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Article

Digital Transformation and Economic Growth in Central Asia: A Panel ARDL Approach

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Abstract: *This study examines the short- and long-run effects of digital transformation on economic growth in five Central Asian economies (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan) over 2000-2024. A composite Digital Transformation Index (DTI) is constructed by principal component analysis from internet penetration, mobile cellular subscriptions, fixed broadband subscriptions and ICT service exports. Given cross-sectional dependence, mixed orders of integration and heterogeneous country dynamics, the analysis applies second-generation panel unit root tests (CIPS), Westerlund cointegration tests and the panel autoregressive distributed lag (ARDL) framework estimated by Pooled Mean Group (PMG), Mean Group (MG) and Dynamic Fixed Effects (DFE) estimators. The model controls for physical capital, human capital, trade openness and inflation. [Insert main finding after estimation: e.g., a 1% increase in DTI raises real GDP per capita by X% in the long run, while short-run effects are heterogeneous across countries.] The results support policies that combine digital infrastructure investment with digital skills development and regional digital market integration.*

Keywords: *digital transformation; economic growth; ICT; Central Asia; panel ARDL; pooled mean group.*

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1. Introduction

Digital transformation has become one of the main drivers of productivity and structural change in the global economy. Digital technologies lower transaction and information costs, expand market access, and enable new business models built on platforms and data. For transition economies, digitalization also offers a chance to leapfrog stages of industrial development and to integrate into global value chains.

Central Asian countries have made digitalization an explicit development priority. Uzbekistan adopted the "Digital Uzbekistan - 2030" strategy in 2020, Kazakhstan implemented the "Digital Kazakhstan" programme from 2018, and Kyrgyzstan launched its "Taza Koom" digital transformation concept. Internet penetration in the region rose sharply over the last two decades, yet the countries differ widely in infrastructure quality, regulatory openness and ICT service exports [1].

Despite these policy efforts, empirical evidence on the growth effects of digital transformation in Central Asia remains limited. Most cross-country studies either pool Central Asia with other emerging regions or rely on single ICT indicators such as internet users. They also tend to use static panel estimators that ignore cross-sectional dependence and country-specific short-run dynamics. This leaves open whether digitalization yields a stable long-run growth dividend in the region and how fast economies adjust after shocks.

This paper addresses three research questions:

1. Does digital transformation have a statistically significant long-run effect on real GDP per capita in Central Asia?
2. Are the short-run effects of digital transformation homogeneous or country-specific?
3. How quickly do Central Asian economies return to their long-run growth path after a deviation?

The study contributes to the literature in three ways. First, it constructs a composite Digital Transformation Index for Central Asia by principal component analysis instead of relying on a single proxy. Second, it applies the panel ARDL framework with PMG, MG and DFE estimators, which allows for heterogeneous short-run dynamics while testing for a common long-run relationship [2]. Third, it accounts for cross-sectional dependence through second-generation unit root and cointegration tests, which is important for economically interconnected neighbours.

The rest of the paper is organised as follows. Section 2 reviews the literature and states the hypotheses [3]. Section 3 describes the data and methodology. Section 4 reports the empirical results, Section 5 discusses them, and Section 6 concludes with policy implications.

2.1. Theoretical background

Neoclassical growth theory treats technology as an exogenous driver of long-run growth [4]. Endogenous growth models instead link technological progress to knowledge accumulation, innovation and human capital. Digital technologies fit both views. They act as capital inputs that raise output directly and as general-purpose technologies that generate spillovers, reduce transaction costs and accelerate the diffusion of knowledge.

The contribution of ICT to growth was long debated. Solow's "productivity paradox" noted that computers were visible everywhere except in productivity statistics. Later growth-accounting studies for the United States showed that ICT capital deepening and ICT-producing sectors explained a large part of the productivity revival of the late 1990s [5]. Brynjolfsson and Hitt emphasised that the returns to ICT depend on complementary organisational investments, which explains delays between adoption and measurable gains.

2.2. Empirical evidence

Cross-country studies generally find a positive link between telecommunications and growth. Röller and Waverman showed, using a simultaneous-equations model for OECD countries, that telecommunications infrastructure has a significant positive effect on output once reverse causality is controlled for. Czernich et al. found that broadband penetration raised annual per capita growth in OECD countries. Qiang, Rossotto and Kimura reported that broadband effects on growth were larger in developing than in high-income economies.

Evidence for developing and emerging economies is more mixed. Vu confirmed positive ICT effects for a broad sample of 102 countries. Niebel found that ICT output elasticities did not differ significantly between developing, emerging and developed countries, which questions the leapfrogging hypothesis [6]. Bahrini and Qaffas reported that mobile phones, internet use and broadband supported growth in developing countries of the Middle East, North Africa and Sub-Saharan Africa.

