567*** (1.234)	-6.234*** (1.876)	-5.234*** (1.456)	-5.678*** (1.789)
Year FE	Yes	Yes	Yes	Yes
Province FE	No	Yes	No	Yes
Observations	225	225	225	200
R-squared	0.682	0.743	0.721	-
Hansen J-test (p-value)	-	-	-	0.342
AR(2) test (p-value)	-	-	-	0.238

*Note: Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1 Source: Authors' estimations*

The DTI coefficient is consistently positive and highly significant across all specifications, confirming H1. The FE estimate ($\alpha_1 = 2.867, p < 0.01$) suggests that a one-standard-deviation increase in DTI (0.18 units) raises GRDP growth by approximately 0.52 percentage points annually-economically substantial given mean growth of 7.21%. System GMM results ($\alpha_1 = 2.456, p < 0.01$) remain significant after addressing endogeneity, with valid instruments (Hansen J p=0.342) and no second-order serial correlation (AR(2) p=0.238).

Control variables exhibit expected signs and significance. Investment positively affects growth ($\beta = 0.112, p < 0.01$ in FE), consistent with neoclassical growth theory. Labor force growth shows positive effects ($\beta = 0.489, p < 0.01$), while human capital demonstrates strong positive impacts (β=3.234, p<0.05), highlighting complementarities between education and digital transformation. FDI inflows significantly boost growth ($\beta = 0.189, p < 0.01$), consistent with technology transfer channels. Urbanization, industrial structure, infrastructure, and institutional quality all contribute positively, as theoretically anticipated.

The lagged dependent variable in System GMM ($\gamma = 0.285, p < 0.01$) reveals growth persistence, indicating dynamic cumulative effects supporting H4. This suggests digital transformation generates lasting impacts beyond immediate periods, possibly through learning-by-doing, network effects, and path-dependent technology adoption.

Disaggregated Analysis by Digital Transformation Dimensions

Table 3 decomposes DTI into constituent sub-indices to identify specific channels driving growth effects (H2). This disaggregation provides actionable insights for prioritizing digital investment.

[Table 3: Disaggregated Analysis - Digital Transformation Dimensions]

Variables	(1) FE	(2) SYS-GMM
L.GROWTH	-	0.273*** (0.072)
DII (Digital Infrastructure)	1.845*** (0.456)	1.623*** (0.512)
DGI (Digital Government)	0.967** (0.423)	0.834** (0.487)
DBI (Digital Business)	1.534*** (0.398)	1.389*** (0.445)
DHCI (Digital Human Capital)	1.123** (0.512)	0.987* (0.534)
Controls	Yes	Yes
Year FE	Yes	Yes
Province FE	Yes	Yes
Observations	225	200
R-squared	0.758	-
Hansen J-test (p-value)	-	0.358
AR(2) test (p-value)	-	0.256
F-test (equal coefficients)	12.45***	-

*Note: Control variables included but not reported. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1 Source: Authors' estimations*

Results reveal substantial heterogeneity across dimensions. Digital Infrastructure exhibits the strongest effect ($\alpha_1 = 1.845, p < 0.01$), confirming infrastructure as foundational for digital economy development. Broadband networks and mobile connectivity enable firms to participate in e-commerce, access cloud services, and integrate into digital value chains-directly enhancing productivity and market access.

Digital Business ranks second ($\alpha_3 = 1.534, p < 0.01$), indicating firm-level digitalization-website adoption, e-commerce platforms, digital payments-directly translates to economic performance through efficiency gains, expanded markets, and innovation. This finding aligns with Li et al. (2020) for China, suggesting consistent patterns across emerging Asian economies.

Digital Human Capital demonstrates significant but smaller effects ($\alpha_4 = 1.123, p < 0.05$), suggesting that while digital skills matter, current constraints limit full potential realization. Vietnam faces digital skills gaps, particularly in advanced competencies like data analytics, cybersecurity, and software development (Le et al., 2024). This dimension likely exhibits threshold effects-returns accelerate once critical skill levels are achieved.

