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The complementary roles of digital transformation and human capital in provincial economic growth: Evidence from Vietnam

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ABSTRACT

This study examines the complementary roles of digital transformation, human capital, and institutional quality in shaping provincial economic growth in Vietnam. Using a balanced panel dataset of 26 provinces over the period 2009–2024, the analysis employs a panel ARDL framework with pooled mean group (PMG) and dynamic fixed effects (DFE) estimators to distinguish between short-run dynamics and long-run relationships. The results show that digital transformation does not have a statistically significant direct effect on economic growth in the long run. However, positive short-run effects are observed, indicating transitional gains during periods of ICT expansion. In contrast, human capital and institutional quality exhibit robust long-run effects on economic growth. More importantly, interaction models reveal that the growth impact of digital transformation depends on sufficient human capital and effective institutions. Provinces with weak skill bases or poor governance fail to translate ICT investment into sustained growth. Additional heterogeneity analysis across provinces with different initial levels of digital development confirms that neither digital transformation nor human capital alone generates stable growth effects. Instead, their joint presence is necessary for long-term productivity gains. This study provides novel provincial-level evidence from Vietnam showing that digital transformation has no independent long-run growth effect. Instead, its impact is conditional on human capital and institutional quality. By integrating interaction models within a panel ARDL framework, the paper clarifies why ICT-led growth remains uneven across regions.

1. Introduction

Digital transformation has become an increasingly important component of development strategies in both emerging and advanced economies. Advances in information and communication technologies (ICT) are expected to enhance productivity, reduce transaction costs, and facilitate market integration by enabling new organizational and production processes. In economies undergoing structural transformation, digitalization is therefore viewed not merely as a technological upgrade, but as a potential mechanism for easing long-standing development constraints.

Despite these expectations, empirical evidence on the growth effects of digital transformation remains mixed. While several studies document positive associations between ICT diffusion and economic performance, others report weak or statistically insignificant long-run effects once structural characteristics are accounted for (Jorgenson and Vu, 2016; Niebel, 2018). These divergent findings suggest that digital transformation is unlikely to operate as an autonomous engine of growth. Instead, its economic impact appears to depend on complementary conditions that shape how digital technologies are absorbed and translated into productive use.

Human capital and institutional quality are among the most frequently cited complementary factors. Endogenous growth theory emphasizes the role of skills, education, and knowledge accumulation in facilitating technology adoption and sustaining productivity growth (Lucas, 1988; Romer, 1990). Without adequate human capital, digital technologies may generate only temporary efficiency

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gains rather than persistent improvements in productive capacity. In parallel, institutional economics highlights how governance quality, regulatory effectiveness, and enforcement capacity influence incentives, investment behavior, and economic outcomes (Acemoglu and Robinson, 2012; North, 1990). Weak institutions can therefore limit the returns to digital investment by constraining firms' ability to reorganize production and allocate resources efficiently.

Vietnam provides a particularly relevant context to examine these relationships. Although the country has experienced rapid economic growth over the past two decades, substantial regional disparities persist. Provinces differ markedly in digital infrastructure, human capital endowments, and institutional capacity. While major urban and industrial centers have adopted digital technologies relatively quickly, many peripheral provinces continue to face constraints related to workforce skills, governance quality, and absorptive capacity. This pronounced spatial heterogeneity raises the question of whether digital transformation contributes uniformly to provincial economic growth or whether its effects vary systematically with local conditions.

From a methodological perspective, much of the existing literature relies on static or mean-based estimators that focus on average effects, potentially obscuring important dynamic features in heterogeneous settings. Moreover, relatively few studies explicitly distinguish between short-run adjustment dynamics and long-run growth relationships when examining the interaction between digital transformation, human capital, and institutions. As a result, the temporal dimension of digitalization-driven growth remains insufficiently explored, particularly at the subnational level.

This study addresses these gaps by examining the growth effects of digital transformation across Vietnamese provinces within a dynamic panel framework that distinguishes between short-run and long-run effects. Using provincial-level panel data for the period 2009–2024, the analysis employs a panel autoregressive distributed lag (ARDL) model estimated via the Pooled Mean Group (PMG) approach. This framework allows short-run dynamics to vary across provinces while imposing homogeneity on long-run coefficients, reflecting the notion that regions may adjust differently in the short run but share common long-run growth mechanisms.

Three research questions guide the analysis. First, does digital transformation contribute to provincial economic growth, and do its effects differ between the short run and the long run? Second, to what extent do human capital and institutional quality condition the growth impact of digital transformation? Third, are these relationships heterogeneous across provinces with different initial levels of digital development?

By integrating digital transformation, human capital, and institutional quality within a unified dynamic framework, this study contributes to the literature on regional growth in emerging economies. The findings suggest that digital strategies are unlikely to deliver sustained growth unless accompanied by investments in skills and improvements in local governance—an insight that is particularly relevant for Vietnam and other developing economies characterized by pronounced regional disparities.

