

“Digital infrastructure and the efficiency, productivity and stability of banking sectors in transition economies”

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DIGITAL INFRASTRUCTURE AND THE EFFICIENCY, PRODUCTIVITY AND STABILITY OF BANKING SECTORS IN TRANSITION ECONOMIES

Abstract

Between 2005 and 2024, the digital divide separating former Soviet economies outside the EU from EU member states shrank from 44.8 to 2.4 points of a composite 0–100 index, and whether banking systems converted this catch-up into better performance is an open question. The paper evaluates the intermediation efficiency and productivity of banking in 24 transition economies during 2010–2024 and quantifies their relationship with digital infrastructure, paying special attention to Armenia, Kazakhstan, and Ukraine. Efficiency is measured with input-oriented window DEA on deposit funding, operating costs, lending, and profitability; productivity with Malmquist indices; and digital infrastructure with a principal-component index of internet, mobile, and broadband penetration. The estimation relies on two-way fixed effects with Driscoll-Kraay and bootstrap inference on 356 country-year observations. Productivity is flat overall with a Malmquist mean of 0.995, yet technological change moves from below unity through 2015 to above unity in 2016–2023, a regime shift robust to the output set and the translation constant. Within countries, the index is unrelated to efficiency levels, productivity growth, cost efficiency, and stability outcomes; the baseline cost-to-income and credit-risk associations dissolve under country-specific trends and differencing. Cumulative productivity reaches 1.162 in Kazakhstan and 1.106 in Armenia by 2024, while Ukraine climbs back to 0.856. Frontier renewal after 2016, rather than a measurable dividend from connectivity, is the substantive finding, and expectations of direct efficiency or stability gains from digital infrastructure should remain modest, particularly in postwar Ukraine.

Keywords

data envelopment analysis, Malmquist index, technological change, cost-to-income ratio, non-performing loans, panel fixed effects, digitalization

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INTRODUCTION

Digital technologies have reshaped the production function of banking, and the transition economies of Central and Eastern Europe and the former Soviet Union have staged one of the fastest digital catch-ups on record. Between 2005 and 2024, the gap in a composite digital infrastructure index between EU members and the non-EU former Soviet economies narrowed from 44.8 to 2.4 points on a 0–100 scale. Whether this convergence has translated into more efficient and more resilient banking remains an open question. The literature offers optimistic assessments of technology-driven gains alongside warnings that the benefits arrive slowly and unevenly (Berger, 2003; Philippon, 2016; Vives, 2019).

The question carries particular weight in this region. Its banking sectors absorbed the global financial crisis of 2008–2009, the Kazakh banking distress of 2009–2012, the Ukrainian balance-sheet crisis of

2014–2017, and the full-scale war in Ukraine after 2022, while the use of digital financial services expanded rapidly (World Bank, 2025). Armenia, Kazakhstan, and Ukraine combine deep crisis episodes with rapid digital adoption and serve as the focus economies of the paper. For policymakers, the practical issue is whether digital infrastructure strengthens the efficiency and stability of banking or merely changes its delivery channels.

The literature on banking efficiency in transition economies concentrates on the pre-digital and early post-crisis periods, with bank-level studies documenting ownership and reform effects (Bonin et al., 2005; Fries & Taci, 2005; Grigorian & Manole, 2006). System-level evidence that reaches 2024 and treats efficiency, productivity, and stability within one framework remains scarce, and the war period has barely entered cross-country samples. This paper addresses the gap with a panel of 24 transition economies over 2005–2024. It relates a composite Digital Infrastructure Index built from internet, mobile, and broadband penetration to the efficiency, productivity, and stability of national banking sectors, with Armenia, Kazakhstan, and Ukraine as focus economies. Coverage through 2024 brings the war years into cross-country evidence and allows the study to test whether the rapid build-up of digital infrastructure has left a measurable imprint on bank intermediation.

1. LITERATURE REVIEW

Research on digital infrastructure treats connectivity as a general-purpose input whose effects extend well beyond any single industry (Krap et al., 2024). Broadband expansion has been linked to faster long-run growth in advanced economies (Czernich et al., 2011), and mobile money has produced durable reductions in poverty, with the strongest gains among female-headed households (Suri & Jack, 2016). Within Europe, digital readiness nevertheless remains uneven (Kolupaieva & Tiesheva, 2023; Valaskova et al., 2025), and asymmetries between and within countries persist despite overall convergence (Obelovska et al., 2025). A rapidly growing applied literature documents efficiency gains from digital technologies across sectors, including supply chains (Golubtsov et al., 2025), energy systems and their security (Vasa et al., 2024; Kuzior et al., 2025), healthcare delivery and access (Tossekbayev et al., 2025; Ndhlovu et al., 2026), municipal waste management (Kajda & Karwot, 2026) and the organization of work and consumption (Quisenberry & Burrell, 2026; Burrell et al., 2025). The payoff is not automatic, however, since the effectiveness of public health spending responds to digitalization along an inverted U (Hrytsenko et al., 2026). Whether banking reproduces this pattern of cost savings with uncertain wider effects is the question that organizes the sector-specific literature.

In banking, digital technologies operate through a supply-side reorganization of production and a

demand-side adoption process. On the supply side, financial technology redraws industry boundaries and intensifies competition from non-bank entrants (Gomber et al., 2017; Vives, 2019), while agenda-setting reviews connect digitization to operational efficiency and identify its enabling conditions (Bueno et al., 2024; Gherțescu et al., 2024). Digital personalization of products reduces the cost of servicing clients (Rysin et al., 2023), internal fintech and firm-level digital transformation raise profitability at the bank level (Berisha & Rayfield, 2025; He et al., 2025), and digital transformation reshapes access to finance for smaller firms under market disruption (Sartamorn et al., 2025). These gains appear double-edged, as fintech and artificial intelligence benefit European bank performance only within limits (Siminică et al., 2025). On the demand side, adoption depends on perceived usefulness, ease of use and self-efficacy (Hedau, 2025; Malaquias & Hwang, 2025), on trust in algorithmic advice and data-driven services (Piotrowski & Orzeszko, 2023; Khaddam & Alhanatleh, 2024), on satisfaction that converts digital wallet use into loyalty (Thi Nguyen et al., 2026) and on the quality of technology-mediated customer support (Glos & Karwot, 2025; Kostiushko et al., 2025), while infrastructure and affordability barriers still limit the expansion of digital bank services in developing systems (Kovalenko et al., 2026). Whether such effects are detected depends heavily on how efficiency itself is measured.

The measurement tradition rests on data envelopment analysis and its dynamic extensions.

Estimation under variable returns to scale separates managerial from scale inefficiency (Banker et al., 1984), window analysis stabilizes scores in small samples by pooling adjacent periods (Charnes et al., 1984), and Malmquist indices extend the framework to productivity through a decomposition into efficiency change and technical change, applied most directly to commercial banks and other deposit institutions (Skvarciany & Jurevičienė, 2024). Applications reach micro-finance under globalization (Kamarudin et al., 2023), insurance markets (Shmygol et al., 2024; K. Kumar & J. Kumar, 2024) and human capital (Yehorova & Drozd, 2024), and the approach anchors syntheses of efficiency and sustainability in banking (Krisciukaityte et al., 2023). Second-stage regressions of efficiency scores on covariates face serially correlated estimates that invalidate conventional inference, which motivates bootstrap procedures (Simar & Wilson, 2007) or, in macroeconomic panels, covariance estimators robust to cross-sectional and temporal dependence (Driscoll & Kraay, 1998). Two-stage designs have recently been combined with convergence analysis to trace how digital diffusion moves banks toward the frontier (Liu et al., 2024), and composite digitalization indices require explicit attention to weighting, aggregation, and robustness (Greco et al., 2019). Measurement choices matter most where efficiency interacts with risk.

