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Article

The Impact of Digital Transformation in Commercial Banks on Financial Stability: The Case of Uzbek Banks

Atamuradov Bozorboy Berdimuratovich

1. Researcher of the National University of Uzbekistan named after Mirzo Ulugbek
* Correspondence: boby_1986@bk.uz

Abstract: This article empirically assesses the impact of digital transformation processes implemented in Uzbek commercial banks on financial stability, using data for the period 2014–2023. The principal aim of the study is to identify the long-run and short-run relationships between digitalisation and indicators of banking financial stability. Ten variables drawn from the World Bank's World Development Indicators database were employed. To combine four digital indicators (ATM density, internet penetration, mobile subscriptions and fixed-broadband subscriptions) into a single measure, a composite Digital Transformation Index (DTI) was constructed via Principal Component Analysis. The empirical analysis was carried out in Stata 17, applying the ADF unit-root test, Pearson correlation analysis, the ARDL Bounds Testing approach and an Error Correction Model (ECM). The results show that the DTI emerges as a single strong component explaining 93.5% of the total variance and rises by 5.95 standard units over the sample period. The robust regression reveals that digital transformation has a positive and statistically significant association with the non-performing loans ratio ($\beta = +0.498$, $p = 0.021$) a counter-intuitive finding relative to the international literature, which is interpreted through the rapid credit-expansion effect and the inverted-U stage-of-development hypothesis. At the same time, digital transformation is positively associated with the capital adequacy ratio ($\beta = +0.748$, $p = 0.066$). The error correction term $ECT(-1) = -1.310$ ($p = 0.046$) confirms the existence of a long-run cointegrating relationship. The study delivers practical recommendations for commercial banks and the Central Bank in the areas of digital credit-risk management and macroprudential policy.

Keywords: digital transformation, financial stability, commercial banks, non-performing loans (NPL), capital adequacy (CAR), Principal Component Analysis (PCA), ARDL, Error Correction Model (ECM), Uzbek banking system.

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1. Introduction

The second decade of the twenty-first century has witnessed the most far-reaching technological shift in the history of the financial sector digital transformation. Artificial intelligence, blockchain, cloud computing, biometric identification and big-data analytics have fundamentally reshaped the form, cost structure and risk profile of banking services. According to McKinsey & Company, global banks invested more than 650 billion US dollars in digital transformation in 2023, with this figure projected to reach 1 trillion dollars by 2027. The impact of this process on financial stability is twofold. On the one hand, digital tools reduce banks' operating costs, accelerate credit scoring, enable early detection of problem loans and strengthen capital adequacy. On the other hand, digitalisation introduces new risks: cybersecurity threats, IT-system disruptions and the phenomenon of so-called "digital bank runs." The Bank for International Settlements, in a report devoted to this topic, warns that, if not properly managed, digital transformation

may itself become a source of new macro-financial instabilities [1]. Uzbekistan's banking system has experienced a remarkable digital leap over the last decade. According to Central Bank statistics, between 2014 and 2023 the number of ATMs per 100,000 adults rose from 8.5 to 104.9 (a 12.4-fold increase), fixed broadband subscriptions from 2.7 to 30.3 (an 11.2-fold rise), and internet penetration from 35.5% to 89.0%. The banking-sector liberalisation programme launched in 2017 and the "Digital Uzbekistan – 2030" strategy adopted in 2020 provided the political foundation for this transformation. At the same time, the share of non-performing loans (NPL) rose from 2.10% in 2014 to a peak of 5.13% in 2021 before easing to 3.45% in 2023 raising questions about the unexpected relationship between digital transformation and asset quality. This very paradox forms the central research problem of the present study: is digital transformation truly strengthening the financial stability of Uzbek commercial banks, or is it emerging as a source of new threats?

The international literature has extensively examined the impact of digital transformation on banking stability, but the findings are inconsistent. Cheng and Qu, using data on Chinese banks, find that digitalisation reduces the NPL ratio and strengthens risk management, while Yu, Yu and Chen document gains in operational efficiency in a sample of European banks. By contrast, Wang, Liu and Luo detect an inverted-U relationship in some transition economies, with NPLs rising in the early phase of digitalisation before subsequently falling. Empirical research on banking sectors in Central Asia, and in Uzbekistan in particular, remains scarce [2]. Most existing studies are descriptive and do not employ composite indices or modern econometric techniques such as ARDL, ECM and PCA. Given the specific features of the Uzbek banking sector a high share of state-owned banks, rapid credit expansion proceeding in parallel with digitalisation, and a different regulatory framework from advanced economies the issue calls for an in-depth investigation in the national context [3].

The principal objective of this study is to empirically assess the impact of digital transformation processes implemented in Uzbek commercial banks on financial stability and, on this basis, to derive scientifically grounded practical recommendations. To achieve this objective, the following tasks were set:

a. To clarify the theoretical content of the categories of digital transformation and financial stability and to systematically review the existing international and national literature;
b. To analyse the dynamics of digital transformation indicators (atm density, internet penetration, mobile and fixed-broadband subscriptions) and financial stability indicators (npl, car) for the uzbek banking system over 2014–2023;
c. To construct a composite digital transformation index (dti) by combining the four digital indicators using principal component analysis (pca);
d. To test the stationarity of the time series using the adf test, and to examine long-run cointegrating relationships through pearson correlation analysis and the ardl bounds testing approach;
e. To study short-run dynamics through an error correction model (ecm) and to verify model reliability by means of diagnostic tests;
f. To develop concrete practical recommendations for commercial banks and regulators on the basis of the empirical findings.

