“Digital financial infrastructure and SME credit access: Systemic evidence across financial inclusion and economic growth channels”

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DIGITAL FINANCIAL INFRASTRUCTURE AND SME CREDIT ACCESS: SYSTEMIC EVIDENCE ACROSS FINANCIAL INCLUSION AND ECONOMIC GROWTH CHANNELS

Abstract

Digital financial infrastructure serves as a key structural correlate of small and medium enterprise (SME) credit availability and systemic financial development across post-Soviet transition economies. This study evaluates the empirical associations between technological connectivity, institutional policy readiness – specifically Digital ID and ISO 20022 standardization – and SME credit access (CreditLine) as the primary outcome of interest, alongside auxiliary supporting analyses of population-level financial inclusion (Ic_Y_norm) and macroeconomic output (lnGDPperCapita). Utilizing a panel dataset for 14 post-Soviet countries from 2011 to 2023 (N = 182) sourced from the World Bank WDI, Global Findex, and official central bank reports, the empirical framework relies on One-Way Country Fixed Effects (FE) specifications with Driscoll–Kraay robust standard errors to account for spatial and temporal dependence, supplemented by a Two-Way Fixed Effects (TWFE) sensitivity analysis. Mobile connectivity demonstrates a positive baseline association with SME credit availability, while internet penetration is identified as a primary empirical correlate of population-level financial inclusion across specifications. The protection of legal rights correlates with enhanced SME credit access, whereas strict AML/CFT compliance shows a strong negative association. Institutional messaging standardization via ISO 20022 exhibits heterogeneous structural differential associations: while positively correlating with SME credit access, it reflects a statistically significant negative association with broader population inclusion. Robustness estimations indicate that exogenous regional shocks (COVID-19, geopolitical conflicts, and energy crises) and macroeconomic slack (inflation, unemployment) correspond to systemic contractions in credit availability.

Keywords digitalization, infrastructure, inclusion, credit, finance, banking, payments, regulation, governance, macroeconomics

JEL Classification G21, O33, G28, C23

INTRODUCTION

According to reports from the World Bank Group and the International Finance Corporation (IFC, 2017), access to credit remains one of the most pressing barriers for small and medium enterprises worldwide. Traditional obstacles, such as high transaction costs, lack of collateral, and information asymmetries, continue to constrain SMEs, leaving a significant global financing gap estimated at USD 5.2 trillion annually. Digital financial services, including electronic invoicing, digital payments, and peer-to-peer lending, are increasingly seen as solutions to overcome these barriers by reducing costs and improving transparency. The COVID-19 pandemic further accelerated the adoption of digital platforms, demonstrating their resilience and importance in maintaining liquidity flows during economic crises.

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Data from the International Monetary Fund (IMF, 2023) demonstrate a significant global surge in digital financial transactions, with mobile money accounts and non-bank access growing at a faster rate than traditional bank deposits in emerging economies. This expansion has brought millions of unbanked individuals and micro, small, and medium enterprises into the formal financial system. Moreover, alternative finance and fintech lending, including marketplace platforms and digital credit tools, have reshaped credit markets in developing regions, particularly in Sub-Saharan Africa and Central Asia, underscoring the catalytic role of digital finance in underserved contexts.

The Survey on the Access to Finance of Enterprises, conducted by the European Central Bank (ECB, 2023), confirms that SMEs continue to face financing constraints driven by rising interest rates and high input costs. However, digital transformation is gradually improving these conditions: firms that adopt electronic payments and digital tools report better access to external financing and more favorable loan terms. While high borrowing costs remain a key hurdle, digital channels and alternative instruments, such as trade credit, digital leasing, and factoring, offer essential complementary avenues for enterprise liquidity.

The relevance of this topic for Ukraine, Kazakhstan, and Armenia lies in the fact that digital financial infrastructure is becoming a decisive factor in expanding SME access to credit. In Ukraine, digital tools are critical for post-war recovery, enhancing financial transparency, and integrating into the European financial space (NBU, 2023). In Kazakhstan, rapid growth in the fintech sector and high mobile network penetration create favorable conditions for diversifying credit sources despite banking sector concentration. In Armenia, digital infrastructure serves as a primary vehicle for economic modernization and trust-building, where financial inclusion has lagged, and credit access remains constrained by stringent collateral requirements. Thus, in all three countries, digital innovations provide a practical mechanism for strengthening economic resilience and supporting small business development.

This convergence of findings underscores that while digital finance is not a panacea, it is a necessary foundation for inclusive growth, resilience, and competitiveness of SMEs in both developing and developed contexts.

1. LITERATURE REVIEW

Academic discourse on digital financial infrastructure (DFI) and enterprise credit accessibility spans multiple interconnected dimensions, reflecting a shift from traditional financial intermediation to data-driven, technology-enabled ecosystems.

Fintech innovations closely correlate with broad economic development patterns, co-occurring with expanded capital access for small and medium-sized enterprises (SMEs) and reduced transaction costs (Ananzeh et al., 2025). In developed contexts like the EU, financial inclusion demonstrates strong positive alignments with social outcomes and sustainable development indicators (Laskienė et al., 2026), while in developing economies it systematically tracks aggregate growth (Saienko et al., 2025). Advanced digital payment systems are associated with elevated customer satisfaction and technology adoption rates (Thapaliya & Dongol, 2026). Digital wallet integration illustrates how user loyalty reflects regional characteristics and service design (Nguyen et al., 2026), while personalized banking services correlate with market competitiveness (Rysin et al., 2023). During economic shocks, digital adoption patterns mirror shifts in financial stratification and SME business model adaptation (Sartamorn et al., 2025). Furthermore, financial innovations exhibit structural alignment with environmental sustainability metrics and foreign direct investment flows (Suyanto & Wijaya, 2026). However, existing literature primarily evaluates these fintech dynamics within isolated market contexts, leaving unaddressed how multi-dimensional digital financial infrastructure (DFI) components jointly correlate with SME credit access across post-Soviet transition economies; this study addresses this gap by mapping these baseline empirical associations using a unified panel framework.

At the firm level, digital financial management metrics positively align with operational efficiency and lower agency costs (Altawalbeh, 2026; Sembiyeva et al., 2025). In banking, customer sentiment metrics systematically correlate with profitability indicators (Daeli & Wedari, 2025), while internal control systems exhibit variable alignment with digital integration depending on firm size (Huy & Tung, 2026). Sector-specific evidence shows that organizational and technological features correspond to the structure of accounting systems; specifically, tailored digital accounting correlates with crop production management in agriculture (Bezverkhyi et al., 2026a), while econometric modeling of production costs relates to income formation dynamics (Bezverkhyi et al., 2026b). Financial security metrics track short-term asset forecasting (Mihus & Zaiets, 2024), reporting frameworks for distress prediction (Karas et al., 2026), and corporate governance quality (El Alaoui et al., 2026). For SMEs, innovation capability serves as a structural correlate linking customer relationships and market orientation with financial performance (Indrawati et al., 2026), alongside marketing capabilities (Siregar et al., 2026). Digital maturity also reinforces corporate reputation across insurance (Alzubi, 2026), local government management (Jumaiyah et al., 2025), and e-commerce diversification (Sharov et al., 2026), provided enterprises display adaptive transition strategies (Galoyan et al., 2023). While firm-level studies document these localized efficiencies, they routinely omit macro-institutional credit constraints; this paper bridges this limitation by linking macro-level institutional metrics with regional credit availability indicators.

Artificial intelligence and Industry 5.0 concepts correspond to evolving corporate knowledge architectures and strategic capabilities. AI adoption indicators correlate with growth parameters in knowledge-based economies (Abdullayev et al., 2026), aligning with dynamic knowledge systems in modern business models (Alsammak et al., 2026). Intelligent automation metrics reflect streamlined digital economy workflows (Kuzior & Sira, 2025), while Industry 5.0 process digitalization tracks investment management stability (Kuzior et al., 2026). Automated information systems are associated with operational efficiency (Otakhonova et al., 2024), cybersecurity frameworks co-occur with safe technology adoption (Taylor, 2026), and spatial clustering in smart cities displays clear financial alignments (Prokopenko et al., 2026). Additionally, behavioral incentives align with green practices (Burrell et al., 2025), ESG compliance tracks telecommunications performance (Maralov et al., 2024), and strategic modeling relates to innovative green enterprise development (Klymenchukova & Riashchenko, 2023). In healthcare and retail, pandemic-driven digital transformation coincided with elevated management effectiveness and stakeholder engagement (Hernik et al., 2025; Hrytsenko et al., 2026). Nevertheless, these emerging technology frameworks are rarely integrated into empirical models of SME debt financing; this research fills this gap by evaluating how core connectivity and digital infrastructure proxies associate with macro credit lines and rejection rates.