A parallel literature ties efficiency to asset quality and stability. Intertemporal links between problem loans and cost efficiency run in both directions, reflecting bad management, bad luck, and deliberate skimping on monitoring (Berger & DeYoung, 1997), while margins and profitability respond to macroeconomic and institutional fundamentals (Demirgüç-Kunt & Huizinga, 1999) and risk-taking varies with ownership and governance under a given regulatory regime (Laeven & Levine, 2009). In Central, Eastern and South-Eastern Europe, non-performing loans respond to macroeconomic conditions and feed back into real activity (Klein, 2013), and regulatory ratios remain central determinants of bank stability (Mursalov et al., 2025). Financial access supports bank performance yet can raise operating expenses (Budhathoki et al., 2025; Kharabsheh, 2023), loan volumes and pricing depend on imperfect competition (Ray, 2026), systemic risk varies with business models and liquid-

ity dynamics (Szüle, 2023; Gondauri et al., 2025), the financial system conditions entrepreneurial development (Prokopenko et al., 2025), and digitalization of finance has been linked to a smaller shadow economy and stronger stability (Bozhenko et al., 2024). In transition economies, these interactions unfold under repeated crises and, most recently, war.

Evidence from Central and Eastern Europe and the former Soviet Union emphasizes structural heterogeneity and shock exposure. Comparative work documents persistent differences across Eastern European banking sectors (Tarasenko et al., 2022), and crisis episodes have produced a stream of studies on anti-crisis management in Ukrainian banking and on forecasting under the European energy shock (Vakhovych et al., 2023; Kuzior et al., 2023). The full-scale war reshaped this agenda. Digital transformation and remittances sustain inclusion under wartime conditions (Kolodiziev et al., 2024; Polishchuk et al., 2025), trade disruption and demographic losses threaten economic security and long-run potential (Tsymbal & Demediuk, 2025; Zahorodnia et al., 2026), credit instruments support agricultural enterprises only when combined with physical security (Pysarenko et al., 2026) and sustainability disclosure remains on the agenda of the largest Ukrainian banks (Antoniuk et al., 2025). A related institutional literature explains why digital investment translates into outcomes unevenly. E-government quality raises quality of life through service-oriented mechanisms (Vasylieva et al., 2026; Yarovenko et al., 2025), GovTech affects social progress non-linearly (Kuzior et al., 2026), digital governance curbs corruption and money laundering (Yefimenko et al., 2025; Lygina et al., 2026), and macro-policy channels such as government expenditure operate alongside these effects (Ahmed, 2025; Ivanenko & Muraviov, 2025). Governance erosion and leadership deficits obstruct institutional convergence (Ugulava, 2026; Kyzenko et al., 2026), institutional trust mediates the conversion of digital maturity into recovery (Topazly et al., 2026), and cyber vulnerability together with privacy risks acts as a brake on digital payoffs (Yarovenko et al., 2023; Wiczorek & Postrzednik-Lotko, 2025), while accumulated technical debt reframes legacy systems as an organizational risk (Thibodeau, 2026). Against this backdrop, what the literature has not yet delivered becomes visible.

Three limitations stand out. First, outcome margins are studied in isolation, with stochastic frontier work concentrating on cost or profit efficiency, envelopment studies on technical efficiency and convergence, and stability research on risk indicators, so whether digitalization moves all of these margins or only some has not been tested within one framework. Second, the evidence base consists mainly of bank-level data from single countries or of averages across advanced European samples, and comparative panels that treat the national banking systems of Central and Eastern Europe and the former Soviet Union as the unit of analysis are missing. Third, digitalization proxies range from bank-level technology spending to text-mined disclosure indices, which complicates comparison and favors a transparent index built from observable infrastructure. This study responds by examining efficiency levels, cost efficiency, productivity, and stability jointly for a panel of transition economies, with digital infrastructure captured by a composite index of internet, mobile, and broadband penetration. In sum, the literature indicates that digital technologies lower costs and reshape banking, that measured payoffs depend on method, aggregation and context, and that institutions condition the conversion of connectivity into performance. What remains open is whether these mechanisms leave a measurable imprint on the efficiency, productivity and stability of entire banking systems in transition economies.

2. METHODOLOGY

2.1. Data and sample

The analysis covers 24 transition economies of Central and Eastern Europe and the former Soviet Union over 2005–2024, a country-year grid of 480 cells (24 economies over 20 years) with unbalanced coverage across variables, comprising eleven EU members, twelve former Soviet economies and four Western Balkan countries, the Baltic states belonging to both of the first two groups. Armenia, Kazakhstan and Ukraine are the focus economies, and Appendix A lists all countries with group and focus markers. Serbia, Azerbaijan and Turkmenistan were screened out because their banking data are unavailable or start only in 2022.

Banking variables come from the IMF Financial Soundness Indicators for deposit takers and the IMF Financial Access Survey; the World Bank Global Financial Development Database adds the bank Z-score through 2021. Digital series are taken from the World Development Indicators, institutional quality from the Worldwide Governance Indicators (Kaufmann et al., 2011), government debt from the IMF Global Debt Database, and e-government indices from the UN E-Government Survey. Appendix B summarizes definitions, source codes, and coverage. The DEA estimation window is 2010–2024, the earliest span in which complete input and output data cover at least 23 of the 24 systems every year; the four missing cells are Latvia in 2010 and Tajikistan in 2022–2024, so the estimation sample holds 356 country-year observations. Complete banking data reach only 7 to 18 systems per year over 2005–2009, which is why no observation before 2010 enters any frontier and the pre-2010 years serve descriptive purposes only. Computations were performed in Python 3.12 with a fixed random seed of 42.

2.2. Measuring intermediation efficiency

Bank production follows the intermediation approach (Sealey & Lindley, 1977). Inputs are deposit funding in percent of GDP and the cost-to-income ratio; outputs are bank loans in percent of GDP and return on assets, so the scores capture how efficiently a system converts funding and operating costs into lending and profitability. Efficiency is estimated with the input-oriented BCC model under variable returns to scale (Charnes et al., 1978; Banker et al., 1984). For country i in year t , the score solves the program in Eq. (1),

$$\theta_{it}^* = \min \left\{ \begin{array}{l} \theta : X_t \lambda \leq \theta x_{it}, \\ Y_t \lambda \geq y_{it}, \\ 1' \lambda = 1, \quad \lambda \geq 0 \end{array} \right\}, \quad (1)$$

where x_{it} and y_{it} are the input and output vectors of the evaluated observation, X_t and Y_t are the input and output matrices of all observations forming the frontier, λ is the vector of intensity weights, the condition $1' \lambda = 1$ imposes variable returns to scale, and $\theta_{it}^* \in (0, ||1]$ equals one for frontier observations. Because the return on assets is negative in

several crisis years, the output side is translated by adding a constant of 13 percentage points to the ROA series, which leaves level scores unaffected under input orientation and variable returns to scale (Ali & Seiford, 1990). Within the 2010–2024 estimation sample, the minimum return on assets equals –12.47%, recorded by Ukraine in 2016, so the smallest translated output equals +0.53, and every output entering a frontier is strictly positive. Deeper losses of the global financial crisis, including the panel-wide minimum of –20.69% posted by Lithuania in 2009, precede the estimation window and enter no frontier. The input side requires no transformation because both inputs are strictly positive throughout the estimation sample; the in-sample minimum of the cost-to-income ratio is 27.78% (Estonia, 2011), while its single negative value in the assembled grid, –71.86% for Estonia in 2009, reflects the negative gross income of the Estonian system at the trough of the crisis and likewise lies outside the window. Baseline scores use pooled three-year window frontiers (Asmild et al., 2004), which enlarge each reference set to roughly seventy observations; annual frontiers on the same sample are retained for the Malmquist analysis.

