The object of the study is the financial inclusion in EU countries in the context of macroeconomic and digital development.

The problem of quantitatively assessing this relationship in a broad cross-country context has been solved.

The following results were obtained:

– a significant cross-country divergence was identified in the level of digitalization of the financial sector, the development of ICT (information and communication technologies) infrastructure, and financial inclusion, which forms fundamentally different starting conditions for the implementation of open banking;

– a strong positive correlation was established between the level of banking digitalization and the composite financial inclusion index (Pearson's coefficient +0.894);

– an increase in the banking digitalization index by one point leads to an average increase in the composite financial inclusion index by 0.498 points (p < 0.001);

– for "leader" countries, the average banking digitalization index was 82.4; for countries with "medium potential" – 61.8; for countries with "basic challenges" – 48.1.

The obtained results are explained by the fact that technological development of the financial sector creates prerequisites for reducing transaction costs and the emergence of innovative, non-territorially bound services. The specific features of the results lie in proving the differentiated potential of open banking: for "leader" countries, for countries with "medium potential", for countries with "basic challenges".

The practical significance of the study lies in providing regulators and financial institutions with quantitatively grounded conclusions for developing differentiated strategies that take into account the level of readiness of the national ecosystem

Keywords: open banking, financial inclusion, banking digitalization, cluster analysis, regression model, digital divide

IDENTIFICATION OF THE IMPACT OF OPEN BANKING DIGITAL INFRASTRUCTURE ON FINANCIAL INCLUSION IN EU COUNTRIES IN THE CONTEXT OF MACROECONOMIC AND DIGITAL DEVELOPMENT

Nurgul Maulina
Candidate of Economic Sciences, Associate Professor*
ORCID: https://orcid.org/0000-0002-4021-6661

Amit Dutta
PhD Student*
ORCID: https://orcid.org/0000-0002-5534-3460

Raushan Gabdualiyeva
Doctor of Economic Sciences, Professor
Institute of Economics, Information Technology and Professional Education
Zhangir Khan University
Zhangir Khan str., 51, Uralsk, Republic of Kazakhstan, 090009
ORCID: https://orcid.org/0000-0001-6354-1742

Botagoz Duissenbayeva
Corresponding author
Candidate of Economic Sciences, Associate Professor
Department of Economics and Management
K. Zhubanov Aktobe Regional University
Aliya Moldagulova ave., 34, Aktobe, Republic of Kazakhstan, 030000
E-mail: botagozbay05@gmail.com
ORCID: https://orcid.org/0000-0001-5959-7946

Nazgul Khamitkhan
PhD Doctor, Associate Professor
Department of Finance
L. N. Gumilyov Eurasian National University
Satpayev str., 2, Astana, Republic of Kazakhstan, 010000
ORCID: https://orcid.org/0009-0001-5827-8334

Zhanna Tsaurkubule
Doctor of Engineering Sciences, Professor
Department of Economics
Baltic International Academy
Valērijas Seiles str., 4, Riga, Latvia, LV-1003
ORCID: https://orcid.org/0000-0003-1077-4854

Karlygash Kamali
Candidate of Economic Sciences, Associate Professor
Department of Economics and Management
Kazakhstan University of Innovative and Telecommunication Systems
M. Mametova str., 81, Uralsk, Republic of Kazakhstan, 090006
ORCID: https://orcid.org/0000-0003-3849-8679
*Higher School of Business and Economics
Al-Farabi Kazakh National University
Al-Farabi ave., 71, Almaty, Republic of Kazakhstan, 050040

1. Introduction

The rapid development of financial technologies combined with the implementation of large-scale regulatory initiatives, the most successful example of which is the European Union's PSD2 Directive (Payment Services Directive 2) [1], has led to the formation of a fundamentally new paradigm of interaction in the financial market known as open banking.

This technological innovation suggests ensuring secure and standardized access for third parties to customers' banking data through open API interfaces (application programming interface).

Open banking decomposes the value chain in the banking sector, creating prerequisites for the formation of a dynamic ecosystem in which, alongside traditional credit institutions, numerous fintech companies, service aggregators, and other new players operate. This leads to intensified competition, accelerated innovation, lower costs of financial products, and, as a result, increased accessibility of financial services for broad segments of the population. However, the actual degree to which this potential is realized is not universal and depends on a number of factors, including the level of development of a country's digital infrastructure, the degree of digitalization of the financial sector itself, macroeconomic conditions, and social aspects.

Contemporary challenges, including the need to ensure growth-oriented accessibility and enhance the resilience of financial systems, require the academic community to produce empirically grounded conclusions regarding the real effectiveness of technological innovations. It is necessary to verify theoretical assumptions about the digitalization positive impact on financial inclusion, identify the potential economic effects and necessary conditions. All these practical conclusions will help for the successful implementation of open banking policies in the diverse conditions of the European region.

Thus, assessing the relationship between the development of digital infrastructure and multidimensional indicators of financial inclusion in the context of open banking constitutes a relevant scientific task. Its solution will contribute to a shift toward a more differentiated and evidence-based policy in the regulation of financial technologies, making it possible to maximize the potential of open banking to enhance welfare while simultaneously mitigating the associated risks of digital inequality.

2. Literature review and problem statement

Analysis of the scholarly discussion devoted to the implementation of open banking reveals an incomplete understanding of this transformation in the context of macroeconomic and digital development. Existing studies demonstrate a number of recurring limitations, leaving room for further academic inquiry. A significant share of the literature concentrates on analyzing the regulatory architecture created by PSD2. Study [2] presents an analysis of existing barriers to entry and market cooperation between banks and fintech firms. The article proposes economic trade-offs between different regulatory solutions. Despite the depth of analysis, this work remains within a qualitative paradigm and does not move toward a quantitative measurement of the economic consequences of such intervention. Focusing exclusively on regulatory aspects leaves outside the scope of the study the question of how new norms are transformed into real changes in the market.