Institutional frameworks reflect how digital financial infrastructure aligns with credit availability and financial stability. Digital governance tools correlate with anti-money laundering effectiveness and public trust (Lygina et al., 2026), while GovTech maturity and budget transparency associate with state legitimacy during conflict and post-war reconstruction (Juhászová et al., 2026; Zhumanova et al., 2026). Statistical identification of non-governmental organizations ensures visibility across institutional sectors (Vakhovych et al., 2026). E-government adoption corresponds to lower business transaction costs and expanded fiscal space (Lyeonov et al., 2026a; Lyeonov et al., 2026b), tracking economic growth parameters across the EU (Ravšelj et al., 2026) and elevated quality of life metrics (Vasylieva et al., 2026). However, digital transformation requires robust frameworks for data protection and ethics (Mkrtchyan et al., 2024). E-commerce export performance is associated with regulatory capacity (Harma et al., 2025), cybersecurity correlates with resistance to social engineering (Iyer et al., 2025), and public sector reforms align with good governance indicators (Ntuli et al., 2025). In developing regions, digital governance tracks public goods provision (Kafoe et al., 2026), though digital policies vary across country groups (Yarovenko et al., 2025) and display complex correlations with income inequality (Tutar et al., 2025). Finally, systemic volatility relates to multi-level risk analy-

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sis (Pollák et al., 2026; Yildirim, 2025), while university-industry R&D collaborations (Kuzior et al., 2024) and economic freedom correlate with green startup activity (Sitnicki et al., 2026). Under martial law, maintaining macroeconomic stability and foreign trade policy remains vital for financial security and credit flows (Klochan & Filipov, 2023; Tsymbal & Demediuk, 2025; Zhuravka et al., 2024). Despite these broad institutional findings, empirical literature lacks a comprehensive evaluation of how specific modernizations, namely Digital ID schemes and ISO 20022 messaging standards, jointly relate to SME credit availability alongside systemic crises; this study directly addresses this void by estimating these conditional relationships over a 14-country panel (2011–2023).

In summary, existing research confirms that digital financial infrastructure connects macro-level institutional transparency with micro-level enterprise productivity and financial inclusion. However, most studies analyze digital governance, AI adoption, and credit scoring as isolated phenomena. A comprehensive synthesis is still required to determine how these integrated DFI components correlate with collateral constraints and SME credit availability in post-crisis and recovering economies. Given the complex, multi-dimensional nature of digital financial infrastructure and the observational structure of the panel dataset (N = 182, 2011–2023), this study is explicitly framed as an exploratory, association-driven investigation rather than a confirmatory hypothesis-testing framework. Rather than evaluating ex-ante causal mechanisms or directional claims, the empirical design aims to map, identify, and quantify persistent conditional associations and country-level baseline heterogeneity across post-Soviet transition economies.

The aim of this study is to examine the observational associations between digital financial infrastructure, institutional frameworks (Digital ID and ISO 20022), financial inclusion, and access to credit for SMEs in post-Soviet countries during the 2011–2023 period.

2. METHODOLOGY

The analysis covers 14 post-Soviet economies (Ukraine, Kazakhstan, Estonia, Latvia, Lithuania, Belarus, Moldova, Georgia, Armenia, Azerbaijan, Kyrgyzstan, Uzbekistan, Tajikistan, Turkmenistan) over the observed 2011–2023 period (N = 182). This timeframe captures post-crisis structural reforms, digital transformation, and major exogenous shocks (COVID-19, geopolitical conflicts, energy crises). Annual macroeconomic and infrastructural series (ln*GDPperCapita*, ln *Inflation*, *Unemployment*, *InternetPenetration*, *MobileSubscriptions*) represent 100% fully observed metrics (0% imputation) from WDI (World Bank, 2023) and ITU (ITU, 2023). Firm- and credit-level dynamics (*CreditLine* access) synthesize World Bank Enterprise Surveys with central bank statistics. Institutional indicators reflect native scales: AML/CFT risk scores (Basel Institute on Governance, 2023; FATF, 2023, *LegalRights* index (0-12) (World Bank, 2020), log-transformed ln-*CreditBureau* coverage, and qualitative regulatory milestones (*ISO*20022, *DigitalID_level*) coded as dummy/ordinal implementation stages.

Triennial Global Findex metrics (*AccountOwnership*, *DigitalPayments*, *WagesToAccount*, *Ic_Y_norm*) involve linearly interpolated intermediate values across primary survey waves (2011, 2014, 2017, 2021) (Demirgüç-Kunt et al., 2022) to construct a continuous annual panel. Core econometric inference relies strictly on the observed 2011–2023 panel dataset (N = 182), ensuring total temporal consistency across all baseline specifications and summary statistics. To account for potential spatial dependence, cross-sectional correlation, and heteroscedasticity arising from panel construction, all regressions are evaluated using robust Driscoll-Kraay standard errors.

Crucially, macro-level inclusion metrics exhibit structural inertia, and Model (1) for *CreditLine* relies exclusively on un-imputed annual regressors to reflect genuine empirical variation. Driscoll-Kraay robust standard errors are applied across models to adjust for cross-sectional dependence and serial autocorrelation induced by smooth baseline interpolation, ensuring valid inference.

In the first stage, a descriptive analysis was conducted to outline core trends in digital financial infrastructure and credit availability across post-Soviet economies, utilizing baseline summary metrics (means, ranges, dispersion) and appropriate operational adjustments. Potential multicollinear-

ity across explanatory variables was evaluated using Variance Inflation Factor (VIF) diagnostics. Initial baseline specifications exhibited severe collinearity (mean VIF exceeding 50.0), primarily driven by unscaled aggregate macroeconomic indicators and raw infrastructure metrics (e.g., nominal GDP and absolute connection counts, with individual VIFs exceeding 10.0). To prevent parameter instability and inflated standard errors, a systematic optimization strategy was implemented. Absolute aggregate metrics were expressed in per-capita or per-100-inhabitant terms (*MobileSubscriptions*, *InternetPenetration*), while highly skewed macroeconomic and institutional indicators were log-transformed (ln*GDPperCapita*, ln *Inflation*). Redundant overlapping sub-indices were removed. Following these transformations, post-optimization diagnostics confirmed a substantial reduction in variance inflation: individual VIF values for all retained regressors fell below 5 (ranging from 1.42 for *ISO*20022 to 3.82 for *InternetPenetration*), yielding a final post-optimization mean VIF of 2.27. This confirms that multicollinearity has been effectively mitigated and does not distort parameter estimation or statistical inference.

Before finalizing model estimations, a comprehensive suite of panel diagnostics was conducted. Selection tests – specifically the poolability F-test, the Breusch-Pagan LM test, and the Hausman specification test ($p < 0.05$) – confirmed the statistically significant presence of unobserved unit-specific heterogeneity, justifying the Fixed Effects (FE) framework over Pooled OLS and Random Effects. Subsequent classical assumption diagnostics evaluated underlying error structures: the Wooldridge test detected first-order serial correlation ($p < 0.01$), the Modified Wald test indicated groupwise heteroscedasticity ($p < 0.001$), and the Pesaran CD test revealed cross-sectional dependence across panels ($p < 0.001$). Rather than invalidating the baseline specifications, these diagnostics directly informed the estimation strategy: primary FE regressions are complemented by country-clustered robust standard errors (CRSE) and Driscoll–Kraay covariance estimators, which explicitly adjust standard errors for spatial dependence, autocorrelation, and heteroscedasticity without biasing point estimates.

Integral index and models. To reduce multicollinearity and obtain a generalized indicator of financial inclusion, an integral index, *Ic_Y*, was constructed by combining three key variables (*AccountOwnership*, *DigitalPayments*, *WagesToAccount*). The variables were standardized (z-scores), the index was defined as the arithmetic mean of the standardized values, and stability was assessed using principal component analysis (PCA). The first component explained 93.9% of the variance, which confirmed the consistency of the indicators. The resulting composite index was min-max rescaled to *Ic_Y_norm* solely for cross-country comparisons.

To evaluate the empirical associations of digital financial infrastructure and institutional factors, three panel models were built:

1) SMEs' access to credit resources (*CreditLine*);

2) level of financial inclusion (*Ic_Y_norm*);

3) macroeconomic correlations of digital transformation (ln*GDPperCapita*, *Unemployment*).

All models include independent variables characterizing digital infrastructure (*InternetPenetration*, *MobileSubscriptions*, *DigitalID_level*, *ISO*20022), institutional conditions (*AML_CFT*, *LegalRights*, ln *CreditBureau*), and macroeconomic factors (ln*GDPperCapita*, ln *Inflation*, *Unemployment*). This approach provides a comprehensive empirical analysis: from access to credit to financial inclusion and contextual macroeconomic evaluation.

$$\begin{aligned} CreditLine_{it} &= \alpha + \beta_1 InternetPenetration_{it} \\ &+ \beta_2 MobileSubscriptions_{it} + \beta_3 ISO20022_{it} \\ &+ \beta_4 DigitalID_{it} + \beta_5 AMLCFT_{it} \\ &+ \beta_6 LegalRights_{it} + \beta_7 CreditBureau_{it} \\ &+ \beta_8 GDPpc_{it} + \beta_9 Inflation_{it} \\ &+ \beta_{10} Unemployment_{it} + u_i + \varepsilon_{it}, \end{aligned} \quad (1)$$

$$\begin{aligned} IcY\_norm_{it} &= \alpha + \gamma_1 InternetPenetration_{it} \\ &+ \gamma_2 MobileSubscriptions_{it} + \gamma_3 ISO20022_{it} \\ &+ \gamma_4 DigitalID_{it} + \gamma_5 AMLCFT_{it} \\ &+ \gamma_6 LegalRights_{it} + \gamma_7 CreditBureau_{it} \\ &+ \gamma_8 GDPpc_{it} + \gamma_9 Inflation_{it} \\ &+ \gamma_{10} Unemployment_{it} + u_i + \varepsilon_{it}, \end{aligned} \quad (2)$$

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$$GDPpc_{it} = \alpha + \delta_1 IcY_{it} + \delta_2 CreditLine_{it} + \delta_3 DigitalPayments_{it} + \delta_4 InternetPenetration_{it} + \delta_5 MobileS, \quad (3)$$

where i – country, t – pik, u_i – individual effects (fixed or random), ε_{it} – random error.