2.3. Measuring productivity change

Productivity dynamics are summarized by the output-oriented Malmquist index computed on annual constant-returns frontiers (Färe et al., 1994) estimated on the same 2010–2024 sample, so the adjacent-year comparisons cover 2011–2024 and yield 332 country-year transitions. The Shephard output distance function of technology s is given in Eq. (2),

$$D_o^s(x, y) = \left(\max \left\{ \phi : X_s \lambda \leq x, \right. \right. \\ \left. \left. Y_s \lambda \geq \phi y, \lambda \geq 0 \right\} \right)^{-1}, \quad (2)$$

where ϕ is the maximal feasible proportional expansion of the output vector under technology s and $D_o^s \leq 1$ holds for observations inside the technology. The index between adjacent years, reported as MPI below, combines four evaluations of Eq. (2) across periods and technologies as shown in Eq. (3),

$$M_{t,t+1} = \left[\frac{D_o^t(x_{t+1}, y_{t+1})}{D_o^t(x_t, y_t)} \cdot \frac{D_o^{t+1}(x_{t+1}, y_{t+1})}{D_o^{t+1}(x_t, y_t)} \right]^{1/2}, \quad (3)$$

and decomposes multiplicatively into efficiency change and technological change following Eq. (4),

$$EC_{t,t+1} = \frac{D_o^{t+1}(x_{t+1}, y_{t+1})}{D_o^t(x_t, y_t)}, \quad (4)$$

$$TC_{t,t+1} = \left[\frac{D_o^t(x_{t+1}, y_{t+1})}{D_o^{t+1}(x_{t+1}, y_{t+1})} \cdot \frac{D_o^t(x_t, y_t)}{D_o^{t+1}(x_t, y_t)} \right]^{1/2},$$

where $EC_{t,t+1}$ measures movement toward or away from the contemporaneous frontier, $TC_{t,t+1}$ the shift of the frontier itself, and $(M_{t,t+1} = EC_{t,t+1} \times TC_{t,t+1})$, with values above one indicating improvement. Constant-returns distance functions are not translation invariant, so robustness adds a single-output variant excluding profitability and a doubled translation constant of 26 percentage points, leaving the window scores virtually unchanged (correlation 1.000). All aggregation uses geometric means.

2.4. Digital infrastructure index and econometric strategy

The explanatory variable of interest is a Digital Infrastructure Index, the first principal component of internet users, mobile cellular subscriptions, and fixed broadband subscriptions, each transformed with $\log(1 + x)$ and standardized before extraction. It explains 83.2% of the joint variance with balanced loadings (0.60, 0.54, and 0.59) and is rescaled to 0–100. A four-component variant adding secure internet servers explains 71.0% and serves as a robustness check. The second stage is the two-way fixed effects specification in Eq. (5),

$$EFF_{it} = \beta DII_{it} + \gamma' Z_{it} + \mu_i + \tau_t + \varepsilon_{it}, \quad (5)$$

where EFF_{it} is the window DEA score of country i in year t , DII_{it} is the digital infrastructure index, Z_{it} is a vector of controls covering government effectiveness, log GDP per capita, GDP growth, inflation, and trade openness, μ_i and τ_t are country and year effects, β and γ are the coefficients, and ε_{it} is the error term. With 24 clusters, inference relies primarily on Driscoll and Kraay (1998) standard errors robust to cross-sectional dependence, with country-clustered errors in

parallel. Robustness uses the fractional logit of Papke and Wooldridge (1996) for a dependent variable in the unit interval, and reverse causality is addressed with one-year lags. Fixed effects are retained after a Hausman test and a poolability F-test, and multicollinearity is checked with variance inflation factors on within-transformed data; Appendices B and C report the correlations. The same specification is applied to the cost-to-income ratio, return on assets, the log Malmquist index and its technological component, the NPL ratio and the Z-score, with the cost-to-income and NPL models re-estimated under country-specific trends, first differences and a one-year lead of the index. Expected signs were fixed before estimation, negative on cost-to-income and positive on productivity, which guards against specification search.

2.5. Inference for the second stage

Because the window scores estimate a jointly determined frontier, three procedures complement the Driscoll-Kraay inference of Eq. (5). First, the homogeneous smoothed bootstrap of Simar and Wilson (1998) runs window by window with 500 replications and returns bias-corrected scores that re-enter Eq. (5). Second, the truncated-regression bootstrap of Simar and Wilson (2007), Algorithm 1, models the reciprocal score in the pooled dimension with year effects and 1,000 parametric replications. Third, a country block bootstrap re-estimates the full two-stage procedure, frontiers included, in each of 240 replicates, so the interval for β carries the first-stage uncertainty. The regressions for the cost-to-income ratio, profitability, credit risk and the Z-score contain no DEA-generated variable and keep the baseline inference. Appendix D compares the procedures.

2.6. Limitations

The unit of analysis is the national banking system, so within-country heterogeneity across banks is not observed. The output set omits securities holdings and excess liquidity, which lowers the measured efficiency of EU systems that accumulated non-loan assets after 2015 and confines the scores to intermediation in the narrow sense. Output translation is innocuous for

the BCC levels but not for the constant-returns index, which is why the single-output variant accompanies all productivity results. The Ukrainian score of 2014 is inflated by the revaluation of foreign-currency loans after the devaluation. Data availability truncates Tajikistan and the Z-score after 2021, and the panel is unbalanced before 2010. With 24 countries, the asymptotics behind cluster-robust inference are demanding, and the focus-economy narrative stays descriptive because the estimates are not identified separately by country.

3. RESULTS

3.1. Descriptive statistics

Table 1 summarizes the variables over the DEA estimation sample of 356 country-year observations defined in subsection 3.1, so the descriptive statistics characterize exactly the data entering the frontiers and the second-stage regressions. Banking intermediation is moderate on average, with commercial bank deposits at 43.0% of GDP and loans at 41.6% of GDP, and both aggregates vary widely across the sample. Profitability is thin and volatile; the mean return on assets equals 1.40% with a standard deviation of 1.62 percentage points and an in-sample minimum of -12.47% recorded by Ukraine in 2016, at the trough of its 2014–2016 banking crisis, so the translated output series of subsection 3.2 stays strictly positive. Asset quality is similarly heterogeneous, since a median NPL ratio of 5.44% coexists with a maximum of 54.82% reached by Ukraine in 2017. Both inputs remain strictly positive throughout, with the cost-to-income ratio spanning 27.78% to 131.42%. The digital block displays the steepest gradients in the dataset, as internet penetration ranges from 11.6% to 94.3% of the population and fixed broadband from near zero to 39.7 subscriptions per 100 people. Figure 1, drawn on the full 2005–2024 grid for descriptive context, traces the average index by country group and shows a pronounced convergence, with the gap between EU members and the non-EU former Soviet economies narrowing from 44.8 points in 2005 to 2.4 points in 2024 and the Western Balkans closing their distance almost completely.

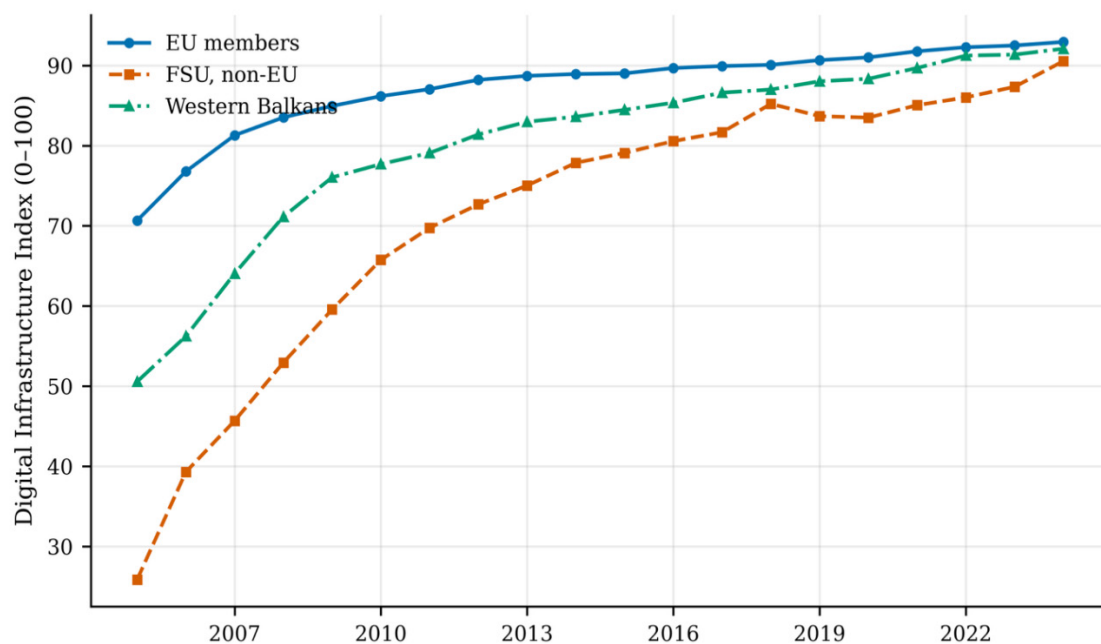
Table 1. Descriptive statistics of the variables, 24 transition economies, DEA estimation sample 2010–2024