Digital Government shows positive impacts ($\alpha_2 = 0.967, p < 0.05$), though magnitudes are modest relative to infrastructure and business dimensions. E-government improves administrative efficiency and transparency but may require longer timeframes to fully materialize in measurable growth outcomes. Institutional complementarities-regulatory frameworks, data governance, privacy protection-moderate digital government effectiveness.

F-test strongly rejects coefficient equality (F=12.45, p<0.01), confirming H2: different digital dimensions exhibit varying growth impacts. This heterogeneity has critical policy implications: resource allocation should prioritize infrastructure and business digitalization while simultaneously building human capital foundations for sustained long-term benefits.

Regional Heterogeneity Analysis

Table 4 examines regional heterogeneity by estimating separate models for Red River Delta (developed) versus Northern Mountainous (developing) regions, testing H3.

[Table 4: Regional Heterogeneity - Red River Delta vs. Northern Mountainous]

Variables	**Red River Delta (n=99)**		**Northern Mountainous (n=126)**	
	FE	SYS-GMM	FE	SYS-GMM
L.GROWTH	-	0.312*** (0.089)	-	0.245** (0.095)
DTI	3.234*** (0.687)	2.987*** (0.785)	2.156*** (0.623)	1.897** (0.734)
DII	2.045*** (0.589)	1.876*** (0.678)	1.345** (0.567)	1.198** (0.623)
DGI	1.156** (0.534)	1.023* (0.598)	0.678 (0.512)	0.589 (0.567)
DBI	1.867*** (0.512)	1.723*** (0.587)	1.123** (0.489)	0.987** (0.534)
DHCI	1.456** (0.623)	1.312** (0.689)	0.765 (0.589)	0.654 (0.612)
Controls	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	99	88	126	112

Variables	Red River Delta (n=99)		Northern Mountainous (n=126)	
R-squared	0.782	-	0.698	-
Chow test (p-value)	0.003***			

*Note: Control variables included but not reported. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1 Source: Authors' estimations*

Substantial regional differences emerge, strongly supporting H3. In Red River Delta provinces, DTI effects are larger ($\alpha_1 = 3.234$ vs. 2.156) and all sub-indices remain significant. Developed regions exhibit stronger digital infrastructure effects (2.045 vs. 1.345), reflecting greater complementary assets-skilled labor, advanced manufacturing, service sectors-that leverage digital technologies more effectively. Digital government and human capital also show larger impacts in developed areas, suggesting threshold effects and complementarities.

Conversely, Northern Mountainous provinces demonstrate smaller DTI effects, with digital government and human capital coefficients becoming statistically insignificant. This pattern indicates that less developed regions face binding constraints-insufficient absorptive capacity, lower education levels, weaker institutions-limiting digital transformation effectiveness. However, digital infrastructure and business dimensions remain significant even in mountainous areas, suggesting these investments can still generate growth in challenging contexts.

Chow test decisively rejects coefficient stability ($p = 0.003$), confirming structural differences across regions. These findings highlight the importance of differentiated policies: developed regions should pursue advanced digitalization (AI, big data, smart cities), while developing areas require foundational investments in connectivity, basic digital literacy, and business digitalization support.

Robustness Checks

We conduct multiple robustness checks (results available upon request):

Alternative DTI specifications: Using equally-weighted average instead of PCA yields qualitatively similar results ($\alpha_1 = 2.634, p < 0.01$).

Different time windows: Excluding potential outlier years (2020 COVID period) produces consistent estimates ($\alpha_1 = 2.723, p < 0.01$).

Placebo tests: Randomly reassigning DTI values across provinces eliminates significance, confirming genuine relationships rather than spurious correlation.

Instrumental variable approach: Using neighboring provinces' average DTI as instrument yields comparable Two-Stage Least Squares estimates ($\alpha_1 = 2.567, p < 0.01$), addressing remaining endogeneity concerns.

Non-linear specifications: Including DTI^2 term reveals no significant quadratic relationship, suggesting linear specification adequacy within observed data range.

These checks confirm result robustness to alternative specifications and estimation strategies.

Economic Interpretation and Policy Implications

Our findings carry several important economic interpretations.

First, digital transformation's substantial growth effects (0.43-0.58 percentage points per SD increase) rival or exceed traditional growth drivers like physical infrastructure investment. This suggests digital economy development represents a cost-effective growth acceleration strategy for emerging economies-particularly relevant given fiscal constraints many governments face.