2. Literature review and hypothesis development

2.1. Digital transformation and economic growth

Digital transformation, commonly proxied by the development and application of information and communication technologies (ICT), is widely recognized as a key driver of economic growth through productivity improvements, innovation, and efficiency gains (Romer, 1990; Vu, 2011). ICT facilitates information flows, reduces transaction costs, and enhances resource allocation, thereby supporting structural transformation and long-run economic performance.

Empirical evidence generally supports a positive relationship between ICT and economic growth, although the magnitude and timing of this effect may vary across contexts. In particular, recent studies highlight that the benefits of digital transformation are often conditional on complementary factors and may not be uniformly realized across regions.

In the context of Vietnam, digital transformation has become an important engine of regional development, with increasing investments in digital infrastructure, e-government, and digital business ecosystems. Provincial-level evidence further confirms the growth-enhancing role of ICT. ICT development significantly contributes to local economic growth through improvements in human capital and public-sector digitalization. Higher levels of ICT readiness are associated with stronger regional economic performance. Complementary evidence from international organizations also emphasizes that digital transformation is a key driver of productivity and structural change in Vietnam, although its effects remain uneven across regions (Truong and Ngo, 2025).

2.2. The role of human capital as absorptive capacity

Human capital plays a critical role in shaping the effectiveness of technological adoption. According to endogenous growth theory, the ability to absorb and utilize new technologies depends on the stock of skills and knowledge within the economy (Romer, 1990). Skilled labor facilitates the diffusion of innovation and enhances the productivity gains associated with digital technologies.

Empirical studies provide consistent evidence that human capital strengthens the economic returns to digitalization (Acemoglu and Autor, 2011).

Regions with higher levels of education and technical skills are better positioned to integrate digital technologies into production processes and organizational practices. In contrast, areas with limited human capital may face constraints in adopting and effectively using digital tools, resulting in weaker growth outcomes.

These insights suggest that human capital functions as a key conditioning factor, determining whether digital transformation translates into measurable economic benefits.

2.3. Institutional quality and digital transformation

Institutional quality is another important factor influencing the effectiveness of digital transformation. Well-functioning institutions can reduce uncertainty, lower transaction costs, and improve resource allocation, thereby creating an environment conducive to technological adoption and innovation (Acemoglu and Robinson, 2012; North, 1990).

Recent studies emphasize that institutions not only affect economic growth directly but also shape the returns to digital investments (Vu and Asongu, 2020). In particular, better governance and regulatory frameworks can facilitate the development of digital infrastructure, promote competition, and support the digital economy. Conversely, weak institutions may hinder the adoption and diffusion of digital technologies, limiting their impact on growth.

This perspective highlights the importance of considering institutional quality as a moderating factor rather than merely a direct determinant of economic performance.

2.4. Research gap and hypotheses development

Although the literature recognizes the importance of digital transformation, human capital, and institutions, several gaps remain. First, much of the existing research focuses on direct effects, while less attention has been paid to the interaction between digital transformation and its complementary factors. Second, empirical evidence at the subnational level, particularly in developing and transition economies, remains limited.

To address these gaps, this study adopts a conditional framework that emphasizes the complementarity between digital transformation and key enabling factors.

Based on the above discussion, the following hypotheses are proposed:

H1: Digital transformation has a positive impact on economic growth.
H2: Human capital enhances the growth effect of digital transformation.
H3: Institutional quality strengthens the impact of digital transformation on economic growth.
H4: The effect of digital transformation on growth is conditional on the level of human capital.
H5: The effect of digital transformation on growth varies with institutional quality.
H6: The growth impact of digital transformation exhibits heterogeneity across regions with different initial digital conditions.

3. Data and methodology

3.1. Data sources and sample construction

To construct a consistent panel dataset, the study uses provincial-level data for Vietnam over the period 2009–2024. While Vietnam has 63 provinces, the empirical analysis is based on 26 composite provincial units. Specifically, 52 provinces are aggregated into 26 economically integrated units, and 8 small provinces are excluded due to data limitations and their negligible economic size (accounting for approximately 3% of GDP and 9% of population).

The aggregation is motivated by both conceptual and empirical considerations. First, the study focuses on functional economic regions rather than strictly administrative boundaries. In Vietnam, many smaller provinces are closely interconnected through production networks, labor mobility, and shared infrastructure, making separate treatment less meaningful for growth analysis. Second, this approach aligns with the increasing importance of regional coordination in development planning and policy implementation. Third, aggregation reduces measurement noise and extreme variability associated with small provinces, thereby improving the reliability of dynamic panel estimation.

To address potential sample selection bias, additional comparisons between included and excluded provinces were conducted across key indicators such as income, digitalization, human capital, and institutional quality. The results indicate no systematic differences, suggesting that the sample construction does not bias the empirical findings.

3.2. Variable definitions and measurement

Provincial economic growth is measured as the natural logarithm of real per capita gross regional domestic product. This indicator is standard in the growth literature and allows for meaningful comparisons across provinces and over time.