Source: Authors' calculations based on IMF FSI and FAS, World Bank WDI, GFDD and WGI, and UN E-Government Survey data.

Group	Variable	N	Mean	SD	Min	Median	Max
Banking efficiency	Return on assets, %	356	1.40	1.62	-12.47	1.39	6.89
	Return on equity, %	356	9.42	13.38	-121.86	10.62	41.13
	Cost-to-income ratio, %	356	59.88	12.85	27.78	58.64	131.42
	NPL ratio, %	356	8.57	8.51	0.40	5.44	54.82
	Liquid assets to total assets, %	351	29.86	10.99	11.46	28.12	78.76
Intermediation (% GDP)	Capital adequacy ratio, %	94	19.68	4.36	14.05	18.65	36.01
	Bank deposits, % of GDP	356	43.01	16.18	8.89	41.52	79.42
	Bank loans, % of GDP	356	41.60	16.02	1.22	42.37	92.31
	Private credit (GFDD), % of GDP	284	43.12	16.58	9.35	46.16	92.77
Stability	Bank Z-score	286	10.97	5.42	-0.33	9.41	26.05
	Net interest margin, %	286	4.38	2.43	1.50	3.70	15.44
Digital infrastructure	Internet users, % of population	356	67.82	19.55	11.55	73.11	94.26
	Mobile subscriptions per 100 people	355	122.51	22.32	62.28	120.21	221.69
	Fixed broadband per 100 people	354	20.87	9.90	0.06	22.39	39.72
	Secure servers per 1 million people	356	11514.80	21890.42	0.07	966.99	139022.30
E-government (EGDI)	E-Government Development Index	189	0.67	0.13	0.34	0.68	0.97
	Telecommunication Infrastructure Index	189	0.57	0.22	0.06	0.58	0.97
	Online Service Index	189	0.61	0.20	0.06	0.63	1.00
	Human Capital Index	189	0.84	0.07	0.62	0.84	0.98
Institutions (WGI)	Government effectiveness (WGI)	356	0.12	0.64	-1.15	0.06	1.37
	Regulatory quality (WGI)	356	0.23	0.69	-1.58	0.29	1.61
	Rule of law (WGI)	356	0.03	0.69	-1.36	-0.07	1.52
	Control of corruption (WGI)	356	-0.09	0.71	-1.44	-0.13	1.67
Macro controls	GDP per capita, constant USD	356	9406.26	6355.11	770.60	7233.48	26134.63
	GDP growth, %	356	3.03	4.01	-28.76	3.31	13.93
	Inflation, %	350	5.19	6.59	-1.58	3.31	59.22
	Trade openness, % of GDP	356	111.32	35.23	29.19	105.77	204.06
	FDI inflows, % of GDP	356	4.27	8.37	-40.11	3.35	105.64
	Government debt, % of GDP	309	45.72	18.57	4.50	44.00	103.47

Note: Statistics are computed on the 356 country-year DEA estimation sample (2010–2024); N counts non-missing observations for each variable.

Source: Authors' calculations based on World Bank WDI data.

**Figure 1.** Digital Infrastructure Index by country group, 2005–2024 (sample means)

3.2. Efficiency of banking intermediation

Table 2 reports window DEA efficiency scores under variable returns to scale and input orientation. Pooling three-year windows improves discrimination substantially relative to annual frontiers, reducing the share of fully efficient observations from 26.4% to 13.2%, while the two sets of scores correlate at 0.944. The mean window score in the regression sample of 348 observations equals 0.772 with a minimum of 0.481, implying average proportional input savings of roughly 23% at unchanged lending and profitability.

Table 2. Window DEA efficiency scores by country and sub-period, 2010–2024

Source: Authors' estimates.

Country	2010–2014	2015–2019	2020–2024	Mean 2010–2024	EU	FSU
UZB	0.973	0.980	0.972	0.975	0	1
GEO	0.910	0.994	0.989	0.964	0	1
TJK	0.963	0.933	1.000	0.957	0	1
KAZ	0.977	0.934	0.941	0.950	0	1
EST	0.963	0.940	0.864	0.922	1	1
ARM	0.986	0.861	0.905	0.917	0	1
UKR	0.848	0.833	0.839	0.840	0	1
BGR	0.705	0.904	0.810	0.807	1	0
KGZ	0.942	0.689	0.728	0.786	0	1
CZE	0.684	0.855	0.769	0.769	1	0
LVA	0.944	0.735	0.619	0.753	1	1
SVK	0.639	0.779	0.773	0.730	1	0
BIH	0.731	0.754	0.701	0.729	0	0
HRV	0.660	0.757	0.764	0.727	1	0
BLR	0.895	0.625	0.656	0.725	0	1
LTU	0.796	0.761	0.608	0.722	1	1
ROU	0.764	0.710	0.668	0.714	1	0
SVN	0.832	0.621	0.666	0.706	1	0
MKD	0.571	0.756	0.789	0.705	0	0
POL	0.729	0.745	0.622	0.699	1	0
MDA	0.657	0.713	0.622	0.664	0	1
MNE	0.716	0.624	0.636	0.658	0	0
HUN	0.709	0.618	0.620	0.649	1	0
ALB	0.537	0.604	0.642	0.594	0	0

Note: Input-oriented BCC scores against pooled three-year window frontiers; 1.000 denotes a fully efficient observation. EU and FSU are membership indicators. Rows in bold denote the focus economies (Armenia, Kazakhstan, and Ukraine).

The ranking is led by Uzbekistan (0.975), Georgia (0.964), Tajikistan (0.957), and Kazakhstan (0.950), followed by Estonia (0.922) and Armenia (0.917), whereas Albania (0.594), Hungary (0.649), Montenegro (0.658), and Moldova (0.664) occupy the lower end. These scores capture the technical efficiency of converting deposit funding and operating costs into lending and profitability rather than the overall development of a banking system. Systems in which lending is large relative to the deposit base and interest margins remain wide therefore operate close to the frontier, while EU banking sectors that accumulated substantial excess liquidity and non-loan assets after 2015 appear less efficient under this metric. The sub-period pattern in Table 2 supports this reading, as scores decline between 2010–2014 and 2020–2024 in Estonia (0.963 to 0.864), Latvia (0.944 to 0.619), Lithuania (0.796 to 0.608) and Poland (0.729 to 0.622). Country ordering is robust to the exclusion of profitability from the output set, with a rank correlation of 0.982 between the baseline and the single-output specification. Ukraine averages 0.840 and follows a pronounced crisis path, falling to 0.652 in 2017 at the peak of the post-2014 balance-sheet clean-up and recovering to 0.923 in 2023 and 0.957 in 2024. The Ukrainian score of 1.000 in 2014 partly reflects the mechanical revaluation of foreign-currency loans after the devaluation and is interpreted with caution.