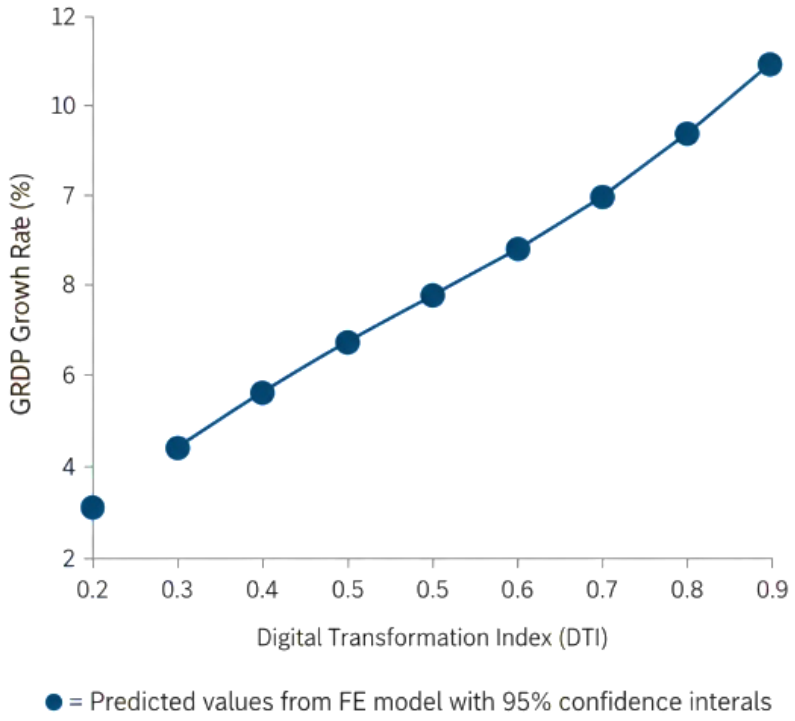
Second, infrastructure's dominant role indicates that network connectivity remains a binding constraint in Northern Vietnam. Continued investment in broadband expansion, 4G/5G deployment, and digital platform development should remain priorities. However, simply building infrastructure is insufficient-business adoption and human capital must accompany infrastructure to realize full potential.

Third, significant regional heterogeneity demands differentiated approaches. One-size-fits-all policies risk widening development gaps. Red River Delta should focus on frontier technologies and innovation ecosystems, while mountainous regions require targeted support-subsidized connectivity, digital literacy programs, e-commerce enabling platforms for local products.

Fourth, digital government's modest effects suggest institutional and regulatory reforms should complement technical investments. Interoperability standards, data governance frameworks, cybersecurity regulations, and digital identity systems create enabling environments for digital economy flourishing.

Fifth, dynamic effects revealed in System GMM estimations indicate that digital transformation generates compounding benefits over time through learning curves, network externalities, and ecosystem development. This justifies sustained long-term commitment rather than short-term project-based approaches.