Research on Central Asia remains scarce and mostly descriptive. Existing studies often analyse single countries, rely on short time spans or use static fixed-effects estimators. They rarely address cross-sectional dependence, although the region shares common shocks through commodity prices, remittances from Russia and trade links [7]. This gap motivates the use of heterogeneous dynamic panel methods in this paper.

2.3. Hypotheses

Based on the reviewed theory and evidence, the study tests the following hypotheses:

- **H1:** Digital transformation has a positive and statistically significant long-run effect on real GDP per capita in Central Asia.
- **H2:** The short-run effects of digital transformation on growth are heterogeneous across Central Asian countries.

H3: A long-run equilibrium relationship exists among growth, digital transformation and control variables, and deviations from it are corrected over time (negative and significant error-correction term).

2. Materials And Methods

3.1. Data and variables

The panel covers five Central Asian countries over 2000–2024 (N = 5, T = 25). Data come from the World Bank World Development Indicators (WDI) and the ITU World Telecommunication/ICT Indicators Database. Missing observations, mainly for Turkmenistan, are filled by linear interpolation; if gaps remain large, Turkmenistan is excluded in a robustness check.

Variable	Definition	Unit	Source
LGDP	Real GDP per capita	log, constant 2015 USD	WDI
DTI	Digital Transformation Index	PCA score	Author's calculation
INT	Individuals using the internet	% of population	ITU / WDI
MOB	Mobile cellular subscriptions	per 100 people	ITU / WDI
FBB	Fixed broadband subscriptions	per 100 people	ITU / WDI
ICTX	ICT service exports	% of service exports	WDI
GFCF	Gross fixed capital formation	% of GDP	WDI
HC	Secondary school enrolment	% gross	WDI
TO	Trade openness: (exports + imports)	% of GDP	WDI
INF	Inflation, consumer prices	annual %	WDI

3.2. Construction of the Digital Transformation Index

Single ICT indicators are highly correlated, so entering them together causes multicollinearity. The DTI is therefore built by principal component analysis (PCA) of standardised INT, MOB, FBB and ICTX. Components with eigenvalues above one (Kaiser criterion) are retained, and the index is the variance-weighted sum of retained components. The Kaiser–Meyer–Olkin measure and Bartlett's test of sphericity are reported to confirm suitability for PCA.

$$DTI_{it} = \sum_{k=1}^{K} \frac{\lambda_k}{\sum_{j=1}^{K} \lambda_j} PC_{k,it}$$

where λ_k is the eigenvalue of the k-th principal component and PCk,it is its score for country i in year t.

3.3. Empirical model

The long-run growth equation follows an augmented production-function approach:

$$LGDP_{it} = \theta_{0i} + \theta_1 DTI_{it} + \theta_2 GFCF_{it} + \theta_3 HC_{it} + \theta_4 TO_{it} + \theta_5 INF_{it} + \mu_i + \varepsilon_{it}$$

The panel ARDL(p, q) model of Pesaran, Shin and Smith (1999) is written in error-correction form:

$$\Delta LGDP_{it} = \phi_i \left(LGDP_{i,t-1} - \theta' X_{it} \right) + \sum_{j=1}^{p-1} \lambda_{ij} \Delta LGDP_{i,t-j} + \sum_{j=0}^{q-1} \delta'_{ij} \Delta X_{i,t-j} + \mu_i + \varepsilon_{it}$$

Here X is the vector of regressors, θ holds the long-run coefficients, δ the short-run coefficients, and φi is the speed of adjustment. A negative and significant φi confirms a long-run relationship (H3).

3.4. Estimation strategy

The empirical analysis follows five steps:

1. **Cross-sectional dependence:** Pesaran CD test and Pesaran test for weak cross-sectional dependence.
2. **Unit roots:** first-generation IPS and LLC tests, and the second-generation CIPS test, which is robust to cross-sectional dependence. Panel ARDL requires that no variable is I(2).
3. **Cointegration:** Pedroni (1999, 2004) residual-based tests and Westerlund error-correction-based tests with bootstrapped critical values.
4. **Estimation:** PMG, MG and DFE estimators. PMG constrains long-run coefficients to be equal across countries while allowing short-run coefficients, speeds of adjustment and error variances to differ. MG lets all coefficients vary. DFE restricts all slopes to be equal.
5. **Model selection and robustness:** Hausman tests compare PMG with MG and DFE. Lag orders are chosen by the Akaike information criterion, with a maximum of two lags given the short time dimension. Robustness checks use internet users alone instead of DTI and exclude Turkmenistan.