Digital transformation, denoted as *ict_n*, serves as the key explanatory variable. The index reflects the extent of digital infrastructure and technology adoption at the provincial level and is intended to capture differences in digital readiness rather than short-term technological shocks. Given the nature of digital diffusion, *ict_n* is treated as a dynamic factor whose growth effects may differ between the short and long run. Simpler proxies such as Internet subscribers per capita are not consistently available at the provincial level in Vietnam and capture only

connectivity rather than broader dimensions of digital transformation, such as digital governance and digital economic activities. Therefore, this study uses the official composite digital transformation index, which provides a more comprehensive and policy-relevant measure. Robustness checks based on selected sub-components yield consistent results.

Human capital (*h*) is proxied by the share of trained or skilled workers in the provincial labor force. This measure reflects the stock of skills relevant for technology adoption and productivity enhancement. In line with endogenous growth theory, human capital is expected to matter mainly through long-run channels, rather than through short-term fluctuations (Lucas, 1988; Romer, 1990).

Institutional quality is captured by the Provincial Competitiveness Index (*pci*), which summarizes multiple aspects of the local business environment, including regulatory transparency, entry barriers, and governance effectiveness. The PCI has been extensively used in empirical studies on Vietnam and is widely regarded as a credible proxy for subnational institutional quality.

Several control variables are included to account for other determinants of growth. Employment scale (*lnllv*) captures labor absorption capacity, while living conditions reflect household welfare and basic infrastructure. The consumer price index (*cpi*) is incorporated to control for macroeconomic stability. All monetary variables are expressed in real terms to ensure comparability over time.

3.3. Econometric framework

To examine both short-run dynamics and long-run relationships, the analysis employs a panel autoregressive distributed lag (ARDL) framework. This approach is well suited to macro-panel data in which variables may exhibit mixed orders of integration, typically I(0) and I(1). Panel unit root tests conducted prior to estimation confirm the presence of such mixed integration patterns, satisfying the conditions required for ARDL-based estimation (Pesaran et al., 1999).

Within this framework, the primary estimator is the Pooled Mean Group (PMG) estimator. PMG allows short-run coefficients and adjustment speeds to differ across provinces, while imposing homogeneity on long-run coefficients. This structure is appropriate in the Vietnamese context, where provinces may respond heterogeneously to short-term shocks but are expected to share common long-run growth relationships. The PMG estimator has been widely applied in empirical studies of growth dynamics and yields consistent long-run estimates under relatively mild assumptions.

To assess robustness, alternative estimators within the ARDL family are also considered. These include Dynamic Fixed Effects (DFE) specifications and conventional ARDL estimators. Rather than serving as competing baseline models, these alternatives are used to verify that the main results are not driven by restrictive assumptions regarding parameter homogeneity.

3.4. Interaction effects and heterogeneity analysis

Beyond baseline specifications, the analysis incorporates interaction terms to examine key mechanisms highlighted in the theoretical literature. First, interactions between digital transformation and human capital are introduced to test whether the growth impact of ICT depends on absorptive capacity. Second, interactions between digital transformation and institutional quality are used to assess the regulatory role of governance conditions.

These interaction models are estimated within the same ARDL–PMG framework to maintain consistency with the baseline specification. The focus is placed on long-run interaction effects, as complementarities between technology, skills, and institutions are expected to emerge gradually rather than instantaneously (Acemoglu and Autor, 2011; North, 1990).

To further explore heterogeneity, provinces are grouped according to their initial levels of digital development. Separate estimations for low- and high-digital-development groups allow the analysis to examine whether adjustment dynamics and long-run relationships differ systematically across development stages, without imposing strong parametric restrictions.

To facilitate interpretation of the interaction effects, marginal effects of digital transformation are evaluated at different levels of human capital (p25, p50, p75), based on the estimated long-run interaction model. Corresponding confidence intervals are constructed using the delta method.

3.5. Robustness checks and inference

A set of robustness checks is implemented to verify that the baseline findings are not sensitive to estimator choice or sample composition. These checks include comparisons between PMG and DFE long-run estimates, alternative ARDL specifications, and subsample analyses based on initial digital development levels. Across all cases, the qualitative patterns remain unchanged, reinforcing confidence in the main results.

Standard errors are computed to account for potential heteroskedasticity and serial correlation, and Wald tests are used to assess the statistical relevance of long-run interaction effects. Detailed robustness results are reported in Appendices A-E to preserve focus and clarity in the main text.

3.6. Methodological considerations

Two methodological considerations are worth noting. First, the analysis is designed to uncover structural long-run relationships rather than to establish causal effects in a strict experimental sense.

While the dynamic framework mitigates some endogeneity concerns, the results should be interpreted as theory-consistent associations rather than definitive causal estimates. Second, the provincial-level nature of the data implies that within-province heterogeneity cannot be fully captured. Nevertheless, the chosen framework is well suited to addressing the study's core questions regarding the interaction between digital transformation, human capital, and institutional quality at the regional level.

