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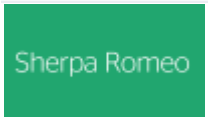	**Sherpa Romeo**
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Interconnectedness and Risk Structure Among Digital Assets: Empirical Findings Based on the Generalized R² Approach (2020–2025)

Dijital Varlıklar Arasındaki Bağlantılılık ve Risk Yapısı: Genelleştirilmiş R² Yaklaşımına Dayalı Ampirik Bulgular (2020–2025)

Burhan ERDOĞAN
Asst. Prof. Dr., Sivas Cumhuriyet University
burhanerdogan@cumhuriyet.edu.tr
https://orcid.org/0000-0002-6171-0554

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ABSTRACT

This study analyzes the time-varying interactions among assets in the digital financial asset market. Within the scope of the study, 1,820 daily observations from the 2020-2025 period for Ethereum, Ripple, Binance Coin, Cardano, Stellar, IOTA, Stacks, and Chainlink are examined using the Generalized R² method proposed by Balli et al. (2023). This approach reveals both contemporaneous and lagged interconnectedness between assets, thereby enabling an understanding of how dynamic relationships evolve over time. The results indicate that market interconnectedness is not stable over time and that the transmission of shocks tends to intensify particularly during periods of uncertainty. The findings show that Ethereum maintained a central role throughout the analysis period, while Cardano, STX, LINK, and IOTA were more exposed to shocks. These results underscore the necessity of policy frameworks that address not only individual asset risks but also contagion risks to promote market stability. From an investor's perspective, it is recommended that portfolio compositions consider both contemporaneous and lagged effects.

Anahtar Kelimeler:
Dijital Finansal Varlıklar, Kripto Varlıklar, Bağlantılılık, Risk, Genelleştirilmiş R²
Jel Kodları:
C02, C30, C44

ÖZET

Bu çalışma, dijital finansal varlık piyasasındaki varlıklar arasındaki zamanla değişen etkileşimleri analiz etmektedir. Çalışma kapsamında, Ethereum, Ripple, Binance Coin, Cardano, Stellar, IOTA, Stacks ve Chainlink için 2020-2025 dönemine ait 1.820 günlük gözlem, Balli ve diğerleri (2023) tarafından önerilen Genelleştirilmiş R² yöntemi kullanılarak incelenmiştir. Bu yaklaşım, varlıklar arasındaki eşzamanlı ve gecikmeli karşılıklı bağlantıları ortaya çıkararak, dinamik ilişkilerin zaman içinde nasıl geliştiğini anlamayı mümkün kılmaktadır. Sonuçlar, piyasa karşılıklı bağlantısının zaman içinde istikrarlı olmadığını ve şokların iletilmesinin özellikle belirsizlik dönemlerinde yoğunlaşma eğiliminde olduğunu göstermektedir. Bulgular, Ethereum'un analiz dönemi boyunca merkezi bir rol sürdürdüğünü, Cardano, STX, LINK ve IOTA'nın ise şoklara daha fazla maruz kaldığını göstermektedir. Bu sonuçlar, piyasa istikrarını teşvik etmek için yalnızca bireysel varlık risklerini değil, aynı zamanda bulaşma risklerini de ele alan politika çerçevelerinin gerekliliğini vurgulamaktadır. Yatırımcıların bakış açısından, portföy bileşimlerinde hem eşzamanlı hem de gecikmeli etkilerin dikkate alınması önerilmektedir.

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1. INTRODUCTION

Digital asset markets have emerged as a prominent alternative to traditional financial instruments, offering innovative investment opportunities and decentralized financial engagement. Since Bitcoin's introduction in 2009, hundreds of digital assets—including high market-capitalization cryptocurrencies such as Ethereum, Binance Coin, Cardano, and Stellar—have been developed, rapidly gaining acceptance among investors (Wątorek et al., 2021; Fang et al., 2022; Corbet et al., 2019).

Key features of driving adoption include decentralization, limited supply, and 24/7 transaction capability, enabling investors to respond flexibly to market fluctuations, preserve capital, and reduce reliance on intermediaries (Bouri et al., 2017; Sutbayeva et al., 2024). These characteristics, combined with the market's rapid growth, underscore why digital assets have become a significant alternative investment class.

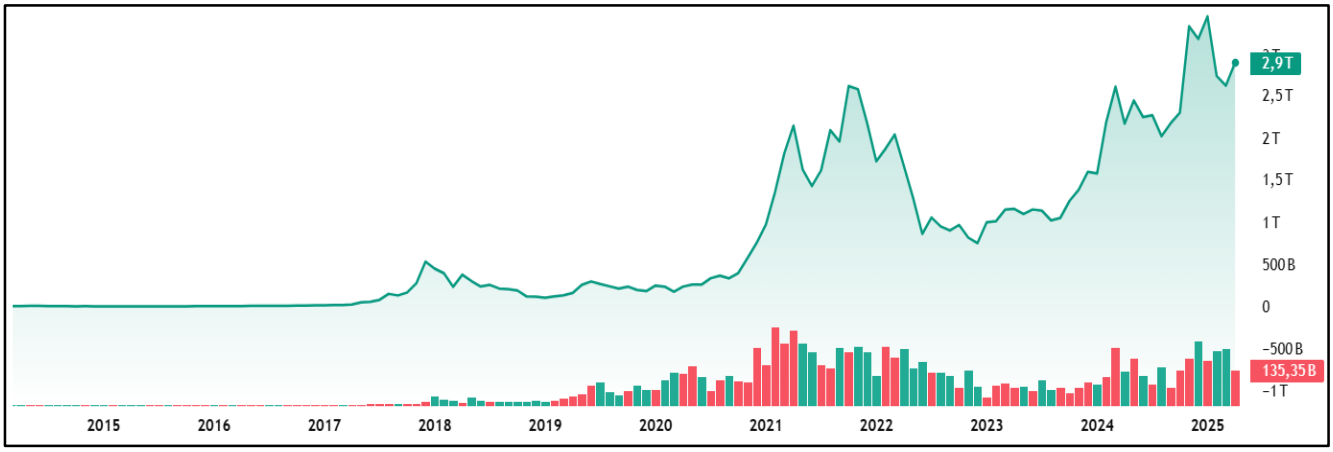

Figure 1. Total Monetary Volume of the Digital Asset Market (Trillion USD)

As shown in Figure 1, the digital asset market grew rapidly from 2020, declined sharply in 2022, and rebounded in 2023-2024, reaching around $3 trillion by 2025. This trend reflects growing investor demand and highlights the need to understand inter-asset interactions and systemic risk propagation.

Despite these advantages, digital assets carry significant risks, including high volatility, regulatory gaps, and limited transparency. Such factors can amplify systemic shocks, making it crucial to examine inter-asset relationships and investor behavior to develop effective risk management strategies (Ji et al., 2019; Umar et al., 2021). Regulatory frameworks such as the EU's Markets in Crypto-Assets (MiCA) regulation, the US Securities and Exchange Commission (SEC) oversight, and cryptocurrency guidelines in Japan and Singapore aim to mitigate systemic risks, enhance market transparency, and provide a structured environment for investors. Unlike traditional financial markets, digital assets are influenced by both macroeconomic conditions and micro-level drivers such as technological innovations, regulatory changes, and exchange-level interventions, resulting in time-varying interconnectedness that standard methods may not fully capture (Balli et al., 2023; Diebold & Yılmaz, 2014).

To address these challenges, this study employs the Generalized R² method on daily data from April 13, 2020, to April 7, 2025, covering eight major digital assets: cryptocurrencies (ETH, XRP, BNB), sustainable tokens (ADA, XLM, IOTA), NFTs (STX), and DeFi assets (LINK). By separating contemporaneous and lagged effects, the method identifies influential and influenced assets, tracks shock propagation, and highlights periods of heightened market interconnectedness.

This research contributes to literature by extending connectedness analysis to a broad set of digital assets within a unified framework, offering insights into contagion dynamics and systemic risk. From a policy perspective, understanding how interconnectedness evolves during crisis periods can support regulators in developing targeted interventions and assist investors in constructing resilient portfolios.

The remainder of the paper is structured as follows. The Introduction presents the background and objectives. The Literature Review synthesizes prior research and identifies the gap. The Data Set and Methodology section details the dataset, variables, and econometric approach. The Analysis Results section reports empirical findings on contemporaneous and lagged connectedness patterns. Finally, the Conclusion and Evaluation summarize key results, implications, and future research directions.

2. LITERATURE REVIEW

A review of the finance literature reveals that thousands of studies have been conducted on digital asset markets in recent years. The shift in investor preferences from traditional investment vehicles to digital assets has redirected scholarly attention toward this emerging field. Cheah & Fry (2015) examined speculative movements in Bitcoin prices, showing that market prices are often driven by irrational behaviors. Kristoufek (2015) highlighted the influence of social media on cryptocurrency markets, while Urquhart (2016) analyzed Bitcoin's market efficiency and concluded that it became increasingly rational over time. Katsiampa (2017) identified Bitcoin's volatility as highly sensitive to news and market interventions. Similarly, Conrad et al. (2018) observed a clustering tendency in Bitcoin's volatility, and Baur et al. (2018) emphasized the asset's inherently volatile and risky nature. Corbet et al. (2018) further investigated the bubble-like behaviors of Bitcoin and Ethereum, underlining their speculative characteristics. Expanding on this, Beneki et al. (2019) documented significant interdependence and intense volatility spillovers among cryptocurrencies. Ji et al. (2019) demonstrated that Bitcoin functions as a critical information transmitter within cryptocurrency markets, while Shahzad et al. (2020) confirmed that volatility spillovers primarily flow from Bitcoin to other altcoins. More recently, Bouri et al. (2021) and Umar et al. (2021) emphasized the vulnerability of cryptocurrency markets to external shocks, noting their exposure to both the COVID-19 pandemic and broader economic crises.

In parallel, a substantial body of research has explored dynamic connectedness and spillover mechanisms across financial, commodity, and digital asset markets. Akkus & Doğan (2024) examine the time-varying linkages among cryptocurrencies, NFTs, and DeFi assets using a TVP-VAR approach, demonstrating that digital markets are highly interconnected and prone to evolving risk transmission. Complementarily, Doğan et al. (2023) investigate the connectedness among clean energy markets, carbon emission allowances, and stock indices, highlighting the intensification of interlinkages during uncertain periods. Beyond digital markets, Balcı (2024) provides evidence of volatility spillovers among global stock markets during crisis episodes through a Diagonal BEKK framework, while Balcı (2025) analyzes the dynamic linkages between the Turkish Islamic stock market and global macroeconomic risk factors using a DCC-GARCH approach, both showing that systemic risks tend to strengthen in times of turbulence. Kyriazis & Corbet (2024) extend this line of research by evaluating the dynamic connectedness of financial assets and banking indices during black-swan events with a Quantile-VAR approach, finding that extreme events amplify systemic interconnectedness. Similarly, Li et al. (2024) assess connectedness between Chinese commodity and stock markets through TVP-VAR and cDCC-FIAPARCH models, emphasizing the role of hedging opportunities under time-varying dynamics.

Emerging research has also incorporated digital finance and FinTech perspectives. Yadav et al. (2025) investigate the time-varying interconnectedness among FinTech, digital assets, and electronic commerce, providing new insights into how technological innovation influences financial linkages. Likewise, Sharma et al. (2024) focus on the connectedness between commodities and ESG stocks in India, offering implications for sustainable investment strategies. Collectively, these studies confirm that financial and digital asset markets exhibit strong dynamic interdependencies, which tend to escalate during periods of stress or structural change.

Despite these advances, the existing literature has largely concentrated either on traditional financial markets, sector-specific indices, or limited segments of the digital asset ecosystem. Few studies have systematically examined the interconnectedness among a broad set of digital financial assets while considering both contemporaneous and lagged effects in a unified framework. Addressing this gap, the present study applies the Generalized R^2 method proposed by Balli et al. (2023) to analyze Ethereum, Ripple, Binance Coin, Cardano, Stellar, IOTA, Stacks, and Chainlink. By capturing time-varying relationships across multiple layers of interaction, this study contributes to a deeper understanding of contagion risk and stability implications in digital financial markets.

3. DATA SET and METHODOLOGY

3.1. Data Description

To examine the contagion dynamics in the digital asset market, the study uses daily price series of selected digital assets. Specifically, daily data from April 13, 2020, to April 7, 2025, are utilized to analyze interactions among eight leading digital assets: Ethereum (ETH), Ripple (XRP), Binance Coin (BNB), Cardano (ADA), Stellar (XLM), IOTA, Stacks (STXK) representing NFTs, and Chainlink (LINK) representing DeFi assets. The data for these variables were obtained from the Investing.com platform.

3.2. Methodology

In this study, the Generalized R² method is employed to examine the interactions among digital assets. The methodological framework and estimation steps of the approach are outlined as follows (Balli et al., 2023; Diebold & Yılmaz, 2012; Diebold & Yılmaz, 2014):

$$y_t = \sum_{i=1}^{p} B_i y_{t-i} + u_t \; and \; u_t \sim N(0, \Sigma) \tag{1}$$

Here, y_t t denotes the vector of log-returns of the interconnected indices at time. The coefficient matrix B_i reflects sectoral interconnectedness across different time periods, capturing the impact of each index on the others. The term u_t represents the error term.

Descriptive statistics for the digital assets included in the analysis are presented in Table 1. According to the figures reported in Table 1, the return series exhibit significant levels of skewness and kurtosis. Notably, STXK stands out with a skewness value of 7.854 and a kurtosis value of 102.46, indicating a highly speculative structure. Results from the Jarque-Bera test reveal that none of the series follow a normal distribution ($p < 0.01$). Moreover, the Q(10) and $Q^2(10)$ test statistics indicate the presence of statistically significant autocorrelation and ARCH effects in all series.

Table 1. Summary Statistics

	ETH	XRP	BNB	ADA	XLM	IOTA	STXK	LINK
Mean	2.924	3.368	2.777	3.621	3.358	3.819	4.58	4.039
Variance	8.947	22.223	13.086	16.538	20.887	16.26	29.208	15.07
Skewness	2.385***	5.411***	6.062***	4.540***	6.588***	3.317***	7.854***	2.431***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Kurtosis	9.563***	49.438***	77.921***	50.367***	74.278***	19.668***	132.840***	10.354***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
JB	8655.189***	194118.592***	471318.556***	198520.412***	431315.145***	32655.306***	1356156.257***	9916.079***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ERS	-12.772***	-9.877***	-6.494***	-7.385***	-9.150***	-8.005***	-9.031***	-12.632***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Q(10)	218.078***	370.897***	649.977***	257.387***	312.339***	256.228***	86.100***	281.917***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$Q^2(10)$	150.243***	36.629***	165.184***	35.274***	38.751***	132.563***	2.494	233.442***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.886)	(0.000)

Note: Skewness: D'Agostino (1970) test; Kurtosis: Anscombe and Glynn (1983) test; JB: Jarque and Bera (1980) normality test; ERS: Elliott et al. (1996) unit root test; Q(10) and $Q^2(10)$: Weighted Portmanteau test statistics proposed by Fisher and Gallagher (2012). P-values are reported in parentheses. Significance levels: * statistically significant at the 10% level, ** at the 5% level, and *** at the 1% level.

In the study, the calculation of total connectedness (TCI) and directional connectedness among assets is performed using Equation (2) (Diebold & Yılmaz, 2012; Diebold & Yılmaz, 2014):

$$TCI = \frac{1}{K} \sum_{k=1}^{K} R_k^2 \tag{2}$$

Using the Generalized R² decomposition, contemporaneous and lagged interactions are calculated as shown below using Equation (3) (Baur & Hoang, 2021):

$$R_{xx} = V \Lambda V' = CC' \tag{3}$$

4. ANALYSIS RESULTS

The findings regarding the levels of connectedness obtained using the Generalized R² method are presented below. The results indicate that information transmission in digital asset markets exhibits a directional, dynamic, and time-varying structure among assets.

Figure 2 illustrates the return series of the digital assets throughout the study period. An examination of Figure 2 reveals that fluctuations in returns occurred across all assets over time, and that similar return patterns emerged during several periods.

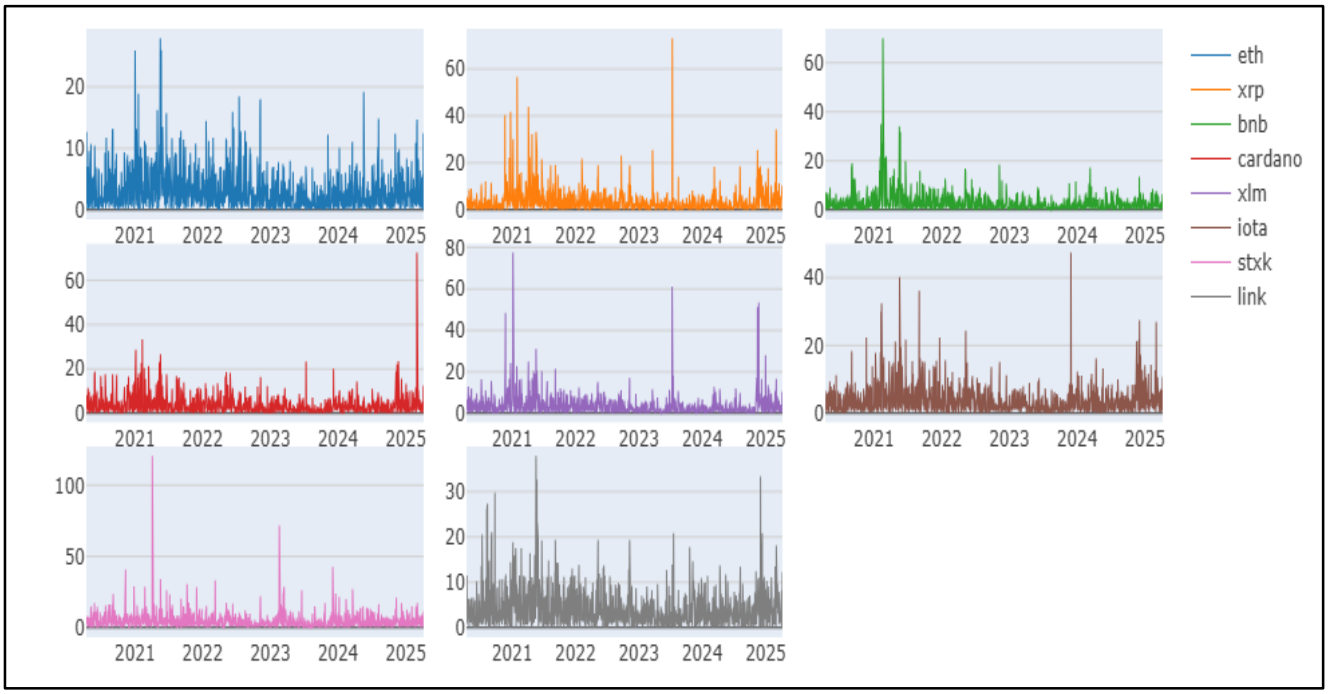

Figure 2. Logarithmic Return Series of Digital Assets

According to the dynamic total connectedness results presented in Figure 3, the Total Connectedness Index (TCI) exhibits a fluctuating pattern over time, with occasional surges above the 50% level, indicating periods of intensified systemic risk. These increases are particularly evident during periods characterized by external shocks. This finding suggests that systemic vulnerability intensifies at certain times, and information transmission triggers a chain reaction across the market.

The figure reveals that the overall connectedness level experienced substantial volatility over the years, peaking at the end of 2022. This result indicates heightened interdependence among assets during that period and a stronger propagation of market shocks. The contemporaneous connectedness level also follows a similarly volatile trend over the years, closely mirroring the behavior of overall connectedness. In contrast, the lagged connectedness level generally displays a lower and more stable pattern.

These findings collectively suggest that shock transmission within the digital asset market intensifies particularly during periods of uncertainty and crises. Moreover, lagged effects appear to exhibit a more dominant structure compared to contemporaneous effects.

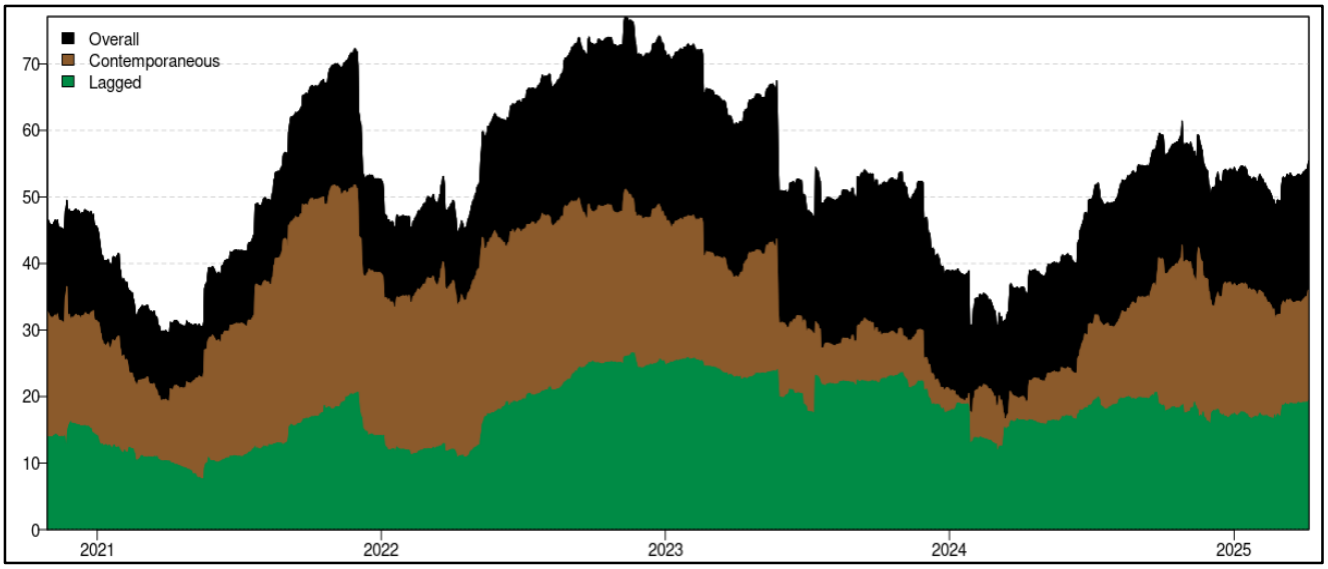

Figure 3. Dynamic Total Connectedness

According to the net total connectedness results presented in Figure 4, Ethereum (ETH) emerges as the most prominent shock transmitter in the market. Notably, there has been a significant increase in TDC values in the most recent periods, indicating that ETH has strengthened its leadership role and systemic impact within the market. Meanwhile, assets such as Cardano (ADA), Chainlink (LINK), and IOTA have exhibited relatively balanced and low levels of connectedness throughout the analysis period, suggesting that they have predominantly acted as shock receivers.