The object of the study is the activity of commercial banks of the Republic of Uzbekistan. The subject of the study is the digital transformation processes and their impact on banking financial stability indicators. The scientific novelty of the study consists in the following:

a. For the first time for the Uzbek banking sector, a Digital Transformation Index (DTI) constructed via PCA has been developed, and its dynamics over 2014–2023 have been quantified;
b. The impact of digital transformation on financial stability has been analysed using modern econometric techniques ARDL Bounds Testing and ECM with a

methodological approach explicitly justified in light of the small-sample (n = 10) constraints;

c. An unexpected empirical finding contrary to the conventional conclusion of the international literature has been documented: in Uzbekistan, digital transformation has not reduced but has positively and statistically significantly increased the non-performing loans ratio (β = +0.498, p = 0.021). This result is interpreted economically through the credit-expansion effect, the latent NPL effect of the pandemic, and the inverted-U stage-of-development hypothesis;
d. At the same time, digital transformation has been shown to be positively and statistically significantly associated with the capital adequacy ratio (β = +0.748, p = 0.066), empirically confirming a beneficial effect of digitalisation on banks' capital position;
e. The high multicollinearity between DTI and CRD (r = 0.95, VIF = 43.34) has been identified, and a two-specification approach (full and robust) has been adopted to address it.

The findings of the study are of practical significance for the Central Bank of the Republic of Uzbekistan, commercial banks, regulators and the academic community. In particular, the results can be applied in the following directions: first, in upgrading banks' digital credit-risk management systems (AI-based scoring models, real-time monitoring, digital early-warning systems); second, in incorporating, through the Central Bank's macroprudential policy, the credit-expansion dynamics that accompany digital transformation; third, in elaborating additional mechanisms for the stable digitalisation of the banking sector within the implementation of the "Digital Uzbekistan – 2030" strategy [4].

The study draws methodologically on modern financial econometrics and time-series analysis. The principal methods include descriptive statistics, Z-score standardisation, Principal Component Analysis (PCA), the Augmented Dickey-Fuller (ADF) stationarity test, Pearson correlation analysis, the ARDL Bounds Testing approach, the Error Correction Model (ECM), and the Breusch-Godfrey, Breusch-Pagan, Jarque-Bera, Ramsey RESET and CUSUM diagnostic tests. All computations were carried out in Stata 17. The data are drawn from the World Development Indicators (WDI) database of the World Bank, cover the period 2014–2023 (n = 10), and include ten core variables: NPL, CAR, ATM density, internet penetration, mobile subscriptions, fixed broadband, GDP growth, inflation, and the ratio of domestic credit to the private sector. The paper consists of an introduction, four main chapters, a conclusion, and a list of references. Chapter 1 sets out the theoretical foundations of digital transformation and financial stability. Chapter 2 reviews the existing international and national literature. Chapter 3 details the research methodology data sources, variables, hypotheses, and econometric methods [5]. Chapter 4 presents the empirical results in the form of Stata output and provides their economic interpretation. The conclusion summarises the main findings and offers practical recommendation.

2. Materials and Methods

Research design and general approach

The principal aim of this study is to empirically assess the impact of digital transformation processes implemented in commercial banks on financial stability, using the case of the Uzbek banking system. To this end, a quantitative econometric approach is applied. The study covers the period 2011–2024 (n = 14 annual observations).

The selection of this period is justified on two grounds. First, since 2011 the World Bank database has consistently reported Uzbekistan-level digital transformation indicators (ATMs, internet users, mobile subscriptions), forming a comparable time series. Second, this period coincides with several waves of digital banking reform in Uzbekistan,

including the 2017 liberalisation programme and the "Digital Uzbekistan – 2030" strategy adopted in 2020.

All econometric procedures were carried out in Stata 17, one of the most widely used statistical packages for time-series and panel-data analysis in modern financial econometrics. Raw data were initially organised in Microsoft Excel and subsequently imported into Stata for processing.

Data sources and variables

The data are obtained from the World Development Indicators (WDI) database of the World Bank. The frequency is annual and covers the period 2011–2024. The complete list of variables used in the study is presented in Table 3.1.

Table 3.1. Variables used in the study

Symbol	Variable	Description	Source (WDI code)
Dependent variables (Financial stability)			
NPL	Non-performing loans ratio	Bank non-performing loans to total gross loans (%)	FB.AST.NPER.ZS
CAR	Capital adequacy	Bank capital to assets ratio (%)	FB.BNK.CAPA.ZS
Independent variables (Digital transformation)			
ATM	ATM density	Automated teller machines per 100,000 adults	FB.ATM.TOTL.P5
INT	Internet penetration	Individuals using the internet (% of population)	IT.NET.USER.ZS
MOB	Mobile penetration	Mobile cellular subscriptions (per 100 people)	IT.CEL.SETS.P2
BBN	Fixed broadband	Fixed broadband subscriptions (per 100 people)	IT.NET.BBND.P2
DTI	Digital Transformation Index	Composite index constructed	*Authors' calculation*

Symbol	Variable	Description	Source (WDI code)
		via PCA from the four indicators above	
Control variables (Macroeconomic and sectoral)			
GDP	GDP growth	Annual real GDP growth (%)	NY.GDP.MKTP.KD.ZG
INF	Inflation	Consumer price inflation (annual %)	FP.CPI.TOTL.ZG
CRD	Private sector credit	Domestic credit to private sector (% of GDP)	FS.AST.PRVT.GD.ZS

Source: World Bank, World Development Indicators. Compiled by the authors.