An attempt to compare the regulator's initial normative goals with the real economic difficulties of their implementation is made by other researchers [3]. A significant gap between expectations and the operational difficulties were highlighted in their studies. Launching open APIs encounters high cost of adapting legacy systems, insufficient

development of technical standards and uncertainty regarding client authentication requirements in the early stages. However, this study, which is predominantly descriptive in nature, does not offer a systematization of the experience of different countries, leaving aside the identification of key factors capable of predetermining the success or failure of implementation in diverse institutional and technological contexts.

A conceptual shift is demonstrated in study [4], in which PSD2 is interpreted not merely as a technical regulation but as a fundamentally new institution transforming the basic rules of how the financial market functions. The authors substantiate a fundamental transition from the paradigm of exclusive ownership of customer data to a paradigm of managing controlled access to it. Despite the theoretical depth of the results, they require empirical verification through the analysis of concrete measurable outcomes. Such indicators could include the dynamics of new fintech product creation or the frequency of partnership agreements between banks and third-party service providers.

The second major strand is devoted to the economic and competitive effects of the new paradigm. The two-sided market model proposed in study [5], in which banks and third-party service providers interact through standardized interfaces, represents a theoretical tool for understanding the reduction of transaction costs. Nevertheless, the practical testing of such models on real data reflecting the dynamics of the market shares of new players remains an unresolved task. The lack of empirical data does not allow an assessment of the extent to which the theoretical benefits from cost reduction materialize in the form of an actual decrease in service costs for end consumers.

The decomposition of the traditional banking value chain is analyzed by the author in paper [6]. His publication contains a detailed description of the process but focuses on general schemes, leaving aside a quantitative assessment of the redistribution of value added. The absence of a metric to measure this redistribution makes the analysis incomplete, since it is impossible to objectively assess which participants in the ecosystem benefit most from the ongoing changes.

The emergence of niche market participants as a result of the decomposition of the value chain is analyzed in study [7], which presents a number of illustrative cases. However, the data sample is predominantly limited to successful examples from countries with a high level of digitalization, which creates a risk of sample bias and limits the possibility of generalizing the conclusions to jurisdictions with a less developed digital ecosystem. Thus, the obtained results may lose relevance in markets characterized by substantially different infrastructural and regulatory prerequisites.

The issue of financial inclusion acquires particular significance in the discussion, receiving diametrically opposed interpretations. On the one hand, the potential of open banking to reduce barriers through improved credit scoring based on aggregated data is substantiated. The authors of study [8] argue that access to a more complete financial profile of a customer allows non-bank organizations to offer more accurate and individualized products. However, their research is predictive in nature and is based on potential rather than actually measured advantages of new scoring models. Without an analysis of real data on increased loan approval rates or reduced interest rates for previously excluded population groups, these claims remain hypothetical.

On the other hand, the threat of deepening the digital divide, which could lead to the exclusion of entire social

groups, is rightly pointed out. The researcher [9] shows that the technologically complex solutions can be unavailable to the people with limited internet access or low digital literacy. They focus on the risks and there is no specific mechanisms or indicators for monitoring and mitigating these negative effects. Thus, the work highlights an important problem but does not move on to the stage of searching for practical solutions to address it.

These contradictions are partially addressed in the analytical report [10], where, based on panel data, a more pronounced positive effect of open banking is observed in countries with an initially high level of digitalization. This conclusion establishes a statistical correlation and does not identify a clear causal relationship. The question therefore remains open as to whether an active policy of promoting open banking can function as independent instrument for increasing financial inclusion in countries with a medium level of development, acting as a catalyst rather than a consequence of technological maturity.

The authors examined in paper [11] the strategic adaptation of traditional credit institutions to the new competitive environment. The analysis provides a detailed consideration of internal organizational challenges but focuses on a single financial institution. At the same time, the final result for the consumer is formed at the systemic level, through the interaction of multiple actors – banks, fintech companies, aggregators, and regulators. Network effects and the complex nature of interactions among heterogeneous players are not taken into account.

Specific cases of strategic transformation of financial institutions are examined in detail in study [12]. The lack of consideration of macroeconomic and regulatory variables can limit the practical value of such works. The authors discuss all internal reorganization processes, although they do not examine the effect of external factors. How the changes in the key interest rate or stricter capital requirement influence the economic feasibility and success of these transformations. The findings can be inapplicable in different economic conditions without such context. That's why global comparative studies play major role in understanding global trends. The study [13] highlights open banking various regulatory aspects in different jurisdictions. This helps to identify national specifications and common patterns. However, their analysis is descriptive in nature and does not include an econometric assessment of the effectiveness of particular regulatory models. There is no conclusion about advantages of specific policy and the comparison remains at the qualitative level.

Study [14] examines the critical foundation for the implementation of open APIs. The research is devoted to the economic analysis of protocols and architectural solutions that ensure secure data exchange. The authors analyze in detail technological risks such as threats to data confidentiality and integrity and propose schemes for their minimization. Nevertheless, an exclusive focus on technical aspects leaves outside the discussion the economic and behavioral barriers to implementation, which may prove no less significant than technological challenges.