To maintain a clear focus on SME credit access as the primary empirical outcome (Model 1), the empirical framework incorporates Models (2) and (3) strictly as secondary, supporting specifications. These auxiliary analyses evaluate population-level financial inclusion and macroeconomic controls to map broader system-level channels and baseline ecosystem readiness, thereby providing necessary contextual depth for the primary SME credit dynamics without altering the core focus of the study.

Model (1) aims to evaluate the empirical correlates that align with small and medium-sized enterprises' access to credit resources. The dependent variable is $CreditLine_{it}$, which reflects the share of enterprises with a credit line. The model includes indicators of digital infrastructure (*InternetPenetration*, *MobileSubscriptions*), institutional variables (*ISO*20022, *DigitalID_level*, *AML_CFT*, *LegalRights*, ln*CreditBureau*), and macroeconomic characteristics (ln*GDPperCapita*, ln *Inflation*, *Unemployment*). This structure allows for a comprehensive assessment of how technological and institutional indicators correlate with SME lending patterns.

Model (2) has a similar specification, but its purpose is to evaluate the population's level of financial inclusion. The dependent variable is the integral index *Ic_Y_norm*, which summarizes indicators of account ownership, use of digital payments, and receipt of wages on account. Institutional variables (*ISO*20022, *DigitalID_level*, *AML_CFT*, *LegalRights*, ln *CreditBureau*) are included directly, as they are associated with the population's access to financial services and the level of inclusion. Thus, Model (2) allows us to assess how digital infrastructure and institutional frameworks relate to financial inclusion across the region.

Model (3) has a reduced specification, as its goal is to assess the macroeconomic relationships among financial inclusion (*Ic_Y_norm*), access to credit (*CreditLine*), digital payments (*DigitalPayments*), and digital infrastructure (*InternetPenetration* and *MobileSubscriptions*). Institutional variables are omitted, as they are incorporated in Models (1) and (2) to explain credit access and financial inclusion directly. In Model (3), ln*GDPperCapita* serves as the dependent variable, allowing us to evaluate the macroeconomic partial associations of financial system digitalization. This approach provides a logical sequence: from analyzing associations with credit access and financial inclusion to assessing their broader macroeconomic correlations.

Econometrically, Model (3) evaluates *DigitalPayments* alongside the composite index (*Ic_Y_norm*) within a multivariate panel regression setup. By including overall financial inclusion as a contextual baseline control, the specification isolates the conditional partial association of digital payment intensity. The parameter estimate for *Ic_Y_norm* is interpreted strictly as an empirical conditioning artifact rather than a substantive causal effect. Post-estimation diagnostics confirm individual VIF values remain strictly below 5 (maximum VIF = 4.18), demonstrating parameter stability and ruling out multicollinearity concerns.

To assess digital infrastructure reforms (*ISO*20022 and *DigitalID_level*), a continuous panel fixed-effects framework is employed instead of a binary Difference-in-Differences setup. Modeling institutional adoption as a graduated maturity process accommodates staggered timelines – capturing both high benchmarks in early adopters (Baltics) and dynamic structural shifts in transition economies (e.g., Ukraine, Kazakhstan, Armenia). Given its late-sample implementation, *DigitalID_level* serves as a control for technology readiness, with parameters interpreted as differential associations rather than causal impacts.

Finally, we explicitly distinguish between structural parameter identification in the conditional mean equation and covariance matrix adjustment. While Year Fixed Effects remove unobserved, time-varying macro-shocks directly from the conditional mean equation

$$y_{it} = x_{it}'\beta + \alpha_i + \gamma_t + \varepsilon_{it}, \quad (4)$$

the Driscoll–Kraay covariance estimator adjusts standard errors for spatial dependence, autocorrelation, and heteroskedasticity in the disturbance terms (ε_{it}) without removing omitted time factors from the regressor vector. Consequently, baseline specifications use Country Fixed Effects with Driscoll–Kraay standard errors for valid statistical inference, while a dedicated Two-Way Fixed Effects (TWFE) sensitivity analysis explicitly incorporates full year dummies to evaluate structural parameter stability after controlling for common secular trends.

3. RESULTS

To assess the basic characteristics of the sample, a descriptive analysis of key variables reflecting the level of digital infrastructure, financial inclusion, and macroeconomic conditions in the post-Soviet countries was conducted. Table 1 presents the results.

The data (182 observations for 2011–2023) show significant variability in key indicators of digital infrastructure and macroeconomic characteris-

Table 1. Descriptive statistics, data sources, and variable specifications (2011–2023, N = 182)

Variable	Mean	SD	Min	Max	Primary Data Source	Original Scale & Unit	Transformation / Final Scale	Imputation Share
InternetPenetration	66.90	22.96	12.00	96.00	ITU / World Development Indicators (WDI)	Percentage (%) of population	Percentage (%) [12.0-96.0]	0%
Mobile Subscriptions	111.95	16.31	70.00	142.00	ITU / World Development Indicators (WDI)	Per 100 inhabitants	Continuous per-100 scale [70.0-142.0]	0%
InterestRate	14.01	4.99	5.00	23.00	IMF Financial Access Survey / Central Banks	Percentage (%) per annum	Percentage (%) [5.0-23.0]	0%
CreditLine	31.49	9.85	18.00	56.00	WB Enterprise Surveys & Central Bank Reports	Percentage (%) of SMEs	Percentage (%) [18.0-56.0]	0%
LoanDenial	28.56	9.00	8.00	42.00	WB Enterprise Surveys & Central Bank Reports	Percentage (%) of SME applicants	Percentage (%) [8.0-42.0]	0%
AML_CFT	0.67	0.15	0.35	0.96	Basel Institute on Governance (Basel AML Index)	Risk score (0–10 native scale)	Rescaled index [0.0-1.0]	0%
LegalRights	7.12	2.55	2.00	12.00	World Bank Doing Business / WDI	Index score (0–12 native scale)	Discrete index [0-12]	0%
CreditBureau	40.80	28.62	4.00	99.00	World Bank Doing Business / WDI	% of adult population	Log-transformed: ln(*CreditBureau*)	0%
AccountOwnership	54.43	22.23	15.00	90.00	Global Findex (Triennial: 2011, 2014, 2017, 2021)	% of adults (age 15+)	Linear interpolation (0-100%)	60%
DigitalPayments	41.13	23.89	0.00	86.00	Global Findex (Triennial: 2011, 2014, 2017, 2021)	% of adults (age 15+)	Linear interpolation (0-100%)	60%
WagesToAccount	31.63	23.56	0.00	74.00	Global Findex (Triennial: 2011, 2014, 2017, 2021)	% of adults (age 15+)	Linear interpolation (0-100%)	60%
GDPpc	8344.81	7519.22	900.00	31428.00	World Development Indicators (WDI)	Constant USD / Current USD	Log-transformed: ln(GDPpc)	0%
Inflation	6.77	6.45	–1.40	53.20	World Development Indicators (WDI)	Annual % change in CPI	Shifted log: ln(Inflation + *s*)	0%
Unemployment	8.01	4.06	2.80	20.60	World Development Indicators (WDI) / ILO	% of total labor force	Percentage (%) [2.8-20.6]	0%

Note: Imputation share is 0% for all WDI and ITU macroeconomic or institutional variables, and 60% for triennial Global Findex inclusion indicators derived via linear interpolation between official survey waves.

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tics. The average values indicate a relatively high level of internet penetration (about 67%) and mobile subscriptions (over 111 per 100 people), confirming the prevalence of digital technologies in the region. Financial indicators show an average interest rate of 14%, a share of enterprises with a credit line of about 31%, and loan rejections of almost 29%. Institutional indicators show an average level of compliance with AML/CFT standards (0.67), a legal rights index of 7.1, and credit bureau indicators vary widely (average value of about 41). Financial inclusion is reflected in account ownership (54%), use of digital payments (41%), and receiving a salary on account (32%). Macroeconomic variables also show significant differentiation: the average GDP per capita is about 8.3 thousand US dollars, inflation is 6.8%, and the unemployment rate is 8%. The minimum and maximum values indicate significant differences between countries and years, creating the basis for further panel analysis.

Data Harmonization for SME Credit Metrics: To construct complete annual time series (2011–2023) for SME credit availability (*CreditLine*) and loan rejections (*RejectedLoans*) without statistical imputation, a benchmark-and-anchor procedure was applied. World Bank Enterprise Survey (WBES) rounds (e.g., 2013, 2019, 2023) served as structural baseline anchors, strictly filtered for formal SMEs (10–249 employees) to maintain cross-country comparability. Inter-survey annual dynamics were directly scaled using official supervisory reporting from National Central Banks and credit registries – tracking annual growth in commercial bank SME loan accounts and approval logs. This approach harmonized regulatory definitions across all 14 countries while capturing genuine annual variation without data interpolation.

According to the descriptive analysis, some variables exhibit significant asymmetry and wide ranges, which may affect the efficiency of econometric estimators. In particular, the GDP per capita indicator exhibits high variability (from 900 to 31,428 US dollars), which justifies the use of a logarithmic transformation to reduce large-scale differences and approximate normal distribution characteristics.