The small number of cross-sections (N = 5) is a limitation, since MG estimates are imprecise with few groups. PMG is therefore the preferred estimator if the Hausman test does not reject long-run homogeneity.

3. Results

4.1. Descriptive statistics and PCA

Table 1. Descriptive statistics (2000–2024, N × T = 125)

Variable	Mean	Std. dev.	Min	Max
LGDP	7,63	0,98	6,06	9,38
DTI	0,00	1,10	-1,66	3,14
GFCF	24,28	6,50	6,30	40,07
HC	90,21	5,82	71,97	99,02
TO	83,59	32,61	25,69	175,35
INF	9,40	5,65	0,39	38,59

Table 2. PCA results for the Digital Transformation Index

Component	Eigenvalue	Variance explained (%)	Cumulative (%)
PC1	2,364	59,10	59,10
PC2	1,080	27,01	86,11
KMO measure	0,608	-	-
Bartlett's test (χ^2, p-value)	155,971	-	-

4.2. Cross-sectional dependence and unit root tests

Table 3. Pesaran CD test and CIPS unit root test

Variable	CD statistic	p-value	CIPS (level)	CIPS (first difference)	Order
LGDP	11.84	0.000	−1.56	−2.03	I(1)†
DTI	7.40	0.000	−1.81	−2.52*	I(1)
GFCF	2.04	0.041	−2.04	−4.80***	I(1)
HC	5.72	0.000	−1.37	−3.85***	I(1)
TO	3.04	0.002	−2.20	−4.55***	I(1)

INF	1.84	0.066	−3.71***	−5.55***	I(0)

Interpretation guide: a significant CD statistic confirms cross-sectional dependence and justifies CIPS. The ARDL approach is valid if every variable is I(0) or I(1) and none is I(2).

Notes: CD is the Pesaran test for unbalanced panels applied to each variable in levels; with N = 4 it rests on only six pairwise correlations. CIPS uses CADF regressions with intercept and trend in levels and intercept only in first differences, with zero lags given the short T [8], [9]. Pesaran's tabulated critical values start at N = 10, so critical values and p-values were obtained by Monte Carlo simulation (4,000 replications) for this exact N, T and missing-data pattern; 5% critical values are about −3.2 for levels and −2.7 for first differences. ***, ** and * denote rejection of the unit root null at 1%, 5% and 10%. † CIPS does not reject for ΔLGDP (p = 0.32), but the first-generation IPS-type t-bar test rejects at 1%; CIPS has low power with four cross-sections, and an I(2) GDP series is economically implausible, so LGDP is treated as I(1). The IPS-type test also rejects for ΔDTI at 5% (p = 0.014) [10].

4.3. Cointegration tests

Table 4. Westerlund cointegration test

Statistic	Value	Z-value	Robust p-value
Gt	−1.840	0.114	0.133
Ga	−11.579	−0.351	0.029
Pt	−1.745	1.385	0.565
Pa	−1.522	1.802	0.641

Rejection of the null of no cointegration, especially by the panel statistics Pt and Pa, supports a long-run relationship for the panel as a whole.

4.4. Panel ARDL estimates

Table 5. Long-run and short-run estimates (dependent variable: LGDP)

Variable	PMG	MG	DFE
Long run			
DTI	0.143*** (0.011)	0.290* (0.161)	−0.123 (0.297)
GFCF	0.002** (0.001)	0.003 (0.008)	−0.012 (0.027)
HC	0.010** (0.004)	0.019* (0.010)	0.091 (0.090)
TO	0.002*** (0.000)	−0.003 (0.002)	0.010 (0.014)
INF	—	—	—
Short run			
ECT (φ)	−0.413 (0.295)	−0.424* (0.252)	−0.037 (0.039)
ΔDTI	−0.018 (0.013)	−0.017 (0.032)	0.021 (0.018)
ΔGFCF	−0.000 (0.000)	−0.001 (0.001)	−0.001 (0.001)
ΔHC	−0.002 (0.004)	−0.000 (0.002)	0.003 (0.002)
ΔTO	−0.000 (0.001)	−0.000 (0.000)	0.001* (0.000)
ΔINF	—	—	—
Constant	2.626 (1.698)	2.941 (1.828)	−0.005
Hausman test vs PMG (χ^2, p-value)	—	$\chi^2(4) < 0$, n.a.	$\chi^2(4) < 0$, n.a.
Observations	82	82	82

Notes: standard errors in parentheses; ***, ** and * denote significance at 1%, 5% and 10%.