On the other hand, assets like Binance Coin (BNB), Ripple (XRP), and Stellar (XLM) have displayed notable fluctuations over time. BNB, for instance, has alternated between acting as a shock transmitter and a shock receiver across different periods. XRP transitioned into a shock transmitter position toward the end of 2024, while XLM increased its influence on the market following 2022 but subsequently lost this impact. Overall, the results confirm that the structure of interconnectedness among digital assets is dynamic and undergoes significant changes over time.

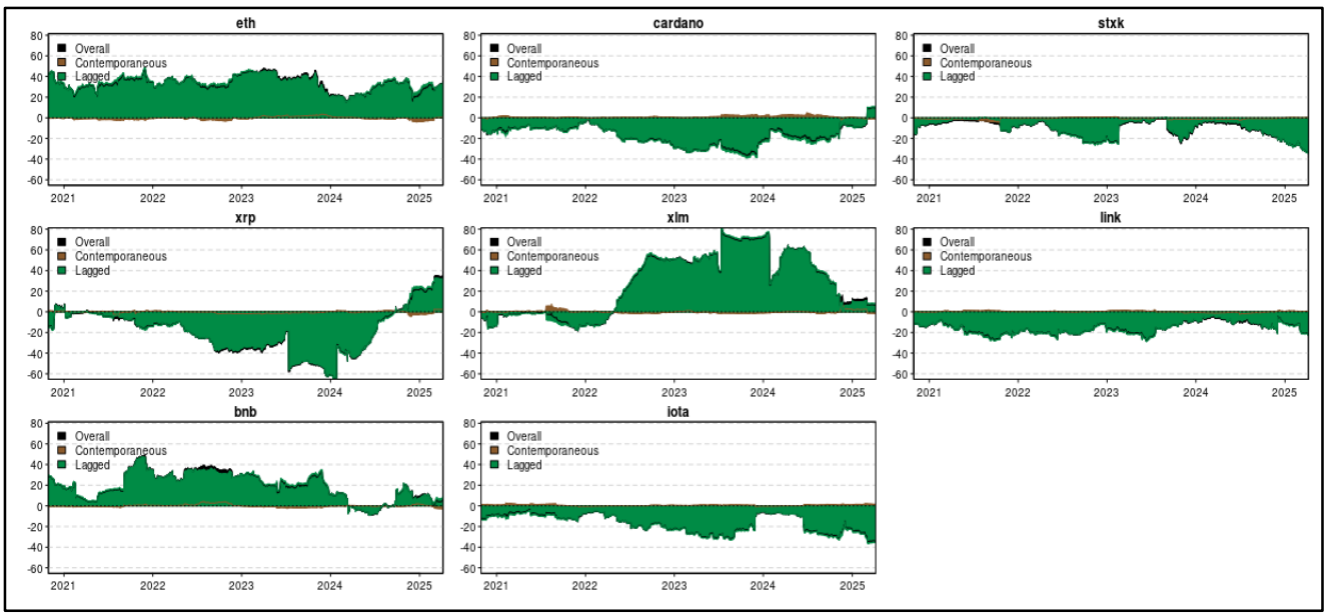

Figure 4. Net Total Directional Connectedness (TDC)

In this study, the interactions among the digital assets included in the analysis are measured through connectedness matrices, which express the impact of a shock occurring in one asset on the others. Table 2 below presents the results of the overall connectedness matrix. According to the results reported in Table 2: Ethereum (ETH) (75.34), Stellar (XLM) (72.77), and Binance Coin (BNB) (60.1) exhibit the highest total impact scores, indicating that these assets exert the strongest influence over the others. Moreover, their positive net impact scores reveal that they predominantly act as shock transmitters within the system. On the other hand, assets such as Cardano (ADA), IOTA, Stacks (STXK), and Chainlink (LINK) are identified as net shock receivers in the system.

Table 2. Overall Connectedness Matrix

FROM	Overall ETH	Overall XRP	Overall BNB	Overall ADA	Overall XLM	Overall IOTA	Overall STXK	Overall LINK	Overall FROM
ETH	0,71	1,91	23,99	1,32	10,64	1,13	0,87	1,97	41,84
XRP	5,67	2,08	4,24	8,8	26,05	5,4	3,39	4,62	58,16
BNB	23,87	2,22	2,61	1,82	7,07	1,88	1,05	2,75	40,66
ADA	8,34	8,51	5,86	1,31	12,49	7,17	3,79	8,98	55,13
XLM	12,09	11,9	7,83	5,56	1,47	2,52	2,05	3,56	45,51
IOTA	7,98	6,32	6,27	7,37	6,61	0,71	4,71	7,94	47,2
STXK	5,69	3,46	5	4,14	3,65	4,53	1,37	3,88	30,36
LINK	11,7	4,81	6,9	8,92	6,27	7,59	3,49	0,59	49,67
TO	75,34	39,13	60,1	37,94	72,77	30,22	19,34	33,7	368,53
Inc.Own	76,05	41,21	62,7	39,25	74,23	30,93	20,71	34,29	cTCI/TCI
NET	33,51	-19,02	19,44	-17,19	27,25	-16,98	-11,02	-15,98	52.65/46.07

When examining the results of the contemporaneous connectedness matrix presented in Table 3: XLM (37.85), ETH (37.33), and BNB (33.87) exhibit the highest contemporaneous impact scores on other assets. These assets possess strong instantaneous influence over others, whereas STXK (15.99), IOTA (26.7), and LINK (28.16) display a more limited contemporaneous impact. An analysis of the net impact scores indicates that all assets are engaged in relatively similar levels of interaction, suggesting a generally homogeneous structure across the system.

Table 3. Contemporaneous Connectedness Matrix

FROM	C+ ETH	C* XRP	C* BNB	C* ADA	C* XLM	C* IOTA	C* STXK	C* LINK	C* FROM
ETH	0	1,39	23,31	0,83	9,94	0,66	0,57	1,12	37,82
XRP	1,25	0	0,8	7,81	10,25	5,02	2,78	3,99	31,91
BNB	23,12	0,84	0	0,86	5,86	1,1	0,65	1,49	33,94
ADA	0,74	7,55	0,77	0	4,98	6,66	3,35	8,19	32,25
XLM	10,05	10,08	5,96	5	0	2,06	1,76	2,95	37,87
IOTA	0,56	4,89	0,98	6,67	2,01	0	3,75	7,21	26,07
STXK	0,59	2,96	0,66	3,57	1,9	3,9	0	3,21	16,79
LINK	1	3,83	1,38	8,43	2,91	7,3	3,12	0	27,98
TO	37,33	31,54	33,87	33,18	37,85	26,7	15,99	28,16	244,62
Inc.Own	37,33	31,54	33,87	33,18	37,85	26,7	15,99	28,16	cTCI/TCI
NET	-0,48	-0,37	-0,07	0,93	-0,02	0,63	-0,8	0,18	34.95/30.58

Note: Contemporaneous

When examining the results of the lagged connectedness matrix presented in Table 4: The assets with the highest lagged effects are ETH (38.01), XLM (34.91), and BNB (26.22). These results suggest that ETH, XLM, and BNB serve as the primary actors in the medium- and long-term transmission of information within the system. Moreover, their positive net values indicate that they also act as shock transmitters in lagged interactions. In particular, Ethereum's net value (33.99) and XLM's net value (27.27) demonstrate that these assets have a strong and lasting influence over the system. On the other hand, XRP (-18.66), ADA (-18.22), and LINK (-16.16) exhibit negative net scores, identifying them as net shock receivers. These findings imply that for some assets, shock effects do not diminish over time but instead continue to propagate throughout the system in a lagged manner.

Table 4. Lagged Connectedness Matrix

FROM	Lagged ETH	Lagged XRP	Lagged BNB	Lagged ADA	Lagged XLM	Lagged IOTA	Lagged STXK	Lagged LINK	Lagged FROM
ETH	0,71	0,53	0,68	0,49	0,7	0,47	0,31	0,85	4,02
XRP	4,41	2,08	3,43	0,99	15,79	0,39	0,6	0,63	26,25
BNB	0,75	1,38	2,61	0,95	1,2	0,77	0,4	1,26	6,71
ADA	7,6	0,96	5,09	1,31	7,51	0,51	0,44	0,79	22,89
XLM	2,03	1,82	1,87	0,57	1,47	0,46	0,29	0,61	7,65
IOTA	7,42	1,44	5,3	0,7	4,6	0,71	0,95	0,73	21,13
STXK	5,1	0,5	4,34	0,57	1,76	0,63	1,37	0,67	13,58
LINK	10,69	0,98	5,52	0,49	3,36	0,29	0,36	0,59	21,7
TO	38,01	7,59	26,22	4,76	34,91	3,52	3,35	5,54	123,91
Inc.Own	38,72	9,67	28,83	6,08	36,38	4,23	4,72	6,13	cTCI/TCI
NET	33,99	-18,66	19,51	-18,12	27,27	-17,61	-10,22	-16,16	17.70/15.49

The total influence of the assets on other assets, as presented in Tables 2, 3, and 4, is illustrated in Figure 5. The data in Figure 5 reveal that Ethereum (ETH) and Binance Coin (BNB) acted as strong shock transmitters particularly during the 2021-2022 period, while Stellar (XLM) assumed a dominant role during 2023-2024. Additionally, Ripple (XRP) has emerged as a prominent shock transmitter in the most recent period.

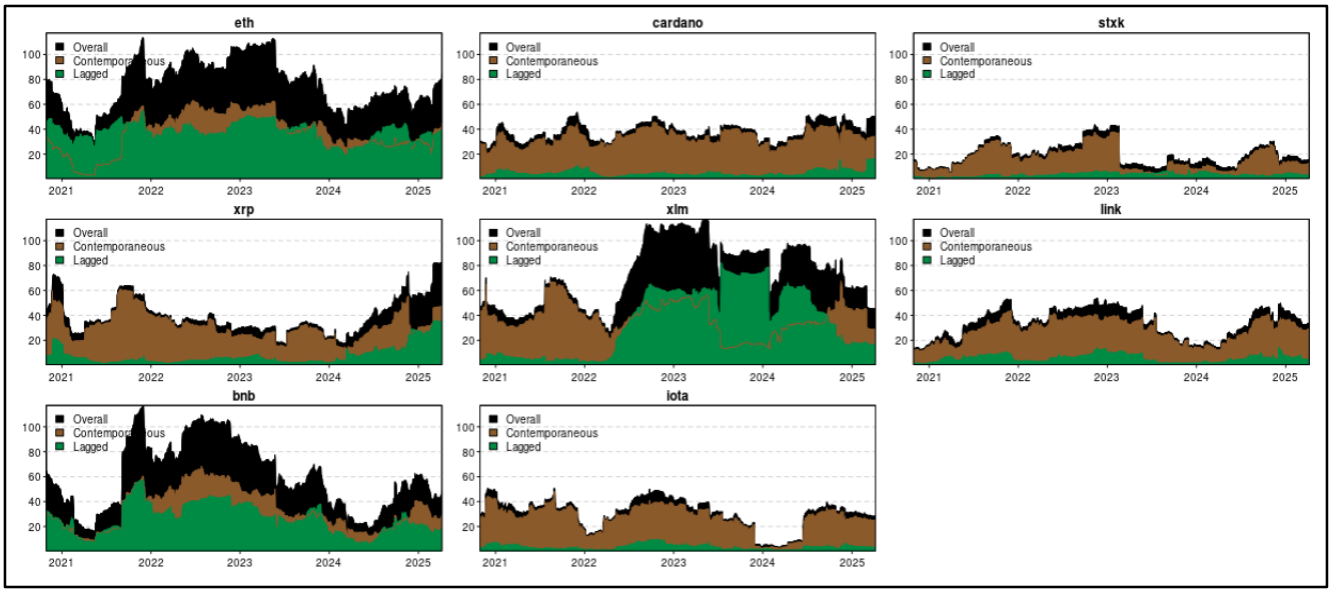

Figure 5. Total Impact on Others

According to the information presented in Figure 6, which illustrates the total shock received by each asset from others (as derived from Tables 2, 3, and 4), the results indicate that assets exhibit varying degrees of shock sensitivity over time. In particular, XRP, ADA, and IOTA appear to have been significantly affected during the post-2023 period. These findings demonstrate that the roles of shock reception and transmission fluctuate over time, highlighting the importance of dynamic analyses in understanding the interactions among digital assets.

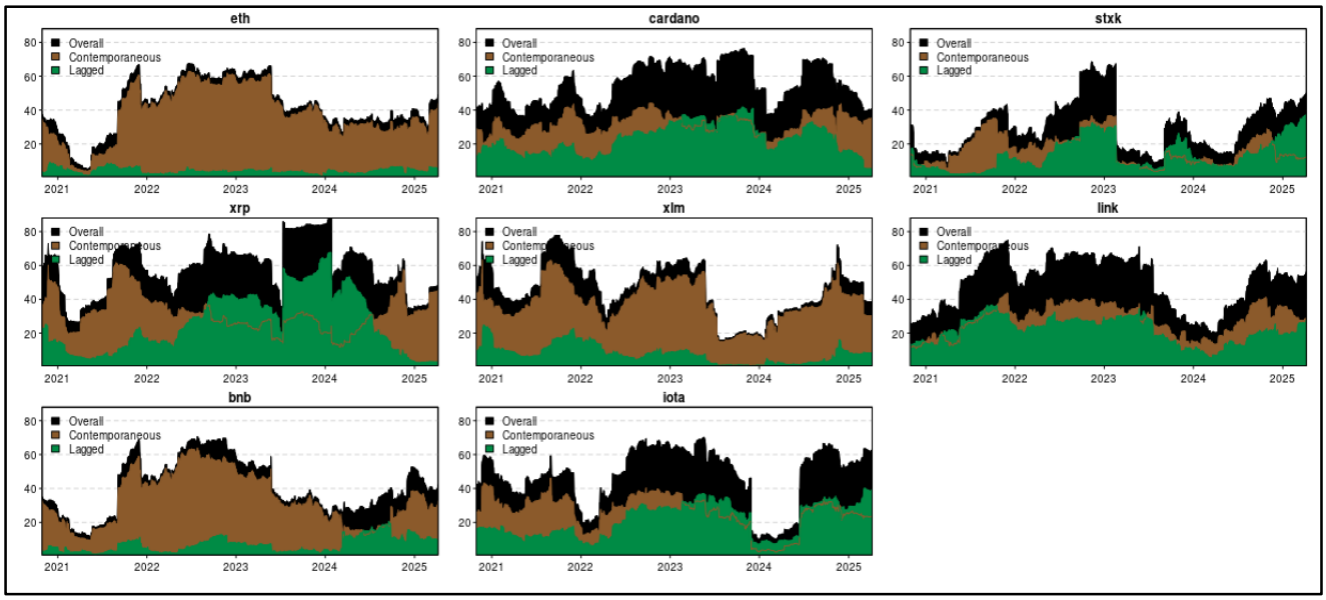

Figure 6. Total Impact from Others

Figure 7 presents the network of connectedness among the digital assets. The visuals in Figure 7 sequentially display contemporaneous, lagged, and overall connectedness relationships. According to the information presented in the figure 7:

Contemporaneous Connectedness: IOTA and ADA exhibit a strong contemporaneous linkage. The connection between these financial assets is relatively high, meaning that their price movements tend to influence each other simultaneously. This suggests that both assets are likely affected by similar underlying factors.

Lagged Connectedness: XRP, LINK, and STXK demonstrate stronger lagged relationships compared to other assets. This implies that these assets tend to react more slowly to market price movements, reflecting delayed responses to shocks.

Overall Connectedness: ADA and IOTA are identified as the most interconnected assets in the market, exhibiting the highest levels of total interaction.

A general assessment of Figure 7 reveals that the nature of connectedness among assets varies between contemporaneous and lagged effects. While the contemporaneous network appears relatively sparse, the lagged network demonstrates denser and more complex interrelationships.

Notably, Ethereum occupies a central position across all three graphs, exerting both immediate and persistent influence over other assets.

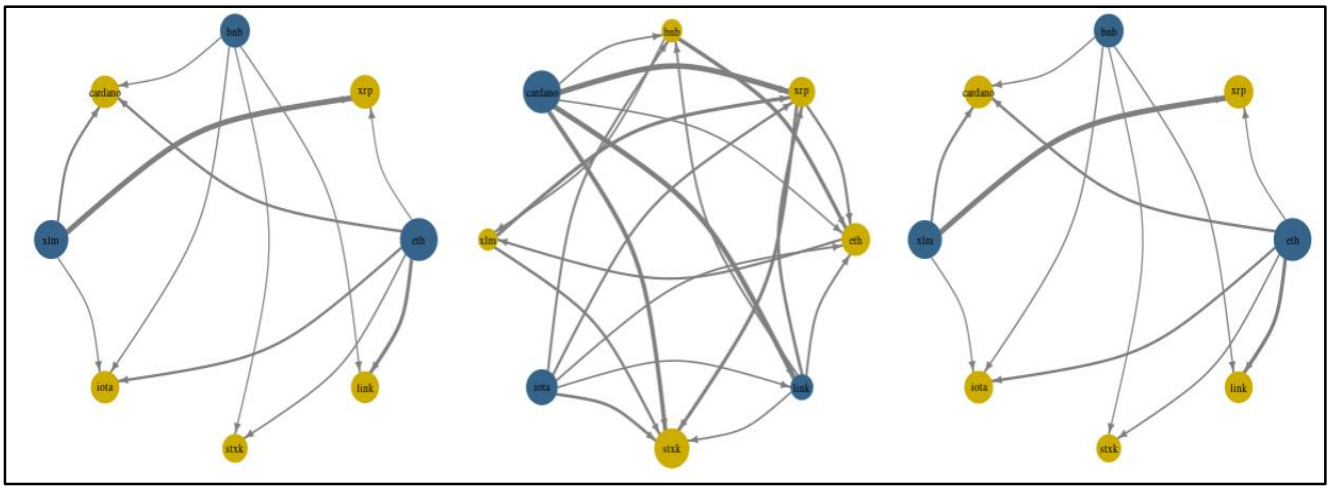

Figure 7. Volatility Spillover Network Graph

5. CONCLUSION and EVALUATION

The findings indicate that the level of interconnectedness in the digital asset market varies significantly over time and intensifies during periods of financial distress. This outcome necessitates the attention not only of individual investors but also of market regulators and policymakers due to the potential for contagion effects across financial markets. From a policy perspective, understanding how interconnectedness evolves during crisis periods can support regulators in developing targeted interventions. These insights can inform ongoing regulatory initiatives, such as the EU MiCA framework, US SEC enforcement policies, and Asian cryptocurrency regulations in Japan and Singapore, to strengthen market stability and manage contagion risks (Balli et al., 2023; Akkus & Doğan, 2024). Accurately analyzing contemporaneous and lagged connectedness effects is essential for designing risk-focused policies that support market resilience.

For investors engaged in portfolio diversification, it is crucial to make decisions not only based on returns but also by considering the interconnectedness characteristics of assets during crisis periods. Taking precautionary measures during periods of heightened volatility can help construct more resilient investment strategies (Ji et al., 2019; Yousaf & Yarovaya, 2022).

When compared with existing literature, the results of this study are broadly consistent with prior evidence emphasizing the time-varying and crisis-sensitive nature of connectedness. For instance, Ji et al. (2019) demonstrated that cryptocurrency markets exhibit strong dynamic integration, particularly during turbulent periods, which aligns with the present study's finding that shocks intensify contagion across digital assets in times of financial distress. Similarly, Li et al. (2023) showed that cryptocurrencies and traditional financial assets in China are subject to time- and frequency-dependent connectedness, underscoring the importance of analyzing both short- and long-term spillovers—an approach also captured by the use of the Generalized R^2 method in this research.

In a related strand of literature, Yousaf & Yarovaya (2022) highlighted significant interconnectedness between NFTs, DeFi, and other assets, with implications for portfolio construction. This complements the current study's results, as both analyses stress that diversification strategies must account for cross-asset contagion rather than relying solely on return correlations. On the other hand, Gong & Xu (2022), focusing on commodity markets under geopolitical risks, found that external shocks can substantially reshape interconnectedness patterns. Although the asset classes differ, this comparison reinforces the broader conclusion that systemic shocks—whether geopolitical or financial—amplify market interdependence.

Taken together, these comparisons show that while prior studies have primarily examined either specific asset classes or particular risk channels, the present research adds value by integrating multiple types of digital assets

(cryptocurrencies, sustainable tokens, NFTs, and DeFi) into a unified framework that distinguishes between contemporaneous and lagged connectedness. This broader scope not only confirms the crisis-sensitivity of connectedness identified in earlier studies but also provides a more nuanced understanding of how shocks propagate through diverse segments of the digital asset ecosystem.

Future research could extend this framework by including additional digital assets, performing cross-country comparisons, or incorporating regulatory shocks to further investigate systemic risk dynamics and market resilience.

AUTHORS' DECLARATION:

This paper complies with Research and Publication Ethics, has no conflict of interest to declare, and has received no financial support.

AUTHORS' CONTRIBUTIONS:

The entire research is written by the author.

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Evaluating Information and Communication Technology (ICT) Levels in Visegrad Countries: A Performance Analysis Using MPSI-LOPCOW-BSS Framework

Visegrad Ülkelerinde Bilgi ve İletişim Teknolojileri (ICT) Düzeylerinin Değerlendirilmesi: MPSI-LOPCOW-BSS Çerçevesini Kullanarak Performans Analizi

Mehmet Akif KARA
Asst. Prof. Dr., Giresun University
akifkara28@gmail.com
https://orcid.org/0000-0003-4308-9933

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ABSTRACT

Information and Communication Technologies (ICT) are the keys to the competitiveness of both states and businesses. The rapid advancements and developments in technology and communication have led to the emergence of information and communication technologies. The policymaking authorities are making the proper arrangements for the maintenance and growth of the infrastructure for information and communication technologies. In this view, the study and assessment of the ICT levels of different countries become a fundamental issue. Therefore, this project is an in-depth study of the Visegrad countries ICT performance, which was analyzed using the selected list of criteria which included; ICT employment, ICT investment, ICT value-added, ICT goods exports, internet access, and home computer access. In this research, the MPSI and LOPCOW methods were applied to determine the weights of the criteria, which were then combined with an aggregation operator to derive the final criteria weights. Soon afterward, the countries' ICT levels were ranked by means of the BSS method. The study proposes an integrated MPSI-LOPCOW-BSS decision support system. As a result of the application, the criterion with the highest weight was found to be "ICT Investment." The country rankings are Czechia, Hungary, Poland, and Slovakia.