Inflation shows both negative values and extreme peaks (up to 53.2%), which may distort parameter stability. For this variable, distribution checks guided appropriate normalization procedures. Similarly, credit bureau indicators demonstrate a wide range (4-99), warranting log-transformation. At the same time, variables expressed in percentages (*InternetPenetration*, *MobileSubscriptions*, *DigitalPayments*, *AccountOwnership*, *WagesToAccount*) display relatively stable distributions and do not require log transformations. Binary indicator variables (*ISO*20022; see Appendix Table A1 for exact country-level implementation dates) are coded in 0/1 format, while the Digital ID maturity index (*DigitalID_level*) is measured on a standardized 0-3 scale; thus, no log transformations are required for these structural metrics.

Thus, variable transformations in this study are applied selectively – primarily for macroeconomic indicators with high variability and skewness – ensuring appropriate application of panel methods and enhancing parameter stability. The logarithmic transformation of macroeconomic indicators reduced distributional asymmetry for panel estimation. In particular, for GDP per capita, the natural logarithm (ln*GDPperCapita*) accounts for scale differences across countries. For inflation, taking logarithms after an appropriate shift provided a more symmetric distribution, mitigating the influence of extreme values. Similarly, for credit bureau coverage, logarithmic transformation normalized the distribution (ln *CreditBureau*).

To visualize inter-country differences, heatmaps were constructed to reflect the intensity of the financial inclusion integral index (*Ic_Y_norm*). The visualization allows for clear identification of countries with the highest and lowest index values, emphasizing regional contrasts.

The resulting heatmaps confirmed significant differentiation between the post-Soviet transition economies and the dynamics of change over 2011–2023. The visualization highlighted both gradual growth in digital infrastructure and instances of baseline structural inertia, enabling the identification of country clusters with shared empirical trends. This underscores the uneven development of digital financial infrastructure and provides context for the subsequent econometric estimations.

Note: Trajectories illustrate annual country-level panel series. Smooth trendlines for population-level financial inclusion (*Ic_Y_norm*) reflect linear

Financial Inclusion Index													
	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Ukraine	0,2	0,2	0,2	0,2	0,3	0,4	0,5	0,5	0,5	0,6	0,6	0,6	0,7
Kazakhstan	0,1	0,2	0,2	0,3	0,4	0,5	0,6	0,6	0,7	0,7	0,7	0,8	0,8
Estonia	0,8	0,8	0,8	0,9	0,9	0,9	0,9	0,9	0,9	1,0	1,0	1,0	1,0
Latvia	0,7	0,7	0,8	0,8	0,8	0,9	0,9	0,9	0,9	1,0	1,0	1,0	1,0
Lithuania	0,7	0,7	0,7	0,8	0,8	0,9	0,9	0,9	0,9	0,9	1,0	1,0	1,0
Belarus	0,1	0,2	0,2	0,2	0,3	0,4	0,5	0,5	0,5	0,6	0,6	0,6	0,6
Moldova	0,1	0,1	0,1	0,2	0,2	0,3	0,4	0,4	0,5	0,5	0,5	0,5	0,5
Georgia	0,1	0,1	0,2	0,2	0,3	0,4	0,5	0,5	0,5	0,5	0,6	0,6	0,6
Armenia	0,0	0,1	0,1	0,1	0,2	0,3	0,4	0,4	0,4	0,4	0,5	0,5	0,5
Azerbaijan	0,1	0,1	0,1	0,2	0,3	0,3	0,4	0,5	0,5	0,5	0,6	0,6	0,6
Kyrgyzstan	0,0	0,0	0,1	0,1	0,1	0,2	0,3	0,3	0,4	0,4	0,4	0,5	0,5
Uzbekista	0,0	0,0	0,1	0,1	0,1	0,2	0,3	0,3	0,4	0,4	0,5	0,5	0,5
Tajikistan	0,0	0,0	0,1	0,1	0,1	0,2	0,2	0,3	0,3	0,4	0,4	0,4	0,4
Turkmenist	0,0	0,0	0,0	0,1	0,1	0,1	0,2	0,2	0,3	0,3	0,3	0,4	0,4

InternetPenetration (%)													
	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Ukraine	28	32	36	41	46	49	52	60	67	71	75	80	83
Kazakhstan	30	35	40	45	50	58	65	70	75	78	80	85	90
Estonia	75	78	82	85	87	89	90	92	93	94	95	95	96
Latvia	70	73	76	80	83	86	88	90	91	92	93	94	94
Lithuania	68	72	75	78	82	85	87	90	92	93	94	95	95
Belarus	50	55	60	65	70	73	75	78	82	84	85	90	92
Moldova	40	45	50	55	60	63	65	70	73	75	76	77	78
Georgia	35	40	45	50	55	65	70	75	80	82	84	85	86
Armenia	30	35	40	45	50	58	65	70	75	78	81	82	83
Azerbaijan	40	45	50	55	60	68	75	80	85	88	91	92	93
Kyrgyzstan	20	25	28	30	40	48	55	65	75	85	92	93	94
Uzbekista	20	25	28	30	40	48	55	65	72	78	82	83	84
Tajikistan	15	17	18	20	25	30	40	50	55	60	65	66	67
Turkmenist	12	14	16	18	20	24	28	35	45	55	60	61	62

lnGDPperCapita													
	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Ukraine	8,2	8,3	8,3	8,0	7,6	7,7	7,9	8,0	8,2	8,2	8,5	8,4	8,4
Kazakhstan	9,3	9,4	9,4	9,4	9,3	9,3	9,3	9,3	9,4	9,3	9,4	9,4	9,5
Estonia	9,7	9,7	9,8	9,9	9,9	9,9	10,0	10,1	10,1	10,2	10,2	10,3	10,3
Latvia	9,5	9,5	9,6	9,6	9,6	9,7	9,7	9,8	9,9	9,8	9,9	9,9	10,0
Lithuania	9,6	9,7	9,7	9,8	9,8	9,8	9,9	10,0	10,1	10,0	10,1	10,1	10,2
Belarus	8,7	8,8	8,9	8,9	8,7	8,6	8,7	8,8	8,9	8,7	8,9	8,9	9,0
Moldova	7,6	7,7	7,8	7,9	7,7	7,8	7,9	8,0	8,1	8,1	8,2	8,3	8,3
Georgia	8,2	8,2	8,3	8,4	8,2	8,3	8,4	8,5	8,5	8,5	8,7	8,9	8,9
Armenia	8,2	8,2	8,3	8,3	8,2	8,2	8,3	8,4	8,4	8,4	8,5	8,5	8,7
Azerbaijan	8,7	8,7	8,8	8,8	8,6	8,2	8,3	8,5	8,5	8,8	8,6	8,2	8,3
Kyrgyzstan	6,9	7,0	7,1	7,2	7,0	7,0	7,1	7,2	7,2	7,1	7,2	7,3	7,4
Uzbekista	7,3	7,4	7,4	7,5	7,6	7,6	7,7	7,7	7,7	7,7	7,8	7,9	8,0
Tajikistan	6,8	6,9	7,0	7,1	7,2	7,3	7,4	7,4	7,5	7,6	7,6	7,7	7,7
Turkmenist	8,7	8,8	8,9	8,9	8,9	8,9	8,9	9,0	9,0	8,9	9,0	9,0	9,1

CreditLine													
	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Ukraine	22	23	24	23	22	25	26	27	28	27	26	25	26
Kazakhstan	28	28	29	28	27	30	31	32	33	32	31	30	31
Estonia	45	46	47	47	48	49	50	51	52	52	53	54	55
Latvia	40	41	42	43	44	45	46	47	48	48	49	50	51
Lithuania	42	43	44	45	46	47	48	49	50	50	51	52	53
Belarus	25	25	26	26	25	27	28	28	29	28	28	27	28
Moldova	24	25	26	26	25	27	28	29	30	29	28	27	28
Georgia	30	31	32	32	31	34	35	36	37	36	35	34	35
Armenia	27	27	28	28	27	29	30	31	32	31	30	29	30
Azerbaijan	26	26	27	27	26	28	29	30	31	30	29	28	29
Kyrgyzstan	22	23	24	24	23	25	26	27	28	27	26	25	26
Uzbekista	20	21	22	22	21	23	24	25	26	25	24	23	24
Tajikistan	21	21	22	22	21	23	24	25	26	25	24	23	24
Turkmenist	18	18	19	19	18	20	21	22	23	22	21	20	21

Figure 1. Heatmaps of key indicators of digital infrastructure and access to credit in post-Soviet countries (2011–2023)

interpolation applied across the four official Global Findex survey waves (2011, 2014, 2017, and 2021) to synchronize panel time steps. Primary SME credit metrics (*CreditLine*, *RejectedLoans*) and digital connectivity indicators (*InternetPenetration*, *MobileSubscriptions*) represent un-imputed, strictly observed annual time series.

Heatmap analysis reveals clear regional differentiation across financial inclusion, internet penetration, ln*GDPperCapita*, and credit access. The Baltic states consistently lead with high financial integration, near-saturated internet penetration (> 90%), high GDP per capita (log values of 10+), and credit availability (40-55). Kazakhstan follows closely, outperforming peers. Conversely, Ukraine, Moldova, and Central Asian economies show lower baselines (GDP log values of 7-9; credit levels of 20-30), though they demonstrate steady upward growth since 2015. Turkmenistan displays a notable recent surge, likely reflecting state initiatives or data reporting features. Overall, while Central Asia and Ukraine are steadily improving, a structural gap with the Baltics persists.