The three focus economies of this study, Armenia, Kazakhstan and Ukraine, all sit in the upper third of the ranking yet follow distinct paths. Kazakhstan averages 0.950 and combines a near-frontier position in 2010–2014 (0.977) with a moderate decline to 0.941 in 2020–2024. Armenia averages 0.917 and traces a pronounced U-shape, moving from 0.986 in 2010–2014 through 0.861 in 2015–2019 back to 0.905 in 2020–2024. Ukraine, whose crisis path is described above, remains the most volatile of the three and the only one whose sub-period means never exceed 0.85. Figure 2 plots the three focus economies against two EU benchmarks, with Kazakhstan and Armenia returning toward the frontier by 2024 (1.000 and 0.944), Ukraine following the path described above, and Estonia and Poland serving as reference cases.

Source: Authors' estimations.

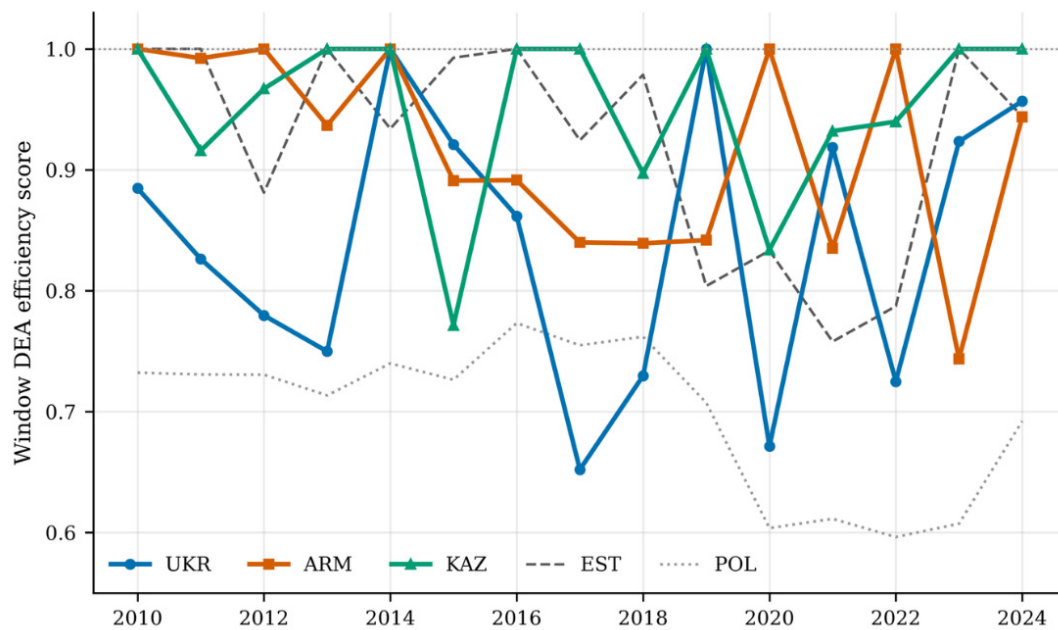


Figure 2. Window DEA efficiency scores, focus economies and EU benchmarks, 2010–2024

3.3. Productivity dynamics

Table 3 presents Malmquist productivity indices computed on annual constant-returns frontiers and decomposed into efficiency change and technological change. Over the full window, the geometric mean of the index equals 0.995, with efficiency change at 0.996 and technological change at 0.999, so aggregate productivity was essentially stagnant. The annual profile nevertheless reveals a clear regime shift. Technological change stays below unity in every year from 2011 to 2015 (0.974, 0.927, 0.980, 0.974 and 0.893), moves above unity in 2016 and remains there in every subsequent year through 2023, peaking at 1.076 in 2021 and 1.089 in 2023, while efficiency change oscillates around one throughout. Figure 3 visualizes the decomposition, with technological change crossing unity in 2016 and staying above it through 2023 while efficiency change fluctuates around one. Figure 4 compares cumulative productivity paths; all three focus economies suffered deeper mid-decade contractions than the sample average, after which Kazakhstan and Armenia end 2024 above their 2010 levels (1.162 and 1.106) while Ukraine recovers to 0.856 against 0.938 for the sample. Frontier renewal rather than catching up therefore accounts for the post-2016 recovery of productivity. This turning point coincides with the accelera-

tion of digital adoption in the region, although the country-level tests reported below do not corroborate a within-country link. Across countries, North Macedonia (1.024), Georgia (1.023) and Slovakia (1.019) record the strongest productivity growth, Latvia (0.958), Belarus (0.963), and Slovenia (0.969) the weakest, and the EU group posts a lower geometric mean than the non-EU group (0.989 against 1.000). Among the focus economies, Kazakhstan and Armenia record average productivity growth of 1.1% and 0.7% per year, respectively, driven in both cases by the technological component (1.011 in each country), whereas Ukraine posts a mild decline of 1.1% per year, in which positive efficiency change (1.003) does not offset the negative technology effect (0.986). The single-output variant that excludes profitability yields an overall index of 0.974, and its country ordering correlates with the baseline only moderately (Spearman 0.57), so cross-country rankings are sensitive to the output set. The regime shift is not, since the geometric mean of technological change rises from 0.949 over 2011–2015 to 1.029 over 2016–2024 in the baseline, from 0.950 to 1.026 under a doubled translation constant and from 0.903 to 1.027 in the single-output variant, while the window level scores are identical to numerical precision and the country ordering of the level scores is nearly invariant to the output set (Spearman 0.98).

Table 3. Malmquist productivity index and its decomposition by country, 2010–2024 (geometric means)

Source: Authors' estimates.

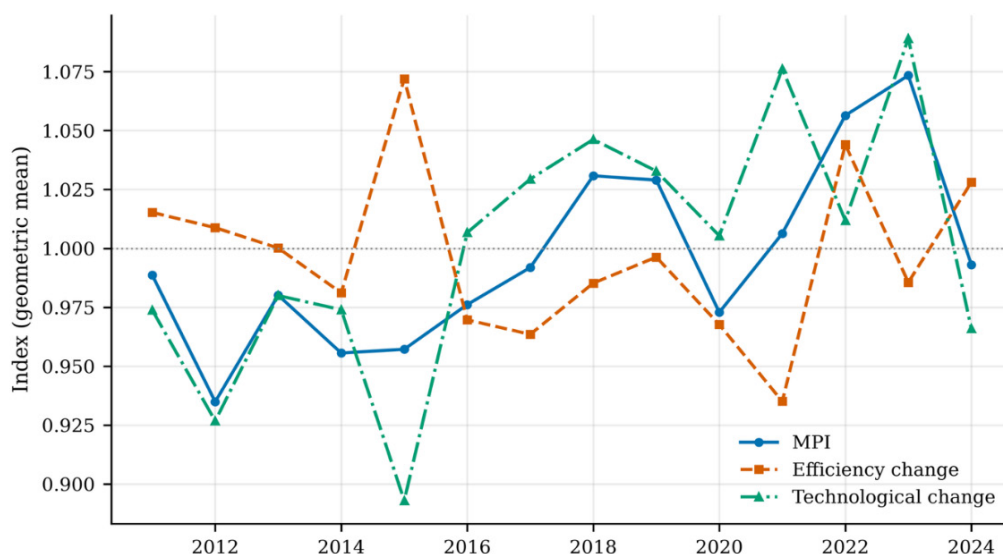
Country	MPI	EC	TC	MPI (single output)	EU	FSU
MKD	1.024	1.025	0.999	1.018	0	0
GEO	1.023	1.014	1.008	1.031	0	1
SVK	1.019	1.017	1.002	1.025	1	0
TJK	1.014	1.000	1.014	0.844	0	1
ALB	1.013	1.010	1.003	1.000	0	0
KAZ	1.011	1.000	1.011	0.963	0	1
UZB	1.008	1.004	1.003	1.046	0	1
ARM	1.007	0.996	1.011	1.010	0	1
HRV	1.002	1.001	1.001	0.981	1	0
MDA	1.002	0.998	1.004	0.975	0	1
ROU	0.998	1.001	0.998	0.958	1	0
BIH	0.997	1.000	0.997	0.988	0	0
BGR	0.996	0.997	0.998	0.977	1	0
HUN	0.994	0.998	0.996	0.962	1	0
CZE	0.993	1.000	0.994	0.998	1	0
POL	0.991	0.986	1.005	0.965	1	0
UKR	0.989	1.003	0.986	0.908	0	1
EST	0.986	0.993	0.993	0.981	1	1
KGZ	0.983	0.983	1.000	0.994	0	1
LTU	0.974	0.976	0.998	0.957	1	1
MNE	0.973	0.981	0.992	0.966	0	0
SVN	0.969	0.977	0.992	0.952	1	0
BLR	0.963	0.982	0.980	0.953	0	1
LVA	0.958	0.956	1.002	0.918	1	1