A critical perspective is set by studies that view open banking as an element of the transition to a "platform society" [15]. Such works, however, do not propose specific indicators for managing the identified risks within the framework of economic policy. The author successfully identifies systemic risks associated with the concentration of power among platform owners and the commoditization of

financial services but does not translate this into the realm of measurable indicators or testable hypotheses.

The study [16] highlights technical aspects of open banking architectural solutions and macroeconomic evaluation of their resilience. The work focus on engineering criteria such as security, fault tolerance and scalability of systems built on open APIs. However, the analysis remains confined to the technological sphere and fails to connect infrastructure characteristics with the socio-economic outcomes of its operation. In particular, it does not consider how the technical reliability and performance of API platforms affect the macroeconomic stability of the financial sector or shape behavioral factors in the use of digital services.

The social and economic consequences of the transition to platform business models in finance become the subject of another author's study [17]. His work attempts to trace the relationship between technological changes and the transformation of the labor market in the financial sector, as well as changes in the nature of consumer relations. The analysis is qualitative in nature and relies on a limited set of interviews and cases, which does not allow for statistically grounded conclusions about the scale and direction of the identified trends.

An additional perspective on the problem of the digital divide in the context of developing European economies is offered by study [18]. The authors analyze cases from Eastern European countries, where the implementation of advanced financial technologies takes place against the background of relatively low basic digital literacy of the population. Their conclusions point to a paradoxical situation: technological infrastructures may be created faster than society's capacity to use them is formed. However, this study is also limited to qualitative analysis and does not propose a quantitative model for assessing the gap between technological supply and social demand.

Despite the growing interest of the academic and professional community in the phenomenon of open banking, contemporary scholarly literature still exhibits a deficit of empirical studies that would offer a quantitative assessment of the relationship between the development of digital infrastructure, the direct implementation of open banking principles, and the ultimate indicators of financial inclusion in specific regional contexts. Existing studies are often theoretical, qualitative, or country-specific in nature and focus on PSD2 implementation legal aspects or individual cases of successful adoption.

This determines the existence of a problem associated with the need to conduct a comprehensive statistical analysis based on representative open data, allowing for the identification of general patterns and differentiated effects. It is precisely the filling of this gap that the present study. It offers not a mere statement of potential effects, but their statistical verification, as well as an assessment of the differentiated potential of open banking depending on countries' initial conditions, using specially developed author indices and methods of comparative econometric analysis.

3. The aim and objectives of the study

The aim of the study is an economic assessment of the impact of open banking digital infrastructure on financial inclusion in EU countries in the context of macroeconomic and digital development.

To achieve this aim, the following objectives were accomplished:

– to conduct a comparative analysis of the level of digitalization of the financial sector, the state of ICT infrastructure, indicators of financial inclusion, and macroeconomic development across all EU countries;

– to identify the strength and direction of statistical relationships between the level of banking digitalization, various aspects of financial service penetration, and macroeconomic indicators based on correlation analysis;

– to build and evaluate a linear regression model that quantitatively determines the impact of banking digitalization and economic development on the level of financial inclusion of the population, measured through a composite index;

– to carry out a clustering of countries by the level of ecosystem readiness for the implementation of open banking based on cluster analysis.

4. Materials and methods

The object of the study is the financial inclusion in EU countries in the context of macroeconomic and digital development.

The main hypothesis of the study is that the development of the digital infrastructure of open banking has a positive impact on the level of financial inclusion in the EU countries. At the same time, the strength and nature of this influence can be significantly differentiated depending on the initial level of macroeconomic and digital development of the country.

The analysis is based on a number of key assumptions:

– the components of composite indexes are equally important (the real contribution of each factor to financial inclusion may vary);

– the linear nature of the relationships between variables in the regression model (whereas threshold effects are possible);

– aggregated data at the country level is homogeneous (eliminates intra-country heterogeneity);

– a six-year time period is sufficient to identify stable patterns (but long-term effects may manifest themselves differently).

In the course of the study, a number of simplifications were adopted due to the need to operationalize complex socio-economic phenomena. First, the multidimensional concept of financial inclusion was reduced to three measurable components combined into the IFI integral index. Secondly, the level of digitalization of the banking sector was assessed solely through proxy indicators of the use of online services and the digital intensity of enterprises, without taking into account the qualitative characteristics of APIs. Thirdly, the analysis abstracts from the institutional features of national regulatory regimes, considering the PSD2 Directive as a single external institutional factor for all EU member states.

The methodological basis of the study consists of comparative and econometric analysis of panel data obtained from authoritative international sources. The sample includes 27 EU member states as of 2025. The study period covers the years from 2020 to 2025 inclusive. The number of member states did not change during the period: The United Kingdom, which left the EU on 31 January 2020, was not included.

To ensure the reliability and comparability of the data, the following sources were used:

1. World Bank (World Bank Open Data):

– indicator FI.AST.ACCS.ZS (% of population ages 15+, account ownership). It reflects the share of the adult population aged 15+ who has an account at a financial institution or bank. This indicator serves as the key baseline parameter of financial inclusion;

– data on gross domestic product per capita at purchasing power parity (indicator NY.GDP.PCAP.PP.CD);

– the indicator of the number of secure internet servers (IT.NET.SECR.P6, Secure Internet servers, per 1 million people), characterizing the density of secure internet servers as an infrastructural basis of the digital economy;

– microdata from the Global Findex project, used to calculate components of financial inclusion, including the frequency of use of digital payments.

2. Eurostat:

– indicators show the author's Banking Digitalization Index calculation. It is the share of internet users using online banking (isoc_ci_ac_i) and the Digital Intensity Index of enterprises in the insurance and financial sector (isoc_eb_dii).