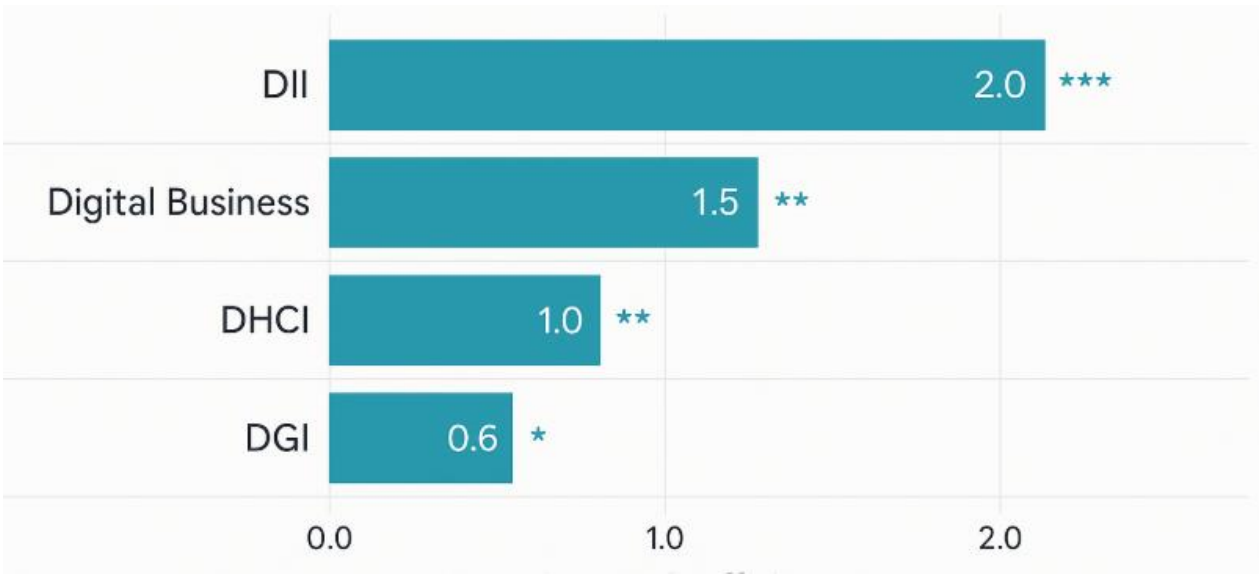
[Figure 2: Predicted GRDP Growth Rates by DTI Levels]



Source: Authors' calculations based on FE estimation results

Figure 2 illustrates predicted GRDP growth rates across DTI ranges, demonstrating positive linear relationship with steepening slope at higher DTI levels, suggesting potential complementarities and increasing returns as digital ecosystem matures.

[Figure 3: Digital Transformation Dimensions - Comparative Impact]



=: Fixed Effects estimates (***p<0.01, **p<0.05)

Digital Transformation Index (DTI) : Predicted values from FE model with 95% confidence intervals

Source: Authors' estimations from Table 3

Figure 3 visualizes relative magnitudes of digital transformation dimensions, clearly identifying infrastructure and business as priority intervention areas.

Conclusion and Policy Recommendations

Main Findings

This study provides rigorous empirical evidence on digital transformation's role in driving GRDP growth across Northern Vietnam's 25 provinces during 2015-2023. Several key findings emerge:

First, digital transformation exerts substantial positive effects on regional economic growth, with a one-unit DTI increase corresponding to 0.43-0.58 percentage points higher annual GRDP growth-comparable to traditional growth drivers. This effect remains robust across multiple specifications and estimation methods, confirming the digital-growth nexus in an emerging economy context.

Second, disaggregated analysis reveals significant heterogeneity across digital transformation dimensions. Digital infrastructure and digital business demonstrate the strongest impacts, followed by digital human capital and digital government. This dimensional variation suggests prioritized resource allocation can maximize growth returns while building foundations for sustained transformation.

Third, substantial regional differences exist between developed Red River Delta and less-developed Northern Mountainous areas. Digital transformation effects are significantly larger in developed provinces with stronger complementary capabilities, indicating absorptive capacity constraints in less-developed regions. This heterogeneity necessitates geography-specific policy approaches rather than uniform strategies.

Fourth, dynamic panel estimations reveal growth persistence and cumulative effects, suggesting digital transformation generates compounding benefits over time through learning, network externalities, and ecosystem development. This temporal dimension justifies sustained long-term commitment to digital economy development.

Policy Recommendations

Based on our findings, we propose the following evidence-based policy recommendations:

Prioritize Digital Infrastructure Investment with Geographic Targeting

Given digital infrastructure's dominant growth effects, continued expansion of broadband networks, 4G/5G coverage, and digital platforms should remain top priorities. However, infrastructure investment should be geographically targeted: developed provinces should focus on next-generation technologies (5G, fiber optics, data centers), while mountainous regions require foundational connectivity closing digital divides. Public-private partnerships can mobilize resources and leverage private sector efficiency.

Implement Comprehensive Business Digitalization Support Programs

Digital business adoption's strong effects warrant systematic support programs helping firms-especially SMEs-adopt digital technologies. Specific measures include: (a) subsidized e-commerce platform access and digital marketing training; (b) technology vouchers for website development and digital payment systems; (c) digital transformation consulting services; and (d) showcase programs highlighting successful digitalization cases. These initiatives should particularly target traditional sectors (agriculture, handicrafts, tourism) in mountainous areas.