Anahtar Kelimeler:

Bilgi ve İletişim Teknolojisi,

Çok Kriterli Karar Verme Yöntemleri,

Karar Destek Sistemleri,

Visegrad Ülkeleri

Jel Kodları:

C02, C44, D80

ÖZET

Bilgi ve İletişim Teknolojileri (ICT), hem devletlerin hem de işletmelerin rekabetçiliği için anahtar konumundadır. Teknoloji ve iletişimdeki hızlı gelişmeler, bilgi ve iletişim teknolojilerinin ortaya çıkmasına yol açmıştır. Politika yapıcı otoriteler, bilgi ve iletişim teknolojileri altyapısının sürdürülebilirliği ve büyümesi için uygun düzenlemeleri yapmaktadır. Bu bağlamda, farklı ülkelerin ICT düzeylerinin incelenmesi ve değerlendirilmesi temel bir konu haline gelmektedir. Bu nedenle, bu proje Visegrad ülkelerinin ICT performansını derinlemesine incelemektedir. Analiz, ICT istihdamı, ICT yatırımı, ICT katma değeri, ICT mal ihracatı, internet erişimi ve ev bilgisayarı erişimi gibi belirlenen kriterler kullanılarak gerçekleştirilmiştir. Araştırmada, kriterlerin ağırlıklarını belirlemek için MPSI ve LOPCOW yöntemleri uygulanmış ve ardından nihai kriter ağırlıklarını elde etmek için bir toplama operatörü ile birleştirilmiştir. Daha sonra, ülkelerin ICT seviyeleri BSS yöntemi ile sıralanmıştır. Çalışma, entegre bir MPSI-LOPCOW-BSS karar destek sistemi önermektedir. Uygulama sonucunda en yüksek ağırlığa sahip kriterin "ICT Yatırımı" olduğu bulunmuştur. Ülke sıralamaları ise Çek Cumhuriyeti, Polonya, Macaristan ve Slovakya'dır.

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1. INTRODUCTION

The rise of globalization have made information and communication technologies (ICTs) pivotal and indeed have become an essential complementary of the context of rapid technological and economic advancements. Nour (2005) states that the most important way to catch up to the industrial economies in development in ICT. Hence, the production and export of the ICT goods are significant competitive factors for countries (Batbaylı, 2024), while the countries that are faced with the problem of lacking technology necessarily spend a huge amount on the importation of necessary goods (Heeks, 2010). The digital convergence process, initiated in the 1980s, revolutionized the processing of text, audio, and images in digital formats. This, combined with the digitalization of telecommunications, enabled the transmission of digital data and information. As a result, information technology and communication technology have become increasingly intertwined, a phenomenon captured by the term ICT. ICT encompasses the processes of processing, storing, transmitting, and presenting various forms of information, including voice, data, text, and images, through hardware, software, networks, and media.

The globalization of markets has been accelerated by the widespread adoption of ICT (Lal, 2007). ICT plays a crucial role in facilitating the collection, processing, storage, and transfer of information among organizations, thereby enhancing access to international trade and fostering collaboration (Harris et al., 2015). This integration allows countries to participate in global markets and the international workforce, driven by technological advancements. Additionally, ICT offers significant advantages to businesses, particularly in terms of efficiency and innovation (Perego et al., 2011). The integration of technology has led to the emergence of new business opportunities and models, triggering transformations in traditional sectors and impacting economic dynamics. Investments in information technologies can further promote sustainable and inclusive economic growth. In recent years, the rapid global proliferation of ICT has had profound effects on both individuals and businesses. The increased use of these technologies is particularly notable in the context of e-commerce and the adaptation of government public operations to new technologies, both of which are critical factors influencing competition (Chen et al., 2021). The initial phase of the digitalization process involved the integration of the Internet and computers into daily life, followed by advancements in software systems and automation that facilitated the development of innovative business models and the rapid dissemination of digital concepts (Klein, 2020).

Information and communication technology provides several key benefits (Demir, 2022): "*(i) rapid and efficient data processing capabilities; (ii) the transformation of information into valuable services, enhancing convenience; (iii) human-centered applications in product and service development, thereby increasing productivity; (iv) rapid identification of errors through analyses conducted in business environments; and (v) rapid access to information, facilitating knowledge sharing*". Evaluating ICT levels in countries is essential for effective strategic policy formulation and planning, as understanding the current state of ICT levels sheds light on policy development.

The primary aim of this study is to develop a hybrid decision support system for determining the Information and Communication Technology (ICT) levels of Visegrad (V4) countries.

This decision support system incorporates multi-criteria decision-making (MCDM) methods that are relatively new to the literature in terms of criteria weighting and ranking, as determining ICT levels is a typical decision-making process. The sub-objectives of the study are as follows:

Case Study Application: To conduct a case study to determine the ICT levels of V4 countries. This study focuses on the Visegrad countries: the Czechia, Hungary, Poland, and Slovakia. The reasons for selecting this sample group include their geographical and cultural proximity, their significant role in EU economic cooperation and integration, their advancements in the ICT sector in recent years, and the opportunity to analyze differences in ICT levels due to historical reform processes and economic developments in the post-communist era. Additionally, the similar structural characteristics among the Visegrad countries ensure the validity and reliability of the rankings performed using multi-criteria decision-making methods.

Methodological Development in MCDM: To contribute to the methodological advancement of MCDM methods, particularly by using two different criteria weighting methods together to determine a final criterion weight. The study also proposes the development of the MPSI-LOPCOW-BSS hybrid method to assess the ICT levels of countries. In this study, the MPSI and LOPCOW methods were chosen for criterion weighting. The MPSI method is selected because it performs simple and effective calculations in the criterion weighting process. It is an improved version of the PSI method, where a step was removed to enhance the accuracy of the final weight coefficients. It aligns closely with other objective weighting methods and considers deviations among the normalized values of the criteria during calculations. The LOPCOW method is preferred because it uses a logarithmic function to calculate the standard deviation for each criterion, ensuring more meaningful and accurate

percentage values. Its simple three-step structure makes it easier for practitioners to follow. The BSS method, chosen for ranking, is relatively new and has been used in very few studies.

Criterion Weighting Approach: The study combines two different objective criterion weighting methods in the decision model.

Final Criterion Weight Calculation: The study calculates final criterion weights by integrating the MPSI and LOPCOW methods, offering a comprehensive criterion weighting approach. The main reason for combining both methods is their suitability for sensitivity analysis.

ICT Levels Scoring: The study utilizes the BSS method to obtain and rank the ICT levels of countries.

Methodological Contribution: This study provides methodological contributions to the fields of information and communication technologies and multi-criteria decision-making approaches, further developing decision support systems in this area.

This study makes several significant contributions to the literature. First, it uses a multi-criteria decision-making (MCDM) approach to evaluate ICT development. Second, it identifies the most important indicators for assessing ICT development in social and economic contexts. Third, it develops an integrated MCDM framework using the MPSI-LOPCOW-BSS methods. Unlike traditional qualitative assessments, this study uses real data obtained from OECD datasets. The MPSI and LOPCOW methods are applied to determine the optimal weighting coefficients of the indicators, followed by the calculation of the final criteria weights using an aggregation operator. Subsequently, real data from the OECD dataset is analyzed using the BSS model to evaluate ICT development, and countries are prioritized according to their performance based on the identified indicators. The contributions of the proposed decision-making model are:

- An actual case study assessing ICT development through social and economic metrics.
- A dependable integrated MCDM framework utilizing the MPSI-LOPCOW-BSS methods.
- Benchmarking to evaluate ICT development in the Visegrad countries.
- Suggestions and strategies for enhancing ICT tools and services across different sectors based on the study's findings.

The proposed methodology and identified indicators can serve as benchmarking case studies for other groups of countries. In summary, this study aims to achieve two main objectives: to evaluate the IT levels of the Visegrad countries and to develop a decision support system using newly developed methods from the literature (MPSI-LOPCOW-BSS) in an integrated framework. The results obtained by the two criteria weighting methods are combined using a combination operator to increase reliability. In addition, sensitivity analysis is performed to demonstrate the robustness of the proposed decision support system.

The remainder of this article is structured as follows: Section 1 (Introduction) presents the theoretical background and literature review. Section 2 describes the MPSI-LOPCOW-BSS method and outlines the research methodology. Section 3 applies performance analyses to the Visegrad countries. Section 4 discusses the research findings, key insights, sensitivity analysis. Finally, Section 5 concludes the study with final evaluations.

2. LITERATURE REVIEW

The level of information technology has been addressed in the literature using various methods across different fields. A literature review on Information and Communication Technology (ICT) reveals that the relationship between ICT levels and economic growth is a frequently studied topic (Yaprakli & Sağlam, 2010; Artan et al., 2014; Albiman & Sulong, 2017; Özkan & Çelik, 2018; Fernández-Portillo et al., 2020; Cheng et al., 2021).

Additionally, studies have been published addressing topics such as the relationship between ICT and development (Jin & Cho, 2015), the effects of ICT on carbon emissions (Wang et al., 2024), the impact of ICT use on PISA performance (Goh et al., 2024), and the relationship between ICT and financial development (Samargandi et al., 2019; Cheng et al., 2021). These studies have employed methods such as panel data analysis, ARDL, Granger causality analysis, regression analysis, and principal component analysis.

Some studies address ICT levels using multi-criteria decision-making methods (Setiawan et al., 2016; Merkevičius & Yadav, 2019; Yakut, 2020; Ersoy, 2021; Torkayesh & Torkayesh, 2021; Ecemiş & Çoşkun, 2022; Demir, 2022; Keleş, 2024; Ecer & Güneş, 2024; Macit, 2024).

In general, methods such as AHP, TOPSIS, MEREC, CRITIC, LBWA, MPSI and MARCOS have been used in the studies. In addition to these studies, research utilizing fuzzy sets has been conducted. Bahnamiri et al. (2015) employed fuzzy entropy and TOPSIS methods, Karabasevic et al. (2021) used fuzzy MULTIMOORA, and Nasri et al. (2022) applied fuzzy AHP-VIKOR methods. Typically, criteria are weighted using a single method. Demir (2022) applied PSI-LOPCOW methods, calculating the final weights through a Bayesian aggregation operator. In the study by Ecer & Güneş (2024), MEREC and CRITIC methods were used, and the final criterion weight was determined using an aggregation operator proposed by Torkayesh et al. (2021). Both studies recommended the use of "different methods" for future research. This study complies with this recommendation by using a different aggregation operator. Additionally, a novel integrated decision support system is proposed, unlike those in previous studies.

Although the MPSI method is relatively new, it is widely used in the literature. Gligorić et al. (2022) integrated the MPSI method with the MARA method to help engineers in the mining sector select appropriate support methods. In his study, Yılmaz (2023) used the MPSI-MARA methods in an integrated manner to determine the financial performances of banks. Akbulut & Aydın (2024) examined the multidimensional sustainability performances of deposit banks using the MPSI, MSD, and RAWEC methods. In their study, Torres et al. (2024) propose an integrated decision support system consisting of the MPSI-SPOTIS methods for the selection of unmanned aerial vehicles. Ersoy et al. (2025) employed the MPSI-RAPS model to determine the progress of EU countries in achieving the Sustainable Development Goals (SDGs). Wittig Vienna et al. (2025) proposed a hybrid ranking methodology consisting of MPSI and CoCoSo methods to assess efforts toward renewable energy transition among OECD member countries. Kara et al. (2025) utilized the MPSI-OPLO-POCOD method to determine the ESG-based sustainability performance levels of 17 software companies listed in the S&P 500 index for the years 2021, 2020, 2019, and 2018.

The LOPCOW method has been applied in various fields in the literature. Ulutaş et al. (2023) used an integrated MCDM model consisting of MEREC, LOPCOW, and MCRAT methods for the natural fiber selection problem in building insulation materials. In their research, Öztaş & Öztaş (2024) apply the LOPCOW method in conjunction with the MAIRCA method to evaluate the innovation performances of G20 countries. Dündar (2024) examined the performance of 200 state and foundation universities operating in Turkey in terms of project submission and execution capacities within the scope of the Research Support Programs Directorate (ARDEB) using the LOPCOW-CRADIS methods. In their study, Dhruva et al. (2025) address the selection of the "Food Waste Treatment Method" (FWTM). The study utilizes q-Rung Orthopair Fuzzy Set and proposes an MCDM framework consisting of LP-LOPCOW-COPRAS methods. Altıntaş (2025) utilizes the most up-to-date data from the Global Food Security Index (GFSI) for 2022 to evaluate the food security performances of G7 countries using the Logarithmic Percentage Change-driven Objective Weighting (LOPCOW) based Double Normalization-Based Multiple Aggregation (DNMA) Multi-Criteria Decision-Making (MCDM) method. Setiawansyah et al. (2025) used the LOPCOW method in conjunction with the AROMAN method for the store selection problem.

The BSS method is a new approach. It has been utilized in two studies developed by Bulut (2024a). In Bulut's (2024a) work, it was applied to measure the capacity of the Turkish Health System, while in Bulut (2024b), it was used in another context. In his research, Bağcı (2025) ranked various countries according to the importance levels of digital finance indicators. This study employed the NMV-BSS methods.

In the existing literature, most studies on Information and Communication Technologies (ICT) have overlooked the MPSI-LOPCOW-BSS methods, particularly in the context of the Visegrad countries. This gap is notable, especially given the economic integration of these countries and their role in the EU digital agenda. Assessing ICT levels using a novel integrated framework not only advances methodological approaches but also holds significant policy relevance. Furthermore, the literature predominantly employs a single weighting method, which emphasizes the need for studies that integrate various methods and multi-criteria decision-making processes. To address this gap, the present research proposes an integrated decision support system utilizing the MPSI-LOPCOW-BSS methods, focusing on the Visegrad countries as a case study. This approach is crucial for evaluating the effects of different weighting methods and for assessing ICT performance specifically within this region.

3. METHODOLOGY

In this section of the study, the steps of the proposed integrated MPSI-LOPCOW-BSS method will be outlined. The criteria identified through a literature review related to the specified topic have been weighted separately using the MPSI and LOPCOW methods. Subsequently, the final criterion weight was obtained using a

combination operator found in the literature, and the problem was solved using the BSS method. The process related to the solution is shown in Figure 1.

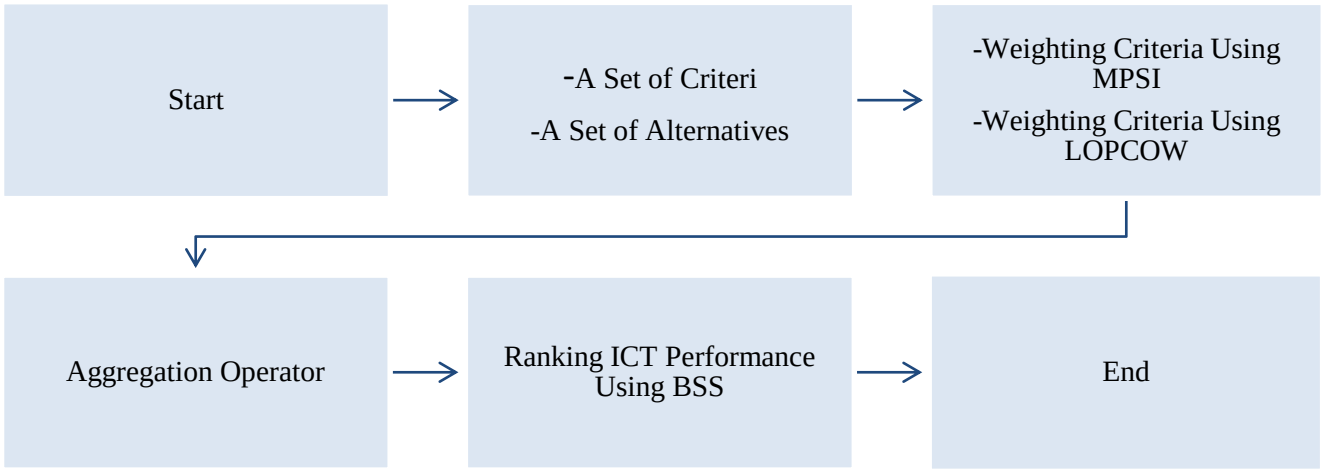

Figure 1. The Structural Foundation of Methodology

3.1. MPSI

The MPSI (Modified Preference Selection Index) method focuses on the fluctuations in preference values of criteria, reflecting the differences between normalized values and the average Euclidean distance (Macit, 2024). This method offers a simple and efficient way to determine the objective weights of criteria. Additionally, the computation of weight coefficients using this newly developed technique is not overly complex, which enhances the MPSI's potential as a widely applicable problem-solving tool. This approach builds upon the PSI method, resulting in an improved version known as the MPSI. The MPSI modifies PSI by removing a single step, thereby increasing the accuracy of weight coefficients. This slight change enhances the accuracy of the final weight coefficient values, aligning them more closely with those generated by other objective weighting methods (Gligorić et al., 2022). The new approach has the following steps (Gligorić et al., 2022; Kara et al., 2025).

Step 1.1. Decision matrix: To calculate the criteria weighing, the initial decision matrix must first be constructed. In the initial decision matrix, the values for each alternative are determined based on the criteria.

Step 1.2. Creating the normalized decision matrix:

$$r_{ij} = \frac{x_{ij}}{max x_{ij}} \qquad i = 1,2,\dots,m \quad \text{for benefit-oriented criteria} \tag{1}$$

$$r_{ij} = \frac{min x_{ij}}{x_{ij}} \qquad i = 1,2,\dots,m \text{ for cost-oriented criteria} \tag{2}$$

Step 1.3. Calculate the mean value v_j of the normalized evaluations of criterion j and it is calculated with the following equation:

$$v_j = \frac{1}{m}\sum_{i=1}^{m} r_{ij} \tag{3}$$

Step 1.4. Calculate the preference variation value p_j as follows:

$$p_j = \frac{1}{m}\sum_{i=1}^{m}(r_{ij-v_j})^2 \tag{4}$$

Step 1.5. The criteria weights w_j are determined using the following equation:

$$w_j = \frac{p_j}{\sum_{j=1}^{n} p_j} \tag{5}$$

3.2. LOPCOW

The LOPCOW method is a criterion weighting approach developed by Ecer and Pamucar in 2022. As an objective method, it establishes criterion weights independently of decision-makers' opinions. A key aspect of this method

is its consideration of negative performance values among alternatives, which aids in accurately determining criterion weights and facilitates the effective analysis of numerous criteria and alternatives (Biswas et al., 2022). The LOPCOW method employs a logarithmic function to calculate the standard deviation for each criterion based on the number of alternatives, resulting in percentage values that more accurately reflect the differences between more and less significant criteria.

The method consists of three steps. First, an internal decision matrix is created, consisting of *m* alternatives and *n* criteria, to identify and solve the decision problem.

Step 2.1. Creating the normalized decision matrix:

$$r_{ij} = \frac{x_{ij} - x_j^{min}}{x_j^{max} - x_j^{min}} \text{ for benefit-oriented criteria} \quad (6)$$

$$r_{ij} = \frac{x_j^{max} - x_{ij}}{x_j^{max} - x_j^{min}} \text{ for cost-oriented criteria} \quad (7)$$

Step 2.2. Creating the PV_{ij} matrix of percentage values for each criterion

$$PV_{ij} = \left| ln\left(\frac{\sqrt{\sum_{i=1}^{m} r_{ij}^2 / m}}{\sigma} \right) 100 \right| \quad (8)$$

Step 2.3. Calculating objective weights (W_j)

$$w_j = \frac{PV_{ij}}{\sum_{i=1}^{n} PV_{ij}} \quad (9)$$

3.3. BSS (Bulut Scoring Systems)

The studies published by Bulut (2024) have contributed to the literature and introduced a ranking method that is used in various fields.

Step 3.1. Building the decision matrix: As with other MCDM methods, the decision matrix is first created. The columns of the decision matrix represent the decision criteria, while the rows represent the decision alternatives.

Step 3.2. Calculation of unstandardized raw scores: This step involves first determining the weights of the decision criteria using any method. The BSS uses the determined weights of the decision criteria as input. Here, w_j Denotes the weights of the decision criteria. Initially, Equation (10) calculates the unstandardized raw value matrix (V) from the decision matrix. Equation (10) is applied to each row in the decision matrix to produce a new matrix of size a*c similar to the decision matrix. This matrix is called the V matrix. Equation (11) then calculates the unstandardized raw scores (R) of each alternative from the V matrix.

$$V = o_1 * w_1 * x_1 + o_2 * w_2 * x_2 + o_3 * w_3 * x_3 + \ldots + o_j * w_j * x_j \quad (10)$$

$$R = \frac{V}{a*c} \text{ where } c>1 \text{ and } a>1 \quad (11)$$

Step 3.3. Calculation of band value: After calculating the non-standardized raw scores (R) of the alternatives, the maximum and minimum scores within the raw scores are determined, and their absolute values are taken and summed. This process ensures that the non-standardized raw scores are 0 and above. This process is given in the equation below. At this stage, the direction of the criteria is determined according to the benefit and cost criteria of the decision criteria, in other words, according to the optimality criteria of the decision criteria. If the decision criterion requires cost, the direction of the decision criterion is determined as minimum, and if it requires a benefit criterion, it is determined as maximum.

$$M = \left|R_j^{max}\right| + \left|R_j^{min}\right| \quad (12)$$

Step 3.4. Calculation of BSS scores: The BPS scores of the decision alternatives are calculated using equation (13). The reason for using the natural logarithm (ln) in the equation is to standardize the scores obtained. Since ln(0) = "undefined", +1 is added to the equation. Thus, the scores obtained are evaluated at 0 and above.

$$BSS = ln(R + M + 1) \tag{13}$$

3.4. Aggregation Operator

It is not unexpected that the weights obtained using different MCDM methods vary from one another. Therefore, a weight aggregation operator can be used to derive an optimal weight from these different weights. In this study, the aggregation operator provided in Equation (14) is utilized (Ecer & Güneş, 2024; Torkayesh et al., 2021).

$$w_{FİNAL} = \Gamma.\, w_{MPSI} + (1 - \Gamma).\, w_{LOBCOW} \tag{14}$$

In Equation (14), Γ is the aggregation coefficient, and it is recommended to use Γ = 0.5 (Ecer & Güneş, 2024).

4. PROBLEM DEFINITION and CASE STUDY

This section presents the proposed integrated MCDM approach for evaluating the ICT development performance of the Visegrad countries, considering economic and social development pillars. First, nine main criteria obtained through a literature review are explained. To obtain realistic and applicable results, real data from OECD datasets for these countries are used. Subsequently, the MPSI, LOPCOW, and BSS methods are used to calculate the relative importance of the indicators and the performance of the countries.

4.1. Identification of Indicators

Various criteria are used in the literature to measure the level of ICT. In the studies of (Ecer & Güneş, 2024; Torkayesh & Torkayesh, 2021), 6 main criteria were used to determine the level of ICT. Unlike these studies, the number of criteria has been increased to 9. All criteria are benefit-oriented. Data on these criteria were obtained from the OECD data bank. The shared data varies between 2017-2024. Therefore, the most recently shared data was taken into account. The variables considered as criteria in the decision model are defined as follows:

ICT Value Added (C_1): ICT value added refers to the difference between the gross output of the ICT sector and its intermediate consumption, expressed as a percentage of gross value added.

ICT Employment (C_2): ICT employment is defined as the number of individuals working within the ICT sector, represented as a percentage of total employment in the sector.

ICT Investment (C_3): ICT investment encompasses the purchase of equipment and software that have been utilized in production for over a year.

ICT Goods (C_4): Exports of ICT goods are categorized according to the World Customs Organization Harmonised System (HS), which identifies various ICT products, including ICT goods.

Home Computer Access (C_5): This metric represents the number of households that possess at least one computer.