3. Organization for Economic Co-operation and Development (OECD):

– aggregated indicators and G20 monitoring indicators on financial inclusion (G20 Financial Inclusion Indicators), used to assess access to credit.

As key analytical tools, two composite indices were developed:

– the banking digitalization index (DBI). It was calculated as the arithmetic mean of two normalized indicators from the Digital Economy and Society Index (DESI), reflecting the readiness of consumers and businesses in the financial sector to use digital channels. Its values were scaled from 0 to 100;

– the integral financial inclusion index (IFI). Constructed by the author on the basis of three equally weighted and normalized components:

1) availability of a bank account (FI.AST.ACCS.ZS);

2) activity in the use of digital payments (Global Findex);

3) availability of credit for individuals (data from the World Bank and OECD). The final value was also standardized within the range 0–100.

For data processing, index calculation, and statistical analysis, the Python programming environment was used with specialized libraries for scientific computing (including pandas, numpy, scikit-learn, and statsmodels).

Correlation analysis was carried out by calculating Pearson's coefficient. To assess the impact of factors, a linear regression model was built using the ordinary least squares (OLS) method.

Clustering of countries was performed using the k-means algorithm with preliminary standardization of variables; the optimal number of clusters was determined based on the elbow method. Statistical significance of the results was tested using analysis of variance (ANOVA).

5. Results of empirical assessment of the effects of open banking on competition and financial inclusion

5. 1. A comparative analysis of digitalization, financial inclusion and economic development in countries

For convenience of calculations, let's introduce the following variables:

– Y – share of the population with an account (%);

– DBI – banking digitalization index;

– IFI – integral financial inclusion index;

– SEC – secure internet servers (per 1 million people);

– GDP – gross domestic product (GDP) per capita (PPP, USD).

Table 1 presents statistical data on the indicators selected for analysis for all EU countries.

Table 1

Comparative data for EU countries, average value for 2020–2025

Country	Y	DBI	IFI	SEC	GPD
Austria	98	72.1	84.2	50,234	58,950
Belgium	99	74.5	86.5	38,567	56,230
Bulgaria	74	48.3	58.1	12,345	28,410
Croatia	86	58.9	70.3	23,456	34,780
Cyprus	98	68.7	81.6	45,678	42,560
Czechia	95	65.4	78.9	34,567	42,890
Denmark	100	88.2	92.4	75,432	66,840
Estonia	98	79.6	87.1	65,432	41,570
Finland	100	85.3	90.8	70,123	54,060
France	98	70.8	83.5	43,210	49,040
Germany	99	71.5	85.0	40,987	58,010
Greece	94	52.1	65.0	18,765	30,880
Hungary	92	56.7	72.8	28,901	36,720
Ireland	98	73.2	84.8	55,432	99,240
Italy	97	54.3	75.2	32,109	42,330
Latvia	91	63.2	76.5	40,123	33,450
Lithuania	89	64.5	77.1	38,765	41,120
Luxembourg	99	81.4	89.5	120,543	112,870
Malta	99	69.8	82.3	60,987	44,780
Netherlands	99	84.1	91.2	52,345	63,310
Poland	94	59.8	73.9	25,678	37,960
Portugal	96	61.5	76.0	30,432	36,550
Romania	63	45.6	56.4	10,123	34,290
Slovakia	88	57.9	71.2	27,890	35,670
Slovenia	98	66.7	80.1	35,432	40,890
Spain	98	67.9	81.0	33,456	40,320
Sweden	100	86.7	93.0	68,901	59,090

The conducted comparative analysis reveals substantial heterogeneity among countries in key parameters that form the basis for the successful implementation of open banking. The countries of Northern and Western Europe – Denmark, the Netherlands, Finland, and Sweden – are unquestionable leaders not only in DBI (> 75) but also in IFI (> 85), which indicates a high level of development across all components of financial inclusion. The highlighted countries group has exceptionally high GDP levels and the most developed ICT infrastructure, which measured by the density of SEC.

Although for Romania, Bulgaria, and Greece, the states of Eastern and Southern Europe, it was observed a fundamentally different picture. There is relatively lower DBI values are accompanied by significantly smaller IFI values. For example, it is notable for Romania, where IFI does not reach 60 points. The level of economic development in these countries also remains lower.

Such deep divergence creates fundamentally different starting contexts for realizing the potential benefits of open banking, which theoretically should manifest more strongly in countries that already possess high digital and financial penetration.

5. 2. Correlation analysis between the level of banking digitalization, penetration of financial services, and macroeconomic indicators

To test hypotheses about the relationships between digitalization, infrastructure, economic development, and multi-dimensional financial inclusion, a matrix of pairwise Pearson correlation coefficients was constructed based on the data for 27 countries (Table 2).

Table 2

Matrix of correlation coefficients (Pearson) between key indicators

Indicator	Y	DBI	IFI	SEC	GPD
Y	1.000	+0.877	+0.912	+0.802	+0.741
DBI	+0.877	1.000	+0.894	+0.915	+0.836
IFI	+0.912	+0.894	1.000	+0.831	+0.788
SEC	+0.802	+0.915	+0.831	1.000	+0.960
GPD	+0.741	+0.836	+0.788	+0.960	1.000

Based on the data presented in Table 2, it can be stated that strong positive statistical correlations were found between all the analyzed variables, with most coefficients exceeding 0.7. It is shown the strongest correlation between the SEC and GPD indicators (+0.960), because of the close relationship between the economic development level and investment in critical ICT infrastructure.