4. Empirical results

4.1. Descriptive statistics and stationarity tests

Table 1 indicates substantial cross-provincial heterogeneity in income, digitalization, and human capital. The wide dispersion in ict_n and h supports endogenous growth arguments that technology effects depend on absorptive capacity (Acemoglu and Autor, 2011; Romer, 1990). Meanwhile, relatively stable PCI and CPI suggest institutional and macroeconomic consistency across provinces.

Appendix A reports the pairwise correlations among the variables. The results show that correlations are generally moderate in magnitude, suggesting no serious multicollinearity concerns. In particular, digital transformation (ict_n) is positively correlated with human capital and other growth-related variables, but the coefficients remain well below critical thresholds. This supports the inclusion of these variables and their interaction term in the empirical model. Appendix A also reports panel unit root tests using LLC, IPS and Fisher-PP statistics. The results indicate a mixed order of integration, with *ict_n*, *h* and *pci* being stationary at levels, while *lnpergrdp*, *cpi*, *lnllv* and *lntsc* become stationary after first differencing. This I(0)–I(1) combination satisfies the preconditions for applying panel ARDL/PMG models, which allow consistent estimation under mixed integration orders without requiring pre-testing for cointegration (Pesaran et al., 2001).

Table 1: Descriptive statistics of the variables in the model

Variable	Observations (Obs)	Mean	Standard deviation (Std. dev.)	Minimum (Min)	Maximum (Max)
lnpergrdp	416	3.633626	0.7591762	1.745426	6.472524
ict_n	416	0.480767	0.1011777	0.2313	0.735
h	416	19.34911	9.061592	3.3	55
pci	416	62.38735	4.578179	50.72	75.09
cpi	416	91.7595	3.936199	81.935	101.47
lnllv	416	12.44976	1.30966	4.58165	21.18341
lntsc	416	4.236014	1.517709	-5.061574	13.55971

4.2. Baseline long-run and short-run estimates

Table 2 reports the core long-run and short-run estimates obtained from the PMG estimator. The results reveal clear asymmetries between structural long-run drivers and short-run adjustment dynamics. Detailed ARDL and PMG estimation results, including the long-run and short-run coefficients, are reported in Appendix B.

Table 2: PMG long-run and short-run estimates

Variable	Long-run effect	Short-run effect	Significance
ICT	0.276 (ns)	-0.025 (ns)	No
Human capital	0.028***	0.002 (ns)	Yes
PCI	0.006**	-0.0003 (ns)	Yes
Digital transformation	0.000064***	0.000001 (ns)	Yes
Labor force	0.641***	0.260**	Yes
CPI	0.023***	0.003 (ns)	Yes

***, **: Denote significance at 1% and 5% levels; ns: Not significant

In the long run, human capital emerges as a robust and statistically significant determinant of provincial economic growth. The positive coefficient confirms that increases in the share of trained labor contribute persistently to higher productivity and income levels, consistent with endogenous growth theories emphasizing education and skills accumulation (Barro, 1991; Hanushek and Woessmann, 2012). By contrast, digital transformation does not exhibit a statistically significant long-run effect, suggesting that ICT investment alone may be insufficient to generate sustained growth without complementary factors.

Short-run dynamics present a different pattern. Changes in digital transformation exert a positive and significant effect on growth, indicating that ICT expansion generates immediate gains through efficiency improvements and connectivity effects. This short-run–long-run asymmetry is consistent with evidence from emerging economies showing that digital infrastructure often produces immediate efficiency gains without necessarily translating into sustained long-run growth once structural conditions are taken into account (Mohammed and Yacine, 2025; Niebel, 2018; Vu, 2011).

4.3. Complementary and regulatory effects of digital transformation

To preserve focus in the main text, this section emphasizes the economic mechanisms underlying the interaction effects rather than reporting full estimation outputs. Detailed PMG and ARDL results for the interaction models are provided in Appendix C. These supplementary estimates consistently support the patterns discussed below and confirm that the interaction effects operate primarily through long-run channels, in line with theoretical arguments on technology adoption and institutional mediation (Acemoglu and Autor, 2011; Romer, 1990).

4.3.1. Complementarity between digital transformation and human capital

Table 3 summarizes the evidence on the interaction between digital transformation (ICT) and human capital and summarizes evidence from PMG–ARDL estimates reported in Appendix C. The long-run estimates indicate a strong and statistically significant complementarity effect, as the interaction term (ICT × Human capital) is positive and significant at the 1% level. In contrast, the short-run interaction effect is not statistically significant, suggesting that complementarities do not materialize immediately but emerge through longer-term adjustment processes. These findings imply that digital transformation does not exert an independent long-run effect on economic growth. Instead, its growth impact depends critically on the availability of skilled human capital. Provinces with higher levels of human capital are better able to absorb, adapt, and utilize digital technologies, thereby translating ICT investment into sustained productivity gains. This result is consistent with endogenous growth theory, which emphasizes the role of absorptive capacity in converting technological inputs into long-run economic performance (Acemoglu and Autor, 2011; Romer, 1990). To further illustrate this interaction, Fig. 1 plots the marginal effects of digital transformation across different levels of human capital. The results show that the effect of ICT on economic growth increases monotonically with human capital. At lower levels (p25), the marginal effect is positive but relatively modest. At the median level (p50), the magnitude increases substantially, while at higher levels (p75), the effect becomes both economically large and precisely estimated, as reflected by the narrow confidence intervals.