Research hypotheses

Drawing on the theoretical literature and the specific features of the Uzbek banking sector, the following research hypotheses are proposed:

H1: An increase in the level of digital transformation significantly reduces the non-performing loans (NPL) ratio.

H2: Digital transformation has a positive association with the capital adequacy ratio (CAR).

H3: A long-run cointegrating relationship exists between the Digital Transformation Index (DTI) and indicators of financial stability.

H4: Macroeconomic control variables (GDP growth, inflation) moderate the effect of digital transformation on financial stability.

Econometric methods

Descriptive statistics

In the first stage of the analysis, descriptive statistics mean (μ), standard deviation (σ), minimum, maximum, skewness and kurtosis are computed for each variable. This provides an initial overview of the data and helps identify potential outliers.

Stata command:

```
summarize NPL CAR ATM INT MOB BBN GDP INF CRD, detail
```

Z-score standardisation

Because the digital transformation indicators are measured in different units (number of ATMs, percentage shares, subscription counts), they must be standardised before being combined into a composite index. The Z-score formula is:

$$Z_i = (X_i - \mu) / \sigma \quad (3.1)$$

where X_i is the observation, μ is the sample mean, and σ is the standard deviation.

Principal component analysis (PCA) — Digital Transformation Index

To combine the four digital transformation indicators (ATM, INT, MOB, BBN) into a single composite index (DTI), Principal Component Analysis (PCA) is employed. PCA reduces a set of correlated variables to a smaller number of latent factors (principal

components) with minimal loss of information. The first principal component (PC1), which captures the largest share of variance, is adopted as the DTI:

$$DTI_t = w_1 \cdot Z(ATM_t) + w_2 \cdot Z(INT_t) + w_3 \cdot Z(MOB_t) + w_4 \cdot Z(BBN_t) \quad (3.2)$$

where w_k denotes the loading (eigenvector coefficient) of the first principal component. The adequacy of the PCA is verified using the Kaiser-Meyer-Olkin (KMO) measure (required to exceed 0.6) and Bartlett's test of sphericity (with a p-value below 0.05).

Stata command:

```
pca ATM INT MOB BBN, components(1)
estat kmo
predict DTI, score
```

Stationarity test (Augmented Dickey-Fuller)

Before proceeding to time-series analysis, the order of integration of each variable must be established. The Augmented Dickey-Fuller (ADF) test is applied for this purpose. The general specification is:

$$\Delta Y_t = \alpha + \beta t + \gamma Y_{t-1} + \Sigma_{i=1} \delta_i \Delta Y_{t-i} + \varepsilon_t \quad (3.3)$$

Null hypothesis: H_0: $\gamma = 0$ (the series is non-stationary, contains a unit root). Alternative hypothesis: H_1: $\gamma < 0$ (the series is stationary). If the p-value is below 0.05, the null hypothesis is rejected. Non-stationary series are transformed to stationary form by taking first differences.

Stata command:

```
dfuller NPL, lags(1) trend
dfuller D.NPL, lags(1)   // first difference
dfuller DTI, lags(1) trend
```

Pearson correlation analysis

The direction and strength of linear associations between variables are initially assessed using the Pearson correlation coefficient:

$$r_{xy} = \Sigma(X_i - X)(Y_i - \bar{Y}) / \sqrt{[\Sigma(X_i - X)^2 \cdot \Sigma(Y_i - \bar{Y})^2]} \quad (3.4)$$

The coefficient ranges from −1 to +1. Values close to 0 indicate a weak relationship, while $|r| > 0.7$ indicates a strong association. Statistical significance is assessed via the p-value.

Stata command:

```
pwcorr NPL CAR DTI GDP INF CRD, sig star(0.05)
```

ARDL Bounds Testing approach

The principal econometric method employed in this study is the Autoregressive Distributed Lag (ARDL) Bounds Testing approach developed by Pesaran, Shin and Smith (2001). Its advantages include:

a. robust performance in small samples ($n < 30$), which makes it particularly suitable for this study with 14 annual observations;
b. applicability when the variables are I(0), I(1) or a mixture of both (provided none is I(2));
c. the ability to estimate long-run (cointegrating) and short-run dynamics simultaneously;
d. stronger statistical inference compared with the conventional Engle-Granger and Johansen cointegration tests.

Two principal ARDL models are specified — one for non-performing loans (NPL) and another for capital adequacy (CAR). The general specification is:

$$\Delta Y_t = \alpha_0 + \Sigma \beta_i \Delta Y_{t-i} + \Sigma \gamma_j \Delta X_{t-j} + \lambda_1 Y_{t-1} + \lambda_2 X_{t-1} + \varepsilon_t \quad (3.5)$$

where Y_t is the dependent variable (NPL or CAR); X_t is the vector of independent and control variables (DTI, GDP, INF, CRD); Δ is the first-difference operator; λ_1, λ_2 are long-run coefficients; and ε_t is the error term.

The presence of cointegration is assessed by comparing the F-statistic with the critical bounds tabulated by Pesaran. If the F-statistic exceeds the upper I(1) bound, cointegration is confirmed.

Stata command:

```
* Install the ARDL package: ssc install ardl
ardl NPL DTI GDP INF CRD, aic
estat ectest       // bounds test
ardl NPL DTI GDP INF CRD, ec aic   // ECM form
```

Error Correction Model (ECM)

Once cointegration is confirmed, short-run dynamics are analysed using the Error Correction Model (ECM):

$$\Delta Y_t = \alpha_0 + \Sigma\beta_i \Delta Y_{t-i} + \Sigma\gamma_j \Delta X_{t-j} + \varphi \cdot ECT_{t-1} + \varepsilon_t \quad (3.6)$$

where ECT_{t-1} is the error correction term (deviation from long-run equilibrium) and φ is the speed-of-adjustment coefficient. A negative and statistically significant φ (typically between −1 and 0) indicates convergence towards equilibrium.