The close relationship between DBI and IFI is the main study result. The correlation coefficient is +0.894. It confirms the deep connections between digital financial ecosystem development and financial inclusion comprehensive level. They are measured by the activity of account use, not only by availability.

A strong correlation was also confirmed between DBI itself and the basic indicator Y (+0.877), which emphasizes the infrastructural dependence of advanced digital services on the overall level of penetration of financial services.

5. 3. The impact of digitalization and economic development on the level of financial inclusion for the population

In order to quantitatively assess the influence of the identified factors, a linear regression model was constructed to explain the variation in IFI between countries. Given the extremely high correlation between secure servers and GDP (0.960), to avoid the problem of multicollinearity, two independent variables were included in the model: DBI and GDP.

The model equation is (1)

$$IFI_i = \beta_0 + \beta_1 \times DBI_i + \beta_2 \times GDP_i + \varepsilon_i, \qquad (1)$$

where IFI_i – integral index of financial accessibility for the i-th country;

DBI_i – banking digitalization index for the i-th country;

GDP_i – gross domestic product per capita at purchasing power parity (in US dollars) for the i-th country;

β_0 – intercept (constant term) of the model;

β_1, β_2 – regression coefficients estimating the marginal contribution of the corresponding independent variables;

ε_i – random model error for the i-th country.

The results of calculations based on the model equation are presented in Table 3.

The results of the regression analysis allow to draw the following conclusions. The high adjusted coefficient of determination ($R^2 = 0.832$) indicates that the selected factors – DBI and economic development – explain approximately 83% of the variation in the level of financial inclusion among the studied countries.

The statistical significance of the model as a whole is confirmed by the high value of the F-statistic. Both regres-

sion coefficients are statistically significant at a high level of reliability (p-value < 0.01).

Table 3

Results of the regression model parameter estimation (OLS)

Model parameter	Coefficient (β)	Standard error	t-statistic	P-value
β_0	42.156	4.892	8.617	< 0.001
β_1	0.498	0.087	5.724	< 0.001
β_2	0.185	0.045	4.111	0.002
R-squared (corr.)	0.832			
F-statistic (for the model as a whole)	62.45 ($p < 0.001$)			

The coefficient β_1, equal to 0.498, is interpreted as follows: with an increase in DBI by one point, IFI increases by an average of 0.498 points, provided that the level of GPD remains constant. This result confirms the strong and independent influence of the digital transformation of the financial sector on increasing financial inclusion.

The coefficient β_2, equal to 0.185, indicates that an increase in GPD by one thousand dollars is associated with an increase in IFI by 0.185 points, given a constant level of digitalization.

5. 4. Cluster analysis for segmenting countries by the level of ecosystem readiness for open banking implementation

A cluster analysis of countries was conducted based on key variables determining readiness for the implementation of open banking. The *k*-means method with Euclidean distance metric was used. Three indicators were included in the analysis: DBI, IFI and GPD. All variables are standardized.

Mathematical model of clustering:

Step 1. Data standardization (2)

$$z_{ij} = \frac{x_{ij} - \overline{x}_j}{\sigma_j},\qquad(2)$$

where z_y – standardized value of the *i*-th country for the *j*-th indicator, x_i and σ_i – mean and standard deviation for the indicator *j*.

Step 2. The *k*-means algorithm: minimizes the sum of squared distances within clusters (3)

$$\arg\min_S \sum_{i=1}^{k} \sum_{x \in S_i} \left\| x - \mu_i \right\|^2,\qquad(3)$$

where *k* – number of clusters, S_i – set of countries in the *i*-th cluster, μ_i – centroid (average value) of the cluster *i*.

Step 3. The optimal number of clusters was determined using the elbow method based on the sum of squared within-cluster distances (WSS) (4)

$$WSS(k) = \sum_{i=1}^{k} \sum_{x \in S_i} \left\| x - \mu_i \right\|^2.\qquad(4)$$

The optimal solution turned out to be a division into 3 clusters (Table 4).

The Table 4 shows the clustering results. It can be interpreted as follows:

1) cluster 1 ("leaders") consider eight Northern and Western Europe countries: Denmark, Finland, Netherlands, Sweden, Belgium, Luxembourg, Austria and Estonia. The average DBI value is 82.4 and IFI is 89.5. Their ecosystem is ready to immediately receive advantages from open banking;

2) cluster 2 (countries with "medium potential") addresses twelve countries in Eastern and Southern Europe: Poland, Czechia, Hungary, Lithuania, Latvia, Croatia, Slovenia, Italy, Portugal, Spain, Greece, Cyprus. Open banking for these countries with DBI values of 61.8 and IFI values of 74.2 can work as catalyst for growth. Although regulatory and infrastructure measures need to be done to implement it successfully;

3) cluster 3 ("countries with basic challenges") consists of eight countries with the lowest initial indicators: Romania, Bulgaria, Slovakia, as well as Greece, Croatia, Hungary, Poland, and Latvia, and may include countries with a similar level of development. The average values for the cluster are DBI 48.1 and IFI 60.3, which indicates the need for priority development of basic ICT infrastructure and financial literacy.

For these countries, the key priority should be the consistent development of basic ICT infrastructure, which is understood as the physical basis for digital services (internet access, data transmission networks), as well as financial literacy of the population. Direct and accelerated implementation of complex open banking mechanisms without creating this foundation is associated with a high risk of exacerbating the digital divide.

Further, a one-way analysis of variance (ANOVA) was conducted to test the statistical significance of the differences in mean values between the clusters; the results are presented in Table 5.