Internet Access in households (C_6): This percentage indicates the proportion of households that report having internet access, defined as those stating they have connectivity to the internet.

***Mobile Broadband - per 100 inhabitants* (C_7):** Refers to the number of mobile broadband subscriptions per 100 inhabitants. This indicates the access rate to mobile internet services.

***Fixed Broadband – per 100 inhabitants* (C_8):** Indicates the number of fixed broadband subscriptions per 100 inhabitants. This measures the prevalence of fixed-line internet services.

***Mobile Data Usage – gigabits per subscription per month* (C_9):** Represents the monthly mobile data usage per subscription in gigabits. This shows the amount of mobile data consumption.

4.2. Information about the Visegrad Countries

The Visegrad Group, often referred to as the Visegrad Four or V4, is a cultural and political alliance comprising four Central European nations: Czechia, Hungary, Poland, and Slovakia. This coalition seeks to enhance collaboration in areas such as military, economic, cultural, and energy matters. Additionally, all four countries are members of the European Union, the North Atlantic Treaty Organization, and the Three Seas Initiative.

The group takes its name "Visegrad" from the city of the same name in Hungary (Visegrad). Although the group's history dates back a long time, it stands out as one of the oldest economic and political collaborations. It was first convened in 1335 in the town of Visegrad, hosted by Hungarian King Charles I. The other participants of the meeting, known as the "Visegrad Congress," were King John of Bohemia and King Casimir III of Poland. The meeting was held to resolve interstate issues, ensure security, cooperate, and improve friendship (Visegrad). Thanks to this meeting, on which the foundations of today's Visegrad Group are based, they have generally followed a coordinated policy to this day (Yeşiltaş & Erdem, 2021).

Table 1. Profile of Visegrad Countries

Country	GDP (current US$)	GDP per capita	Population
Czechia	343.21	31,591.2	10.864.042
Hungary	212.39	22,141.9	9.592.186
Poland	809.2	22,056.7	36.687.353
Slovakia	132.91	24,491.38	5.426.740

Source: World Bank, 2023.

As shown in Table 1, Czechia stands out in terms of economic welfare with the highest GDP per capita. Slovakia also has a high GDP per capita, but its total economic size is lower. Poland leads in total GDP, yet its GDP per capita lags behind that of the other countries. Hungary has a similar GDP per capita to Poland but has a lower total GDP, indicating a balance that highlights important considerations for economic development.

5. RESULTS

The dataset used in the study is shown in Table 2. All the criteria in the study are benefit-oriented criteria. In Table 2, the alternatives are listed in the rows, while the criteria are presented in the columns.

Table 2. Dataset

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
Country Code	**Max**	**Max**	**Max**	**Max**	**Max**	**Max**	**Max**	**Max**	**Max**
Czechia-A1	4,9	3,7	4,32	16,1	82,18	94,56	107,22	38,19	9,89
Hungary-A2	5,5	4	1,73	10,3	79,67	94,78	88,36	37,05	13,89
Poland-A3	4	3,2	0,8	6,5	81,78	95,89	135,55	25,17	14,94
Slovakia-A4	4,5	3,7	1,4	10,5	81,80	90,54	94,41	33,10	11,89

Source: OECD, Eurostat, World Bank.

5.1. MPSI Results

Equations 1 and 2 have been used to normalize the decision matrix presented in Table 2. The normalized decision matrix is shown in Table 3.

Table 3. The Normalized Initial Decision-Making Matrix

Country Code	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
A1	0,8909	0,925	1	1	1	0,986	0,791	1	0,6619
A2	1	1	0,4004	0,6397	0,9694	0,9884	0,6518	0,9701	0,9297
A3	0,7272	0,8	0,1851	0,40372	0,9951	1	1	0,6590	1
A4	0,8181	0,925	0,3240	0,6521	0,9953	0,9442	0,6964	0,8667	0,7958

Values of v_j, p_j, and w_j have been calculated using Equations 3, 4, and 5. These values are shown in Table 4.

Table 4. The v_j, p_j, and $w_j$values

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
v_j	0,8590	0,9125	0,4774	0,6739	0,9899	0,9796	0,7848	0,8739	0,8468
p_j	0,0399	0,0206	0,3879	0,1809	0,0005	0,0017	0,0718	0,0713	0,0671
w_j	0,0474	0,0244	0,4606	0,2149	0,0006	0,0021	0,0852	0,0847	0,0796
Ranking	7	6	1	2	9	8	3	4	5

5.2. LOPCOW Results

The decision matrix provided in Table 1 has been used. Since all criteria are maximized, the decision matrix has been normalized using Equation 2. This is shown in Table 5.

Table 5. Normalized Decision Matrix

Country Code	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
A1	0,6	0,6250	1	1	1	0,7514	0,3996	1	0
A2	1	1	0,2642	0,3958	0	0,7925	0	0,9124	0,7920
A3	0	0	0	0	0,8406	1	1	0	1
A4	0,3333	0,6250	0,1704	0,4166	0,8486	0	0,1282	0,6090	0,3960

Subsequently, the percentage values and the weight values of the criteria have been calculated using Equations 4 and 5. These are shown in Table 6.

Table 6. PV_{ij}, w_j Values

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
PV_{ij}	42,14	51,70	27,55	37,11	67,1	62,09	30,95	62,34	51,79
w_j	0,0973	0,1194	0,0636	0,0857	0,1551	0,1434	0,0715	0,1440	0,1196

5.3. Aggregation Operator

The calculation made using Equation 14 has resulted in the final W value shown in Table 7.

Table 7. W_{last} Values

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
W_{MPSI}	0,0474	0,0244	0,4606	0,2149	0,0006	0,0021	0,0852	0,0847	0,0796
W_{LOBCOW}	0,0973	0,1194	0,0636	0,0857	0,1551	0,1434	0,0715	0,1440	0,1196
W_{last}	0,0723	0,0719	0,2621	0,1503	0,0779	0,0727	0,0783	0,1143	0,0996

As shown in the table, the criterion with the highest final weight is C_3 (ICT Investment). Figure 3 displays the results related to MPSI, LOPCOW, and the final weights.

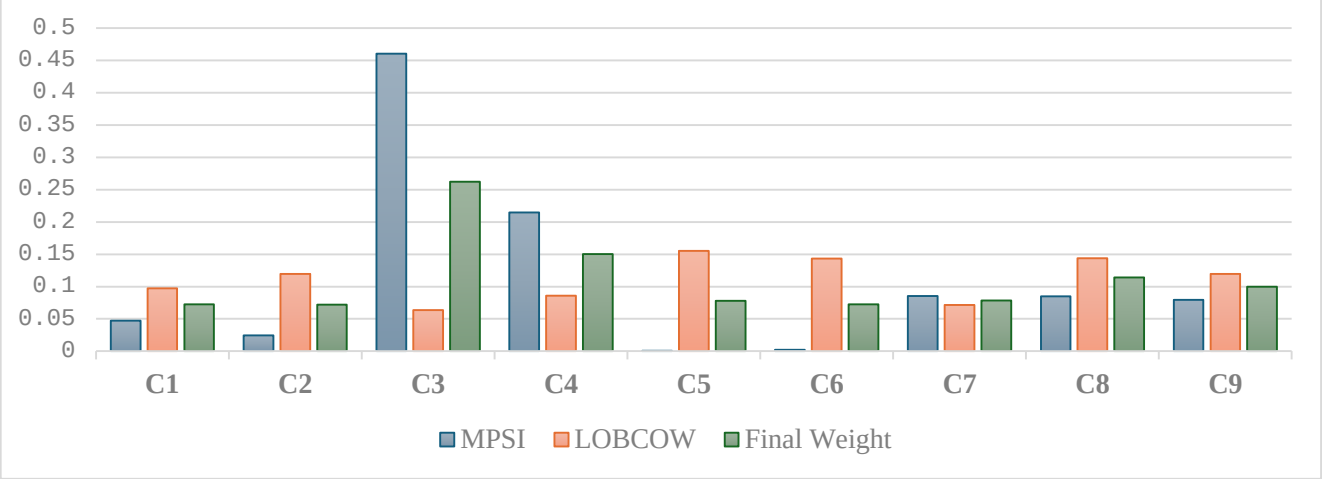

Figure 2. Criterion Weights

5.4. BSS Results

The decision matrix used in the study is shown in Table 1. Additionally, the criterion weights used in the BSS calculations are provided in Table 7. The decision matrix has been normalized using Equation 10.

Table 8. Standardized Decision Matrix

Country Code	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
A1	0,3547	0,2663	1,1325	2,4202	6,4042	6,883	8,4058	4,3684	0,9857
A2	0,3981	0,2879	0,4535	1,5483	6,2086	6,899	6,9272	4,238	1,3843
A3	0,2895	0,2303	0,2097	0,9771	6,373	6,9798	10,6268	2,8791	1,489
A4	0,3257	0,2663	0,367	1,5784	6,3746	6,5904	7,4016	3,7862	1,185

The R value has been calculated using Equation 11, the M value using Equation 12, and the BSS value using Equation 13, as shown in Table 9.

Table 9. BSS Scores

Alternatives	R	BSS	M	Rank
A1	0,8672	1,2553	1,6416	1
A2	0,7874	1,2322	1,6416	3
A3	0,8348	1,246	1,6416	2
A4	0,7743	1,2284	1,6416	4

The alternatives are ranked according to the Bulut Scoring System (BSS) values. BSS values represent the performance of alternatives, where a higher BSS value indicates better performance.

4.5. Sensitivity Analysis

In this study, the aggregation coefficient value was taken as $\Gamma = 0.5$, and the results of the research were obtained. To test the robustness of the model, this coefficient was considered as different values between 0.1 and 0.9, and the rankings were determined.

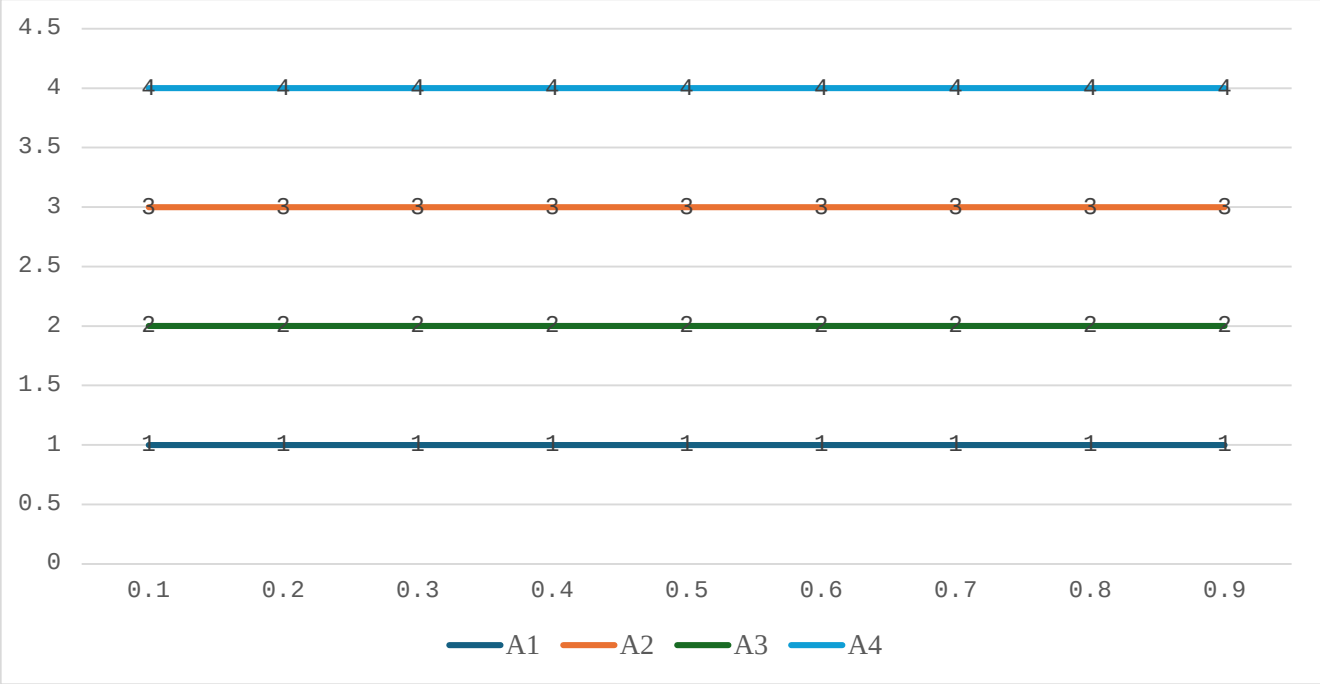

Figure 3. Alternative Rankings for Different Merging Coefficient Values

According to Figure 3, the positions of all alternatives are the same across all scenarios. These results demonstrate the robustness of the model.

4.6. Comparative Analysis

The proposed decision support system is compared using different ranking methods. The problem was solved using the criterion weights obtained from the MPSI-LOPCOW methods along with the EDAS, OCRA, WASPAS, and GRA methods. The results regarding these methods are presented in Table 10.

Table 10. Comparative Analysis

Alternatives	BSS	EDAS	OCRA	GRA	WASPAS
A1	1	1	1	1	1
A2	3	2	3	2	3
A3	2	4	2	4	2
A4	4	3	4	3	4

The obtained results were compared statistically using the Spearman Rank Correlation Coefficient test. The results of the analysis are presented in Table 11.

Table 11. Results of the Spearman Rank Correlation Coefficient Test

Correlations							
			BSS	**EDAS**	**OCRA**	**GRA**	**WASPAS**
Spearman's rho	**BSS**	Correlation Coefficient	1,000	,400	1,000**	,400	1,000**
		Sig. (2-tailed)	.	,600	.	,600	.
		N	4	4	4	4	4
	EDAS	Correlation Coefficient	,400	1,000	,400	1,000**	,400
		Sig. (2-tailed)	,600	.	,600	.	,600
		N	4	4	4	4	4
	OCRA	Correlation Coefficient	1,000**	,400	1,000	,400	1,000**
		Sig. (2-tailed)	.	,600	.	,600	.
		N	4	4	4	4	4
	GRA	Correlation Coefficient	,400	1,000**	,400	1,000	,400
		Sig. (2-tailed)	,600	.	,600	.	,600
		N	4	4	4	4	4
	WASPAS	Correlation Coefficient	1,000**	,400	1,000**	,400	1,000
		Sig. (2-tailed)	.	,600	.	,600	.
		N	4	4	4	4	4

Note: ** Correlation is significant at the 0.01 level (2-tailed).

There are perfect positive correlations between the rankings of BSS and OCRA, BSS and WASPAS, EDAS and GRA, as well as OCRA and WASPAS; this indicates that the rankings among these methods are identical. Some pairs, such as BSS with EDAS and GRA, and EDAS with OCRA and WASPAS, show moderate correlations, but these are not statistically significant.

6. CONCLUSION

The levels of information and communication technologies are highly important for international competition. As seen in the literature, there is a positive relationship between the levels of information and communication technologies and economic growth, development, etc.

Determining the information and communication technology levels of the Visegrad countries is important in terms of revealing the situation of the countries. In this study, the Visegrad countries were evaluated with various criteria using OECD data. For this purpose, a model was developed by integrating MPSI-LOPCOW-BSS methods, which are among the MCDM methods. In the model, two different objective criteria weighting methods were used. The results obtained from these two methods were used to obtain the final criteria weights with the help of a merging operator. Afterward, the final criteria weights found were used in the BSS method to reach the ICT development performances of the V4 countries.

In the weighting conducted using the MPSI method, the C_3-ICT Investment criterion was found to have the highest weight. In the LOPCOW method, the C_5-Home Computer Access criterion holds the highest weight. After using the aggregation operator, the highest weight among the criteria was again assigned to the C_3-ICT Investment criterion. Subsequently, the C_4-ICT Goods and C_8-Fixed Broadband criteria were identified as having high weights. The criterion with the lowest weight was C_2-ICT Employment. In the literature, different results have been found. Ecer & Güneş (2024) identified the export of ICT products as the criterion with the highest weight in their study. In the study by Torkayesh & Torkayesh (2021), ICT employment was also identified as the criterion with the highest weight. This discrepancy arises from both differences in sample selection and the varying number of total criteria used. In the ranking conducted using the BSS method, the country with the highest ICT level was Czechia. It was followed by Poland, Hungary, and Slovakia. To strengthen the implications of these findings, it is essential to delve deeper into the political and strategic effects of the results. The high weighting of the C_3-ICT Investment criterion suggests that investment in ICT infrastructure is crucial for enhancing the competitive standing of the Visegrad countries in the global market. Policymakers should focus on allocating resources to ICT investments as a means to stimulate economic growth and improve overall development. Furthermore, the significant weight assigned to the C_5-Home Computer Access criterion indicates the importance of digital inclusion in fostering a technologically adept society. Strategies aimed at increasing access to home computing

can facilitate skill development and enhance productivity, ultimately contributing to economic advancement. Given the findings, it is recommended that V4 countries adopt coordinated policies that prioritize ICT investments and promote accessibility to technology. Collaborative initiatives, such as public-private partnerships, can be effective in maximizing the impact of ICT on economic growth.

Based on the findings, countries, especially Slovakia, which ranks lowest among the Visegrad countries, need to focus on various criteria in accordance with the Digital Agenda for Europe 2030 policies:

- Visegrad countries should increase their investments in ICT infrastructure. This will help enhance their global competitiveness. Specifically, the high weight of the C_3-ICT Investment criterion indicates how critical investments in this area are.
- Based on the importance of criteria such as home computer access (C_5) and internet access (C_6), strategies should be developed to enhance digital inclusion. Governments should create programs to ensure access to digital tools for disadvantaged groups.
- Educational programs and workshops should be organized to improve digital literacy. This will enhance individual competencies and contribute to the growth of the digital economy.
- Policies should be developed to promote public-private partnerships that accelerate ICT investments. Such partnerships can ensure the effective use of resources.
- To enhance competitiveness in Europe's digital market, the standardization of data and digital services is necessary. This will facilitate cross-border data flow and make business operations more efficient.

These recommendations will help Visegrad countries develop important policies to support their digital transformation processes and align with the EU's digital goals for 2030.

The contribution of the study to the literature has been twofold. First, the results were presented consistently with the integrated model proposed in the study. Secondly, the concrete situations of the countries were determined by revealing the ICT development performances of the Visegrad countries.

Limitation:

- The research is limited to Visegrad countries only.
- The research uses only quantitative data; subjective methods or fuzzy set-based methods can be used.

There are various implications for future studies. The first is the use of different MCDM methods. The second is to reveal the effects on the results by using different merging operators, and the third is to determine the levels of different country groups.

AUTHORS' DECLARATION:

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The entire research is written by the author.

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The Effect of Cost Efficiency on The Financial Performance of Banks: A Research on Public Banks in Turkey

Maliyet Etkinliğinin Bankaların Finansal Performansına Etkisi: Türkiye'de Halka Açık Bankalar Üzerine Bir Araştırma

Gökhan KILIÇ
Asst. Prof. Dr., Başkent University
gokhankilic@baskent.edu.tr
https://orcid.org/0000-0002-0605-2798

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ABSTRACT

This research seeks to elucidate the impact of cost efficiency within banking institutions on their overall financial performance. The empirical data utilized in this investigation was sourced from the Bloomberg Terminal database. The research sample comprises public deposit banks operating within the Republic of Turkey. Eight banks were selected for data sampling, with the temporal scope of analysis spanning from 2009 to 2022. Initially, the study employed stochastic frontier analysis to assess cost efficiency, subsequently utilizing the technical efficiency metrics derived from this analysis to evaluate its influence on the financial performance of deposit banks via panel regression methodologies. In the stochastic frontier analysis conducted according to the model of Battese and Coelli (1995), it was concluded that the variables selected as input (Personnel Costs and Interest Costs) affected the output (Loans and Financial Assets) at a 1% significance level. Return on Assets (ROA), Return on Equity (ROE) and Net Interest Margin (NIM), which are financial performance indicators of banks, were selected as dependent variables. Logarithm of Total Assets (LNASSETS), Total Equity/Total Assets (TETA), Total Loans/Total Deposits (TLTD) and Non-Performing Loans/Total Loans (NPL), which are important variables for banks with cost efficiency levels, were used as independent variables in this study. As a result of the panel regression, it was seen that Cost efficiency affected the dependent variables ROA, ROE and NIM at 5% significance level. This result indicates that banks need to review their credit risk management, non-interest expense control, and capital adequacy strategies with a focus on cost efficiency; for regulators, it highlights the need for close monitoring of high TLTD and rising NPL ratios and the implementation of countercyclical measures.

Keywords:
Cost Efficiency,
Stochastic Frontier Analysis,
Bank Performance

Jel Codes:
M40, M41

ÖZET

Bu araştırma, bankacılık kurumlarında maliyet verimliliğinin genel finansal performansları üzerindeki etkisini aydınlatmayı amaçlamaktadır. Bu araştırmada kullanılan ampirik veriler Bloomberg Terminal veri tabanından elde edilmiştir. Araştırma örneklemi, Türkiye Cumhuriyeti sınırları içinde faaliyet gösteren halka açık bankalardan oluşmaktadır. Veri örneklemi için sekiz banka seçilmiş ve analiz zaman aralığı 2009 ile 2022 yılları arasında belirlenmiştir. Çalışmada ilk olarak, maliyet verimliliğini değerlendirmek için stokastik frontier analizi kullanılmış, ardından bu analizden elde edilen teknik verimlilik ölçütleri, panel regresyon yöntemi ile halka açık bankaların finansal performansı üzerindeki etkisini değerlendirmek için kullanılmıştır. Battese ve Coelli (1995) modeline göre yapılan stokastik sınır analizinde, girdi olarak seçilen değişkenlerin (Personel Maliyetleri ve Faiz Maliyetleri) çıktıları (Krediler ve Finansal Varlıklar) %1 anlamlılık düzeyinde etkilediği sonucuna varılmıştır. Bankaların finansal performans göstergeleri olan Aktif Kârlılığı (ROA), Özkaynak Kârlılığı (ROE) ve Net Faiz Marjı (NIM) bağımlı değişkenler olarak seçilmiştir. Maliyet etkinlik seviyeleri ile bankalar için önemli değişkenlerden Toplam Varlıkların Logaritması (LNASSETS), Toplam Özkaynaklar/Toplam Varlıklar (TETA), Toplam Krediler/Toplam Mevduatlar (TLTD) ve Donuk Krediler/Toplam Krediler (NPL) bu çalışmada bağımsız değişkenler olarak kullanılmıştır. Panel regresyon sonucunda maliyet etkinliğinin ROA, ROE ve NIM bağımlı değişkenlerini %5 anlamlılık düzeyinde etkilediği görülmüştür. Bu sonuç, bankaların özellikle kredi risk yönetimi, faiz dışı gider kontrolü ve sermaye yeterliliği stratejilerini maliyet etkinliği ekseninde gözden geçirmeleri gerektiğini ortaya koymaktadır; düzenleyiciler içinse yüksek TLTD ve artan NPL oranlarının yakın takibi ve karşı-döngüsel önlemler alınması gerektiğini göstermektedir.