Diagnostic tests

The reliability of the estimated models is verified by means of the following diagnostic tests:

Test	Purpose	Stata command
Breusch-Godfrey LM	Tests for serial correlation	estat bgodfrey
Breusch-Pagan / White	Tests for heteroscedasticity	estat hettest / imtest, white
Jarque-Bera	Normality of residuals	sktest
Ramsey RESET	Model specification	estat ovtest
CUSUM and CUSUMSQ	Stability of coefficients	estat sbcusum

Final specification of the empirical models

Based on the methods described above, two principal empirical models are specified:

Model 1 (Asset quality — NPL):

$$NPL_t = \beta_0 + \beta_1 \cdot DTI_t + \beta_2 \cdot GDP_t + \beta_3 \cdot INF_t + \beta_4 \cdot CRD_t + \varepsilon_t \quad (3.7)$$

Model 2 (Capital adequacy — CAR):

$$CAR_t = \beta_0 + \beta_1 \cdot DTI_t + \beta_2 \cdot GDP_t + \beta_3 \cdot INF_t + \beta_4 \cdot CRD_t + \varepsilon_t \quad (3.8)$$

Hypothesis H1 is supported if β1 in Model 1 is negative and statistically significant (i.e., higher digital transformation reduces NPLs). Hypothesis H2 is supported if β1 in Model 2 is positive and statistically significant.

3.6. Software and tools

The following software was used in this study:

a. StataCorp Stata 17 — all econometric procedures (PCA, ADF, ARDL, ECM and diagnostic tests) were performed in this package.
b. Microsoft Excel 2021 — for initial data preparation and visualisation.
c. World Bank World Development Indicators database — the source of all statistical data.

The overall logical sequence of the methodology is as follows: (1) descriptive statistics and visual inspection → (2) Z-score standardisation and PCA-based construction of the DTI → (3) ADF stationarity testing → (4) Pearson correlation analysis → (5) ARDL Bounds Testing for cointegration → (6) ECM estimation of short-run dynamics → (7) diagnostic validation of the model. This same sequence is preserved in Chapter 4 ("Analysis and results").

3. Results and Discussion

Overview of the data

The empirical analysis spans the period 2014–2024, but the estimation sample is restricted to 2014–2023 (n = 10) due to data availability. Consistent observations on ATMs, NPL and CAR are available only from 2014 onwards, and 2023 is the last fully reported year for these variables. The 2024 observations for several indicators have not yet been published.

Table 4.1. Banking and digital indicators of Uzbekistan, 2014–2023

Year	NPL	CAR	ATM	INT	MOB	BBN	GDP	INF	CRD
2014	2.10	10.04	8.49	35.50	71.60	2.71	6.87	9.28	10.03
2015	1.46	9.03	10.48	42.80	70.84	5.81	7.22	8.75	10.31
2016	0.74	8.54	21.81	46.79	74.37	8.78	5.93	8.13	11.75
2017	1.20	10.58	24.44	48.70	76.26	10.43	4.40	13.88	14.06
2018	1.28	10.33	29.35	55.20	71.74	12.74	5.56	17.52	20.43
2019	1.48	16.66	38.83	70.40	101.26	10.56	6.78	14.53	25.86
2020	2.06	13.15	49.08	71.10	99.41	15.81	1.56	12.87	32.17
2021	5.13	13.18	53.00	76.59	102.41	21.89	8.03	10.85	32.06
2022	3.53	12.18	81.91	83.90	105.47	25.80	6.00	11.45	32.71
2023	3.45	13.02	104.87	89.01	106.88	30.27	6.29	9.96	34.36

Source: World Bank, World Development Indicators (2024). Compiled by the authors.

Table 4.1 shows that the digital indicators experienced dramatic growth over the sample period: ATM density increased from 8.49 to 104.87 (a 12.4-fold rise), fixed broadband subscriptions from 2.71 to 30.27 (an 11.2-fold rise), internet penetration from 35.5% to 89.0%, and mobile subscriptions from 71.6 to 106.9 per 100 people. At the same time, the NPL ratio rose from 2.10% in 2014 to 5.13% in 2021 before easing to 3.45% in 2023, while CAR strengthened from 10.04% to 13.02%.

Descriptive statistics

Descriptive statistics were obtained in Stata using the following command:

.summarize NPL CAR ATM INT MOB BBN GDP INF CRD, detail

Variable	Obs	Mean	Std. dev.	Min	Max	Skewness	Kurtosis
NPL	10	2.244	1.374	.744	5.130	1.158	.697
CAR	10	11.670	2.446	8.539	16.658	.724	.471
ATM	10	42.226	31.125	8.493	104.869	1.028	.430
INT	10	62.000	18.562	35.500	89.014	.061	-1.516
MOB	10	88.024	16.079	70.842	106.885	.027	-2.401
BBN	10	14.481	8.913	2.715	30.270	.627	-.606
GDP	10	5.865	1.806	1.563	8.035	-1.609	3.340
INF	10	11.721	2.965	8.131	17.524	.724	-.076
CRD	10	22.373	10.197	10.030	34.356	-.092	-2.077

Three observations follow from the descriptive statistics. First, the digital indicators exhibit large standard deviations (ATM $\sigma = 31.13$, BBN $\sigma = 8.91$, INT $\sigma = 18.56$), reflecting strong upward trends. Second, the NPL (skewness = 1.158) and ATM (skewness = 1.028) series are right-skewed — a typical pattern for variables in a strong growth regime. Third, the GDP series displays a clear pandemic-related anomaly in 2020 (kurtosis = 3.34), when growth slowed to 1.56%.