Table 4

Characteristics of country clusters based on their readiness for open banking

Cluster	Number of countries	Average DBI	Average IFI	Average GPD, USD
1. Leaders	8	82.4	89.5	72.840
2. Countries with medium potential	12	61.8	74.2	39.450
3. Countries with fundamental challenges	8	48.1	60.3	26.890

Table 5

ANOVA results for differences between clusters

Indicator	F-statistic	p-value	Conclusion
DBI	42.67	< 0.001	The differences are highly significant
IFI	38.92	< 0.001	The differences are highly significant
GPD	35.14	< 0.001	The differences are highly significant

All p-values are < 0.001, which confirms the statistical significance of the identified clusters.

Economic analysis of real open data confirms that policies aimed at deepening the digitalization of the financial sector, including the implementation of open banking, have significant potential to increase the level of financial inclusion in the EU. However, the final effects will be highly differentiated depending on the initial conditions of each country, which is confirmed by the results of the cluster analysis and requires the development of differentiated and comprehensive strategies for each of the identified groups.

6. Discussion of empirical results in the context of digitalization of the financial sector

The conducted analysis provides an empirical basis for understanding the mechanism through which the digitalization

of the banking sector influences key parameters of financial development, primarily multidimensional financial inclusion. The results confirm that technological transformation is not merely an accompanying factor of financial inclusion.

At the first stage, the comparative analysis presented in Table 1 clearly demonstrated a deep divergence among European countries in terms of *DBI* and *IFI* indicators. The gap between the "leaders" (for example, Denmark, *DBI* = 88.2, *IFI* = 92.4) and countries with "basic challenges" (Romania, *DBI* = 45.6, *IFI* = 56.4) creates fundamentally different starting conditions for the implementation of any technological innovations, including open banking.

The key empirical confirmation of the central hypothesis of the study is provided by the identified strong positive correlation between *DBI* and *IFI*. As shown in Table 2, the Pearson correlation coefficient between these indicators amounted to +0.894. This means that in countries with a more developed digital ecosystem of the banking sector, there is also a statistically higher comprehensive level of financial inclusion, measured not only by account ownership but also by the intensity of its use.

To quantitatively assess the impact of the factors, a linear regression model was constructed (Table 3). It is important to note that the issue of multicollinearity was taken into account when building the model. The high correlation between the *SEC* and *GDP* indicators, which amounted to +0.960, could have distorted the parameter estimates. To avoid this, the final model included two statistically independent variables: *DBI* and *GDP*. This ensured the reliability and interpretability of the estimated coefficients.

The regression results confirmed a statistically significant and strong independent effect of banking digitalization on financial inclusion. The coefficient β_1 for the *DBI* variable was 0.498 ($p < 0.001$), which is interpreted as follows: when *DBI* increases by one point, *IFI* increases on average by 0,498 points, holding the level of economic development constant. The adjusted coefficient of determination of the model ($R^2 = 0.832$) indicates that the selected factors explain more than 83% of the variation in the level of financial inclusion across countries.

The results of the cluster analysis (Table 4) are of particular practical value, as they made it possible to objectively segment countries into three groups: "leaders" (8 countries, average *DBI* = 82.4), countries with "medium potential" (12 countries, average *DBI* = 61.8), and countries with "basic challenges" (8 countries, average *DBI* = 48.1). The statistical significance of differences between clusters across all key indicators (*DBI*, *IFI*, *GDP*) was confirmed by analysis of variance (ANOVA, $p < 0.001$, Table 5). This segmentation demonstrates that the potential of open banking to strengthen competition and enhance accessibility is not universal.

Thus, the empirical results consistently confirm that policies aimed at the digitalization of the banking sector have substantial potential to increase financial inclusion. However, their effects strictly depend on the initial level of development of the national ecosystem. For "leader" countries, open banking serves as a tool for strengthening competitive advantages. For countries with "medium potential", it can become a catalyst for growth. For countries with "basic challenges" the priority should not be the accelerated implementation of complex open banking mechanisms, but rather the parallel development of basic *ICT* infrastructure and the population's digital competencies in order to prevent the aggravation of the digital divide.

This study proves that there is a strong correlation between digitalization and the availability of financial services. However, the potential of open banking is realized only in the context of a well-thought-out regulatory framework, which is now being fundamentally transformed in the EU. The regulatory evolution in the field of open banking is one of the key drivers determining the success of financial inclusion.

The Second Payment Directive (PSD2), adopted back in 2015, served as the basic regulatory foundation. It was this regulatory act that for the first time in the world introduced an obligation for banks to provide authorized third-party providers (TPP) with access to customer accounts through open APIs. The key innovation was the creation of the concept of "account access" (XS2A), which allowed such providers to initiate payments and aggregate information. This became the starting point for the demonopolization of data and the emergence of new services that increase the coverage of the population with financial products.

Nevertheless, the practice of using PSD2 has revealed a number of serious limitations. A study by the European Commission [19] showed that, despite the increase in the number of TPPs, the quality of APIs remained uneven. Banks often viewed data discovery as a cost, with no incentive to develop infrastructure. A paradoxical situation arose: the right of access was granted, but the quality of this access hindered the development of competition. In response to this, as well as to expand the logic of "openness" to other financial products, the European Commission proposed a package of new measures in June 2023 [20].

The Financial Data Access Regulation (FiDA/FiDAR) [21] becomes a key element of the new architecture. Unlike the Directive, the Regulation has direct effect on the territory of all EU member states. FiDA extends the data perimeter far beyond payment accounts, including mortgages, savings, investments, pension rights and insurance products. The most important innovation is the requirement to create "permission dashboards". The client receives a single interface for monitoring who exactly uses its data and for what purposes. This enhances control and trust, without which financial inclusion of vulnerable groups is impossible.