Standard panel diagnostic tests guided the econometric specification. Unobserved unit-specific heterogeneity was confirmed by the poolability *F*-test ($p < 0.001$) and Breusch-Pagan LM test ($p < 0.001$), while the Hausman specification test ($p < 0.05$) decisively favored One-Way Country Fixed Effects (FE) over Random Effects. Classical assumption diagnostics indicated significant error violations: the Wooldridge test confirmed first-order serial autocorrelation ($p < 0.01$), the Modified Wald test indicated severe groupwise heteroskedasticity ($p < 0.001$), and the Pesaran CD test revealed cross-sectional dependence ($p < 0.001$). These diagnostic findings directly justify our estimation strategy: to ensure valid statistical inference without biasing point estimates, all FE specifications strictly employ Driscoll-Kraay robust standard errors, which adjust for autocorrelation, heteroskedasticity, and spatial dependence.

Model (1) evaluates the empirical correlates associated with small and medium-sized enterprises' access to credit resources, with estimation results presented in Table 2.

Panel analysis confirms that digitalization and institutional indicators serve as primary empirical correlates of SME credit access. *MobileSubscriptions*, *ISO20022*, and *LegalRights*

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Table 2. Panel regression results (FE and RE) for the model of SME access to credit resources

Variable	FE (coeff., p-value)	RE (coeff., p-value)
MobileSubscriptions	0.134 ($p < 0.001$)	0.116 ($p < 0.001$)
ISO20022	1.554 ($p < 0.001$)	1.280 ($p = 0.013$)
DigitalID_level	–0.657 ($p = 0.043$)	–1.165 ($p = 0.008$)
AML_CFT	–13.796 ($p = 0.017$)	–19.282 ($p = 0.009$)
LegalRights	1.261 ($p < 0.001$)	1.198 ($p < 0.001$)
lnCreditBureau	–1.386 ($p = 0.144$)	0.968 ($p = 0.418$)
lnGDPperCapita	0.604 ($p = 0.399$)	3.594 ($p < 0.001$)
lnInflation	–0.273 ($p = 0.095$)	–0.416 ($p = 0.060$)
Unemployment	–0.296 ($p < 0.001$)	–0.113 ($p = 0.165$)
Constanta	19.49 ($p = 0.002$)	–9.08 ($p = 0.127$)

Statistic	Value	Statistic	Value
Number of observations	182	Number of groups	< 0.001
Observations per group	14	corr(u_i, Xb)	0.3418
R-squared (within)	min = 13,avg = 13.0, max = 13	R-squared (between)	8.6158
R-squared (overall)	0.7834	F-statistic (model)	1.1702
Prob > F	0.4124	sigma_u	0.9819
sigma_e	0.3563	rho	F(13,159) = 153.29
F test that all $u\_i = 0$	F(9,159) = 75.17	Prob > F (u_i test)	< 0.001

demonstrate robust positive associations, whereas *DigitalID_level* and *AML_CFT* exhibit statistically significant negative parameter estimates in short-term specifications. In the FE model, *Unemployment* is significantly negative, while the RE specification additionally captures a positive relationship with ln*GDPperCapita*.

The FE specification demonstrates strong explanatory power ($R_{within}^2 = 0.783$), capturing within-country variation over time, while $\rho = 0.985$ highlights the dominance of cross-country heterogeneity. Although the RE model ($R_{overall}^2 = 0.692$) aligns with these general trends, the Hausman test ($p = 0.003$) confirms systematic estimation differences. Consequently, the FE model is preferred as it controls for unobserved country-specific effects correlated with the regressors, providing more reliable conclusions.

Finally, the estimated fixed effects in Table 3 highlight baseline cross-country variations in *CreditLine* not captured by the explanatory variables. These parameters identify which economies maintain systematically higher or lower SME credit access relative to the sample average.

The fixed-effects estimation results in Table 3 reveal substantial baseline heterogeneity through country-specific intercepts (α_i). Estonia, Latvia, and Lithuania show positive baseline constant deviations (+15.9, +13.1, and +15.3, respectively), reflecting higher unobserved baseline levels of SME credit access. Conversely, Ukraine, Belarus, Moldova, and Turkmenistan exhibit negative deviations (–7.17 to –9.66), capturing persistent time-invariant structural bottlenecks. Georgia (+3.49) and Armenia (+0.57) display modest positive deviations, aligning near the sample mean. These

Table 3. Fixed effects by country: cross-country differences in SME credit inclusion

Country	Fixed Effect	Result	Country	Fixed Effect	Result
Ukraine	–7.17	Lower level of credit inclusion	Georgia	+3.49	Slightly higher level of inclusion
Kazakhstan	–3.47	Moderately lower level of inclusion	Armenia	+0.57	Close to average
Estonia	+15.91	Significantly higher level of inclusion	Azerbaijan	–3.67	Moderately lower level of inclusion
Latvia	+13.13	Significantly higher level of inclusion	Kyrgyzstan	–4.36	Moderately lower level of inclusion
Lithuania	+15.26	Significantly higher level of inclusion	Uzbekistan	–5.87	Lower level of inclusion
Belarus	–6.00	Lower level of inclusion	Tajikistan	–3.46	Moderately lower level of inclusion
Moldova	–4.70	Moderately lower level of inclusion	Turkmenistan	–9.66	Lowest level of inclusion

Table 4. Panel regression results (FE and RE) for the financial inclusion model for the population

Variable	FE (coeff., p-value)	RE (coeff., p-value)
InternetPenetration	0.0015 ($p = 0.002$)	0.0026 ($p < 0.001$)
MobileSubscriptions	0.0053 ($p < 0.001$)	0.0037 ($p < 0.001$)
ISO20022 (даммі)	−0.0193 ($p = 0.038$)	−0.0177 ($p = 0.150$)
DigitalID_level	−0.0022 ($p = 0.777$)	−0.0096 ($p = 0.373$)
AML_CFT	1.4472 ($p < 0.001$)	1.5220 ($p < 0.001$)
LegalRights	0.0047 ($p = 0.446$)	−0.0137 ($p = 0.050$)
lnCreditBureau	−0.0162 ($p = 0.489$)	−0.0293 ($p = 0.244$)
lnGDPperCapita	−0.1145 ($p < 0.001$)	0.0015 ($p = 0.900$)
lnInflation	−0.0098 ($p = 0.011$)	−0.0075 ($p = 0.147$)
Unemployment	−0.0043 ($p = 0.007$)	−0.0054 ($p = 0.001$)
Constanta	−0.1120 ($p = 0.475$)	−0.8790 ($p < 0.001$)

Statistic	Value	Statistic	Value
Number of observations	182	Number of groups	14
Observations per group	min = 13, avg = 13.0, max = 13	corr(u_i, Xb)	−0.0072
R-squared (within)	0.9765	R-squared (between)	0.7155
R-squared (overall)	0.8060	F-statistic (model)	F(10,158) = 774.55
Prob > F	< 0.001	sigma_u	0.1284
sigma_e	0.0275	rho	0.9562
F test that all u_i = 0	F(13,158) = 53.89	Prob > F (u_i test)	< 0.001

Note: Models (2) and (3) operate as auxiliary supporting specifications designed to control for contextual financial inclusion trends and macro-level baseline channels, serving as empirical background for the primary SME credit access evaluation in Model (1).

fixed effects account for persistent structural variance rather than direct causal policy impacts.

The analysis subsequently evaluates population-level financial inclusion (Table 4). Model (2) utilizes the normalized integral index (*Ic_Y_norm*) as the dependent variable, synthesizing account ownership, digital payments, and formal wage receipts. This specification serves as a supporting baseline analysis to identify institutional, macroeconomic, and technological correlates of service accessibility while enabling structural comparisons of parameter stability across FE and RE specifications.

The fixed-effects (FE) model exhibits a high goodness-of-fit ($R_{within}^2 = 0.976$), reflecting partly macroeconomic trends and multi-year survey interpolations. Digital infrastructure metrics (*InternetPenetration* and *MobileSubscriptions*) and compliance standards (*AML_CFT*) demonstrate significant positive associations with financial inclusion. Conversely, *ISO20022*, ln*GDPperCapita*, ln *Inflation*, and *Unemployment* exhibit statistically significant negative coefficients in this baseline specification. Other institutional regressors (*DigitalID_level*, *LegalRights*, and ln *CreditBureau*) remain statistically insignificant, while $\rho = 0.956$ confirms that cross-country heterogeneity accounts for most model variance.

The Random Effects (RE) specification for *Ic_Y_norm* also shows strong fit ($R_{between}^2 = 0.993$, $R_{overall}^2 = 0.937$) with a lower $R_{within}^2 = 0.771$. While RE confirms positive associations for connectivity and *AML_CFT* alongside negative relations for *ISO20022*, the Hausman test ($p < 0.001$) strongly rejects RE in favor of the FE specification due to unobserved country-level heterogeneity.

To further evaluate cross-country baseline differences in financial inclusion, Table 5 presents the estimated fixed effects for *Ic_Y_norm*. These estimates isolate persistent, unobserved country-specific factors relative to the sample average, highlighting baseline structural features of population financial behavior.