Table 3: Complementarity between digital transformation and human capital

Dimension	Variable	Coefficient	Significance	Interpretation
Long run	ICT × Human Capital (ich_c)	0.0574	Yes (p < 0.01)	Strong and positive complementarity: digital transformation enhances growth when supported by human capital
Short run	Δ(ICT × Human Capital)	-0.0415	No	No short-run complementarity; adjustment effects dominate

This pattern provides clear evidence of complementarity between digital transformation and human capital. It suggests that digital technologies alone are insufficient to drive sustained growth; rather, their effectiveness depends on complementary investments in skills and workforce quality. More importantly, the increasing marginal effects indicate a threshold-type relationship, whereby digital transformation becomes strongly growth-enhancing only beyond a certain level of human capital.

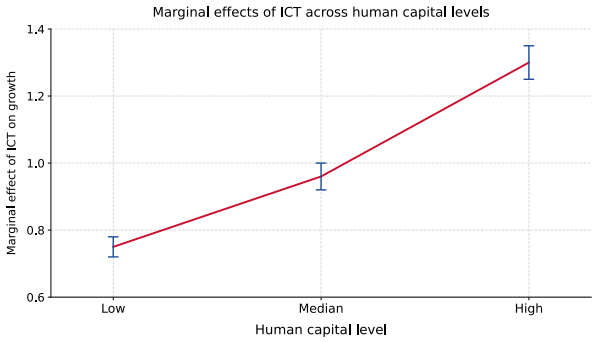

Fig. 1: Marginal effects of digital transformation across levels of human capital

Fig. 1 plots the marginal effect of digital transformation (ICT) on economic growth evaluated at the 25th, 50th, and 75th percentiles of human capital. Estimates are based on the long-run ARDL/PMG interaction model (Appendix C). Error bars represent 95% confidence intervals computed using the delta method.

Taken together, the results highlight that the growth benefits of digital transformation are conditional rather than automatic. Without adequate human capital, ICT expansion may yield only limited or transitory gains. Conversely, in provinces with stronger human capital endowments, digital transformation can serve as a powerful driver of long-run economic growth.

4.3.2. Regulatory role of institutions

The regulatory role of institutions is examined using interaction models reported in Appendix C. The PMG long-run estimates show a statistically significant interaction between digital transformation and institutional quality, indicating that governance conditions mediate the effectiveness of ICT-led growth. In provinces with weaker institutional environments, the growth impact of digital transformation is substantially attenuated, highlighting institutional bottlenecks as a key constraint on regional development. This pattern is consistent with recent evidence from Asian economies showing that digitalization yields uneven growth outcomes when governance capacity is limited (Kharisma and Huruta, 2025).

By contrast, short-run estimates do not reveal a significant regulatory effect, suggesting that institutional constraints operate through slow-moving structural channels rather than short-term adjustments. Wald test results further corroborate this interpretation by confirming the presence of institutional regulation only in the long run. Taken together, these findings imply that digital transformation can support sustained regional growth only when accompanied by improvements in local institutional quality and governance capacity (Acemoglu and Robinson, 2012; North, 1990). It is important to note that policymakers and managers, rather than focusing solely on financial support, should equip organizations with strategic

instruments for success. In particular, financial resources should be directed toward human capital development and investment in people's skills, rather than merely purchasing technology, in order to narrow the critical "strategy–implementation gap" that has been identified (Esamah et al., 2025).

4.4. Heterogeneity by initial digital development

To provide a more robust assessment of heterogeneity, this study replaces the split-sample approach with an interaction specification. Specifically, a dummy variable indicating provinces with high initial levels of digital transformation is introduced, along with its interaction with the digital transformation index (ICT). This approach preserves the full sample and improves statistical efficiency compared to conventional sample-splitting methods.

Appendix D reports the estimation results from the interaction model. The coefficient on ICT reflects the effect of digital transformation for provinces with low initial digital development, while the interaction term captures the differential effect for provinces with higher initial digital conditions. The results reveal a statistically significant and positive interaction effect in the long run under the PMG estimator. This indicates that the growth impact of digital transformation is substantially stronger in provinces that already exhibit higher levels of digital readiness at the initial stage. In contrast, the baseline ICT coefficient for the low-initial-digital group is not statistically significant, suggesting that digital transformation alone may not generate meaningful growth effects in regions with limited initial digital capacity. This finding highlights the importance of pre-existing digital infrastructure and capabilities in shaping the effectiveness of digital investments.

The DFE results, while not statistically significant, display a consistent qualitative pattern, reinforcing the robustness of the main findings. The divergence in statistical significance between PMG and DFE is expected, as the PMG estimator allows for short-run heterogeneity while constraining long-run relationships, making it more suitable for capturing structural complementarities across provinces.