Note: Geometric means of year-to-year indices under constant returns to scale; values above one indicate improvement. MPI (single output) excludes profitability from the output set. Rows in bold denote the focus economies (Armenia, Kazakhstan and Ukraine).

3.4. Determinants of efficiency levels

Table 4 reports two-way fixed effects estimates of the determinants of window efficiency scores over 2010–2024 (348 observations, 24 countries). The digital infrastructure index is not associated with intermediation efficiency within countries. In the baseline specification, the coefficient equals 0.0010 with a Driscoll-Kraay standard error of 0.0016 ($p = 0.547$), and the estimate remains indistinguishable from zero when the index enters with a one-year lag, when internet penetration replaces the composite index, when the index is interacted with EU membership, and when the Ukrainian observations of 2014–2015 are excluded. The fractional logit estimator corroborates this conclusion, with an average marginal effect of 0.0002 per index point ($p = 0.972$). The estimator corrections of subsection 3.5 lead to the same conclusion. Subtracting the mean bootstrap bias of 0.076 from the scores turns the coefficient to -0.0040 with a cluster p -value of 0.233 and a country block bootstrap interval of $[-0.012, 0.003]$. The two-stage bootstrap that re-estimates the frontiers inside every replicate widens the standard error to 0.0041 against the Driscoll-Kraay 0.0016, so conventional panel inference understates the uncertainty of Eq. (5) by a factor of about 2.5, and the interval $[-0.006, 0.011]$ still covers zero. The truncated regression of Simar and Wilson (2007) returns 0.0102 on the reciprocal score with a bootstrap interval of $[0.002, 0.018]$; the estimate reflects the between-country

Source: Authors' estimates.

**Figure 3.** Malmquist productivity index and its components, annual geometric means, 2011–2024

Source: Authors' estimates.

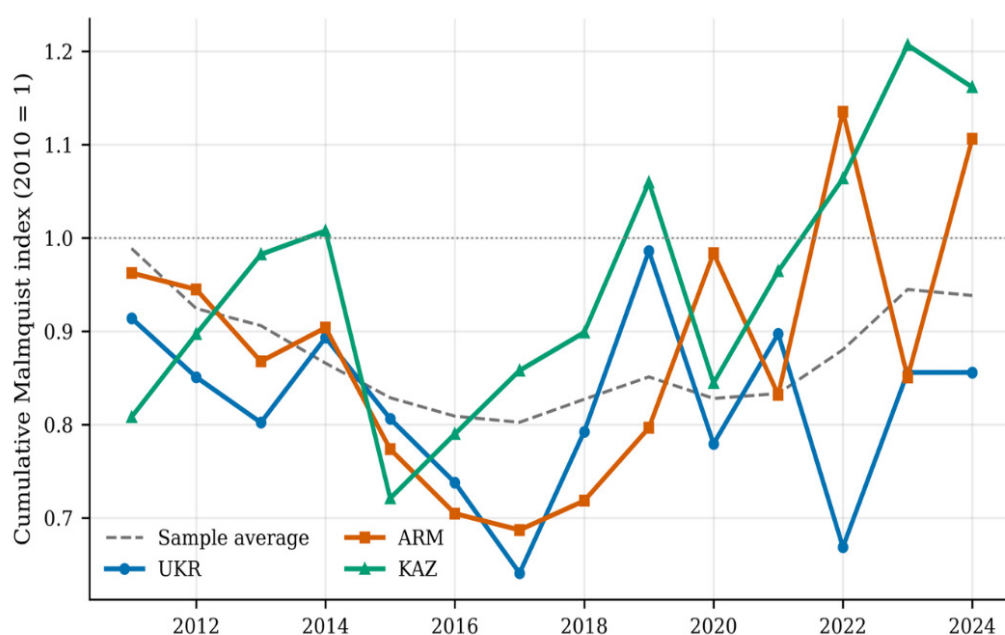


Figure 4. Cumulative Malmquist productivity index, focus economies and sample average (2010 = 1)

composition absent from Eq. (5) and, if anything, only inflation enters positively with p below 0.01 points away from efficiency gains. Appendix D (0.0027, $p = 0.005$), consistent with the mechanical widening of nominal margins during infla-

Table 4. Determinants of bank intermediation efficiency, two-way fixed effects estimates, 2010–2024

Source: Authors' estimates.

Variable	(1)	(2)	(3)	(4)	(5)	(6)
Digital Infrastructure Index	-0.000 (0.004)	0.001 (0.004)			0.001 (0.004)	0.001 (0.004)
DII (t-1)			0.000 (0.003)			
Internet users				-0.001 (0.002)		
DII × EU					0.002 (0.010)	
Government effectiveness		-0.049 (0.044)	-0.049 (0.044)	-0.049 (0.044)	-0.050 (0.044)	-0.049 (0.044)
ln GDP per capita		-0.032 (0.180)	-0.028 (0.179)	-0.018 (0.176)	-0.034 (0.184)	-0.056 (0.189)
GDP growth		0.002 (0.002)	0.002 (0.002)	0.002 (0.002)	0.002 (0.002)	0.003 (0.003)
Inflation		0.003** (0.001)	0.003** (0.001)	0.002** (0.001)	0.003** (0.001)	0.003** (0.001)
Trade openness		0.001 (0.001)	0.001 (0.001)	0.001 (0.001)	0.001 (0.001)	0.001 (0.001)
Country and year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	348	348	348	348	348	346
R ²	0.626	0.644	0.644	0.645	0.645	0.644

Note: The dependent variable is the window DEA score. Standard errors clustered by country in parentheses. Column (2) is the baseline; Driscoll-Kraay inference for column (2) is reported in the text. Column (6) excludes Ukraine in 2014–2015. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

tionary episodes. The within R-squared equals 0.012, so the covariates explain little of the within-country movement in scores. Multicollinearity is not a concern in the within dimension, since the largest variance inflation factor equals 1.29. The Hausman statistic equals 5.31 ($p = 0.505$) and does not reject random effects; fixed effects are retained as the conservative choice and are supported by the poolability F-test ($F = 11.64$, $p < 0.001$).

3.5. Channels and financial stability

Table 5 examines the channels through which digital infrastructure could operate, and the cost channel does not survive closer scrutiny of the time dynamics. The baseline association is negative, with a one-point increase in the index linked to a 0.410 percentage point lower cost-to-income ratio ($p = 0.047$ under Driscoll-Kraay and 0.070 under country-clustered errors). Three checks in Table 5 dissolve it. Country-specific linear trends flip the coefficient to 0.108 ($p = 0.850$), first differences give -0.395 ($p = 0.444$), and a placebo that replaces the index with its one-year lead returns

-0.499 ($p = 0.059$ clustered, 0.048 under Driscoll-Kraay), an estimate as large as the baseline, although future infrastructure cannot lower current costs. Country-specific linear trends absorb 90.9% of the within-country variance of the index, and panel unit-root diagnostics do not reject a unit root in the cost ratio in levels ($t\text{-bar} = -1.63$, $p = 0.28$) while rejecting it in first differences ($p < 0.001$), so the baseline estimate is attributed to trend confounding, mirroring the NPL association in Table 6. Profitability shows no comparable response (0.013, $p = 0.692$), and the lagged index does not predict either the Malmquist index or its technological component in any specification, with point estimates close to zero under country fixed effects and negative with p above 0.09 under two-way fixed effects (-0.0025 , $p = 0.098$ for the productivity index and -0.0026 , $p = 0.123$ for technological change).