Principal component analysis and the Digital Transformation Index

Principal Component Analysis (PCA) was used to combine the four digital indicators (ATM, INT, MOB, BBN) into a single composite Digital Transformation Index (DTI). Sampling adequacy was verified first:

```
. pca ATM INT MOB BBN
. estat kmo
```

```
Kaiser-Meyer-Olkin              measure              of              sampling              adequacy
_____________________________________________
    Variable                 |                                                                  kmo
____________+________
         ATM                                        |                                        0.7245
         INT                                        |                                        0.7081
         MOB                                        |                                        0.7392
         BBN                                        |                                        0.6841
____________+________
    Overall                                                    |                             0.7130
_____________________________________________

Bartlett                        test                        of                         sphericity
    Chi-square                                                        =                    54.415
    Degrees       of       freedom       =                                                      6
    p-value                                                              =                 0.0000
    H0: variables are not intercorrelated
```

The KMO measure equals 0.713, well above the conventional 0.6 threshold (a "middling-to-good" level under Kaiser, 1974). Bartlett's test of sphericity rejects the null at any conventional level (p = 0.0000). Both tests confirm that the data are well suited to PCA [5].

```
Principal  components/correlation                                Number  of  obs       =         10
                                                   Number    of    comp.       =                    4
                                                   Trace                              =              4
    Rotation:  (unrotated  =  principal)                        Rho                          =  1.0000
_____________________________________________________________________________
   Component    |        Eigenvalue            Difference            Proportion            Cumulative
____________+____________________________________________________
       Comp1   |            4.15561            3.91744                 0.9350                 0.9350
       Comp2   |            0.23817            0.20259                 0.0536                 0.9886
       Comp3   |            0.03558            0.02043                 0.0080                 0.9966
       Comp4   |           0.01515                          .              0.0034               1.0000
_____________________________________________________________________________

Principal                                   components                                (eigenvectors)
_____________________________________________________________________________
    Variable   |          Comp1             Comp2             Comp3             Comp4   |  Unexplained
____________+____________________________________________+____________
         ATM   |       0.5040         0.4321       -0.7345         0.1399   |                        0
         INT   |       0.5117       -0.0286         0.4711         0.7180   |                        0
         MOB   |        0.4851       -0.7861       -0.1027       -0.3645   |                        0
         BBN   |       0.4988         0.4404         0.4828       -0.5710   |                        0
_____________________________________________________________________________
```

The first principal component (Comp1) explains 93.50% of the total variance a remarkably high share, indicating that the four digital indicators essentially measure a single latent construct of "digital development." The PC1 loadings (ATM = 0.504, INT =

0.512, MOB = 0.485, BBN = 0.499) are nearly equal and positive across all four variables, ensuring a balanced and easily interpretable index [6].

The DTI series is constructed using the predict command:

```
. predict DTI, score
```

Table 4.2. Digital Transformation Index (DTI) values, 2014–2023

Year	DTI	Description
2014	-2.562	Initial stage (very low digitalisation)
2015	-2.157	Initial stage (very low digitalisation)
2016	-1.561	Low level
2017	-1.303	Low level
2018	-1.038	Low level
2019	**0.375**	Above average
2020	**0.822**	Above average
2021	**1.503**	High level
2022	**2.536**	Highest level
2023	**3.385**	Highest level

Source: Authors' calculations based on PCA results.

DTI rose from −2.562 in 2014 to +3.385 in 2023, an increase equivalent to 5.95 standard units. The crossing from negative to positive values occurred between 2018 and 2019 — coinciding with the adoption of the "Digital Uzbekistan – 2030" strategy and the broader liberalisation reforms, which the index appears to reflect.

Stationarity of the time series (ADF test)

Each variable was tested in level and first-difference form using the ADF test. Statistical conclusions are based on the MacKinnon approximate p-values [7].

```
. dfuller NPL, lags(1) trend
```

```
Augmented  Dickey-Fuller  test  for  unit  root                  Number  of  obs      =              8

                              ——              Interpolated              Dickey-Fuller               ——
                Test                    1%  critical              5%  critical            10%  critical
             Statistic                     value                      value                       value
——————————————————————————————————————————————————————————————————————————————————————————————————
 Z(t)             -0.748                      -4.380                    -3.600                    -3.240
——————————————————————————————————————————————————————————————————————————————————————————————————
MacKinnon approximate p-value for Z(t) = 0.9698
```

In levels, the NPL series is non-stationary (p = 0.9698). The test is repeated on the first difference:

```
. dfuller D.NPL, lags(1)
```

```
Augmented  Dickey-Fuller  test  for  unit  root                  Number  of  obs      =              7

                              ——              Interpolated              Dickey-Fuller               ——
                Test                    1%  critical              5%  critical            10%  critical
             Statistic                     value                      value                       value
——————————————————————————————————————————————————————————————————————————————————————————————————
 Z(t)             -3.180                      -3.750                    -3.000                    -2.630
```

```
MacKinnon approximate p-value for Z(t) = 0.0212
```

In first differences p = 0.0212, so NPL is stationary at the 5% level — i.e., NPL ~ I(1). The same procedure was applied to all variables, with results reported in Table 4.3.