Anahtar Kelimeler:
Maliyet Verimliliği,
Stokastik Sınır Analizi,
Banka Performansı

Jel Kodları:
M40, M41

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1. INTRODUCTION

The banking sector is of key importance for the healthy growth of the Turkish economy. Banks both collect resources and transfer these resources to the areas in need, thus sustaining the economic cycle. However, the continuity of this functioning depends on the banks' survival power, in other words their sustainability. At this point, profitability comes to the fore. Profitable banks can secure themselves in terms of capital, make new investments, improve their technological infrastructure and expand their services. This situation has positive consequences not only for the banks but also for the national economy. On the other hand, the sector is in constant change. Factors such as legal regulations, the rise of digital competitors and changes in customer habits require banks to constantly review their plans for the future. To survive in this complex environment, efficiency is no longer a luxury but a necessity.

The notion of efficiency occupies a pivotal position in enhancing the profitability of financial institutions. The meticulous execution of each phase of banking operations with a high degree of precision and efficiency constitutes the cornerstone of attaining fiscal success. Among these operational processes, efficiency concerning costs and profits emerges as one of the most significant determinants that directly influence the financial architecture of banks. Consequently, banks must scrutinize their expenditure items. Given the inherent characteristics of the sector, there exists a propensity for expenses to escalate rapidly within banking operations. Specifically, strategic decisions such as the establishment of new branches or the recruitment of additional personnel can impose a substantial burden on financial statements. Hence, it becomes essential to formulate strategies aimed at managing costs in a manner that is both balanced and rational.

One of the most important indicators of how effective a bank is in this area is its cost efficiency. In particular, the cost-to-income ratio reveals the extent to which the bank uses its available resources efficiently. A low cost-to-income ratio indicates that waste is prevented and available resources are utilised more profitably. In addition, the success of human resources policies is another factor that directly affects productivity. Indicators such as employee turnover and productivity levels can reflect the effectiveness of personnel management. A well-structured human resources system not only contributes to cost reduction but also increases employee satisfaction and loyalty to the organisation, thereby increasing corporate value in the long term.

Berger & Mester (1997) showed in their study that cost efficiency and profit efficiency are negatively correlated. In this study, it is aimed to reveal whether it is valid for commercial banks operating in Turkey. Cost efficiency is measured by stochastic frontier analysis in the studies in the literature. One of the objectives of this study is to measure the cost efficiency of banks operating in Turkey with this method. Another objective is to reveal to what extent this cost efficiency affects financial performance.

In the present examination, the variables utilized in the Stochastic Frontier Analysis consist of labor-related expenditures in conjunction with interest liabilities, while the outputs are characterized by loans and financial assets. The cost efficiency metrics obtained from this evaluation are subsequently integrated into the model as an input for the Panel Data Analysis. Within this analytical framework, the effect of cost efficiency on the financial performance of commercial banking institutions is meticulously scrutinized. Financial performance indicators pertinent to commercial banks, including return on assets, return on equity, and net interest margin, are frequently cited in the academic discourse. Consequently, this investigation clarifies the cost efficiency of banking institutions and articulates the ramifications of this efficiency on their financial performance. It is anticipated that the results will provide valuable insights for policymakers in their strategic deliberations regarding commercial banks.

In the subsequent sections of this study, the results from previous research that explores the nexus between cost efficiency and financial performance will be presented, followed by a detailed exposition of the data, methodologies, variables, and analytical outcomes employed; concluding remarks and evaluations will subsequently be provided.

2. LITERATURE

There are numerous studies in the literature concerning cost efficiency. Some studies merely calculate cost efficiency values, while others have conducted research on the determinants of cost efficiency. In some studies, the effects of cost efficiency values on other variables have been examined.

Maudos et al. (2002) evaluated the relationship between cost efficiency and profit efficiency on European banks. They stated that the number of articles discussing the efficiency of banks has increased and especially the articles

investigating cost efficiency constitute the majority of them. They found that efficiency values vary from country to country and that medium-sized banks have the highest efficiency values. They also revealed that efficiency increases as the Total Loans/Total Assets ratio increases.

Pasiouras et al. (2009) examined the effect of legal regulations on banks' profit and cost efficiency. Using the data of 615 banks traded on the stock exchange between 2000 and 2004, the study's results show that legal regulations increase banks' efficiency and that competition will increase when this market is not regulated.

Hanif Akhtar (2013) estimates the cost efficiency value of banks before and after the crisis. As a result of the study, the author showed that the cost efficiency of Saudi Arabian banks decreased slightly during the crisis periods.

Nițoi & Spulbar (2015) investigated the differences in the cost efficiency of commercial banks operating in central and western European countries between 2005 and 2011. The study revealed that as long as macroeconomic factors are stable, the cost efficiency of commercial banks will be high. In addition, the cost-efficiency values of banks with high risks were found to be low.

Acar et al. (2015) conducted an efficiency analysis using the data of banks operating in Turkey between 2009 and 2013. As a result of the study, it was determined that the most efficient banks are state-owned banks.

Yalçinkaya & Kök (2016) determined the cost efficiency of 21 banks operating in Turkey by using the data between 2005-2013 and made policy recommendations on how to eliminate inefficiency. According to the results of the authors, the year in which the cost efficiency of banks is the highest is 2011.

In another study, Adeabah & Andoh (2020) tried to reveal the relationship between cost efficiency and social costs of banks operating in Ghana by using data between 2009-2017. The results of the study showed that banks with high-cost efficiency are better able to cover their social costs.

Khalifaturofi'ah (2023), in his study on the factors affecting the financial performance of Indonesian banks, examined factors such as financial innovations, financial ratios and cost efficiency. One of the striking findings of the study was that cost efficiency has a negative impact on bank performance. Nevertheless, it was emphasized that both cost efficiency and financial innovations play a decisive role in the overall financial success of banks.

Rakshit (2023) examines the effects of cost, revenue, and profit efficiency on profitability for 70 Indian commercial banks during the period 1997-2017. In the first stage, cost, revenue, and profit efficiency scores are estimated using stochastic frontier analysis (SFA); in the second stage, the effects of these scores on ROA/ROE/NIM are tested using a two-stage system GMM dynamic panel model. The findings show that all types of efficiency significantly increase banks' profitability and that public banks are the most cost-efficient group; bank-specific, macro and institutional variables also play a role in determining profitability. As a policy recommendation, the study emphasises that banks should focus on increasing profit, cost and revenue efficiency simultaneously to counter declining profitability in the sector.

Wang et al., (2024) analyzed the effect of the efficiency of banks operating in Türkiye on their financial performance. In the study, first, the efficiency values of the banks were determined and then panel data analysis was performed. As a result of the study, it was shown that the unemployment rate, debts to the state, and exchange rates had a significant effect on the efficiency of banks. The results of the study also showed that rising inflation jeopardized financial sustainability.

Hamarat (2024) posits that traditional banking institutions within Türkiye display enhanced cost efficiency in comparison to participation banks during the period from 2011 to 2016. The application of stochastic frontier analysis (SFA) elucidates that extrinsic factors, notably inflation and interest rates, exert a considerable detrimental effect on the cost-effectiveness of Turkish banking institutions, particularly in the interval from 2012 to 2014. This implies that while commercial banks exhibit superior efficiency, their financial outcomes are concurrently shaped by overarching economic circumstances.

Diko (2024) articulates that Turkish banking institutions exhibit a relatively enhanced cost efficiency when juxtaposed with profit efficiency. It underscores a diminishing trend in profit efficiency, thus raising apprehensions regarding the overarching health and stability of the banking sector. Factors such as Total Assets, Deposit Share, Asset Growth, Time Deposits, Non-Performing Loans (NPL), and Ownership Structure exert a considerable influence on both cost and profit efficiency. Notably, foreign banking institutions demonstrate inferior performance in efficiency relative to their domestic counterparts, indicating divergent financial outcomes across various ownership models within the Turkish banking environment.

Studies show that cost efficiency is an important value for banks. Banks should take cost efficiency into account when determining their future strategies. To strengthen this policy recommendation, the purpose of this study is to determine whether cost efficiency has a significant effect on financial performance.

In studies conducted specifically in Turkey, cost efficiency values have been calculated, but their effects have not been empirically examined, leaving this area unexplored. This study aims to contribute to the literature in this field by revealing the impact of cost efficiency data on the financial performance of banks traded on the BIST.

In this study, initially, the levels of cost efficiency are ascertained through stochastic frontier analysis. Subsequently, this data is incorporated into the panel data model as an independent variable. The ratios indicative of the financial performance of banking institutions are identified as return on assets (ROA), return on equity (ROE), and net interest margin (NIM) by existing literature. Based on the information provided, the hypotheses are articulated as follows;

H_o: The degree of cost efficiency does not affect the financial performance of deposit banks.

H_1: The degree of cost efficiency affects the financial performance of deposit banks.

H_{1a}: The degree of cost efficiency affects the return on assets of deposit banks.

H_{1b}: The degree of cost efficiency affects the return on equity of deposit banks.

H_{1c}: The degree of cost efficiency affects the net interest margin of deposit banks.

3. METHODOLOGY and RESULTS

By the purpose of the study, the sample was selected as deposit banks traded in BIST. The data used in this study was obtained from the Bloomberg Terminal Database. Eight deposit banks were selected from this sample according to data availability, and their data between 2009 and 2022 was used in the analysis. The banks included in the sample are given in Table 1.

Table 1. Banks Included in the Sample

QNB FİNANSBANK	ŞEKERBANK
AKBANK	TÜRKİYE İŞ BANKASI
TÜRKİYE HALK BANKASI	TÜRKİYE GARANTİ BANKASI
VAKIFBANK	YAPI KREDİ

Source: The table was created by the author.

The Data Envelopment Analysis (DEA) method and the Stochastic Frontier Analysis (SFA) method are the primary methods used in cost-efficiency analysis. It is used the SFA method in our study. The reason for this is that SFA separates noise in the data from inefficiency and yields better results in panel data (Greene, 2008).

Table 2. Methods And Variables Used in The Study

Panel Regression Analysis		**Stochastic Frontier Analysis**	
Dependent Variables	**Independent Variables**	**Dependent Variables (Outputs)**	**Independent Variables (Inputs)**
ROA (Return on Assets)	LNASSETS (Natural Logarithm of Assets)	Loans	Personnel Expenses
ROE (Return on Equity)	TETA (Total Equity / Total Assets)	Financial Assets	Interest Expenses
NIM (Net Interest Profit)	TLTD (Total Loans / Total Deposits)		
	NPL (Non-Performing Loans/Total Loans)		
	CEF (Cost Effectiveness)		

Source: The table was created by the author.

The Panel data analysis method is used to test the hypotheses. The variables used in the analysis are shown in Table 2. Descriptive statistics of the data used in the analysis are given in Table 3.

Table 3. Descriptive Statistics

	ROA	ROE	TETA	TLTD	NPL	NIM	LNASSETS	CEF
Mean	1,6652	16,5236	0,1031	1,0548	0,0425	5,2272	12,1564	0,7675
Median	1,4872	14,8230	0,1067	1,0587	0,0389	4,8637	12,1973	0,7832
Maximum	6,2851	55,5943	0,1494	1,3516	0,1398	10,8391	14,8660	0,9729
Minimum	-2,3622	-35,3349	0,0472	0,7600	0,0119	2,8088	9,1291	0,0123
Std. Dev.	1,0223	10,6465	0,0213	0,1522	0,0199	1,5992	1,1630	0,1642
Skewness	1,3098	0,6015	-0,4887	-0,1470	1,4359	1,5768	-0,3176	-1,7668
Kurtosis	10,0472	10,8148	2,8501	2,1587	7,2147	5,7718	2,9228	8,7416
Jarque-Bera	263,7923	291,7537	4,5634	3,7063	121,3920	80,2698	1,9107	212,1214
Probability	0,0000	0,0000	0,1021	0,1567	0,0000	0,0000	0,3846	0,0000
Sum	186,5078	1850,653	11,5483	118,1469	4,7691	585,4559	1361,525	85,9630
Sum Sq. Dev.	116,0150	12581,51	0,0505	2,5741	0,0441	283,8844	150,1577	2,9938
Observations	112	112	112	112	112	112	112	112

Source: The table was created by the author.

Stochastic Frontier Analysis model used by Battese & Coelli (1995) was used to determine the cost-efficiency. As indicated in Table 2, Financial Assets and Loans are taken as dependent variables. Independent variables consist of Personnel Expenses and Interest Expenses (Khalifaturofi'ah, 2023). It is tried to determine the efficiency with which the expenses incurred are converted into income. Dependent variables represent total output, and independent variables represent total input. The results of the stochastic frontier analysis are shown in Table 4.

Table 4. Stochastic Frontier Analysis Results

	COEFFICIENT	PROBABILITY
TOTAL OUTPUT		
LABORCOST	0.7756	0.000
INTERESTCOST	0.4331	0.000
CONSTANT	2.3132	0.000

Source: The table was created by the author.

It is seen that the model is significant, and the independent variables affect the dependent variable at a 1% significance level. Therefore, the Technical Efficiency values to be estimated from this model were included in the panel analysis by using them as cost efficiency values and the following models were formed.

$$ROA_{it}=\beta_0+\beta_1 CEF_{it} + \beta_2 NPL_{it} + \beta_3 LNASSETS_{it} + \beta_4 TETA_{it} + \beta_5 TLTD_{it} + e_{it} \quad (1)$$

$$ROE_{it}=\beta_0+\beta_1 CEF_{it} + \beta_2 NPL_{it} + \beta_3 LNASSETS_{it} + \beta_4 TETA_{it} + \beta_5 TLTD_{it} + e_{it} \quad (2)$$

$$NIM_{it}=\beta_0+\beta_1 CEF_{it} + \beta_2 NPL_{it} + \beta_3 LNASSETS_{it} + \beta_4 TETA_{it} + \beta_5 TLTD_{it} + e_{it} \quad (3)$$

At the beginning of the panel analysis, the relationship coefficients between the independent variables are calculated and presented in Table 5.

Table 5. Relationship Between Variables

	ROA	ROE	TETA	TLTD	NPL	NIM	LNASSETS	CEF
ROA	1,0000							
ROE	0,9294	1,0000						
TETA	0,4404	0,1676	1,0000					
TLTD	-0,3431	-0,3650	0,0509	1,0000				
NPL	-0,4003	-0,4325	-0,1275	-0,0552	1,0000			
NIM	0,5663	0,5868	0,2048	-0,3453	0,2589	1,0000		
LNASSETS	0,2134	0,3246	-0,2791	0,0035	-0,4069	-0,1085	1,0000	
CEF	-0,3497	-0,2852	-0,1997	0,3862	-0,2607	-0,5296	0,0293	1,0000

Source: The table was created by the author.

As seen in Table 5, the correlation coefficients between independent variables are not greater than 0.70. Therefore, there is no multicollinearity problem. Then, Breesch-Pagan LM, Paseran Scaled LM, and Paseran CD tests were

conducted to determine whether the three models established to test the hypotheses have horizontal cross-section dependence. The test results are shown in Table 6.

Table 6. Cross-Section Dependence Test Results

MODELS	TEST	PROBABILITY
ROA	Breesch-Pagan LM	0,0000
	Paseran Scaled LM	0,0000
	Paseran CD	0,0009
ROE	Breesch-Pagan LM	0,0000
	Paseran Scaled LM	0,0000
	Paseran CD	0,0000
NIM	Breesch-Pagan LM	0,0000
	Paseran Scaled LM	0,0000
	Paseran CD	0,0000

Source: The table was created by the author.

As indicated in Table 6, the presence of horizontal cross-section dependence was identified across all three analytical models. Consequently, it became imperative to employ second-generation unit root tests to ascertain the stationarity of the examined variables. Table 7 delineates the findings of the unit root tests conducted. As illustrated in Table 7, none of the variables exhibits stationarity at the same significance level. Therefore, the implementation of a cointegration test is essential before advancing to the panel data analysis.

Table 7. 2nd Generation Unit Root Test Results

VARIABLES	AT LEVEL	AT 1ST LEVEL
ROA	**X**	
ROE	**X**	
NIM		**X**
CEF		**X**
NPL	**X**	
LNASSETS		**X**
TETA		**X**
TLTD		**X**

Source: The table was created by the author.

Table 8 presents the outcomes of the Kao (1999) cointegration test. As demonstrated in Table 8, the null hypothesis asserting the absence of cointegration is rejected at the 5% significance threshold. Given the presence of cointegration, it is feasible to conduct panel data analysis.

Table 8. KAO Cointegration Test Result

MODELS	T STAT	PROBABILITY
ROA	-1,8451	0,0325
ROE	-1,8357	0,0332
NIM	-1,9302	0,0268

Source: The table was created by the author.

The Panel-Corrected Standard Error (PCSE) estimation technique is used to test hypotheses. PCSE is used as the primary estimator due to its robustness in addressing issues such as CSD, heteroskedasticity, and serial correlation (Tawiah et al., 2024; Zhu et al., 2024). PCSE results by models are shown in Table 9.

TETA exhibits statistical significance exclusively within the Return on Assets (ROA) model and exerts a positive influence on asset returns. Conversely, TLTD demonstrates statistical significance across all models while manifesting a negative impact. NPL is statistically significant in both the ROA and ROE models, revealing a detrimental effect on ROA and ROE. The degrees of cost efficiency were determined to have a statistically significant and adverse effect across all three models incorporating variables indicative of the financial performance of deposit banks. Consequently, the null hypothesis (H0) was repudiated, whereas the alternative hypothesis (H1), along with its corresponding sub-hypotheses, could not be rejected.

Khalifaturofi'ah (2023) found that cost efficiency has a negative and significant effect on ROA and NIM and there is no significant effect on ROE. Contrary to Khalifaturofi'ah (2023)'s study, this study found a significant

and negative relationship between ROE and cost efficiency. This result shows us that there may be differences between the capital structures of banks in Turkey and those in Indonesia. These differences may stem from legal regulations between countries or regulations imposed by other regulatory bodies.

Rakshit (2023) found that cost efficiency in public sector banks has a positive and significant effect on ROA and ROE variables. Contrary to Rakshit (2023)'s study, this study found that cost efficiency had a negative impact on ROA and ROE.

According to these results, banks listed on the BIST operating in Turkey may face problems that will reduce revenue while optimising costs. For example, banks with high cost efficiency can apply the savings they achieve here as interest rate reductions. In this case, a decline in the bank's profitability will also be observed. Another example is that cost efficiency does not always mean profit efficiency. Berger & Mester (1997) demonstrated this in his study.

Banks can also increase cost efficiency by shifting towards low-risk portfolios. However, this shift will also lead to a decrease in returns. Therefore, while cost efficiency increases, profitability will decrease (Hughes & Mester, 2012).

Table 9. Panel Data Analysis

	COEFFICIENT	T STAT	PROBABILITY
ROA MODEL			
LNASSETS	0,1561	1,81	0,070
TETA	19,6878	4,15	0,000
TLTD	-1,9504	-3,84	0,000
CEF	-1,5110	-2,56	0,010
NPL	-18,1960	-2,85	0,004
CONSTANT	1,7287	1	0,319
ROE MODEL			
LNASSETS	1,6723	1,71	0,087
TETA	65,0426	1,34	0,179
TLTD	-20,9603	-3,23	0,001
CEF	-16,0980	-2,42	0,016
NPL	-225,7787	-3,12	0,002
CONSTANT	33,5671	1,76	0,079
NIM MODEL			
LNASSETS	-0,0091	-0,05	0,959
TETA	11,9014	1,49	0,137
TLTD	-2,0812	-1,84	0,066
CEF	-3,6810	-3,12	0,002
NPL	13,3958	1,06	0,290
CONSTANT	8,5609	2,64	0,008

Source: The table was created by the author.

4. CONCLUSION

This research endeavors to examine the influence of cost efficiency on the financial performance of deposit banks listed on BIST. The dataset utilized in this investigation was sourced from the Bloomberg database. Based on the availability of data, the analysis encompasses the years 2009 to 2022 and includes a sample of eight banks.

Cost efficiency represents a critical variable regarding financial performance across numerous sectors. In the context of assessing cost efficiency within the banking sector, personnel expenditures and interest costs were utilized as input parameters, while loans and financial assets were designated as output measures. By employing these variables, the levels of cost efficiency among deposit banks were ascertained and incorporated into the models as an independent variable.

The results derived from the PCSE estimator indicate that cost efficiency exhibits statistical significance across all three performance metrics and exerts a negative influence on the financial performance of the sampled banks.

The models reveal that as the conversion rate of deposits into loans escalates, the banks' financial performance is adversely impacted. This phenomenon may be attributed to the propensity for extending a greater volume of loans, particularly to high-risk groups, which could lead to an increase in non-performing loans. Consequently, in the process of converting deposits into loans, it may be prudent to consider lending to lower-risk groups, even at reduced interest rates. As anticipated, an abundance of non-performing loans detrimentally impacts the financial performance of banks within the model.

The analytical results suggest that banks ought to enhance their cost efficiency while simultaneously striving to improve their financial performance. Additionally, banks should augment their shareholders' equity and mitigate their non-performing loans to bolster their overall financial performance.

The outcomes of this study indicate that deposit banks should exercise caution and refrain from overly aggressive strategies in converting deposits into loans. The adverse impact of the TLTD ratio on financial performance suggests that banks have engaged in high-risk lending practices. It is anticipated that when banks avoid high-risk loans, the TLTD ratio will yield a positive effect on financial performance metrics. Furthermore, the analysis disclosed that total assets do not exert a statistically significant influence on NIM.

The financial performance and cost efficiency of banks are interrelated dimensions that fundamentally influence their competitiveness and long-term viability within the market. By prioritizing enhancements to their financial indicators and operational efficiency, banks can improve profitability, deliver superior services to clients, and adeptly navigate the complexities of the financial environment. This comprehensive strategy not only positions banks for immediate achievement but also cultivates resilience against potential economic fluctuations and regulatory transformations.

On the other hand, regulatory bodies cannot directly improve banks' cost efficiency, but the incentives, rules and infrastructure they introduce can enable banks to take the same risks at lower costs. They can play a significant role in increasing cost efficiency by developing technology/regulation for regulatory bodies, crisis management and resolution, process simplification and proportionality, transparency and benchmarking, and operational efficiency.

This study demonstrates the impact of cost efficiency on banks' financial performance through econometric model tests. Following this study, a separate study could be conducted to determine what factors influence the cost efficiency of BIST banks operating in Turkey.

AUTHORS' DECLARATION:

This paper complies with Research and Publication Ethics, has no conflict of interest to declare, and has received no financial support.

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The entire research is written by the author.