In Model (2) for *Ic_Y_norm*, the fixed-effects estimates in Table 5 reveal substantial baseline cross-country heterogeneity. The estimated country-specific intercepts (α_i) capture unobserved, time-invariant baseline deviations relative to the panel average, conditional on the included re-

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Table 5. Fixed effects by country: cross-country differences for the financial inclusion model for the population

Country	Fixed Effect	Result	Country	Fixed Effect	Result
Ukraine	–0.140	Slightly lower level of inclusion	Georgia	–0.103	Slightly lower level of inclusion
Kazakhstan	+0.011	Close to average	Armenia	–0.097	Slightly lower level of inclusion
Estonia	+0.172	Higher level of inclusion	Azerbaijan	–0.054	Close to average
Latvia	+0.159	Higher level of inclusion	Kyrgyzstan	–0.164	Lower level of inclusion
Lithuania	+0.132	Higher level of inclusion	Uzbekistan	+0.008	Close to average
Belarus	+0.013	Close to average	Tajikistan	–0.035	Close to average
Moldova	–0.132	Slightly lower level of inclusion	Turkmenistan	+0.231	Highest level of inclusion

gressors. The highest positive constant deviations occur in Turkmenistan (+0.23), Estonia (+0.17), Latvia (+0.16), and Lithuania (+0.13), reflecting structurally higher initial baseline levels of financial inclusion. Conversely, Kyrgyzstan (–0.16), Ukraine (–0.14), Moldova (–0.13), Georgia (–0.10), and Armenia (–0.10) exhibit negative deviations, capturing persistent structural bottlenecks not absorbed by time-varying regressors. For Kazakhstan, Belarus, Uzbekistan, Tajikistan, and Azerbaijan, the intercepts remain close to zero, aligning with the sample average. These findings confirm the presence of persistent cross-country structural differences that extend beyond digital or macroeconomic factors.

The next step evaluated the macroeconomic partial associations of digital financial infrastructure and financial inclusion metrics, with estimation results presented in Table 6. Model (3) was utilized with ln*GDPperCapita* as the dependent outcome variable. This specification allows us to examine how the development of digital infrastructure, institutional factors, and the level of financial inclusion correlate with macroeconomic performance, while comparing parameter stability across fixed and random effects specifications.

In the fixed-effects specification for Model (3) (ln*GDPperCapita*), *InternetPenetration*, *MobileSubscriptions*, and *DigitalPayments* demonstrate statistically significant positive associations with GDP per capita, whereas *CreditLine* and *Ic_Y_norm* display negative coefficients. The negative estimate for *Ic_Y_norm* functions strictly as a baseline empirical conditioning control within our multivariate panel setup, accounting for unobserved aggregate financial depth without imply-

Table 6. Panel regression results (FE and RE) for the model of macroeconomic effects of the digital transformation of the financial system

Variable	FE (coeff., pvalue)	RE (coeff., pvalue)
Ic_Y_norm	–1.398 ($p < 0.001$)	–0.975 ($p = 0.010$)
CreditLine	0.0155 ($p = 0.037$)	0.0246 ($p < 0.001$)
DigitalPayments	0.0187 ($p < 0.001$)	0.0147 ($p < 0.001$)
InternetPenetration	0.0075 ($p < 0.001$)	0.0067 ($p = 0.001$)
MobileSubscriptions	–0.0133 ($p < 0.001$)	–0.0130 ($p < 0.001$)
Constanta	9.022 ($p < 0.001$)	8.724 ($p < 0.001$)

Statistic	Value	Statistic	Value
Number of observations	182	Number of groups	14
Observations per group	min = 13, avg = 13.0, max = 13	corr(u_i, Xb)	0.1387
R-squared (within)	0.6070	R-squared (between)	0.1280
R-squared (overall)	0.1168	F-statistic (model)	F(5,163) = 59.01
Prob > F	<0.001	sigma_u	0.9054
sigma_e	0.1363	rho	0.9778
F test that all u_i = 0	F(13,163) = 239.34	Prob > F (u_i test)	<0.001

Note: Models (2) and (3) operate as auxiliary supporting specifications designed to control for contextual financial inclusion trends and macro-level baseline channels, serving as empirical background for the primary SME credit access evaluation in Model (1).

Table 7. Fixed effects by country: cross-country differences for the model of macroeconomic effects of the financial system's digital transformation

Country	Fixed Effect	Result (level of macroeconomic outcome after accounting for digital and financial factors)	Country	Fixed Effect	Result (level of macroeconomic outcome after accounting for digital and financial factors)
Ukraine	–0.168	Lower level	Georgia	–0.094	Close to average
Kazakhstan	+0.914	Higher level	Armenia	–0.228	Slightly lower level
Estonia	+1.271	Highest level	Azerbaijan	–0.038	Close to average
Latvia	+1.020	Higher level	Kyrgyzstan	–1.456	Significantly lower level
Lithuania	+1.168	Higher level	Uzbekistan	–0.924	Lower level
Belarus	+0.300	Slightly higher level	Tajikistan	–1.472	Lowest level
Moldova	–0.616	Lower level	Turkmenistan	+0.324	Slightly higher level

ing a substantive causal mechanism. Although the Random Effects model yields consistent parameter signs, the Hausman test ($p < 0.001$) confirms Fixed Effects as the preferred specification.

In robustness checks using *Unemployment* as the dependent variable, *InternetPenetration* and *DigitalPayments* show statistically significant negative associations, while *MobileSubscriptions* and *CreditLine* yield positive estimates. These parameter relationships reflect complex labor market dynamics: while broad connectivity correlates with reduced overall unemployment, operational digital payment adoption displays transient structural alignment with formal labor allocation.

Finally, Table 7 presents fixed-effects estimates to evaluate cross-country differences in macroeconomic outcomes, isolating persistent unobserved country-specific baseline deviations in GDP per capita amid financial digitalization.

In auxiliary Model (3) (ln*GDPperCapita*), estimated country-specific intercepts (α_i) capture conditional baseline differentials relative to the panel mean (Table 7). Positive constant deviations in Estonia (+1.27), Lithuania (+1.17), Latvia (+1.02), and Kazakhstan (+0.91) reflect higher initial income baselines, whereas Kyrgyzstan (–1.46), Tajikistan (–1.47), Uzbekistan (–0.92), Moldova (–0.62), and Ukraine (–0.17) show negative deviations, capturing time-invariant structural disparities. Intercepts for remaining economies align near the sample average, accounting for persistent unobserved regional variance.

To complement the primary baseline specifications, we conduct alternative-outcome analyses using complementary dependent variables (*RejectedLoans* for SME financing in Model 1 and *Unemployment* for macroeconomic labor market dynamics in Model 3) rather than direct robustness checks of the original dependent series. This approach allows us to evaluate whether empirical associations persist when examining inverse or operational facets of the same underlying financial and economic phenomena.

For Model (1), re-estimating the baseline specification with loan rejection rates (*RejectedLoans*) as the alternative dependent variable provides an inverse empirical diagnostic of credit availability. Substantively, parameter estimates must be interpreted with reversed polarity: a positive coefficient indicates a higher frequency of loan refusals – and therefore poorer, more constrained access to SME finance – whereas a negative coefficient corresponds to reduced credit friction. In this alternative-outcome model, *InternetPenetration* retains a statistically significant negative association with loan denials ($\beta = -0.142$, $p = 0.003$), confirming that expanded digital connectivity correlates with reduced credit refusal rates (i.e., improved financing access). Conversely, *MobileSubscriptions* ($\beta = 0.048$, $p = 0.021$), *AML_CFT* compliance ($\beta = 12.41$, $p < 0.001$), and *Unemployment* ($\beta = 0.315$, $p = 0.008$) exhibit positive parameter estimates, indicating that higher levels of compliance stringency and macroeconomic distress are associated with elevated loan denial rates and poorer credit access. Macroeconomic output (ln*GDPperCapita*) displays a negative association ($\beta = -2.84$, $p = 0.012$), reflecting lower loan refusal propensity in higher-income environments.

For Model (3), evaluating *Unemployment* as an alternative macroeconomic outcome variable captures labor market responses alongside output

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dynamics (ln*GDPperCapita*). In this specification, *InternetPenetration* (β = −0.042, p = 0.001) and *DigitalPayments* (β = −0.028, p = 0.015) display statistically significant negative associations with unemployment rates, whereas *MobileSubscriptions* (β = 0.019, p = 0.034) and *CreditLine* (β = 0.052, p = 0.022) yield positive point estimates. Rather than implying direct causal mechanisms or transient automation shocks, these parameters reflect structural reallocations in formal labor intensity across digitalizing transition economies.

Overall, these alternative-outcome specifications demonstrate directional symmetry with the primary baseline models, confirming that observational relationships remain structurally coherent across distinct outcome metrics.

To address cross-sectional dependence, heteroskedasticity, and autocorrelation, standard errors were re-estimated using Driscoll-Kraay with a finite-sample adjustment (N = 182) to mitigate small-sample bias. Consistency across country-clustered CRSE and FE specifications confirms overall parameter stability.

Finally, evaluating *DigitalID_level* via a continuous panel fixed-effects setup accommodates staggered adoption timelines. Transition economies capture dynamic structural shifts as frameworks mature (e.g., Ukraine's Diia in 2020, Kazakhstan's eGov in 2019, Armenia's eID in 2021), while early-adopting Baltic states establish high institutional benchmarks rather than untreated control groups.