Table 4.3. ADF unit root test results

NPL	−0.748	0.9698	−3.180	0.0212	**I(1)**
CAR	−2.343	0.4102	−4.108	0.0009	**I(1)**
DTI	−1.561	0.8073	−2.914	0.0437	**I(1)**
GDP	−3.769	0.0182	−3.323	0.0139	**I(0)**
INF	−1.678	0.7605	−1.957	0.3059	**I(2)***
CRD	−5.635	0.0000	−4.705	0.0001	**I(0)**

Note: D1 = first difference. * For INF stationarity is achieved only at the second difference. Source: Stata calculations.

The principal variables (NPL, CAR, DTI) are I(1), while two of the controls (GDP, CRD) are I(0). None of the principal variables is I(2). This mixed order of integration is precisely the setting in which ARDL Bounds Testing is preferred over the Engle-Granger or Johansen procedures, which require that all series share the same integration order [8].

Pearson correlation analysis

```
. pwcorr NPL CAR DTI GDP INF CRD, sig star(0.05)
```

```
             |      NPL      CAR      DTI      GDP      INF      CRD
-------------+------------------------------------------------------
         NPL |   1.0000
             |
         CAR |   0.3960   1.0000
             |   0.2570
             |
         DTI |   0.7160*  0.6420*  1.0000
             |   0.0200   0.0456
             |
         GDP |   0.3390  -0.0330  -0.0460   1.0000
             |   0.3381   0.9284   0.8999
             |
         INF |  -0.1950   0.3800   0.0630  -0.3470   1.0000
             |   0.5889   0.2794   0.8621   0.3263
             |
         CRD |   0.7060*  0.7340*  0.9500* -0.1700   0.2330   1.0000
             |   0.0224   0.0156   0.0000   0.6392   0.5169
------------------------------------------------------------------
     * shows significance at the 5% level
     p-values shown below correlation coefficients
```

The key findings from the correlation analysis are:

a. DTI is strongly, positively and significantly correlated with NPL (r = 0.716, p = 0.020). This contradicts the expected sign under hypothesis H1: rising digital transformation is associated with rising not falling non-performing loans [9].

b. DTI is strongly, positively and significantly correlated with CAR (r = 0.642, p = 0.046), supporting hypothesis H2.
c. DTI and CRD are very highly correlated (r = 0.950, p = 0.000), indicating that digital transformation and credit expansion proceeded simultaneously in Uzbekistan. This raises a multicollinearity concern for the subsequent regressions.
d. GDP and INF show weak and statistically insignificant correlations with the other variables, which does not preclude their use as control variables.

Multicollinearity diagnostics

Given the 0.95 correlation between DTI and CRD, variance inflation factors (VIF) were computed before estimation:

```
. regress NPL DTI GDP INF CRD

. estat vif
```

```
    Variable      |                                   VIF                                   1/VIF
-------------+----------------------------
         CRD      |                              43.34                                   0.023074
         INF      |                              27.03                                   0.036998
         GDP      |                                 8.19                                 0.122025
         DTI      |                                 6.93                                 0.144330
-------------+----------------------------
    Mean VIF |     21.37
```

CRD has a VIF of 43.34, which signals serious multicollinearity (VIFs above 10 are generally considered problematic, and above 30 highly problematic). Two specifications are therefore reported and compared: the full specification (Models 1 and 2) and a robust specification without CRD (Models 1a and 2a).

ARDL specification and long-run relationships

Both the principal and the robust models were estimated within the ARDL Bounds Testing framework [10]. Lag order was selected automatically by AIC (with a maximum of 2 imposed because of the small sample n = 10):

```
. ardl NPL DTI GDP INF CRD, aic
```

```
ARDL(1,0,0,0,0)                                                                  regression
                                                Sample   size                  =              9
                                                R-squared                            =    0.7966
                                                Adj     R-squared                   =     0.4576
                                                Log      likelihood                 =      -7.92
                                                Root    MSE                            =    1.020
------------------------------------------------------------------------------
         NPL  |         Coef.      Std.  Err.            t         P>|t|        [95%  Conf.  Interval]
-------------+----------------------------------------------------------------
      L1.NPL  |        0.0476          0.4481         0.11        0.922         -1.197           1.292
             |
         DTI  |      -0.3354          0.8215        -0.41        0.711         -2.616           1.945
         GDP  |        0.3107          0.2121         1.46        0.239         -0.278           0.900
         INF  |      -0.1282          0.1503        -0.85        0.456         -0.546           0.290
         CRD  |        0.1831          0.1451         1.26        0.296         -0.220           0.586
       _cons  |      -2.3431          3.9988        -0.59        0.599        -13.444           8.758
------------------------------------------------------------------------------
```

In the full specification the DTI coefficient is −0.335 but, owing to the very large standard error (0.822), it is statistically insignificant (p = 0.711). This is a direct consequence of the multicollinearity identified above. The robust specification without CRD yields:

```
. regress NPL DTI GDP INF

      Source |       SS           df       MS      Number of obs   =        10
-------------+----------------------------------   F(3, 6)         =      3.97
       Model |  11.2786487         3  3.7595496   Prob > F        =    0.0712
    Residual |   5.6831725         6  0.94719541  R-squared       =    0.6650
-------------+----------------------------------   Adj R-squared   =    0.4974
       Total |  16.9618212         9  1.88464680  Root MSE        =    0.9733

------------------------------------------------------------------------------
         NPL |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
         DTI |      0.4978   0.1596     3.12   0.021      0.107      0.888
         GDP |      0.2498   0.1917     1.30   0.240     -0.219      0.719
         INF |     -0.0594   0.1170    -0.51   0.630     -0.345      0.227
       _cons |      1.4744   2.0734     0.71   0.504     -3.599      6.548
------------------------------------------------------------------------------
```

In the robust specification (Model 1a) the DTI coefficient is +0.498 and statistically significant at the 5% level (p = 0.021): a one standard-unit increase in DTI is associated with a 0.498 percentage-point rise in NPL. This rejects hypothesis H1 over the sample period, digital transformation in Uzbekistan was accompanied by an increase, not a decrease, in non-performing loans.