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Empirical Analysis of the Impact of Remote Customer Acquisition on the Performance of the Turkish Banking Sector

Uzaktan Müşteri Ediniminin Türk Bankacılık Sektörü Performansına Etkisinin Ampirik Analizi

Sultan SARI
Dr., Ostim Technical University
sultan.sari@ostimteknik.edu.tr
https://orcid.org/0000-0002-8670-3625

Bahar ERDAL
Assoc. Prof. Dr., Ostim Technical University
bahar.erdal@ostimteknik.edu.tr
https://orcid.org/0000-0002-0684-8999

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ABSTRACT

This study examines the impact of remote customer acquisition on bank profitability and credit risk in Turkey, using monthly data from May 2021 to February 2025. Applying Robust Least Squares estimation, the analysis investigates how fully digital and hybrid onboarding channels affect Return on Assets (ROA), Return on Equity (ROE), and Non-Performing Loan (NPL) ratios. Findings indicate that the number of fully remote applications is positively associated with higher NPL ratios, suggesting increased credit risk due to limited human oversight. Conversely, applications finalized through representatives or couriers show a significant negative relationship with NPLs, implying improved credit quality via human verification. Remote applications have positive but statistically insignificant effects on ROA and ROE. In contrast, customers finalized in physical branches positively and significantly impact profitability measures at the 1% significance level. Additionally, interest income relative to average assets strongly supports profitability, while higher NPL and loan-to-deposit ratios negatively affect it. A strong equity ratio also contributes positively to bank performance. These results emphasize the importance of integrating digital tools with traditional banking and human oversight to achieve sustainable profitability and effective risk management during digital transformation.

Anahtar Kelimeler:
Dijital Bankacılık,
Uzaktan Müşteri Edinimi,
Robust EKK

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C58 G20 G21

ÖZET

Bu çalışma, Mayıs 2021'den Şubat 2025'e kadar aylık veriler kullanarak Türkiye'de uzaktan müşteri ediniminin banka kârlılığı ve kredi riski üzerindeki etkisini incelemektedir. Robust En Küçük Kareler yöntemi kullanılarak, tamamen dijital ve hibrit müşteri edinim kanallarının Aktif Karlılığı (ROA), Özsermaye Karlılığı (ROE) ve Takipteki Krediler (NPL) oranları üzerindeki etkileri analiz edilmiştir. Bulgular, tamamen uzaktan yapılan başvuruların NPL oranları ile pozitif ilişkilendirildiğini, bunun da insan denetiminin sınırlı olması nedeniyle kredi riskinin arttığını göstermektedir. Buna karşılık, müşteri temsilcileri veya kuryeler aracılığıyla tamamlanan başvuruların NPL ile anlamlı negatif ilişkisi bulunmuş, bu durum insan kontrolünün kredi kalitesini iyileştirdiğini göstermektedir. Uzaktan başvuruların ROA ve ROE üzerinde pozitif ancak istatistiksel olarak anlamlı olmayan etkileri tespit edilmiştir. Buna karşılık, fiziksel şubelerde tamamlanan işlemler, kârlılık üzerinde %1 anlamlılık düzeyinde pozitif ve anlamlı etkiler göstermektedir. Ayrıca, ortalama aktiflere göre faiz gelirinin kârlılığı güçlü şekilde desteklediği, yüksek NPL ve kredi/mevduat oranlarının ise olumsuz etkilediği belirlenmiştir. Güçlü bir özsermaye oranı da banka performansına pozitif katkı sağlamaktadır. Bu sonuçlar, dijital dönüşüm sürecinde sürdürülebilir kârlılık ve etkin risk yönetimi için dijital araçların geleneksel bankacılık ve insan denetimi ile entegre edilmesinin önemini vurgulamaktadır.

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1. INTRODUCTION

In recent years, the concepts of "banking and digitalization" have gained increasing importance in parallel with rapidly advancing technology and changing societal needs. Scientific and technological advancements have not only introduced new possibilities but also made fundamental changes in many sectors. Following the widespread use of the internet, concepts such as cloud technologies, artificial intelligence, the Internet of Things (IoT), augmented reality and virtual reality have entered our lives and the banking sector has also been affected by this digital transformation process.

Digital transformation is a comprehensive process that encompasses a variety of technologies, organizational changes, and strategic shifts. It goes beyond simply adopting new tools; it signifies a fundamental shift in how organizations operate, think, and create value. The process involves the transition from outdated methods of operation to modern, digitally-driven ways of working and thinking, utilizing technologies such as digital, social, and mobile platforms. In summary, digital transformation is a multifaceted process that involves not only the adoption of new technologies but also significant organizational and cultural changes. The goal is to improve business operations, create new value propositions, and meet the evolving demands of the market (Diener & Špaček, 2021).

The digital transformation in the banking sector has fundamentally altered the way institutions manage customer relationships. Customers can now conduct banking transactions through various digital channels, such as computers, mobile applications, ATMs, and phone calls, in addition to traditional banking services. This transformation has created a banking experience that is more cost-effective, efficient, and available 24/7, compared to traditional banking. As a result, customers gain significant advantages in terms of both time and cost. The advantages offered by digital banking have not only provided a better customer experience but have also paved the way for some of the major trends in the sector. Today, technologies such as mobile banking, open-source APIs, artificial intelligence, and data analytics are among the prominent features of banking systems (Bakırtaş & Ustaömer, 2019; Çelik & Mangır, 2020; Gümüş et al., 2020; Demirel, 2021).

In this study, it is examined the impact of remote customer acquisition practices on sectoral performance in Turkey's banking sector, focusing on profitability ratios (ROA and ROE) and non-performing loans (NPL). International literature frequently highlights the positive effects of digital banking applications on bank performance (Berger, 2003; Ciciretti et al., 2009; Yang et al., 2018; Hakizimana et al., 2023). Many studies in Turkey also conclude that digital banking has positive effects on the banking sector and the economy (Danacı & Çetintaş, 2020; Bulut & Akyüz, 2020; Ulusoy & Demirel, 2022; Çetiner & Karaman, 2021; Akyüz, 2023; Deniz, 2023; Ergün, 2023; Çalış et al., 2025). However, studies on digital customer acquisition following remote customer acquisition are limited, and most of them are qualitative (Ezrokh, 2020; Beybur, 2022; Dağıdır Çakan et al., 2022; Yıldırım, 2024).

This study aims to make a significant contribution to the existing literature by addressing the topic at an empirical level. It is important because it looks at how remote customer acquisition affects the performance of banks in Turkey using real data. Even though many studies talk about digital banking, most of them do not focus on this specific topic, and many are based on opinions rather than numbers. By looking at profitability indicators like ROA and ROE, this study helps us better understand how digital tools are really changing banking. The results can help banks, decision-makers, and developers make smarter choices about using digital technology.

Digital transformation has initiated a rapid digitalization process in the banking sector, driven by consumer preferences and increasing competition. With this transformation, consumers can access fast, easy, and low-cost services without having to visit bank branches. For banks, it offers advantages such as increased efficiency, cost reduction and improved customer experience. Digital banking has become a significant investment area for banks in Turkey due to its cost advantages (Akın, 2020; Çon & Arıca, 2024).

In the "CEO Perspective on Digital Transformation in Turkey" report, published by TÜSİAD in 2016 with the support of Samsung Electronics, in collaboration with Deloitte Turkey and GfK, the primary reasons for the banking sector's shift towards digitalization were found to be competitive advantage (36%), followed by increased efficiency (20%) and quicker response to customer needs (18%) (TÜSİAD, 2016). Profitability (16%) and customer loyalty along with new customer acquisition (16%) were also among the other factors. The most significant external factors identified for banks were macroeconomic factors (26%), regulatory issues (19%), and digital technologies (19%). These findings emphasize the importance of digital change in banks and suggest that banks need to have clear and understandable digital strategies.

The digital transformation process in Turkey coincides with a period of rapid increase in the use of the internet and mobile banking. The first internet banking application in Turkey's banking sector was launched in 1997, followed by the mobile banking application in 2007 by İşbank (Türkiye İş Bankası, 2025). Since then, digital banking has become widespread in the sector because of technological development and the advantages of smart mobil phone such as easy usage, improved applications and so customer loyalty (Pilatin, 2023). Particularly after the pandemic started in March 2020, there was a significant rise in digital banking usage. This period helped minimize the negative impacts of the pandemic on the banking sector, while simultaneously accelerating the digitalization process by providing easy access to banking services. Mobile banking has been one of the fastest-growing areas in this transformation (Demirel, 2021; Uzun, 2021).

As shown in the figure below, after 2016, the number of mobile banking users surpassed the number of internet banking users. The global pandemic accelerated this transformation. At the beginning of the global pandemic in March 2020, the number of active mobile banking customers in Turkey was 52,481,204, which increased to 65,344,894 a year later, and reached 78,259,643 by March 2022. As of December 2024, this number is expected to reach 117,754,684.

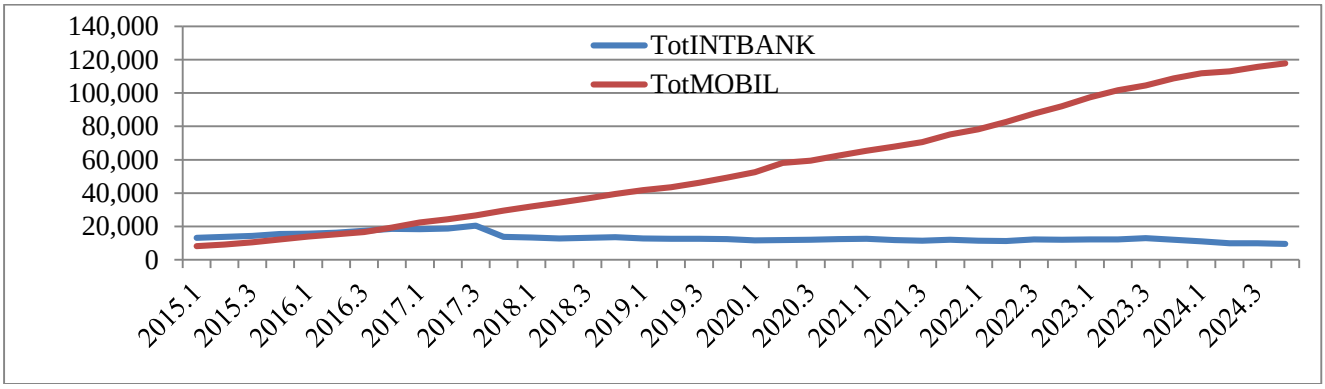

Figure 1. Active Internet and Mobile Banking Customers in the Banking Sector (Thousands)

The digital banking products and services in Turkey's banking sector are as follows (TBB, 2022):

- Remote customer acquisition,
- All types of money transfers, investments, bill payments, and credit card transactions conducted via internet banking and mobile applications,
- Loan application processes,
- Investment transactions,
- Insurance premium payments,
- Traffic fine payments,
- Tax payments,
- Banking products and services developed for people with disabilities (e.g., accessibility in branches, internet, mobile, and ATMs for physical and service access),
- The electronic arrangement of account statements and their transmission to requesting customers via digital platforms,
- Use of virtual POS (with the rise of e-commerce),
- Contactless card usage on POS devices,
- Presentation of a list of deposit accounts at banks on the e-government platform,
- Mortgage and deed-related processes carried out electronically,
- The use of 3D security in e-commerce transactions,
- QR code-based transactions (e.g., ATM withdrawals, etc.),
- The use of the Turkish QR code (TR QR) in payment systems,

- The electronic preparation and transmission of documents created by banks in foreign trade,
- Implementation of document and information verification systems (identity sharing system, address sharing system, verification of documents received from institutions and organizations electronically—e.g., student documents).

According to TBB (2025) data, the most commonly used transactions in internet and mobile banking include money transfers, investment transactions, payments, and credit card transactions. Remote customer acquisition which was introduced in 2021 in Turkey's banking sector, is a significant step in the digital transformation process. In this context, the "Regulation on the Remote Identification Methods to be Used by Banks and the Establishment of the Contractual Relationship in Electronic Environment" prepared by the Banking Regulation and Supervision Agency (BRSA) and effective as of May 1, 2021 (Resmi Gazete, 2021a), established the legal framework for remote customer acquisition. This regulation allows banks to acquire new customers without the need for a physical branch. Furthermore, the "Regulation on the Operational Principles of Digital Banks and Service Model Banking" published on January 29, 2021, and effective as of January 1, 2022 (Resmi Gazete, 2021b), enabled the establishment of digital banks and laid the foundational steps for digital and service model banking.

The "Regulation on the Operational Principles of Digital Banks and Service Model Banking" defines "digital bank" as a credit institution that provides banking services via electronic banking distribution channels instead of physical branches. "Service model banking" is defined as a service model where customers connect directly with service bank systems through open banking services offered via the interfaces of interface providers to perform banking transactions.

In this model, banks share their infrastructure with third parties via API (Application Programming Interface). This allows platforms, such as electronic stores, to offer bank products through their own systems. As a result, banks can expand their customer networks while businesses provide seamless and fast services to their customers. In March 2023, Turkey's first digital bank, Hayat Finans Katılım Bankası, received its operational license from BRSA (Akbaş, 2023).

On May 25, 2023, the "Regulation on Amendments to the Regulation on the Remote Identification Methods to be Used by Banks and the Establishment of the Contractual Relationship in Electronic Environment" was published, allowing legal entities to also participate in the remote customer acquisition process. This development further expanded the scope of digital banking and remote customer acquisition practices (Resmi Gazete, 2023).

Remote customer acquisition allows customers to start banking transactions without visiting physical branches by using advanced technologies such as identity verification, facial recognition, and digital signatures. This system has not only increased competition in the banking sector but has also transformed the customer experience, making access to banking services easier. Customers can open accounts via digital channels, while banks expand their customer portfolios, reduce operational costs, and increase digital competitiveness without needing physical branches.

According to data from the Turkish Banks Association (TBB, 2025), over 2 million new customers joined the banking system through digital channels in the first year of remote customer acquisition. As shown in Figure 2 below, this number rapidly increased in 2022 and 2023, and the sector became even more dynamic with the launch of digital banks.

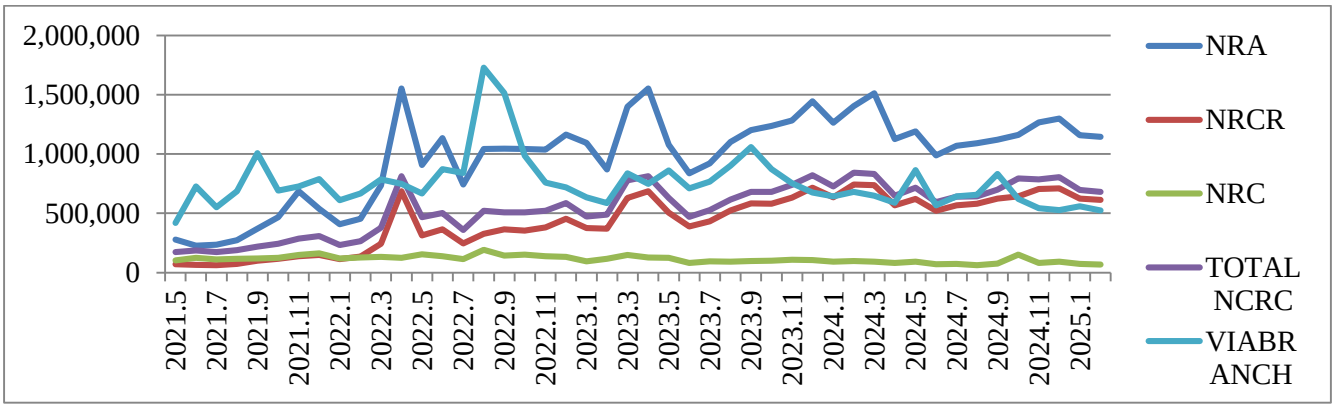

Figure 2. The Impact of Remote Customer Acquisition on Sector Performance

After this brief introduction, the second section of the study presents selected studies from international and national literature on the subject. In the third section, information is provided about the dataset and model used in

the study, while the empirical findings of the model are discussed in the fourth section. The study finishes with a conclusion section.

2. LITERATURE REVIEW

Banks are heavy users of both information technology (IT) and financial technologies, and they possess big data resources that help to understand the general effects of technological change. Many studies have been conducted in the literature on the positive impacts of financial technologies on the banking sector (Berger, 2003; Danacı & Çetintaş, 2020).

Berger's (2003) study shows that improvements in "back office" technologies have led to cost reductions and increased lending capacity, while developments in "front office" technologies have benefited consumers. Research also reveals significant improvements in overall efficiency, particularly in terms of the quality and diversity of banking services. For example, Danacı & Çetintaş (2020), in their study on financial innovations and technology in banks, concluded that innovations in the banking sector make human life easier and lead to increases in profitability and efficiency.

Ciciretti et al. (2009), in their study analyzing whether internet banking adds value to the services of traditional banks, support this result. The study compares internet banking with traditional banking services using various indicators such as bank efficiency, cost structures, profitability ratios, and customer satisfaction. The study shows that internet banking is a significant value creation tool for banks and provides them with a competitive advantage in the digitalization process. Internet activities reduce costs while enhancing service quality, which also strengthens customer satisfaction. However, the effectiveness of internet banking varies depending on the banks' digital strategies and how these strategies are implemented. In particular, internet activities hold more potential for value creation, especially for larger banks.

Sadr (2013) study, using data from Asian countries between 1990 and 2010, examined the relationship between internet banking, profitability, economic growth (GDP), and total deposits, employing panel cointegration and panel error correction models. According to the study's findings, internet banking began to contribute to the banks' return on equity after three years, while an increase in spending on information technology caused a negative effect with a one-year delay.

In a study by Abaenewe et al. (2013) on Nigerian banks, the impact of electronic banking on bank performance was investigated, and a significant improvement was observed in return on equity, although no significant difference was found in return on assets.

Tunay & Akhisar (2017) analyzed the "long-term interaction between internet banking and bank profitability performance" using data from European Union (EU) countries for the 2005-2014 period, applying Pedroni cointegration tests and error correction models. They used ROA and ROE as bank performance measures and found a long-term relationship between internet banking and bank profitability in EU countries outside the Eurozone.

Yang et al. (2018) investigated whether electronic banking and internet banking improve the performance of Chinese banks (ROA, ROE, NIM, Operating Margin, and efficiency ratio) using data from five major banks for the 2003-2013 period. They concluded that internet banking significantly improved ROA, ROE, and operating margin, but had limited effects on NIM and efficiency ratio.

Ulusoy & Demirel (2022) demonstrated that the number of customers using mobile and internet banking, as well as transaction volumes, positively affected active profitability. Çetiner & Karaman (2021) stated that the increase in transactions conducted through internet banking had a positive impact on banks' operating profits, while Korkmazgöz & Ege (2020) examined the effect of mobile banking applications on the financial performance of the banking sector and identified a significant impact. Islamoğlu & Bayrak (2022), in their study on the impact of digital banking services (internet banking transaction volumes) on banks' financial performance, also concluded that the relationship was positive. Moreover, Bulut & Akyüz (2020) stated that digital banking accelerates economic activity, speeding up the flow of money and thereby contributing to economic growth by increasing the volume of financial transactions. On the other hand, some studies found a negative relationship between digital banking and economical growth (Sarı, 2022) while some studies attempt to explain theoretically the relationship between digital banking and economic growth in Turkey (Karadeniz & Karadeniz, 2023).

The role of financial markets in economic development has long been accepted by many economists. Schumpeter emphasized that banks play a crucial role in directing resources to more productive investments (Capasso, 2004).

It is believed that banks, through technological investments, will not only enhance their own capabilities but also contribute to the transformation processes of other sectors (Bakırtaş & Ustaömer, 2019).

Hakizimana et al. (2023) examine the transformation of digital banking in the sector and its effects on performance. The study concludes that digital banking reduces operational costs, increases financial efficiency, and provides greater financial access by expanding the customer base. While digitalization helps banks perform transactions faster and increase revenues, it also promotes financial inclusion. However, there are challenges related to security and regulation in digital banking. The study emphasizes that governments should assist commercial banks in combating technological crimes, as such crimes can negatively affect not only the financial system but also other businesses through the financial system.

Akyüz (2023), using data from the Turkish banking sector for the period 2011:Q1-2023:Q2 and employing the Topsis method, examined the relationship between banking sector performance and internet-mobile banking applications through correlation analysis and found a positive and significant relationship. Deniz (2023), who studied the impact of digital banking services (internet and mobile banking) on bank performance using data from the 2011-2022 period and multiple regression analysis, also found a positive and significant relationship. Çalış et al. (2025) also found that digital banking has a significant and positive effect on both active profitability and return on equity.

This study empirically investigates the impact of remote customer acquisition, a part of the digital transformation process, on the banking sector. As noted above, many studies in the literature have concluded that digital banking positively affects bank performance. However, there are limited empirical studies measuring these effects through a specific subtopic like remote customer acquisition. Most of the existing studies in this field are qualitative analyses. In this context, the study is expected to provide a distinctive and timely contribution to the digitalization literature by revealing the effects of digital customer acquisition on profitability and credit risk in the Turkish banking sector, offering guiding findings for both practitioners and researchers. Moreover, linking digital banking applications to financial performance indicators is believed to enable a more comprehensive evaluation of the digitalization process and increase theoretical and methodological diversity in the literature.

3. DATA SET AND METHODOLOGY

3.1 Dataset

In the study, the dependent variables used are the return on assets (ROA) and return on equity (ROE), which are commonly preferred in the literature (Turkmen & Yigit, 2012; Sadr, 2013; Tunay & Akhisar 2017; Yang et al., 2018; Sarı & Konukman, 2021; Akyüz, 2023; Çalış et al., 2025).

Non-performing loans ratio (NPL), which refers to the ratio of non-performing loans, known as a credit risk, is used in this study as both dependent and independent variable. Because it directly affects banking profitability and bank lending decisions. It is also a good indicator of asset quality (Sarı & Konukman, 2021), so it can be used as a financial performance indicator in the banking sector.

The explanatory independent variables of the study are the number of remote applications and the total number of customers concluded through customer representatives and couriers. The number of remote applications (NRA) shows the number of potential customers who initiated the process for remote acquisition during the relevant period (month) under the framework of the Regulation on Remote Identity Detection Methods to be Used by Banks and the Establishment of an Electronic Contractual Relationship. It should be noted that the applications of current bank customers are not included. The total number of customers concluded via customer representatives and couriers is obtained by summing the number of customers concluded through remote customer representatives and those who applied online and concluded via courier. A list of the banks included in the sector's remote customer acquisition data is provided in Appendix 1.

Branch-based – Concluded Customer Number (VIABRANCH): This variable shows the number of customers acquired during the relevant period (month) where the customer and the branch staff were physically in the same environment, and it is one of the independent variables in the study.

Other banking-specific independent variables include:

- Loan-to-deposit ratio (LOANDEP).
- Equity ratio (EQUITY).

- Interest income to interest-earning assets ratio (INTINCOME).

As both a banking-specific financial indicator and a macroeconomic indicator, the Weighted Commercial TL Loan Interest Rate (INT) is also chosen as an independent variable. These variables serve as control variables in the model.

Other macroeconomic indicators have not been used in the study. This is because it has been stated that after the 2007 Global Crisis, the effects of macroeconomic variables on Turkish banks have been less significant (Ganioğlu & Us, 2014).

All the variables used in the study and their sources are summarized in Table 1 below.