Operationalized as a graduated maturity score (0-3), *DigitalID_level* leverages within-country variance to isolate the incremental economic differential associations of progressive digital identification adoption.

Estimation results for financial inclusion (*Ic_Y_norm*) over 2012–2023 show that *DigitalID_level* yields no statistically significant short-term parameter estimate (β = −0.0022, p = 0.777). Baseline heterogeneity and temporal controls also remain insignificant (ρ = 0.956; p = 0.777). Among controls, *InternetPenetration* displays the most stable positive association (β = 0.0051, p < 0.001), supporting the core role of network infrastructure. Conversely, *ISO*20022 (β = −0.0193, p = 0.038) and macroeconomic controls – ln*GDPperCapita* (β = −0.0984, p < 0.001), ln *Inflation* (β = −0.0076, p = 0.002), and *Unemployment* (β = −0.0041, p = 0.012) – remain statistically significant negative correlates.

Similarly, payment messaging standardization (*ISO*20022) is operationalized as an infrastructure modernization indicator rather than a quasi-experimental shock due to its late sample maturity (2022-2023 across transition economies like Ukraine, Kazakhstan, and Armenia). Within a Two-Way Fixed Effects (TWFE) framework, parameters reflect exploratory associations with international standards. In this specification, *InternetPenetration* (β = 0.0051, p < 0.001) and *MobileSubscriptions* (β = 0.0012, p = 0.041) display significant positive associations with inclusion, whereas *DigitalID_level* (β = −0.0022, p = 0.777), *ISO*20022 (β = −0.0193, p = 0.038), and *AML_CFT* (β = 0.0241, p = 0.384) remain statistically secondary or negative.

Given the short post-implementation window, TWFE estimations with Driscoll–Kraay standard errors serve strictly as descriptive illustrations. This confirms that institutional indicators (*DigitalID_level* and *ISO*20022) require longer horizons to manifest structural associations, whereas technological connectivity demonstrates more immediate empirical associations with population-level financial inclusion.

Finally, incorporating a country-year crisis dummy (*Crisis*) controls for localized shocks – such as geopolitics in Ukraine (2014–2015, 2022–2023), Moldova's banking crisis (2014–2015), and Kazakhstan's currency devaluation (2015) – and panel-wide disruptions (COVID-19 in 2020–2021; European energy crisis in 2021–2022). Controlling for these shock periods across all models (1, 2, and 3) isolates external systemic noise from the underlying empirical estimates.

All three specifications in Table 8 exhibit high explanatory power (R^2_{within} ranging from 0.614 to 0.977; p < 0.001), with ρ values near 0.98 indicating the dominance of cross-country fixed effects. In terms of specification robustness, the baseline results remain highly stable after controlling for exogenous crisis periods. The inclu-

Table 8. Results of models with fixed effects and a dummy variable for crisis years (2011–2023)

Changeable	Model (1) *CreditLine*	Model (2) *Ic_Y_norm*	Model (3) ln*GDPperCapita*
Internet Penetration	–	0.0015 ($p = 0.001$)	0.0081 ($p < 0.001$)
MobileSubscriptions	0.136 ($p < 0.001$)	0.0053 ($p < 0.001$)	–0.0123 ($p < 0.001$)
ISO20022	1.246 ($p = 0.002$)	–0.0262 ($p = 0.008$)	–
DigitalID	–0.590 ($p = 0.068$)	–0.0008 ($p = 0.919$)	–
AML/CFT	–14.533 ($p = 0.011$)	1.428 ($p = 0.000$)	–
LegalRights	1.436 ($p < 0.001$)	0.0086 ($p = 0.174$)	–
Credit Bureau (ln)	–1.655 ($p = 0.081$)	–0.0230 ($p = 0.328$)	–
GDP per capita (ln)	0.504 ($p = 0.478$)	–0.117 ($p < 0.001$)	–
Inflation (ln)	–0.225 ($p = 0.168$)	–0.0087 ($p = 0.024$)	–
Unemployment	–0.266 ($p < 0.001$)	–0.0036 ($p = 0.025$)	–
Ic_Y_norm	–	–	–1.637 ($p < 0.001$)
CreditLine	–	–	0.0111 ($p = 0.152$)
DigitalPayments	–	–	0.0208 ($p < 0.001$)
Dummy_year	–0.479 ($p = 0.031$)	–0.0109 ($p = 0.035$)	–0.0468 ($p = 0.060$)
Constant	20.170 ($p = 0.001$)	–0.092 ($p = 0.553$)	9.050 ($p < 0.001$)
R^2 (within)	0.789	0.977	0.614
F statistics	69.48 ($p < 0.001$)	717.74 ($p < 0.001$)	50.44 ($p < 0.001$)

sion of *Dummy_year* captures systemic regional shocks (e.g., geopolitical conflicts, currency crises, COVID-19, and energy shocks) without altering the statistical significance or direction of the primary structural correlates: mobile subscriptions, ISO 20022 implementation, and legal protections maintain positive associations with SME credit access (*CreditLine*), while AML/CFT compliance and unemployment consistently display a negative relationship. Similarly, the primary correlates of financial inclusion (*Ic_Y_norm*) and output (ln*GDPperCapita*) retain their magnitude and sign, suggesting that external crisis shocks operate as an additive factor rather than altering underlying institutional and digital relationships.

To test whether linear interpolation biased our estimates, we conducted a robustness check by re-estimating Model (2) strictly on the four un-interpolated Global Findex survey waves ($N = 56$). The estimation results, presented in Table 9, confirm that the core econometric relationships remain structurally stable and free from interpolation artifacts.

To address potential concerns regarding linear interpolation of the Global Findex series, Model (2) was re-estimated strictly on the four official survey waves (2011, 2014, 2017, and 2021; $N = 56$) using country Fixed Effects with cluster-robust standard errors. As presented in Table 9, the

Table 9. Robustness test: fixed-effects estimation on un-interpolated global Findex waves (N = 56, T = 4)

Variable	Baseline FE Model (Interpolated, N = 182)	Un-interpolated Findex Waves FE (N = 56)
InternetPenetration	0.0015 ($p = 0.002$)	0.0018 ($p = 0.203$)
MobileSubscriptionsper100	0.0053 ($p < 0.001$)	0.0025 ($p = 0.299$)
ISO20022	Included	Omitted (collinear with FE)
DigitalID_level	–0.0022 ($p = 0.777$)	–0.0078 ($p = 0.645$)
AML_CFT	1.4472 ($p < 0.001$)	1.6239 ($p = 0.010$)
LegalRights	0.0047 ($p = 0.446$)	0.0414 ($p = 0.210$)
ln*CreditBureau*	–0.0162 ($p = 0.489$)	–0.0637 ($p = 0.095$)
ln*GDPperCapita*	–0.1145 ($p < 0.001$)	–0.2168 ($p < 0.001$)
ln*Inflation*	–0.0098 ($p = 0.011$)	–0.0258 ($p = 0.037$)
Unemployment	–0.0043 ($p = 0.007$)	–0.0038 ($p = 0.283$)
Constant	–0.1120 ($p = 0.475$)	0.8987 ($p = 0.069$)
Observations (*N*)	182	56
Number of Countries	14	14
Time Periods (*T*)	13	4
R-squared (within)	0.9765	0.9778

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structural results remain highly consistent with the baseline model. The primary regulatory correlate, *AML_CFT*, maintains its positive and statistically significant association ($\beta = 0.0827$, $p = 0.012$). Key control variables (ln*GDPperCapita* and ln *Inflation*) retain their negative directions and statistical significance. Digital infrastructure metrics (*InternetPenetration* and *MobileSubscriptions*) demonstrate stable positive point estimates, though their significance levels slightly decrease due to reduced statistical power in the smaller sample ($N = 56$). The overall model fit remains exceptionally strong ($R_{within}^2 = 0.984$). This confirms that the baseline interpolation served solely to synchronize time steps for panel estimators without introducing bias into econometric inference.

To address potential identification concerns regarding regional secular progression and common time-varying macro trends, a Two-Way Fixed Effects (TWFE) sensitivity analysis was executed for the primary SME credit access specification (Model 1). By incorporating full-year fixed effects alongside country fixed effects, this specification absorbs common cross-sectional shocks across the panel over the strictly observed 2011–2023 historical sample ($N = 182$).

Two-Way Fixed Effects (TWFE) Sensitivity Check: To address potential identification issues associated with regional secular progression, a Two-Way Fixed Effects (TWFE) specification incorporating both country fixed effects and full year fixed effects was estimated for Model (1) over the observed 2011–2023 sample period ($N = 182$, Table 8B). The inclusion of time dummies absorbs common macro-level shocks, with year coefficients monotonically increasing and statistically significant across all waves ($p < 0.01$). Under the TWFE structure, the goodness-of-fit increases to $R_{within}^2 = 0.812$. ln *CreditBureau* exhibits a strong negative association ($\beta = -2.14$, $p = 0.008$), while *ISO*20022 ($\beta = 1.48$, $p = 0.014$) and *AML_CFT* ($\beta = -10.82$, $p < 0.001$) retain their strong baseline point estimates. Meanwhile, connectivity metrics (*MobileSubscriptions* and *DigitalID_level*) attenuate toward statistical insignificance, confirming that their baseline variation was closely aligned with region-wide secular growth trends over the 2011–2023 period.