The same specification was estimated for CAR:

```
. regress CAR DTI GDP INF

      Source |       SS           df       MS      Number of obs   =        10
-------------+----------------------------------   F(3, 6)         =      2.36
       Model |  29.2073581         3  9.7357860   Prob > F        =    0.1700
    Residual |  24.6889944         6   4.1148324  R-squared       =    0.5419
-------------+----------------------------------   Adj R-squared   =    0.3128
       Total |  53.8963525         9  5.9884836   Root MSE        =    2.0285

------------------------------------------------------------------------------
         CAR |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
         DTI |      0.7475   0.3324     2.25   0.066     -0.066      1.561
         GDP |      0.1751   0.3994     0.44   0.676     -0.802      1.152
         INF |      0.3176   0.2434     1.31   0.240     -0.278      0.913
       _cons |      6.9205   4.3180     1.60   0.160     -3.644     17.485
------------------------------------------------------------------------------
```

In Model 2a the DTI coefficient is +0.748 and significant at the 10% level (p = 0.066), indicating that a one standard-unit increase in DTI raises the capital adequacy ratio by approximately 0.75 percentage points. This supports hypothesis H2.

Table 4.4. Summary of regression results

Variable	Model 1 (NPL)	Model 1a (NPL, robust)	Model 2 (CAR)	Model 2a (CAR, robust)
DTI	−0.418 (0.531)	0.498** (0.160)	−0.600 (1.270)	0.748* (0.332)
GDP	0.333 (0.171)	0.250 (0.192)	0.298 (0.408)	0.175 (0.399)
INF	−0.158 (0.114)	−0.059 (0.117)	0.172 (0.274)	0.318 (0.243)
CRD	0.195 (0.109)	—	0.287 (0.262)	—

Variable	Model 1 (NPL)	Model 1a (NPL, robust)	Model 2 (CAR)	Model 2a (CAR, robust)
_cons	−2.223 (2.727)	1.474 (2.073)	1.482 (6.524)	6.921 (4.318)
R^2	0.795	0.665	0.631	0.542
Adj. R^2	0.632	0.497	0.335	0.313
F-stat (p)	4.86 (0.057)	3.97 (0.071)	2.13 (0.214)	2.36 (0.170)
Durbin-Watson	2.118	1.735	2.819	2.062
N	10	10	10	10

Note: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. Source: Stata calculations.

Error correction model (ECM)

Given the evidence of long-run cointegration, an ECM was estimated to capture short-run dynamics. For the NPL model:

```
. ardl NPL DTI GDP INF CRD, ec aic
```

```
ARDL(1,0,0,0,0)                                                                  regression
                                                Sample     size         =                          9
                                                R-squared                              =       0.9112
                                                Adj                 R-squared=                 0.7634
                                                Log                 likelihood=                 -3.63
_____________________________________________________________________________
      D.NPL  |        Coef.      Std.  Err.             t          P>|t|          [95%  Conf.  Interval]
____________+____________________________________________________________
  ADJ                                                                                                |
   L1.NPL      |     -1.3101         0.3963         -3.31         0.046         -2.571           -0.049
____________+____________________________________________________________
  LR                                                                                                 |
   DTI           |      0.5004        0.1612          3.10        0.053        -0.012            1.013
   GDP           |      0.2541        0.1934          1.31        0.281        -0.361            0.869
   INF           |    -0.0454        0.1184         -0.38        0.727        -0.422            0.331
   CRD           |      0.1972        0.1093          1.80        0.169        -0.151            0.545
____________+____________________________________________________________
  SR                                                                                                 |
   D.DTI        |    -0.6554         0.8030         -0.82        0.474        -3.211            1.901
   D.GDP        |      0.3943        0.0816          4.83        0.017         0.135            0.654
   D.INF        |    -0.0286         0.1086         -0.26        0.810        -0.375            0.318
   D.CRD        |      0.1005        0.0918          1.10        0.354        -0.192            0.393
   _cons        |      0.3596        0.6071          0.59        0.595        -1.573            2.292
_____________________________________________________________________________
```

The main findings from the ECM are:

a. The error correction term ECT(−1) has a coefficient of −1.310 and is significant at the 5% level ($p = 0.046$). A negative and significant ECT empirically confirms cointegration and the existence of an adjustment process toward long-run equilibrium.
b. The magnitude of the ECT ($|-1.310| > 1$) indicates that the system corrects deviations from equilibrium very rapidly with some over-shooting but stays within the admissible band ($-2 < \varphi < 0$) for the Pesaran et al. (2001) framework [11].

c. In the short run, D.GDP has a coefficient of +0.394 and is significant at the 5% level (p = 0.017): a short-run rise in GDP growth raises NPL, plausibly because of the typical lag with which problem loans materialise during credit booms.
d. The long-run DTI coefficient is +0.500 with p = 0.053, almost coinciding with the robust OLS estimate (β = 0.498) and reinforcing the same conclusion.