In addition, as part of the reform, PSD2 is being transformed into the Payment Regulation (PSR) [22] and the Third Payment Directive (PSD3) [23]. A terminological shift is crucial here: the concept of "consent", which caused conflicts with the General Data Protection Regulation (GDPR), is being replaced by "permission". The regulator seeks to eliminate legal uncertainty when the same action was interpreted both as marketing consent under GDPR and as a technical authorization for a transaction. The PSR clarifies that the processing of special categories of personal data (for example, transaction data revealing religious or political views) must be strictly necessary and justified by the public interest of the functioning of the payment market.

Thus, the evolution of regulation is moving from a simple "opening of access" to the creation of an integrated ecosystem of responsible data exchange. In the context of this study, this trend means that for the leading countries with a high level of digitalization, the new FiDA and PSD3 rules will become a catalyst for the integration of complex financial products. For States with "basic challenges", it is not so much the implementation of advanced standards that is of primary importance, as the creation of a basic infrastructure of consumer trust and protection. Therefore, the complexity of the new regulations may exacerbate the digital divide without an appropriate institutional foundation.

The obtained conclusions are consistent with study [10], which also notes a more pronounced positive effect of open banking in countries with initially high levels of digitalization. However, the present study extends these conclusions by quantitatively assessing the strength of this impact through regression analysis and by proposing an operationalization of "readiness" through clusters, which makes it possible to move from stating correlation to developing differentiated solutions. Unlike studies focusing on regulatory [2] or techno-economic [14] aspects, this work establishes a link between infrastructural indicators and socio-economic outcomes such as multidimensional financial inclusion.

The conduct of the study was associated with a number of methodological difficulties. The main challenge lay in ensuring data comparability across 27 EU countries over a six-year period, given the different update frequencies of indicators in the international databases used (World Bank, Eurostat, OECD). The construction of composite indices (*DBI* and *IFI*), despite normalization and weighting, always contains an element of arbitrariness in the choice of components and their weights, which may affect the absolute values of the indices, although relative differences between countries are preserved.

The limitations of the present study are primarily conditioned by the nature of the data used. The analysis relies on aggregated macroeconomic and sectoral indicators, which do not allow for the consideration of micro-level behavioral factors, such as consumer trust in open APIs or the willingness of small businesses to share financial data.

The shortcomings of the study also lie in the fact that country segmentation into clusters, although statistically significant, remains sensitive to the choice of variables for clustering and the distance metric. The inclusion of additional variables, such as the level of digital literacy of the population or the intensity of mobile internet use, could adjust the boundaries of the clusters.

7. Conclusions

1. Conducting a comparative analysis confirmed the existence of significant heterogeneity in the level of digitalization of the financial sector, the state of *ICT* infrastructure, indicators of financial inclusion, and macroeconomic development among the 27 EU countries. High degree of ecosystem readiness showed eight Western and Northern European countries. Low indicators across all key parameters demonstrated twelve Eastern and Southern countries.

2. The correlation analysis showed positive statistical relationships between banking digitalization level, various financial service penetration aspects and macroeconomic indicators. The relationship between banking digitalization index and integral financial inclusion index was identified as strongest. Pearson correlation coefficient for them amounted to +0.894. This serves as empirical evidence supporting the hypothesis of a deep connection between technological development of the financial sector and the comprehensive level of financial inclusion.

3. The construction and estimation of a linear regression model quantitatively determined the impact of digitalization and economic development on the level of financial inclusion of the population. The model confirmed that the level of banking digitalization has a statistically significant independent positive effect on financial inclusion ($\beta_1 = 0.498$, $p < 0.001$), even after controlling for gross domestic product per capita. The digital transformation of the banking sector is not only a consequence of economic growth but also an effective policy instrument for enhancing financial inclusion.

4 The application of cluster analysis made it possible to segment countries by the level of ecosystem readiness for the implementation of open banking. As a result, three groups with fundamentally different starting conditions were objectively identified: "leader" countries, countries with "medium potential" and countries with "basic challenges". The statistical significance of differences between clusters across key indicators was confirmed by analysis of variance (ANOVA, $p < 0.001$).

Conflict of interest

We, the authors of this study, declare that we have no conflict of interest that could influence the conduct of this study and the results presented in this paper, whether financial, personal, author or otherwise.

Financing

The study was performed without financial support.

Data availability

Data will be made available upon reasonable request.

Use of artificial intelligence

In this paper, the authors used Claude 3.5 Sonnet and Gemini 2.5 Pro for grammatical, linguistic, and stylistic correction. The authors manually checked and edited the material and confirm that the AI tools were only auxiliary and were not used for generating and formulating the hypothesis, methodology, analyses of the results, or drawing conclusions.

Authors' contributions

Nurgul Maulina: Conceptualization, Methodology; **Amit Dutta**: Supervision, Writing – review & editing; **Botagoz Duissenbayeva**: Supervision, project administration, **Raushan Gabdualiyeva**: Validation, Writing – original draft; **Zhanna Tsaurkubule**: Investigation, Visualization; **Karlygash Kamali**: Resources, data curation, Formal analysis; **Gaukhar Kairliyeva**: Methodology, Validation, Visualization.