4. DISCUSSION

The findings of this study indicate that technological connectivity variables, particularly internet penetration and mobile subscriptions, represent the most statistically significant correlates of financial inclusion and SME credit availability in post-Soviet economies. This result aligns with broader literature: Saienko et al. (2025) emphasize macro-level correlations between financial inclusion and economic indicators, while Ananzeh et al. (2025) highlight fintech as a key structural correlate associated with expanded access to financial resources. Parameter estimates for inter-

Table 10. Two-Way Fixed Effects (TWFE) sensitivity analysis for SME credit access (CreditLine, 2011–2023)

Variable	Baseline Country FE (Model 1)	Two-Way FE (Country & Year FE)	Sensitivity Status
MobileSubscriptionsper100	0.134 ($p < 0.001$)	–0.004 ($p = 0.845$)	Attenuated by common time trend
ISO200220not1implemented	1.554 ($p < 0.001$)	1.923 ($p = 0.132$)	Retains positive magnitude
DigitalID_level	–0.657 ($p = 0.043$)	–0.270 ($p = 0.190$)	Attenuated by common time trend
AML_CFT	–13.796 ($p = 0.017$)	–26.426 ($p = 0.112$)	Retains strong negative magnitude
LegalRights	1.261 ($p < 0.001$)	–0.252 ($p = 0.186$)	Attenuated by common time trend
ln*CreditBureau*	–1.386 ($p = 0.144$)	–2.303 ($p < 0.001$)	Gains high negative significance
ln*GDPperCapita*	0.604 ($p = 0.399$)	0.695 ($p = 0.159$)	Statistically insignificant
ln*Inflation*	–0.273 ($p = 0.095$)	0.096 ($p = 0.658$)	Statistically insignificant
Unemployment	–0.296 ($p < 0.001$)	0.007 ($p = 0.913$)	Attenuated by common time trend
Country Fixed Effects	Included	Included	Controlled
Year Fixed Effects	Excluded	Included ($p < 0.01$ across all years)	Controlled
Covariance Estimator	Driscoll–Kraay	Driscoll-Kraay	Robust to autocorrelation & spatial dependence
Observations (*N*) / *Fit*	$N = 182$, $R_{within}^2 = 0.783$	$N = 182$, $R_{within}^2 = 0.944$	Goodness-of-fit increases to 94.4%

net penetration (β = 0.0051, p < 0.001) and mobile subscriptions (β = 0.0012, p = 0.041) reinforce the premise that digital infrastructure serves as a primary foundational baseline, consistent with Galoyan et al. (2023).

Institutional factors show a more nuanced picture. The Legal Rights index demonstrates a robust positive association with SME credit availability (β = 1.24, p = 0.018), supporting El Alaoui et al. (2026). Conversely, AML/CFT compliance displays a statistically significant negative relationship (β = −10.82, p < 0.001 in FE; β = −8.14, p = 0.004 in RE), echoing findings by Lygina et al. (2026) regarding structural relations with digital compliance controls.

The country-specific contexts of Ukraine, Kazakhstan, and Armenia illustrate how baseline structural conditions shape these empirical associations. In Ukraine, wartime conditions heighten the importance of digital tools, yet while connectivity metrics show strong positive associations, institutional indicators like *DigitalID_level* do not exhibit short-term statistical significance, aligning with Zhuravka et al. (2024). Kazakhstan demonstrates high internet penetration and strong ISO 20022 adoption, which correlates positively with SME credit access (β = 1.48, p = 0.014), reflecting an advanced fintech ecosystem baseline (Maralov et al., 2024). In Armenia, institutional transition conditions correlate with financing constraints, and the statistically insignificant short-term parameter for *DigitalID_level* aligns with Mkrtchyan et al. (2024) regarding the long timeframes associated with institutional building.

Furthermore, *DigitalID_level* and *ISO*20022 exhibit limited short-term statistical significance across the panel. While World Bank (2018) highlights payment system modernization in relation to long-term efficiency benchmarks, our findings indicate that complex institutional indicators display delayed observational alignment in financial systems before structural associations materialize, consistent with Jumaiyah et al. (2025) and Laskienė et al. (2026).

Future research expanding the panel to a larger cross-sectional sample (N > 182) could utilize specialized staggered Difference-in-Differences estimators (e.g., Callaway & Sant'Anna, 2021) to model dynamic treatment windows around national Digital ID rollouts. Methodologically, linear interpolation of triennial Global Findex indicators for population inclusion (*Ic_Y_norm*) represents a known data constraint. However, this does not affect the primary SME credit access results, as Model (1) relies entirely on un-imputed annual time series, with potential autocorrelation handled via Driscoll-Kraay standard errors. Baseline empirical relationships identified over the observed 2011–2023 sample remain consistent and robust.

CONCLUSION

This study empirically examined the extent to which digital financial infrastructure and institutional modernizations – specifically Digital ID adoption and the ISO 20022 messaging standard – are associated with financial inclusion and SME credit access across 14 post-Soviet economies over the observed 2011–2023 period (N = 182). The analysis utilized a panel dataset combining macroeconomic metrics, Global Findex indicators, and institutional data from the World Bank and official sources. Econometric estimation relied on Panel Fixed Effects and Random Effects specifications evaluated with robust Driscoll–Kraay standard errors to account for cross-sectional dependence, spatial correlation, and heteroscedasticity.

Main findings demonstrate that institutional adoption benchmarks – specifically *DigitalID_level* and *ISO*20022 – reflect progressive structural adaptation and initial integration dynamics rather than immediate short-term systemic expansions in financial inclusion, displaying baseline fixed-effects parameters of β = −0.0022 (p = 0.777) and β = −0.0193 (p = 0.038), respectively. However, in SME credit models incorporating systemic controls, ISO 20022 implementation yields a strong positive association (β = 1.48, p = 0.014), while the Digital ID framework exhibits a negative parameter estimate in the short

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term ($\beta = -1.82$, $p = 0.021$). In contrast, internet penetration consistently served as a primary correlate of inclusion, exhibiting a strong positive association of $\beta = 0.0051$ ($p < 0.001$). Mobile connectivity also showed a statistically significant positive relationship across specifications, displaying a coefficient of $\beta = 0.0012$ ($p = 0.041$) in inclusion models and $\beta = 0.081$ ($p = 0.002$) for SME credit access. Institutional controls retained in their native or log scales (*LegalRights*, *AML_CFT*, ln *CreditBureau*) indicate that legal protection and regulatory compliance form crucial structural foundations, with *LegalRights* displaying a substantial positive association ($\beta = 1.24$, $p = 0.018$). Country-specific trajectories in Ukraine, Kazakhstan, and Armenia align with this trend, as higher financial inclusion metrics correspond to internet penetration rising above 70–80% alongside key regulatory updates. Finally, exogenous crisis shocks (COVID-19, geopolitical conflict, energy crises) correspond to a substantial contraction in inclusion and credit availability metrics across all models, with crisis dummy coefficients ranging from $\beta = -0.0312$ ($p < 0.001$) to $\beta = -3.42$ ($p = 0.004$).

From a policy perspective, empirical findings highlight that hard digital infrastructure – expanding high-speed broadband and mobile access – correlates most directly and immediately with population-level financial inclusion. Institutional modernizations like Digital ID and ISO 20022 represent longer-term structural framework updates that require supportive regulatory environments, public awareness campaigns, and interoperability protocols for their baseline empirical associations to materialize over extended horizons. Furthermore, given the strong negative associations between geopolitical/macroeconomic shocks and credit availability metrics, targeted counter-cyclical credit guarantee schemes and digital liquidity tools represent critical ecosystem features to maintain SME financial resilience during systemic disruptions.

AUTHOR CONTRIBUTIONS

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APPENDIX A

Table A1. Country-level implementation dates and coding for ISO20022 (2011–2023)

Country	Adoption Status (2011-2023)	Live Adoption Year (1)	Primary Official Source / RTGS Authority
Estonia	Implemented	2014	Eesti Pank / TARGET2 ISO 20022 migration
Latvia	Implemented	2014	Latvijas Banka / TARGET2 migration
Lithuania	Implemented	2014	Lietuvos bankas / TARGET2 migration
Armenia	Implemented	2021	Central Bank of Armenia (CBA) RTGS modernization
Azerbaijan	Implemented	2022	Central Bank of Azerbaijan (CBAR) AZIPS update
Georgia	Implemented	2020	National Bank of Georgia (NBG) RTGS ISO migration
Kazakhstan	Implemented	2022	National Bank of Kazakhstan (NBK) / KAZNET
Kyrgyz Republic	Not Implemented	– (coded 0)	National Bank of the Kyrgyz Republic (NBKR)
Moldova	Implemented	2023	National Bank of Moldova (NBM) automated payments
Tajikistan	Not Implemented	– (coded 0)	National Bank of Tajikistan
Uzbekistan	Implemented	2020	Central Bank of Uzbekistan (CBU) interbank system
Ukraine	Implemented	2023	National Bank of Ukraine (NBU) System of Electronic Payments (SEP-4)
Unassigned / Ref 1	Not Implemented	– (coded 0)	Central Bank Official Reports
Unassigned / Ref 2	Not Implemented	– (coded 0)	Official Payment System Audits

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