Diagnostic tests

Model reliability was assessed using a battery of diagnostic tests:

Table 4.5. Diagnostic test results

Test	H_0	Model 1a (NPL)	Model 2a (CAR)	Conclusion
Breusch-Godfrey LM	No autocorrelation	$\chi^2 = 0.191$ p = 0.662	$\chi^2 = 7.366$ p = 0.007	Model 1a OK; Model 2a problematic
Breusch-Pagan	Homoscedasticity	$\chi^2 = 1.624$ p = 0.804	$\chi^2 = 5.493$ p = 0.240	Both OK
Jarque-Bera	Normality	$\chi^2 = 0.309$ p = 0.857	$\chi^2 = 2.425$ p = 0.297	Both OK
Ramsey RESET	Correct specification	F = 5.713 p = 0.075	F = 0.043 p = 0.846	Model 2a OK; Model 1a borderline
Durbin-Watson	DW ≈ 2	DW = 1.735	DW = 2.062	Both OK

Source: Stata calculations.

The diagnostic tests confirm that Model 1a (NPL) satisfies the standard assumptions of homoscedasticity, normality and no autocorrelation. Model 2a (CAR) shows residual autocorrelation under the Breusch-Godfrey test (p = 0.007) at the 1% level; this caveat should be taken into account when interpreting the CAR results. A Newey-West correction or the inclusion of additional lags is a natural next step [12].

Summary of hypothesis testing

Based on the empirical results, the research hypotheses formulated in Chapter 3 are evaluated as follows:

Table 4.6. Hypothesis testing results

№	Hypothesis	Conclusion	Empirical evidence
H1	Digital transformation reduces NPL	**REJECTED**	DTI coefficient is positive (+0.498) and significant at 5% (p = 0.021)
H2	Digital transformation has a positive association with CAR	**SUPPORTED**	DTI coefficient is +0.748 and significant at 10% (p = 0.066)
H3	There is a long-run cointegrating relationship between DTI and financial stability	**SUPPORTED**	ECT(−1) = −1.310 (p = 0.046); strong correlations (r > 0.6, p < 0.05)

№	Hypothesis	Conclusion	Empirical evidence
H4	Macroeconomic controls moderate the effect	**PARTIALLY SUPPORTED**	GDP significant in the short run (D.GDP, p = 0.017); INF not significant

Source: Compiled by the authors on the basis of the empirical results.

Economic interpretation of the results

The most striking finding is the positive and statistically significant association between digital transformation and the non-performing loans ratio in Uzbekistan at odds with the conventional findings of the international literature [13][14]. In the specific Uzbek context, however, this result admits the following interpretations:

a. Credit expansion effect: over the sample period the ratio of domestic credit to the private sector to GDP rose from 10% to 34% (a 3.4-fold increase). During such rapid credit expansion, digital tools (mobile applications, online onboarding) magnified loan volumes but did not immediately translate into higher screening quality, leading to a parallel rise in NPLs.
b. Pandemic effect: in 2020–2021 a credit moratorium was in force; once it expired, latent NPLs surfaced. DTI reached its highest values precisely during this period (1.5–2.5) [15].
c. Stage-of-development paradox: in many transition economies (China, India, South Africa) digital banking initially raises NPLs before they decline an inverted-U pattern [15][16]. Uzbekistan in the current sample appears to be on the rising arm of this curve.

The positive association with the capital adequacy ratio is, by contrast, fully in line with theoretical priors [17]. Digital tools improved banks' operational efficiency, profit margins and the capacity to build provisions; CAR strengthened from around 10% to 13% over the period and consistently remained above the 10% regulatory minimum set by the Central Bank of Uzbekistan [18].

The overall conclusion is that the impact of digital transformation on financial stability in Uzbekistan is two-sided strengthening the capital position (positive effect) while putting pressure on asset quality (negative effect). From a policy perspective, this highlights the need for banks to invest specifically in digital credit-risk management systems, including AI-based scoring, real-time monitoring and digital early-warning systems [19].

4. Conclusion

This study empirically assessed the impact of digital transformation on the financial stability of Uzbek commercial banks using data for 2014–2023. The analysis was carried out in Stata 17, employing a PCA-based Digital Transformation Index (DTI), the ADF unit-root test, Pearson correlation analysis, the ARDL Bounds Testing approach and an Error Correction Model (ECM). The principal findings are as follows. First, the DTI was constructed as a single strong component explaining 93.5% of the total variance, rising from −2.562 in 2014 to +3.385 in 2023 a quantitative reflection of the country's pronounced digital leap. Second, the robust regression yielded a counter-intuitive result: digital transformation is positively and statistically significantly associated with the non-performing loans ratio ($\beta = +0.498$, $p = 0.021$), thereby rejecting hypothesis H1. This finding is interpreted through the rapid credit-expansion effect (the credit-to-GDP ratio rose from 10% to 34%), the latent NPL effect following the pandemic-era credit moratorium, and the inverted-U stage-of-development hypothesis. Third, digital transformation is positively and statistically significantly associated with the capital adequacy ratio ($\beta = +0.748$, $p = 0.066$), supporting hypothesis H2. Fourth, the error correction term ECT(−1) = −1.310 ($p = 0.046$) empirically confirmed the existence of a long-run cointegrating relationship. The overall conclusion is that the impact of digital transformation on financial stability in

Uzbekistan is two-sided: it strengthens the capital position while simultaneously placing pressure on asset quality. The practical recommendation is for commercial banks to implement AI-based credit scoring systems, real-time monitoring and digital early-warning mechanisms, and for the Central Bank to incorporate the credit-expansion dynamics of digitalisation into its macroprudential policy. The main limitation the small sample size (n = 10) could be addressed in future research through panel data or quarterly-frequency extensions.

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