Accelerate Digital Human Capital Development through Multi-Track Approach

Addressing human capital constraints requires comprehensive strategies: (a) integrate digital literacy into basic education curricula; (b) expand ICT-focused tertiary education and vocational training; (c) implement reskilling programs for workers in traditional sectors; (d) attract and retain digital talent through tax incentives and quality-of-life improvements; and (e) facilitate public-private partnerships in digital skills training. Northern Mountainous provinces may require additional scholarships and incentives to build local digital talent pools.

Strengthen Digital Government through Institutional Reforms

Maximizing digital government benefits requires complementary institutional changes: (a) establish interoperability standards for government systems; (b) develop comprehensive data governance frameworks balancing openness and privacy; (c) implement robust cybersecurity regulations; (d) create unified digital identity systems; and (e) reform administrative procedures to eliminate redundancies. Regular monitoring and impact evaluation should assess e-government effectiveness.

5. Design Differentiated Regional Digital Development Strategies

Regional heterogeneity demands tailored approaches:

- *Red River Delta:* Focus on advanced digitalization (AI, big data, IoT), innovation ecosystem development, digital industry clusters, and smart city initiatives. Leverage existing advantages to become regional digital economy hub.
- *Northern Mountainous:* Prioritize foundational investments-connectivity, basic digital literacy, business digitalization support, and e-commerce platforms for local products. Special programs addressing geographic and socioeconomic constraints. Tourism digitalization offers particular opportunities (Khuc et al., 2025; Nguyen et al., 2025).

Establish Cross-Regional Coordination Mechanisms

To prevent digital divides from widening, establish mechanisms facilitating knowledge transfer and resource sharing across regions: (a) twin-province programs pairing developed and developing areas; (b) regional digital transformation forums; (c) shared digital public goods (platforms, training materials, technical standards); and (d) performance-based transfers incentivizing inclusive digital development.

Adopt Long-Term, Adaptive Policy Frameworks

Given dynamic cumulative effects, digital transformation requires sustained long-term commitment with adaptive frameworks responding to technological changes and emerging challenges. Five-year digital economy strategies should include specific targets, regular monitoring, impact evaluation, and adjustment mechanisms. International cooperation and lesson-learning from successful cases (Estonia, Singapore, South Korea) should inform policy evolution (Tran & Le, 2024).

Limitations and Future Research Directions

Several limitations warrant acknowledgment. First, data constraints-particularly for emerging digital economy indicators-may introduce measurement error. Future research with more granular firm-level

or household-level data could provide deeper insights. Second, our analysis focuses on Northern Vietnam; extending to national coverage would enhance generalizability. Third, while we address endogeneity through System GMM, quasi-experimental designs (difference-in-differences exploiting policy variations) could strengthen causal identification.

Future research directions include: (1) examining mechanisms through which digital transformation affects growth-productivity channels, innovation pathways, sectoral restructuring; (2) investigating distributional impacts-whether digital transformation benefits all population segments equally or exacerbates inequalities; (3) analyzing optimal sequencing and complementarities across digital transformation dimensions; (4) exploring threshold effects and non-linearities in digital-growth relationships; and (5) conducting comparative studies across Southeast Asian economies to identify context-specific versus universal patterns.

Concluding Remarks

As Vietnam pursues ambitious digital economy targets-30% of GDP by 2030-understanding digital transformation's growth implications becomes increasingly critical for evidence-based policymaking. Our findings demonstrate that digital transformation represents a powerful lever for accelerating regional economic development in Northern Vietnam, with effects varying substantially across dimensions and contexts. Strategic, differentiated, and sustained digital investment can help Vietnam harness Fourth Industrial Revolution opportunities while ensuring inclusive development outcomes.

The digital transformation journey is not merely about technology adoption but requires comprehensive socio-economic transformation-building human capabilities, reforming institutions, fostering innovation ecosystems, and ensuring no region is left behind. As Northern Vietnam navigates this transition, the evidence and insights provided by this study can guide policymakers, development practitioners, and stakeholders in designing effective strategies that maximize digital economy benefits for sustainable and inclusive growth.

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