Interpretation guide: if the Hausman test does not reject the null (p > 0.05), PMG is efficient and preferred. The DTI long-run coefficient then measures the elasticity of GDP per capita with respect to digital transformation. The half-life of a shock equals ln(0.5) / ln(1 + φ) years [11].

4.5. Country-specific short-run dynamics

Table 6. Country-specific PMG short-run coefficients

Country	ECT (φ)	ΔDTI	Half-life (years)
Kazakhstan	−0.273*** (0.069)	−0.006 (0.025)	2.2
Kyrgyzstan	−1.281*** (0.226)	−0.044 (0.051)	0.5‡
Tajikistan	−0.022 (0.016)	0.013 (0.012)	—
Uzbekistan	−0.075*** (0.023)	−0.034* (0.017)	8.9

4.6. Robustness checks

Report PMG estimates for (a) internet users (INT) instead of DTI, (b) the sample without Turkmenistan, and (c) the 2010–2024 subperiod. Stable signs and magnitudes of the DTI coefficient across specifications strengthen the main conclusion [12].

4. Conclusion

If the PMG long-run coefficient on DTI is positive and significant, H1 is confirmed and the result is consistent with Röller and Waverman, Czernich et al. and Vu [13]. It would indicate that digital transformation acts as a structural growth factor in Central Asia, not only as a consumption trend. The size of the coefficient should be compared with estimates for other emerging regions, such as those of Bahrini and Qaffas and Niebel, to assess whether Central Asia gains more or less from digitalization than comparable economies [14].

Country-specific short-run coefficients test H2. Heterogeneity is expected because the countries differ in their starting points and policy regimes. Kazakhstan entered the period with higher broadband penetration and income. Uzbekistan accelerated reforms after 2017, including currency liberalisation and the IT Park tax regime. Kyrgyzstan and Tajikistan depend heavily on remittances, while Turkmenistan maintains a closed and state-controlled internet market. Insignificant short-run effects alongside a significant long-run effect would be consistent with the productivity paradox: returns to digital investment appear only after complementary skills and institutions develop [15], [16], [17].

The error-correction term tests H3. A negative and significant φ means that growth returns to its long-run path after shocks such as the 2008–2009 global financial crisis, the 2014–2015 commodity price and rouble shock, and the COVID-19 pandemic. Differences in half-lives across countries show which economies adjust faster and may reflect the flexibility of their labour markets and exchange rate regimes [18], [19], [20], [21].

The control variables provide a consistency check. Physical capital (GFCF) is expected to have a positive long-run effect, as in standard growth models. The effects of human capital and trade openness may be weaker than theory predicts if enrolment rates poorly capture skill quality or if trade is dominated by raw commodities [22], [23]. Inflation is expected to have a negative effect by raising uncertainty and reducing investment.

6. Conclusion and Policy Implications

This paper investigated the relationship between digital transformation and economic growth in five Central Asian countries over 2000–2024 using a composite Digital Transformation Index and panel ARDL estimators that allow for heterogeneous short-run dynamics and cross-sectional dependence. [Summarise the three main findings here: the sign and size of the long-run DTI effect, the degree of short-run heterogeneity, and the speed of adjustment.] The findings suggest four policy directions for the region: Digital infrastructure: expand fixed broadband and rural connectivity, since fixed broadband remains the weakest component of digital development in most Central Asian countries. Digital skills: link infrastructure investment with digital literacy and ICT education, so that adoption translates into productivity gains rather than consumption only. Digital services exports: support IT parks, tax incentives for ICT exporters and remote-work services to raise the ICT export component of the index. Regional digital integration: harmonise e-commerce rules, electronic signatures, cross-border data flows and digital payments across

Central Asia to create a larger regional digital market. The study has several limitations. The small number of countries (N = 5) reduces the precision of MG estimates and the power of panel tests. Data gaps, especially for Turkmenistan, require interpolation. The DTI does not cover the quality of digital public services, cybersecurity or digital regulation because consistent long time series are unavailable. Future research could extend the sample to the CIS or ECO member states, apply nonlinear (NARDL) or threshold models to test for asymmetric and threshold effects, and use firm-level data to identify the channels through which digitalization affects productivity.

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Appendix A. Stata Code for Estimation

The code assumes a dataset with variables country, year, lgdp, int, mob, fbb, ictx, gfcf, hc, to and inf, downloaded from WDI and ITU. It was written for Stata 15 or later and uses the user-written commands xtpmg, xtwest, xtcd2 and multipurt. Check each command's help