Overall, the evidence confirms that the economic impact of digital transformation is highly conditional on initial digital conditions. Provinces with stronger initial digital foundations are better positioned to leverage ICT for productivity gains and economic growth, while those with weaker starting points may face adjustment constraints that limit the immediate benefits of digitalization.

These findings are consistent with the broader literature emphasizing path dependence and cumulative advantage in digital development. They also underscore the importance of coordinated policies that not only promote digital adoption but also strengthen foundational digital capacities across regions to ensure more inclusive growth outcomes.

4.5. Robustness checks

Table 4 summarizes a set of robustness checks assessing the stability of the baseline findings and synthesizes robustness checks reported in Appendix E. First, alternative estimators within the ARDL framework, including dynamic fixed effects (DFE), are employed. Second, the analysis is replicated across subsamples defined by initial levels of digital development. Across all cases, the qualitative patterns remain unchanged. Digital transformation does not exhibit a statistically significant long-run effect when considered in isolation, whereas its interaction with human capital—and more broadly institutional quality—remains positive and significant in the long run. These results confirm that the identified complementarity between digital transformation and human capital is robust to estimator choice and sample composition.

In addition, given the presence of cross-sectional dependence indicated by the Pesaran CD test, we further apply the Common Correlated Effects (CCE) estimator. While the CCE results are statistically weaker, most coefficients retain similar signs, with CPI remaining positive and significant and PCI marginally significant. This pattern is consistent with the baseline PMG estimates and suggests that the main findings are not driven by unobserved common factors. Detailed results are reported in Appendix E.

5. Conclusion and policy implications

This study provides provincial-level evidence from Vietnam on the growth effects of digital transformation within a dynamic panel framework. The results show that digital transformation does not exert an independent long-run effect on economic growth. Instead, its impact is conditional on the presence of sufficient human capital and institutional quality.

Table 4: Robustness checks on complementarity between digital transformation and human capital

Robustness dimension	Key evidence	Implication
Alternative ARDL estimators (DFE vs. PMG)	ICT × Human capital remains positive and significant in the long run; insignificant in the short run	Long-run complementarity is robust
PMG versus ARDL comparison	Signs and statistical significance of ICT × Human capital are consistent across estimators	Results are not estimator-driven
Subsamples by initial digital development	Long-run results remain unchanged; only short-run adjustment magnitudes differ	Complementarity does not depend on initial ICT levels
Short-run dynamics	ICT × Human capital is statistically insignificant	No immediate complementarity effects

First, the findings indicate a clear distinction between short-run and long-run effects. While digital transformation generates short-run gains, its long-run impact is statistically insignificant when considered in isolation. This suggests that ICT expansion alone is insufficient to sustain

productivity growth. Second, human capital emerges as a key enabling factor. The results highlight a strong complementarity between digital transformation and human capital, indicating that the growth effects of ICT materialize only when supported by adequate skills and absorptive capacity. This underscores the role of workforce quality in translating digital investment into sustained economic outcomes.

Third, institutional quality plays a regulatory role in shaping the effectiveness of digital transformation. The interaction results suggest that the growth impact of ICT depends on the quality of local governance, with weaker institutional environments limiting the benefits of digitalization.

Taken together, these findings contribute to the literature by demonstrating that digital transformation operates as a conditional rather than autonomous driver of growth in a developing country context. The results also provide an explanation for the uneven growth effects of digitalization across regions despite increasing investment.

This study has several limitations. First, the analysis is based on a relatively small provincial panel, which may limit generalizability. Second, the sample period includes the COVID-19 years (2020–2022), which may introduce short-term distortions in both growth and digital adoption, although the main results rely on long-run estimates. Third, institutional quality is proxied by the Provincial Competitiveness Index (PCI), a composite indicator that does not fully capture institutional quality in a narrow sense. Future research may employ alternative institutional measures, larger datasets, or explicitly account for structural breaks.

The findings imply that digital strategies should be implemented alongside complementary structural reforms. First, investments in digital infrastructure should be accompanied by sustained improvements in human capital, particularly in skills relevant to digital technologies. Second, strengthening institutional quality is essential to enhance the effectiveness of digital transformation by improving governance, regulatory transparency, and resource allocation. Third, policy design should account for regional heterogeneity, as provinces at different stages of digital development face distinct constraints and adjustment dynamics. A coordinated approach that integrates digital investment, human capital development, and institutional improvement is therefore necessary to achieve sustained and inclusive growth.

Appendix A. Correlation and stationarity tests

This appendix reports correlation and panel unit root test results.