Table 6 addresses financial stability. The baseline fixed effects estimate links the index positively to NPL ratios (0.550, $p = 0.002$), yet this association is fragile. Adding country-specific linear trends

Table 5. Channel regressions for cost efficiency, profitability and productivity

Source: Authors' estimates.

Dependent variable / specification	DII coefficient	Std. error	p-value	N
Cost-to-income ratio, baseline two-way FE	-0.410*	0.206	0.047	348
Cost-to-income ratio, FE with country trends	0.108	0.565	0.850	348
Cost-to-income ratio, first differences	-0.395	0.507	0.444	343
Cost-to-income ratio, one-year lead of DII (placebo)	-0.499	0.252	0.059	325
Return on assets	0.013	0.032	0.692	348
ln Malmquist index, country FE	-0.000	0.002	0.994	327
ln Malmquist index, two-way FE	-0.0025	0.0015	0.098	327
ln Technological change, country FE	-0.0003	0.0022	0.879	327
ln Technological change, two-way FE	-0.0026	0.0016	0.123	327

Note: Each row is a separate fixed effects regression with the full set of controls. The cost-to-income baseline reports Driscoll-Kraay inference (country-clustered $p = 0.070$); the trend, first-difference, and lead rows use country-clustered errors, and the lead row has $p = 0.048$ under Driscoll-Kraay. First differences include year effects; the lead row replaces the index with its value one year ahead. The productivity rows use the index lagged one year; remaining rows use country-clustered errors. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 6. Digital infrastructure and financial stability outcomes

Source: Authors' estimates.

Specification	DII coefficient	Std. error	p-value	N
NPL ratio, baseline two-way FE	0.550**	0.154	0.002	348
NPL ratio, FE with country trends	0.360	0.241	0.148	348
NPL ratio, first differences	-0.164	0.164	0.329	342
Bank Z-score, two-way FE	0.016	0.076	0.830	281

Note: Two-way fixed effects with the full set of controls; NPL rows use country-clustered errors, the Z-score row uses Driscoll-Kraay errors; the trend specification adds country-specific linear trends; first differences include year effects. NPL sample 2010–2024, Z-score sample 2010–2021. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

reduces the coefficient to 0.360 ($p = 0.148$), and the first-difference specification reverses the sign (-0.164 , $p = 0.329$), so the baseline estimate is attributed to trend confounding rather than a stable relationship. The bank Z-score is unrelated to the index (0.016 , $p = 0.830$, $N = 281$).

Taken together, the second-stage evidence yields no robust within-country association between digital infrastructure and efficiency levels, productivity growth, cost efficiency, or stability outcomes in this sample; the baseline cost-to-income and NPL associations dissolve identically once country-specific trends or differencing absorb the common drift of the series.

4. DISCUSSION

The estimated efficiency levels and productivity dynamics sit within the range reported for developing and transition systems. Comparable technical efficiency has been documented for banks in Pakistan (Liu et al., 2024), and envelopment studies of deposit institutions offer a similar benchmark of moderate efficiency with unstable productivity (Skvarciany & Jurevičienė, 2024). The turn of technical change from regress to progress after the mid-2010s is consistent with accelerating bank technology spending in Europe (Ayadi et al., 2025). Flatter aggregate dynamics than in micro evidence are plausibly an aggregation effect, since rapid catch-up by individual banks (Liu et al., 2024) averages out across national systems exposed to common shocks.

The dissolution of the cost association under country-specific trends and differencing separates this macro panel from micro evidence that financial technology lowers operating costs where digital channels replace physical networks, as found for Ethiopian banks (Ebissa & Lakew,

2025). It sits more comfortably with European bank-level results in which technology investment supports profit rather than cost efficiency and turns harmful beyond a threshold (Ayadi et al., 2025), and with findings that fintech and artificial intelligence cut both ways for performance (Siminică et al., 2025), a heterogeneity that plausibly averages toward zero at the system level. The proxy matters as well, since infrastructure penetration captures customer-side access rather than banks' own technology outlays, and a common drift in access and cost ratios is exactly what country-specific trends absorb. That neither the cost margin nor asset quality shows a robust link echoes the classic finding that cost efficiency and loan performance follow distinct processes (Berger & DeYoung, 1997).

The absence of measurable links to intermediation efficiency, productivity, and stability invites an institutional rather than technological reading. Digitalization of finance has been linked to a smaller shadow economy and, through it, to stronger stability (Bozhenko et al., 2024), suggesting that stability gains run through transaction formalization rather than connectivity itself. Evidence that digital maturity aids recovery mainly through institutional trust and government effectiveness rather than directly (Topazly et al., 2026) is consistent with the null results here, since these mediators vary widely across the sample. What the data do document is a frontier phenomenon: the shift of technological change above unity after 2016 that is robust to the output set and the translation constant, and its timing alongside regional digital acceleration remains an aggregate coincidence that the within-country tests do not elevate to a causal link. The comparisons therefore caution against reading connectivity as a self-standing driver of banking performance and point to institutions as the conditioning layer.

CONCLUSION

The aim of the study was to assess the intermediation efficiency and productivity of the banking sectors of 24 transition economies over 2010–2024 and to quantify their relationship with digital infrastructure, with particular attention to Armenia, Kazakhstan and Ukraine. Efficiency was measured by window DEA, productivity by Malmquist indices, and second-stage associations were estimated with two-way fixed effects under Driscoll-Kraay and bootstrap inference.

Three results summarize the evidence. The focus economies occupy the upper third of the efficiency ranking, with Kazakhstan at 0.950, Armenia at 0.917, and Ukraine at 0.840, and the ordering changes little when profitability is excluded from the output set. Aggregate productivity was flat at a Malmquist mean of 0.995, yet technological change stayed below unity through 2015 and above it in every year from 2016 to 2023, while digital infrastructure shows no robust within-country association with efficiency levels, productivity growth, cost efficiency, or stability once country-specific trends and differencing absorb the common drift of the series.

The conclusions go beyond these results. The convergence of connectivity has not by itself translated into measurable system-level gains for bank intermediation, so digital infrastructure is better understood as an enabling layer whose dividends are conditional on institutions and on banks' own technology adoption, which penetration proxies do not capture. The post-2016 turn of technological change indicates that the frontier of transition banking is being renewed, and the relevant margin for policy and management is sustaining that frontier movement rather than closing distance to a static benchmark. A methodological conclusion is that second-stage inference on DEA scores should carry first-stage uncertainty and absorb country-specific trends, since conventional panel errors understate the former and common drift can manufacture spurious channels.

For Ukraine, still below its 2010 productivity level, digital investment should accompany balance-sheet repair and the revival of lending rather than substitute for them; for Kazakhstan and Armenia, the task is to keep efficiency gains attached to a moving frontier. Extending the evidence to bank-level data and to direct measures of digital service adoption is a natural next step.

DATA AVAILABILITY STATEMENT

The study relies exclusively on publicly accessible databases. Banking soundness indicators for deposit takers come from the IMF Financial Soundness Indicators (International Monetary Fund, 2026b); outstanding deposits and loans of commercial banks from the IMF Financial Access Survey (International Monetary Fund, 2026a); the bank Z-score, private credit and net interest margin from the World Bank Global Financial Development Database, whose latest release extends through 2021 (World Bank, 2022); digital penetration series and macroeconomic controls from the World Development Indicators (World Bank, 2026a); institutional quality from the Worldwide Governance Indicators (World Bank, 2026b); general government debt from the IMF Global Debt Database (International Monetary Fund, 2026c); and e-government indices from the United Nations E-Government Survey (United Nations Department of Economic and Social Affairs, 2024). Indicator codes for all variables are listed in Appendix B.