Table 1. Model Variables and Sources

Variables	Variable Type	Explanation	Source
NRA	Explanatory / Independent Variables	Number of Remote Applications	BAT
TOTALNCRC	Explanatory / Independent Variables	Total Number of Customers Concluded with Customer Representatives and Couriers	BAT
VIABRANCH	Explanatory / Independent Variables	Number of Customers Concluded via Branch	BAT
ROA	Dependent Variable	Return on Assets	BRSA
ROE	Dependent Variable	Return on Equity	BRSA
NPL	Dependent and Control Variable	Non-performing Loans (Gross) / Total Cash Loans	BRSA
LOANDEP	Control Variable	Total Cash Loans / Total Deposits	BRSA
EQUITY	Control Variable	Legal Equity / Total Risk-Weighted Assets	BRSA
INTINCOME	Control Variable	Interest Income / Average Interest-Bearing Assets	BRSA
INT	Control Variable	Weighted Commercial TL Loan Interest Rate	CBRT

3.2 Method

In the study, the econometric method initially chosen is the Ordinary Least Squares (OLS) method. This is because the OLS method is a technique that predicts the relationship between dependent and independent variables most accurately under certain assumptions. These assumptions are as follows: "The error term is a stochastic variable with a mean of zero, is normally distributed, and has constant variance. Additionally, there is no autocorrelation between the error terms, no relationship between the independent variable(s) and the error term, and the independent variable(s) have fixed values. There is no multicollinearity among the independent variables, the independent variables are not stochastic, and there are no measurement errors. Lastly, the model setup is correct" (Tarı, 2008). Under these assumptions, OLS is the best linear estimator, and parameters are estimated based on the least squares criterion.

However, in practice, data is often heteroscedastic, autocorrelated, or sensitive to other shocks. Indeed, as a result of diagnostic tests, it was observed that the error terms of the models did not follow a normal distribution. Based on these findings, the influence statistics of the models were examined in the first stage. As shown below, deviations appeared in the influence statistics.

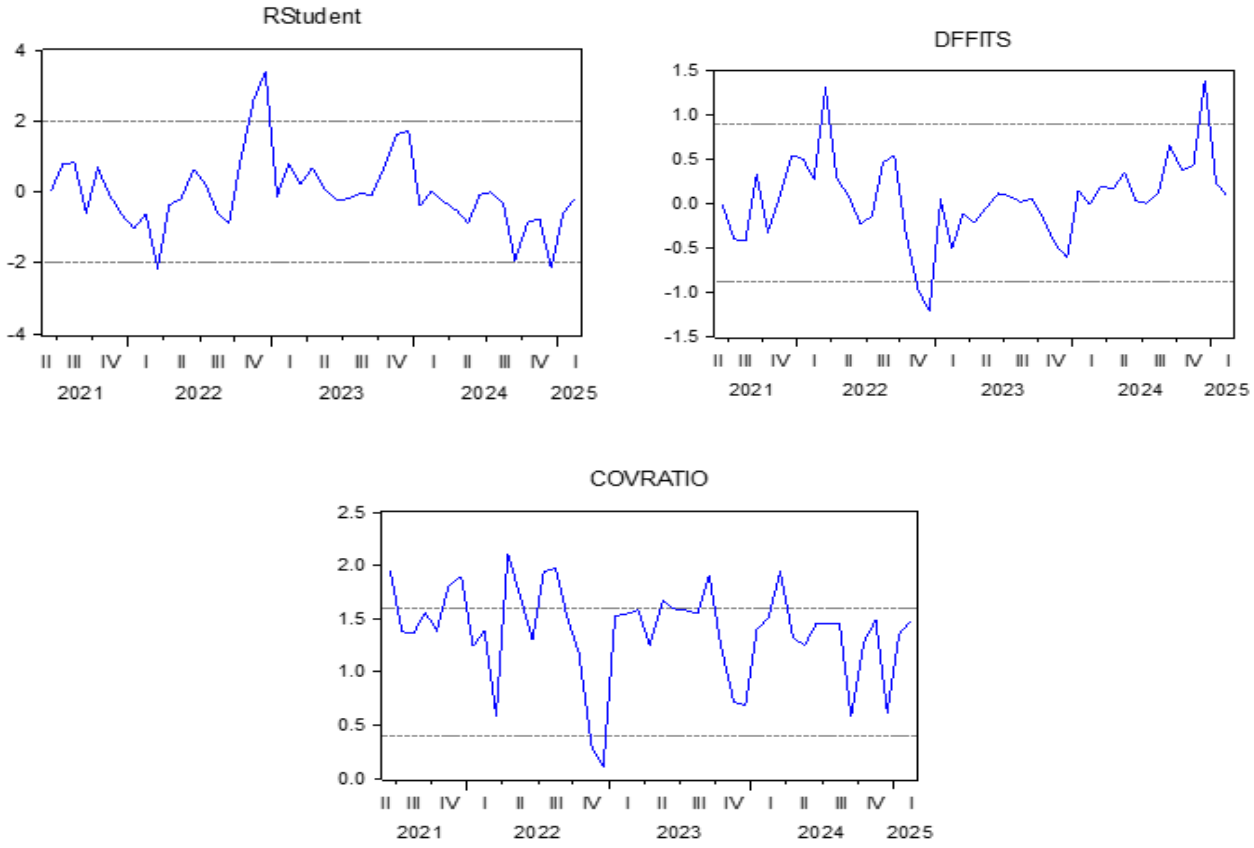

Figure 3. Influence Statistics of the Model 1

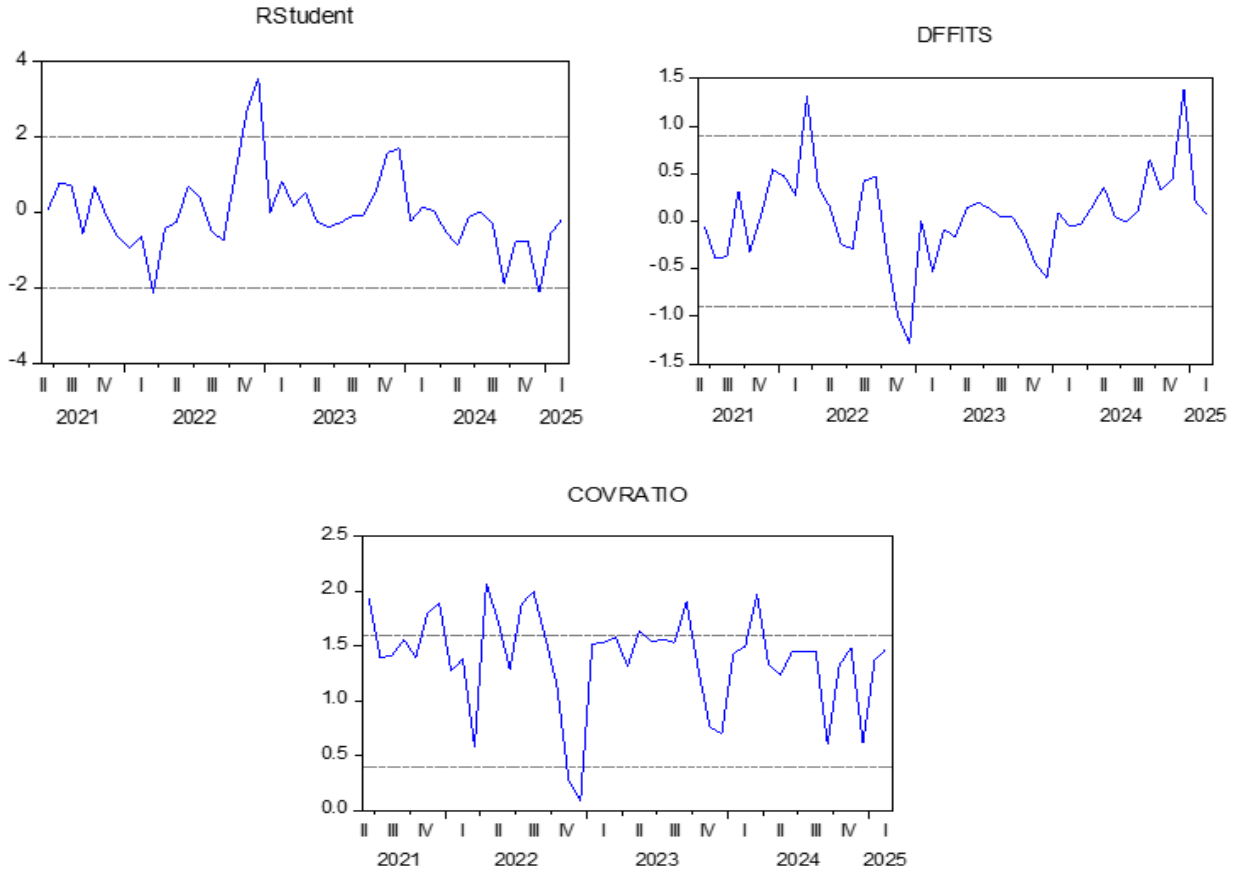

Figure 4. Influence Statistics of the Model 2

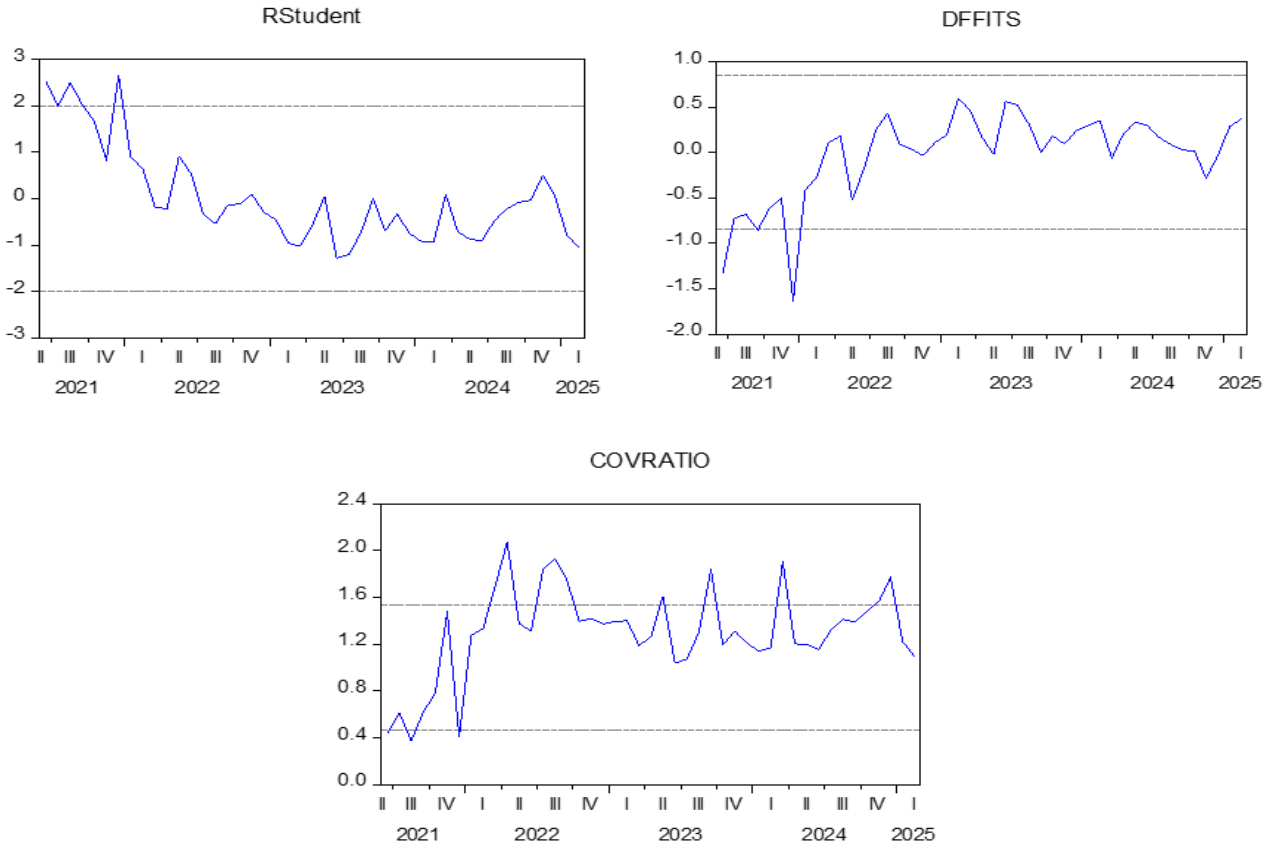

Figure 5. Influence Statistics of the Model 3

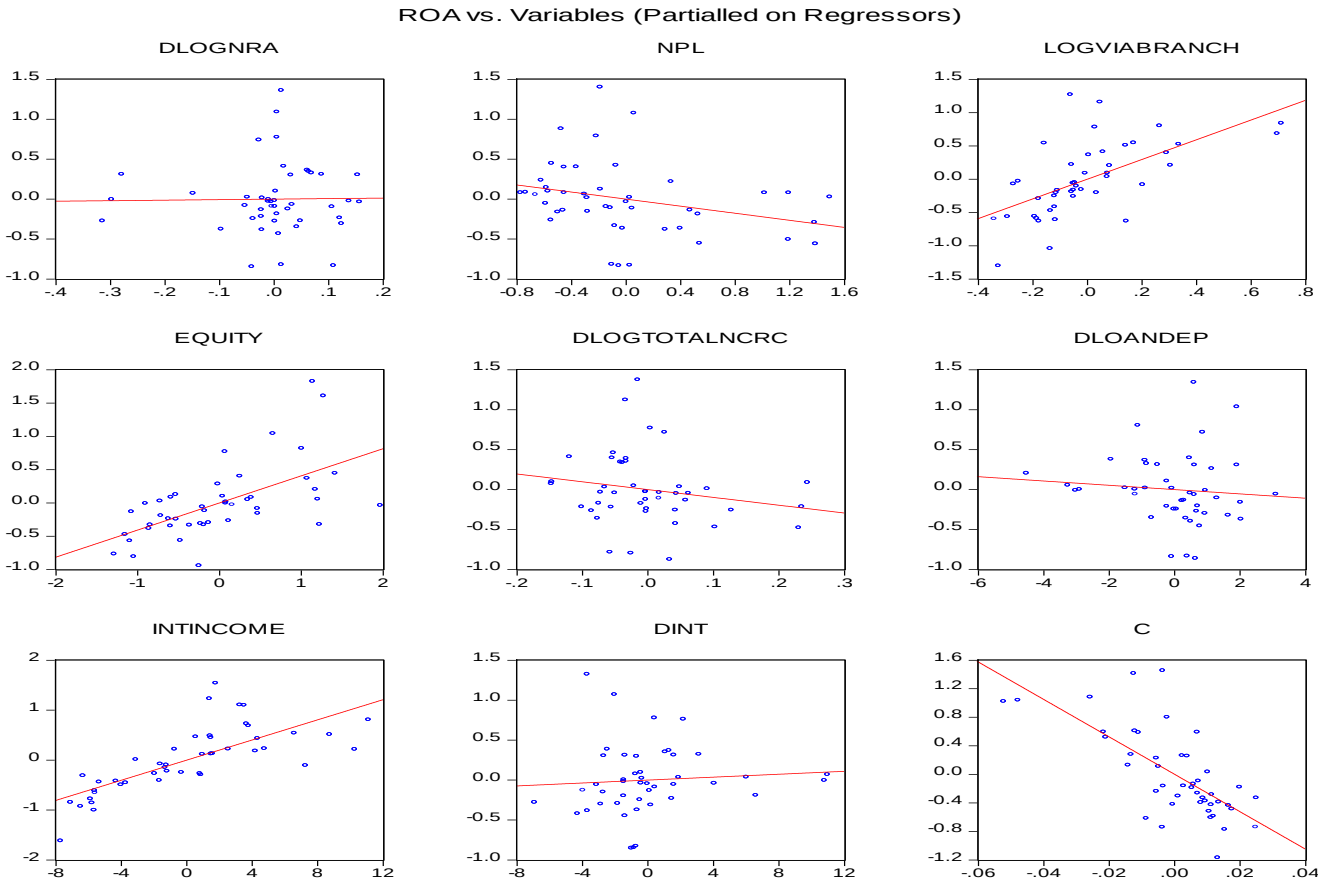

Figure 6. Leverage Plots of the Model 1

In the next stage, the leverage plots of the models were also examined, and outliers were detected in the variables. Outliers are observations that do not follow the typical distribution of the rest of the data and do not conform to

the characteristic pattern of the dataset (Öztürk & Türkay, 2005). The leverage plots of the models are presented in Figures 6, 7 and 8.

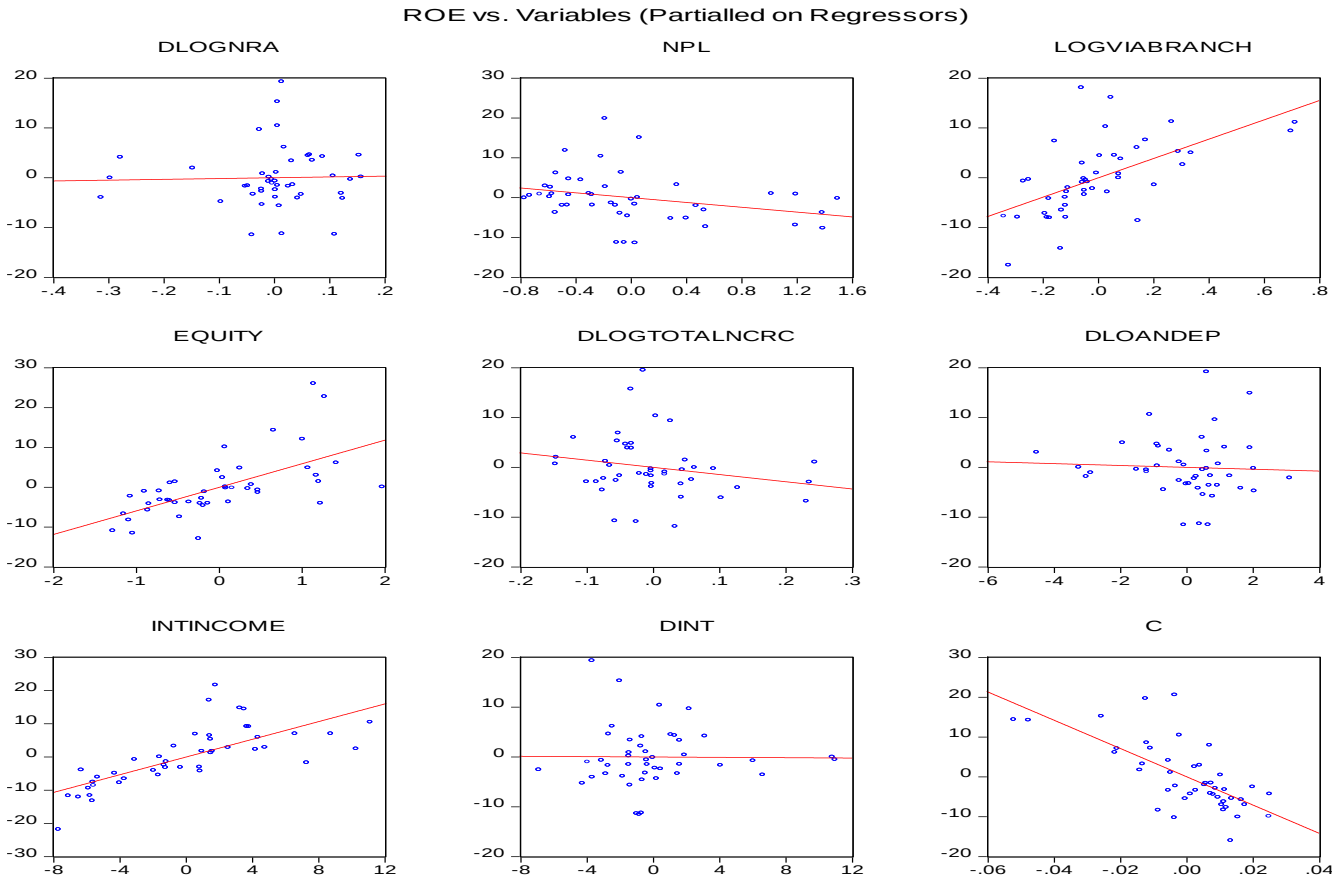

Figure 7. Leverage Plots of the Model 2

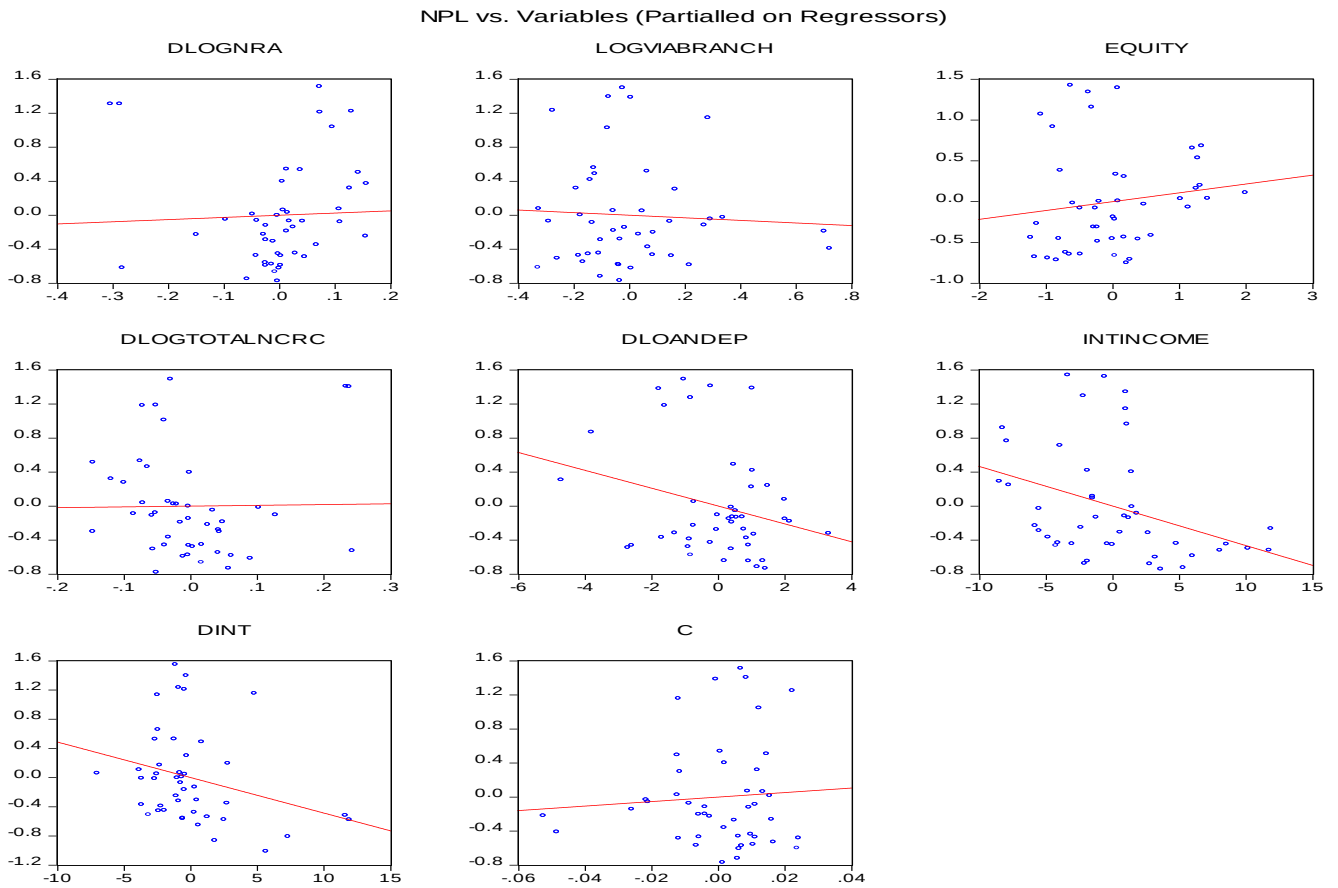

Figure 8. Leverage Plots of the Model 3

In cases where outliers are present in the series or the error terms deviate from normal distribution, the OLS method, which is highly sensitive even to small deviations from the assumptions mentioned above, may not be a reliable estimator. In such cases, using regression methods that can reduce the impact of outliers will lead to more reliable results. To overcome these issues and adopt an approach less sensitive to outliers, the Robust OLS method has been developed as a resilient regression technique (Öztürk & Türkay, 2005; Coşkuntuncel, 2009; Susanti et al., 2014; Zaman & Alakuş, 2016).