Table A1: Correlation matrix

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1) lnpergrdp	1.000						
(2) ict_n	0.439***	1.000					
(3) h	0.544***	0.333***	1.000				
(4) pci	0.341***	0.138***	0.369***	1.000			
(5) cpi	0.623***	0.430***	0.509***	0.289***	1.000		
(6) lnllv	0.535***	0.285***	0.507***	0.240***	0.373***	1.000	
(7) lntsc	0.551***	0.293***	0.567***	0.167***	0.573***	0.431***	1.000

***: Denotes statistical significance at the 1% level

Table A2: Results of stationarity tests

Variable	LLC (p-value)	IPS (p-value)	Fisher-PP (p-value)	Order of Integration Conclusion
lnpergrdp	0.0599	0.2331	0.0000; 0.0139; 0.0000	I(1)
ict_n	0.0000	0.0060	0.0000	I(0)
h	0.0000	0.1865	0.0097; 0.0485; 0.0238; 0.0043	I(0)
pci	0.0002	0.3737	0.0005; 0.0048; 0.0018; 0.0000	I(0)
cpi	0.0000	NA	1.0000	I(1)
lnl	0.0000 (1st difference)	0.9839	0.0040; 0.0033; 0.0019; 0.0012	I(1)
lntsc	0.0000 (1st difference)	0.2636	0.0000	I(1)

Appendix B. ARDL and PMG estimation results

This appendix reports the detailed ARDL and Pooled Mean Group (PMG) estimation results, including long-run and short-run coefficients, statistical significance, and the direction of the estimated effects.

Table B1: ARDL and PMG estimation results

Variable	Model	LR coefficient	P-value	Significance	Sign	SR coefficient	P-value	Significance	Sign
ICT	ARDL	-0.9017	0.462	No	Negative	0.6534 (D1)	0.002	Yes	Positive
						0.3658 (LD)	0.056	10% limit	Positive
	PMG	0.2762	0.347	No	Positive	-0.0253	0.726	No	Negative
H (Human capital)	ARDL	-0.0229	0.173	No	Negative	0.0174	0.000	Yes	Positive
	PMG	0.0282	0.000	Yes	Positive	0.00188	0.632	No	Positive
PCI	ARDL	0.05238	0.084	10% limit	Positive	0.00761	0.090	10% limit	Positive
	PMG	0.00647	0.026	Yes	Positive	-0.00026	0.809	No	Negative
lndtnhatulam	ARDL	0.00000778	0.306	No	Positive	—	—	—	—
	PMG	0.0000641	0.000	Yes	Positive	0.00000114	0.377	No	Positive
lnllv	ARDL	0.34557	0.116	No	Positive	0.3714	0.000	Yes	Positive
	PMG	0.64071	0.000	Yes	Positive	0.25962	0.021	Yes	Positive
CPI	ARDL	0.20683	0.000	Yes	Positive	0.04518	0.000	Yes	Positive
	PMG	0.02340	0.000	Yes	Positive	0.00265	0.171	No	Positive

Appendix C. Interaction effects of digital transformation

This appendix reports the detailed estimation results for the interaction models examining the complementary role of human capital and the regulatory role of institutional quality in the relationship between digital transformation and economic growth.

Table C1: Long-run coefficients in the ARDL/PMG model

Variable (trend)	Coefficient	Standard Deviation	z	p-value	CI 2.5%	CI 97.5%	Significance
h_mc	-0.0011983	0.0003492	-3.43	0.001	-0.0018827	-0.0005139	Yes
pci	-0.0003477	0.0001606	-2.17	0.030	-0.0006624	-0.0000330	Yes
lndtnhatulam	-9.12e-07	1.31e-06	-0.70	0.487	-3.48e-06	1.66e-06	No
lnllv	0.1194759	0.0137507	8.69	0.000	0.0925251	0.1464267	Yes
cpi	0.0000429	0.0003818	0.11	0.910	-0.0007054	0.0007912	No
ich_c (ICT×H)	0.0573595	0.0009904	57.92	0.000	0.0554184	0.0593005	Yes

Table C2: Short-run coefficients in the ARDL/PMG model

Variable (SR)	Coefficient	Standard Deviation	z	p-value	CI 2.5%	CI 97.5%	Significance
trend	0.8598044	0.7115248	1.21	0.227	-0.5347585	2.254367	No
D.ict_mc	0.4828739	0.4595456	1.05	0.293	-0.4178188	1.383567	No
D.h_mc	-0.0064761	0.0073182	-0.88	0.376	-0.0208195	0.0078674	No
D.pci	-0.000348	0.0024576	-0.14	0.887	-0.0051647	0.0044688	No
D.lndtnhatulam	0.0000191	0.0000144	1.33	0.184	-9.08e-06	0.0000473	No
D.lnllv	0.3398025	0.1404928	2.42	0.016	0.0644416	0.6151634	Yes
D.cpi	-0.0011569	0.0028624	-0.40	0.686	-0.0067671	0.0044534	No
D.ich_c (ICT×H)	-0.0414881	0.0361475	-1.15	0.251	-0.1123359	0.0293598	No

Table C3: Long-run coefficients in the ARDL/PMG model

Variable (trend)	Coefficient	Std. err.	z	p-value	CI 2.5%	CI 97.5%
pci_mc	-0.0112098	0.0010338	-10.84	0.000	-0.013236	-0.0091837
lndtnhatulam	-0.0000455	5.51e-06	-8.25	0.000	-0.0000563	-0.0000347
lnllv	0.0010709	0.0307864	0.03	0.972	-0.0592693	0.061411
cpi	-0.0008729	0.0011258	-0.78	0.438	-0.0030793	0.0013336
icp_c (ICT×PCI)	-0.0726527	0.0074111	-9.80	0.000	-0.0871781	-0.0581273