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APPENDIX A

Table A1. Sample composition, group membership and focus economies

Source: Compiled by the authors.

Country	ISO3	EU	FSU	Focus economy
Albania	ALB	0	0	
Armenia	ARM	0	1	Yes
Belarus	BLR	0	1	
Bosnia and Herzegovina	BIH	0	0	
Bulgaria	BGR	1	0	
Croatia	HRV	1	0	
Czechia	CZE	1	0	
Estonia	EST	1	1	
Georgia	GEO	0	1	
Hungary	HUN	1	0	
Kazakhstan	KAZ	0	1	Yes
Kyrgyzstan	KGZ	0	1	
Latvia	LVA	1	1	
Lithuania	LTU	1	1	
Moldova	MDA	0	1	
Montenegro	MNE	0	0	
North Macedonia	MKD	0	0	
Poland	POL	1	0	
Romania	ROU	1	0	
Slovakia	SVK	1	0	
Slovenia	SVN	1	0	
Tajikistan	TJK	0	1	
Ukraine	UKR	0	1	Yes
Uzbekistan	UZB	0	1	

Note: EU and FSU are membership indicators; the Baltic states belong to both groups. Countries that are neither EU members nor former Soviet economies form the Western Balkans group. Rows in bold denote the focus economies.

APPENDIX B

Table B1. Variable definitions, sources and coverage

Source: Compiled by the authors.

Variable (units)	Source and code	Coverage
Return on assets, %	IMF FSI, ROA_CFSI_PT	2005–2024
Return on equity, %	IMF FSI, ROE_CFSI_PT	2005–2024
Cost-to-income ratio, %	IMF FSI, FSI107_CFSI_PT	2005–2024
NPL ratio, %	IMF FSI, AQ12_CFSI_PT	2005–2024
Liquid assets to total assets, %	IMF FSI, FSI283_LIQATTA_PT	2010–2024
Capital adequacy ratio, %	IMF FSI, FSI15_CFSI_PT	2005–2024
Bank deposits, % of GDP	IMF FAS, OUTD_COMBANK	2004–2024
Bank loans, % of GDP	IMF FAS, OUTL_COMBANK	2004–2024
Private credit, % of GDP	GFDD, GFDD.DI.01	2000–2021
Bank Z-score	GFDD, GFDD.SI.01	2000–2021
Net interest margin, %	GFDD, GFDD.EI.01	2000–2021
Internet users, % of population	WDI, IT.NET.USER.ZS	2000–2024
Mobile subscriptions per 100 people	WDI, IT.CEL.SETS.P2	2000–2024
Fixed broadband per 100 people	WDI, IT.NET.BBND.P2	2000–2024
Secure servers per 1 million people	WDI, IT.NET.SECR.P6	2010–2024
Digital Infrastructure Index (dii3)	PC1 of internet, mobile, broadband (log, z-score), scaled 0-100	2005–2024
Digital Infrastructure Index, 4 comp. (dii4)	PC1 of the three series plus servers	2010–2024
E-Government Development Index	UN EGDI	2003–2024, biennial
Telecommunication Infrastructure Index	UN EGDI, TII	2003–2024, biennial
Online Service Index	UN EGDI, OSI	2003–2024, biennial

Table B1 (cont.). Variable definitions, sources and coverage

Variable (units)	Source and code	Coverage
Human Capital Index	UN EGD, HCI	2003–2024, biennial
Government effectiveness	WGI, ge	2000–2024
Regulatory quality	WGI, rq	2000–2024
Rule of law	WGI, rl	2000–2024
Control of corruption	WGI, cc	2000–2024
GDP per capita, constant USD	WDI, NY.GDP.PCAP.KD	2000–2024
GDP growth, %	WDI, NY.GDP.MKTP.KD.ZG	2000–2024
Inflation, %	WDI, FP.CPI.TOTL.ZG	2000–2024
Trade openness, % of GDP	WDI, NE.TRD.GNFS.ZS	2000–2024
FDI inflows, % of GDP	WDI, BX.KLT.DINV.WD.GD.ZS	2000–2024
Government debt, % of GDP	IMF GDD, FL_S1311MIXED_POGDP_PT	2000–2024

Note: FSI codes refer to the deposit-taker sector (S12CFSI). The two-index rows are constructed by the authors as described in the Methodology section.

APPENDIX C

Table C1. Correlation matrix of the main variables, 2005–2024

Source: Authors' calculations.

Variables	roa	ci	npl	z	loans	dii3	int	ge	rq	rl	gdppc	gr	infl	tr	fdi
roa	1.000														
ci	−0.160	1.000													
npl	−0.248	0.145	1.000												
z	0.233	0.241	−0.095	1.000											
loans	−0.279	−0.230	−0.135	−0.327	1.000										
dii3	0.037	−0.188	−0.276	−0.152	0.454	1.000									
int	0.156	−0.209	−0.335	−0.106	0.308	0.887	1.000								
ge	−0.018	−0.273	−0.372	−0.245	0.470	0.624	0.629	1.000							
rq	−0.022	−0.375	−0.323	−0.218	0.512	0.529	0.482	0.897	1.000						
rl	−0.067	−0.284	−0.358	−0.286	0.538	0.579	0.551	0.930	0.930	1.000					
gdppc	−0.039	−0.223	−0.374	−0.279	0.448	0.549	0.598	0.866	0.739	0.856	1.000				
gr	0.370	0.079	−0.123	0.104	−0.294	−0.287	−0.243	−0.168	−0.149	−0.178	−0.143	1.000			
infl	0.052	0.084	0.074	−0.011	−0.188	−0.175	−0.163	−0.355	−0.388	−0.341	−0.219	0.013	1.000		
tr	−0.010	0.036	−0.260	0.035	0.335	0.382	0.409	0.523	0.495	0.533	0.600	−0.056	−0.012	1.000	
fdi	−0.015	0.017	−0.028	−0.079	0.081	−0.056	−0.120	0.042	0.105	0.066	−0.024	0.055	−0.006	0.070	1.000

Note: Pearson correlations, lower triangle. roa = roa; ci = cost_income; npl = npl; z = zscore; loans = loans_gdp; dii3 = dii3; int = internet; ge = wgi_ge; rq = wgi_rq; rl = wgi_rl; gdppc = gdp_pc; gr = gdp_growth; infl = inflation; tr = trade; fdi = fdi.

APPENDIX D

Table D1. Second-stage inference for the efficiency regression under the DEA-generated dependent variable

Source: Authors' estimations.

Procedure	Estimate	Uncertainty	p
Two-way FE on window scores, Driscoll-Kraay (Table 4, column 2)	0.0010	SE = 0.0016	0.547
Two-way FE on bias-corrected scores (Simar and Wilson, 1998; B = 500), country-clustered	−0.0040	SE = 0.0033	0.233
Country block bootstrap of the bias-corrected estimate (2,000 replications)	−0.0040	CI [−0.012, 0.003]	0.237
Truncated regression on the reciprocal score (Simar and Wilson, 2007; 1,000 replications)	0.0102	CI [0.002, 0.018]	0.008
Two-stage country block bootstrap, frontiers re-estimated in every replicate (240 replications)	0.0010	CI [−0.006, 0.011]	0.575

Note: Rows 1–3 and 5 report β on the digital infrastructure index in Eq. (5); row 4 reports γ on the reciprocal score $1/\theta$, positive values indicating lower efficiency. Row 4 is estimated in the pooled dimension with year effects, and its parametric bootstrap treats errors as independent, so the interval understates within-country dependence. All specifications include the control vector of Eq. (5). Replication counts in parentheses; random seed 42.