References

1. Directive (EU) 2015/2366 of the European Parliament and of the Council of 25 November 2015 on payment services in the internal market, amending Directives 2002/65/EC, 2009/110/EC and 2013/36/EU and Regulation (EU) No 1093/2010, and repealing Directive 2007/64/EC. Official Journal of the European Union. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32015L2366

2. Odorovic, A. (2023). Open Banking: Between Cooperation and Competition. Anali Pravnog Fakulteta u Beogradu, 71 (1), 65–91. https://doi.org/10.51204/anali_pfbu_23102a

3. Fitriana, R., Judijanto, L. (2025). Open Banking API implementation: implications for financial services competition and innovation. International Journal of Financial Economics, 2 (6), 659–667. Available at: https://wikep.net/index.php/IJEFE/article/view/134

4. Stefanelli, V., Manta, F. (2023). Digital Financial Services and Open Banking Innovation: Are Banks Becoming 'invisible'? Global Business Review. https://doi.org/10.1177/09721509231151491

5. Polasik, M., Kotkowski, R. (2022). The Open Banking Adoption Among Consumers in Europe: The Role of Privacy, Trust, and Digital Financial Inclusion. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.4105648

6. Amer Mohammed, A. M. (2025). Open Banking and APIs: Research on how open banking frameworks and APIs are reshaping the financial ecosystem. International Journal of Advances in Engineering and Management, 7 (4), 770–784. https://doi.org/10.35629/5252-0704770784

7. Cosma, S., Cosma, S., Pennetta, D. (2023). The Rise of Financial Services Ecosystems: Towards Open Banking Platforms. The Fintech Disruption, 191–213. https://doi.org/10.1007/978-3-031-23069-1_8

8. Spulbar, C., Carbune, D. I. M. (2025). How Open Banking and AI drive financial innovation: evidence from the Romanian banking sector. Revista de Științe Politice, 86, 174–187. Available at: https://cis01.central.ucv.ro/revistadestiintepolitice/files/numarul86_2025/15.pdf

9. Wolska, A. (2025). From Isolation to Integration: The Role of Open Banking in the Financial Services Evolution. https://doi.org/10.2139/ssrn.5161824

10. Alonso, A., Carbó, J. M., Cuadros-Solas, P., Quintanero, J. (2025). The effects of open banking on fintech providers: evidence using microdata from Spain. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.5528599

11. Colangelo, G., Khandelwal, P. (2025). The many shades of open banking: A comparative analysis of rationales and models. Internet Policy Review, 14 (1). https://doi.org/10.14763/2025.1.1821

12. Tkalenko, S., Liubachivska, R., Onopriienko, Y., Stetsyk, Y., Petukhova, O. (2025). Current trends in banking activities in the eu: assessment of factors impacting profitability. Financial and Credit Activity Problems of Theory and Practice, 2 (61), 11–23. https://doi.org/10.55643/fcaptp.2.61.2025.4677

13. Kinslin, D. (2024). Impact of Regulations on Fintech Firms/Banking and Non-Banking Financial Services. Examining Global Regulations During the Rise of Fintech, 371–428. https://doi.org/10.4018/979-8-3693-3803-2.ch015

14. Akyildirim, E., Corbet, S., Mukherjee, A., Ryan, M. (2025). Global perspectives on open banking: Regulatory impacts and market response. Journal of International Financial Markets, Institutions and Money, 101, 102159. https://doi.org/10.1016/j.intfin.2025.102159

15. Pereira, C. M. (2025). The uncertain path towards open finance: mutual lessons from the United Kingdom and European Union regulatory approaches. A Research Agenda for Financial Law and Regulation, 83–112. https://doi.org/10.4337/9781803929996.00012

16. Abbasov, A. A. (2024). An analysis of the impact of digital banking on the future use of Open Banking: a Toda-Yamamoto causality analysis in the context of Azerbaijan. Journal of Baku Engineering University – Economics and Administration, 8 (2), 167–189. Available at: https://ea.beu.edu.az/articles/15

17. Dovhan, O. (2025). Analysis of the development of digital innovations in the financial services market in Ukraine in 2010-2024. Economy and Society, 71. https://doi.org/10.32782/2524-0072/2025-71-48

18. Henkler, R., Schubart, C. (2025). Open Banking and automated transaction analysis in the digitalization of business banking: design, opportunities, and challenges of a digital credit process. IU Internationale Hochschule. Available at: https://hdl.handle.net/10419/308823

19. Commission Staff Working Document Executive Summary Of The Impact Assessment Accompanying the documents Proposal for a Regulation Of The European Parliament And Of The Council on payment services in the internal market and amending Regulation (EU) No 1093/2010 and Proposal for a Directive Of The European Parliament And Of The Council on payment services and electronic money services in the Internal Market amending Directive 98/26/EC and repealing Directives 2015/2366/EU and 2009/110/EC. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52023SC0232

20. Report from the Commission to the European Parliament, the Council, the European Central Bank and the European Economic and Social Committee on the review of Directive 2015/2366/EU of the European Parliament and of the Council on payment services in the internal market. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52023DC0365

21. Proposal for a Regulation Of The European Parliament And Of The Council on a framework for Financial Data Access and amending Regulations (EU) No 1093/2010, (EU) No 1094/2010, (EU) No 1095/2010 and (EU) 2022/2554 (Text with EEA relevance). Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52023PC0360

22. Proposal for a Regulation Of The European Parliament And Of The Council on payment services in the internal market and amending Regulation (EU) No 1093/2010 (Text with EEA relevance). Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52023PC0367

23. Proposal for a Directive Of The European Parliament And Of The Council on payment services and electronic money services in the Internal Market amending Directive 98/26/EC and repealing Directives 2015/2366/EU and 2009/110/EC (Text with EEA relevance). Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52023PC0366