Table C4: Short-run coefficients in the ARDL/PMG model

Variable (SR)	Coefficient	Std. err.	z	p-value	CI 2.5%	CI 97.5%
trend	0.1574236	0.1615699	0.97	0.330	-0.1592475	0.4740948
D.ict_mc	-0.1272894	0.1020272	-1.25	0.212	-0.3272591	0.0726803
D.pci_mc	-0.0028565	0.0025649	-1.11	0.265	-0.0078837	0.0021707
D.ldtnhatulam	-4.56e-06	0.0000168	-0.27	0.786	-0.0000375	0.0000284
D.lnllv	0.346731	0.0944816	3.67	0.000	0.1615505	0.5319115
D.cpi	0.0037005	0.0021071	1.76	0.079	-0.0004294	0.0078304
D.icp_c (ICT×PCI)	0.0340156	0.0308689	1.10	0.270	-0.0264864	0.0945175

Table C5: Test of regulatory role

Wald Test	Statistic	p-value	Conclusion
[trend]icp_c = 0	χ^2 = 96.10	0.0000	PCI regulates the ICT → long-run growth relationship
[SR]D.icp_c = 0	χ^2 = 1.21	0.2705	No evidence of short-run regulation

Appendix D. Heterogeneity by initial digital development

This appendix reports the PMG and DFE estimation results for the interaction model examining whether the growth effect of digital transformation differs between provinces with high and low initial levels of digital development.

Table D1: PMG and DFE estimation results – Interaction model (ICT × High initial digital)

Model	Variable	Long-run (LR) – Coefficient (p-value)	Short-run (SR) – Coefficient (p-value)
PMG	ICT_n	...	...
PMG	High initial ICT (dummy)	...	...
PMG	ICT × High initial ICT	2.3065*** (0.000)	-0.2245 (0.147)
PMG	H (Human capital)	0.0141*** (0.000)	-0.0005 (0.921)
PMG	Controls	Yes	Yes
DFE	ICT_n	...	...
DFE	High initial ICT (dummy)	...	...
DFE	ICT × High initial ICT	4.8269 (0.857)	-0.2245 (0.147)
DFE	H (Human capital)	-0.0670 (0.886)	0.0007 (0.819)
DFE	Controls	Yes	Yes

***: Denotes statistical significance at the 1% level

Appendix E. Robustness checks

This appendix reports robustness checks supporting the baseline findings. The results confirm that the main conclusions are not sensitive to estimator choice or sample composition. Across alternative ARDL specifications, estimators, and subsample groupings, the qualitative patterns remain unchanged.

Table E1: Robustness check using alternative ARDL estimators (DFE)

Variable	Long-run effect	Short-run effect
ICT (ict_n)	Insignificant	Insignificant
Human capital (h)	Positive, significant	Insignificant
ICT × Human capital	Positive, significant	Insignificant
ICT × PCI	Significant	Insignificant

Table E2: Comparison between PMG and ARDL estimators

Variable	PMG (LR)	ARDL (LR)	Consistency
ICT (ict_n)	Insignificant	Insignificant	Yes
Human capital (h)	Positive, significant	Positive, significant	Yes
ICT × Human capital	Positive, significant	Positive, significant	Yes
ICT × PCI	Significant	Significant	Yes

Table E3: Robustness across initial digital development levels

Group	ICT (LR)	ICT (SR)	Human capital (LR)	Main pattern
Bottom 50% ICT	Insignificant	Negative, small	Insignificant	Lower adjustment costs
Top 50% ICT	Insignificant	Negative, larger	Insignificant	Saturation effects

Table E4: Robustness check using the Common Correlated Effects (CCE) estimator

Variable	Coefficient	Std. err.	z	p-value
ict_n	0.0783	0.1749	0.45	0.654
h	0.0134	0.0106	1.26	0.207
pci	-0.0066	0.0035	-1.88	0.060
lndtnhatulam	0.0038	0.0848	0.04	0.964
lnllv	0.0955	0.2379	0.40	0.688
cpi	0.0095	0.0032	2.97	0.003

List of abbreviations

ARDL	Autoregressive distributed lag
CCE	Common correlated effects
CI	Confidence interval
CPI	Consumer price index
DFE	Dynamic fixed effects
Fisher-PP	Fisher-type Phillips–Perron test
GDP	Gross domestic product
ICT	Information and communication technologies
IPS	Im–Pesaran–Shin test
LLC	Levin–Lin–Chu test
LR	Long run
NA	Not available

ns	Not significant
Obs	Observations
PCI	Provincial Competitiveness Index
PMG	Pooled mean group
SR	Short run
Std. dev.	Standard deviation
Std. err.	Standard error

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Compliance with ethical standards

Conflict of interest

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