These methods are resistant to anomalies such as outliers and external shocks in the dataset. In situations where the variances of the data are not constant, robust estimators provide more accurate results compared to traditional OLS methods. Especially in time series analysis, autocorrelation between observations can be effectively controlled with robust methods. Due to these advantages, M-estimators of robust regression are used in conjunction with machine learning techniques (Ibidoja et al., 2023). The combined use of machine learning and M-robust regression is particularly recommended for big data and high-performance computing (Mukhtar et al., 2022).

M-estimation (Huber, 1964; 1973) is one of the three different regression estimators in the Robust OLS method. Along with M-estimation, which focuses on outliers in dependent variables, S-estimation (Rousseeuw & Yohai, 1984) focuses mainly on outliers in independent variables, and MM-estimation (Yohai, 1987) are a combination of both M-estimation and S-estimation, considering outliers in both dependent and independent variables.

In this study, the M-estimation, which focuses on outliers in the dependent variable and adapts the model accordingly, has been preferred. The M-estimation is an extension of the maximum likelihood estimation (MLE) method and is also a robust estimation technique (Susanti et al., 2014).

4. EMPIRICAL FINDINGS

In the first stage, the stationarity of all variables used in the model was examined. Because, to be able to obtain meaningful and reliable relationships from an econometric perspective, the series of the variables being analyzed should not contain a unit root. Otherwise, the resulting relationship might lead to a misleading outcome, known as a spurious regression, rather than a genuine relationship (Mert & Çağlar, 2019). In this context, the Augmented Dickey-Fuller (ADF) unit root test was applied using the Eviews 10 software to determine the stationarity of the variables. The results of the unit root tests are presented in the table below. As a result of the tests, it was observed that some variables were not stationary at the level, but became stationary when their first differences were taken.

Table 2. Results of the Unit Root Test for the Series

	ADF (H_0: There is a unit root)					
	Level			**First Difference**		
Serial	**Test Sta. (No-trend)**	**.05 Critical value (No-Trend)**	**Stationary**	**Test Sta. (No-Trend)**	**.05 Critical Value (No-Trend)**	**Stationary**
LOGNRA	-2,44	-2,92	Not Stationary	-7,37	-2,93	Stationary
LOGTOTALNCRC	-2,35	-2,92	Not Stationary	-6,77	-2,93	Stationary
ROA	-3,16	-2,92	Stationary			
ROE	-3,13	-2,92	Stationary			
NPL	-3,45	-2,92	Stationary			
LOGVIABRANCH	-3,94	-2,92	Stationary			
EQUITY	-3,19	-2,92	Stationary			
LOANDEP	-2,56	-2,92	Not Stationary	-5,47	-2,93	Stationary
INTINCOME	-3,12	-2,92	Stationary			
INT	-0,93	-2,92	Not Stationary	-4,00	-2,93	Stationary

Model 1 is as follows:

$$ROA = C(1)*DLOGNRA + C(2)*NPL + C(3)*LOGVIABRANCH + C(4)*EQUITY + C(5)*DLOGTOTALNCRC + C(6)*DLOANDEP + C(7)*INTINCOME + C(8)*DINT + C(9) \quad (1)$$

In the model, ROA is the dependent variable, and DLOGNRA, NPL, LOGVIABRANCH, EQUITY, DLOGTOTALNCRC, DLOANDEP, INTINCOME, and DINT are the independent variables.

Model 2 is as follows:

$$ROE = C(1)*DLOGNRA + C(2)*NPL + C(3)*LOGVIABRANCH + C(4)*EQUTY + C(5)*DLOGTOTALNCRC + C(6)*DLOANDEP + C(7)*INTINCOME + C(8)*DINT + C(9) \quad (2)$$

In the model, ROE is the dependent variable, and DLOGNRA, NPL, LOGVIABRANCH, EQUITY, DLOGTOTALNCRC, DLOANDEP, INTINCOME and DINT are the independent variables.

Model 3 is as follows:

$$NPL = C(1)*DLOGNRA + C(2)*LOGVIABRANCH + C(3)*EQUITY + C(4)*DLOGTOTALNCRC + C(5)*DLOANDEP + C(6)*INTINCOME + C(7)*DINT + C(8) \quad (3)$$

In the model, NPL is the dependent variable, and DLOGNRA, LOGVIABRANCH, EQUITY, DLOGTOTALNCRC, DLOANDEP, INTINCOME and DINT are the independent variables.

The findings obtained using this method are presented in the table below.

Table 3. Robust M Estimator Results

		Model 1		
Variable	**Variable**	**Variable**	**Variable**	**Variable**
DLOGNRA	0.025896	0.417573	0.062017	0.9505
NPL	-0.140648	0.069779	-2.015640	0.0438
LOGVIABRANCH	1.489892	0.189159	7.876397	0.0000
EQUITY	0.198866	0.052803	3.766199	0.0002
DLOGTOTALNCRC	-0.707123	0.484305	-1.460078	0.1443
DLOANDEP	-0.067491	0.028257	-2.388441	0.0169
INTINCOME	0.087624	0.008957	9.783278	0.0000
DINT	0.025984	0.012229	2.124811	0.0336
C	-22.86612	2.618835	-8.731410	0.0000
R-Squared	0.647296	Adjusted R- squared		0.568917
Rw-squared	0.923400	Adjusted Rw-squared		0.923400
Rn-squared statistic	270.0086	Prob (Rn-squared stat.)		0.000000
		Model 2		
Variable	**Coefficient**	**Std. Error**	**Z**	**p**
DLOGNRA	1.018243	5.071076	0.200794	0.8409
NPL	-1.880055	0.847402	-2.218610	0.0265
LOGVIABRANCH	19.42352	2.297181	8.455371	0.0000
EQUITY	2.886317	0.641247	4.501098	0.0000
DLOGTOTALNCRC	-10.33631	5.881487	-1.757432	0.0788
DLOANDEP	-0.773289	0.343163	-2.253414	0.0242
INTINCOME	1.153828	0.108769	10.60803	0.0000
DINT	0.227825	0.148512	1.534052	0.1250
C	-304.2157	31.80358	-9.565456	0.0000
R-squared	0.637034	Adjusted R-squared		0.556375
Rw-squared	0.930714	Adjusted Rw-squared		0.930714
Rn-squared statistic	314.9757	Prob (Rn-squared stat.)		0.000000
		Model 3		
Variable	**Coefficient**	**Std. Error**	**Z**	**p**
DLOGNRA	1.937172	0.640993	3.022140	0.0025
LOGVIABRANCH	-0.010965	0.290177	-0.037789	0.9699
EQUITY	0.250280	0.080296	3.116947	0.0018
DLOGTOTALNCRC	-2.092334	0.744051	-2.812085	0.0049
DLOANDEP	-0.050041	0.041934	-1.193319	0.2327
INTINCOME	-0.039450	0.012827	-3.075446	0.0021
DINT	-0.052445	0.018049	-2.905673	0.0037
C	-2.052435	4.013683	-0.511360	0.6091
R-Squared	0.315435	Adjusted R- squared		0.185923
Rw-squared	0.612184	Adjusted Rw-squared		0.612184
Rn-squared statistic	38.76951	Prob (Rn-squared stat.)		0.000002

As seen in the table above, the findings obtained from Model 1 provide significant insights into the effects of digital transformation and traditional banking activities on financial performance in the banking sector. The F-statistic (or the P-value) for Model 1, which determines whether the model is statistically significant as a whole, was found to be 0.0, indicating that the model is statistically significant. The R-squared value, which shows the proportion of variation in the dependent variable explained by the independent variables, is 0.64, while the Adjusted R-squared value is 0.56. According to the R-squared value, it can be said that the independent variables explain 64% of the changes in the dependent variable. On the other hand, the Rw-squared value is 0.92, which is considered a more robust and therefore more appropriate measurement tool than the R-squared value, even for small samples (Renaud & Victoria-Feser, 2010).

Excluding the variables related to remote customer acquisition, it has been observed that the relationships of other variables with Return on Assets (ROA) are statistically significant. Specifically, the number of remote applications (DLOGNRA) and the number of applications processed via customer representatives and couriers (DLOGTOTALNCRC) do not show a statistically significant relationship with ROA.

However, transactions concluded through branches (LOGVIABRANCH) have a positive and statistically significant relationship with ROA at the 1% error level. Similarly, the ratio of interest income to average assets (INTINCOME) also shows a positive and statistically significant relationship with ROA at the 1% error level. These results indicate that credit activities carried out through traditional branches have a positive impact on banks' return on assets. The positive and significant relationship between branch-based applications and ROA suggests that traditional banking activities still play an important role. The positive relationship between interest income and ROA also confirms that traditional credit activities contribute positively to banks' profitability. This finding shows that, despite digitalization, branch channels continue to perform the main functions of banking, and interest income remains an important source of profit.

After all, it is remarkable that the number of remote applications (DLOGNRA) and applications concluded through couriers does not show a statistically significant relationship with ROA. This finding suggests that the impact of digitalization on bank performance may not be immediately evident when compared to traditional methods. Specifically, applications concluded via customer representatives and couriers may show lower efficiency compared to applications processed in physical branches. This suggests that such digital services may not yet directly affect banks' profitability, which could be related to the risks associated with remote customer acquisition (Yıldırım, 2024; Ezrokh, 2020). Therefore, as these risks decrease and digital banking services develop, this result may change over time.

Moreover, the relationship between the credit interest rate (DINT) and asset profitability is positive and statistically significant. The finding that credit interest rates positively affect profitability is coherent with some studies in the economic literature (Macit, 2012), while other studies present the opposite view (Al-Homaidi et al., 2018).

The relationship between the equity ratio and ROA is also positive and statistically significant at the 1% error level. This indicates that a strong equity structure positively influences banks' lending behavior, helping to increase asset profitability. The positive relationship between equity ratio and ROA demonstrates that a strong equity structure in banks positively affects their lending behavior, which in turn increases asset profitability. This finding confirms that having strong capital structures in lending processes contributes to increased credibility and financial success.

On the other hand, the relationship between the loan-to-deposit ratio (DLOANDEP) and ROA is negative and statistically significant at the 5% error level. This can be explained by the fact that as lending increases, credit risk also rises. In addition, the ratio of non-performing loans to cash loans (NPL) also has a negative and statistically significant relationship with ROA at the 5% error level.

Furthermore, the negative relationships between the loan-to-deposit ratio (DLOANDEP) and non-performing loans (NPL) with ROA indicate that banks are facing credit risks and that an increase in non-performing loans negatively impacts profitability. This shows that banks' efforts to increase their loan portfolios and acquire new customers do not always have a positive effect; rather, they may increase risk and weaken financial performance. It is important for banks to manage their credit risks carefully and optimize their lending strategies.

Looking at the findings of Model 2, the F-statistic and P-value were found to be zero (0.0), which also indicates that the model is statistically significant. This result suggests that the independent variables in the model are sufficient to explain the changes observed in the dependent variable. The R-squared value is 63%, and the Adjusted R-squared value is 55%. The R-squared value shows that the independent variables explain 63% of the

changes in the dependent variable, while the Adjusted R-squared value of 55% suggests that some variables may have limited contribution to the model, considering that the model includes more independent variables. Furthermore, the Rw-squared value of 0.93 indicates that it is a more reliable measure than R-squared. This view, as expressed by Renaud and Victoria-Feser (2010), confirms that Rw-squared provides a more robust evaluation criterion.

The relationship between the number of remote applications (DLOGNRA) and Return on Equity (ROE) is not statistically significant. This shows that remote applications through digital channels do not contribute to banks' equity profitability. The results suggest that digitalization, compared to traditional banking methods, does not create a direct and significant impact on banks' profitability in the short term. This indicates that the potential of digitalization for remote customer acquisition has not yet been fully realized. This result could change if data from all banks in the sector are included.

The relationship between transactions concluded through customer representatives and couriers (DLOGTOTALNCRC) and equity profitability (ROE) is negative and statistically significant at the 10% level. This suggests that remote applications may have a negative effect on equity profitability. However, it should be noted that the remote customer acquisition application is relatively new, and its usage may be limited due to certain risks associated with its implementation. As the application becomes more widespread and data from all banks in the sector are obtained, the result may change.

The relationship between branch-based applications (LOGVIABRANCH) and equity profitability is positive and statistically significant at the 1% error level, indicating that traditional banking still has a strong influence on profitability. Despite the increase in digitalization, branches continue to play an important role in increasing equity profitability, particularly through credit activities. In addition, the ratio of interest income to average assets (INTINCOME) also shows a positive and statistically significant relationship with equity profitability. This demonstrates that interest income, particularly from credit transactions conducted through branch channels, continues to be an important tool for increasing equity profitability.

Although the relationship between credit interest rate (DINT) and equity profitability (ROE) is positive, it is not statistically significant. This suggests that credit interest rates may have a limited or indirect effect on banks' profitability. However, it is important to note that there are varying results in the literature on this topic. For example, some studies have concluded that the INT variable positively affects equity profitability (Alper & Anbar, 2011) while other studies have reached the opposite conclusion (Al-Homaidi et al., 2018).

The positive and significant relationship between the equity ratio and ROE shows that a strong capital structure positively influences banks' lending behavior and increases their equity profit. Banks with a high equity structure are better equipped to manage credit risks effectively, thereby enhancing their financial stability. This finding is in line with existing literature, suggesting that banks can improve the security and efficiency of future credit activities by strengthening their capital structures (Sarı & Konukman, 2021).

The negative relationship between the loan-to-deposit ratio (DLOANDEP) and ROE suggests that as lending increases, credit risk rises, which negatively impacts profitability. This finding emphasizes the importance of banks managing credit risk and optimizing deposit management and loan conversion rates. Furthermore, the negative relationship between the non-performing loan ratio (NPL) and ROE indicates that banks need to manage their credit portfolios more effectively, as credit risk negatively impacts profitability.

Model 3 examines the impact of different digital customer acquisition channels on the non-performing loan (NPL) ratio in the Turkish banking sector. The F-statistic (or the P-value) for Model 3 was found to be 0.0, indicating that the model is statistically significant. As expressed above, the Rw-squared value of 0.61 indicates that it is a more reliable, more robust measure than R-squared. The results indicate that an increase in the number of remote applications (DLOGNRA) is positively and significantly associated with higher NPL ratios. On the other hand, remote applications that are finalized through customer representatives or couriers (DLOGTOTALNCRC)—a hybrid model that combines digital initiation with human-assisted completion—are negatively and significantly associated with NPLs. This indicates that incorporating human involvement into digital onboarding processes enhances credit quality, likely through more effective identity verification and borrower assessment procedures.

The equity ratio (EQUITY) is found to have a positive and significant relationship with the NPL ratio. This may reflect increased risk-taking behavior by better-capitalized banks, as strong capital buffers allow greater flexibility in extending credit to higher-risk segments (Tunay, 2015). This finding is coherent with some studies' results (Tabak et al., 2012; Sarı & Konukman, 2021). Meanwhile, both higher interest income (INTINCOME) and increases in commercial loan interest rates (DINT) are associated with lower NPLs. In the literature, NPL is

expected to be positively related with interest rates (Nkusu, 2011). However, the higher interest rates affects NLP negatively. These findings suggest that banks with more profitable lending operations and those adjusting lending rates in response to market conditions tend the o maintain better asset quality.

Customer acquisition through physical branches (LOGVIABRANCH) and the loan-to-deposit ratio (DLOANDEP) exhibit negative but statistically insignificant relationships with NPLs. This implies that these factors do not have a significant explanatory effect on credit risk within the current sample period.

Overall, the results highlight the importance of balancing digital efficiency with human oversight in the customer acquisition process. In particular, the findings support the strategic value of hybrid onboarding models—where digital tools are supported by human interaction—in managing credit risk during the ongoing digital transformation of the banking sector.

5. CONCLUSION

This study investigates the effects of remote customer acquisition on the profitability and credit risk performance of the Turkish banking sector, offering key insights into the ongoing digital transformation. The empirical results based on robust least squares models reveal that, while digital customer acquisition practices are expanding, their direct contribution to profitability—measured by Return on Assets (ROA) and Return on Equity (ROE)—remains statistically limited in the short term. In contrast, traditional banking activities, particularly branch-based customer acquisition and interest income from lending, continue to have a strong and significant impact on bank profitability.

A critical finding of this research is the differentiated impact of digital onboarding channels on credit risk. Fully digital applications (DLOGNRA), are associated with higher non-performing loan (NPL) ratios, indicating elevated credit risk. However, remote applications completed through customer representatives or couriers (DLOGTOTALNCRC)—representing a hybrid approach—are significantly associated with lower NPLs**,** suggesting that integrating human oversight into digital processes enhances loan quality and risk control. These findings highlight that the design and execution of digital banking services play a crucial role in managing credit risk.

Additionally, the study confirms that a strong equity structure affects positively both profitability and credit risk. Higher equity ratios are positively related to ROA and ROE, but also to NPLs, possibly due to more aggressive lending behavior by well-capitalized banks. These findings suggest that, despite digitalization, banks need to develop careful and strategic approaches in critical areas such as credit risk and deposit management. The combination of digitalization strategies and traditional banking practices may yield more effective results in enhancing profitability. In this context, effective management of risks will be crucial for the success of digital transformation strategies.

Moreover, higher interest income and elevated loan interest rates are associated with reduced NPL ratios, indicating stronger asset quality under tighter credit conditions. Conversely, the loan-to-deposit ratio shows a negative and significant relationship with profitability, underlining the risks associated with aggressive lending strategies.

In conclusion, while strong empirical evidence was not found that remote customer acquisition directly contributes to profitability, it is believed that this application gives banks a competitive advantage and plays a significant role in developing sustainable digital banking strategies. The findings emphasize the importance of balancing technological efficiency with human judgment**,** particularly in credit risk assessment. Hybrid customer acquisition models appear to offer a more sustainable and risk-sensitive path forward in the digitalization of banking services. Although there were challenges in the early stages of the implementation, such as security risks, remote customer acquisition is expected to become more widespread and play a critical role in the digitalization processes of banks. The impact of digitalization on financial performance is expected to become more evident in the long term. However, it should be noted that the impact of digital banking on financial performance may vary depending on the banks' institutional structures, capacity, risk management culture, and ability to integrate digital tools with traditional practices. As data obtained from the application increases over time, the results of the analysis are expected to become more concrete and evident.

AUTHORS' DECLARATION:

There is no need to obtain ethical permission for the current study as per the legislation.

AUTHORS' CONTRIBUTIONS:

Conceptualization, writing-original draft, editing – **SS** and **BE**, data collection, methodology, formal analysis – **SS** and **BE**, Final Approval and Accountability – **SS** and **BE**

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Appendix 1. List of Banks Providing Information on Remote Customer Acquisition as of 2025

1	Akbank T.A.Ş.	10	Misyon Yatırım Bankası A.Ş.
2	Alternatifbank A.Ş.	11	Odea Bank A.Ş.
3	Anadolubank A.Ş.	12	QNB Bank A.Ş.
4	Burganbank A.Ş.	13	Şekerbank T.A.Ş.
5	Denizbank A.Ş.	14	Türk Ekonomi Bankası A.Ş.
6	Fibabanka A.Ş.	15	Türkiye Cumhuriyeti Ziraat Bankası A.Ş.
7	Golden Global Yatırım Bankası A.Ş.	16	Türkiye Garanti Bankası A.Ş.
8	HSBC Bank A.Ş.	17	Türkiye Halk Bankası A.Ş.
9	ING Bank A.Ş.	18	Türkiye İş Bankası A.Ş.
10	Misyon Yatırım Bankası A.Ş.	19	Türkiye Vakıflar Bankası T.A.O.
11	Odea Bank A.Ş.	20	Yapı ve Kredi Bankası A.Ş.

Appendix 2. Program Output of the Model 1

Dependent Variable: ROA
Method: Robust Least Squares
Date: 04/28/25 Time: 21:28
Sample (adjusted): 2021M06 2025M02
Included observations: 45 after adjustments
Method: M-estimation
M settings: weight=Bisquare, tuning=4.685, scale=MAD (median centered)
Huber Type I Standard Errors & Covariance

Variable	Coefficient	Std. Error	z-Statistic	Prob.
DLOGNRA	0.025896	0.417573	0.062017	0.9505
NPL	-0.140648	0.069779	-2.015640	0.0438
LOGVIABRANCH	1.489892	0.189159	7.876397	0.0000
EQUITY	0.198866	0.052803	3.766199	0.0002
DLOGTOTALNCRC	-0.707123	0.484305	-1.460078	0.1443
DLOANDEP	-0.067491	0.028257	-2.388441	0.0169
INTINCOME	0.087624	0.008957	9.783278	0.0000
DINT	0.025984	0.012229	2.124811	0.0336
C	-22.86612	2.618835	-8.731410	0.0000

Robust Statistics

R-squared	0.647296	Adjusted R-squared	0.568917
Rw-squared	0.923400	Adjust Rw-squared	0.923400
Akaike info criterion	80.54416	Schwarz criterion	101.9872
Deviance	3.476173	Scale	0.226553
Rn-squared statistic	270.0086	Prob (Rn-squared stat.)	0.000000

Non-robust Statistics

Mean dependent var	1.412956	S.D. dependent var	0.950091
S.E. of regression	0.564534	Sum squared resid	11.47316

Appendix 3. Program Output of the Model 2

Dependent Variable: ROE
Method: Robust Least Squares
Date: 05/15/25 Time: 18:48
Sample (adjusted): 2021M06 2025M02
Included observations: 45 after adjustments
Method: M-estimation
M settings: weight=Bisquare, tuning=4.685, scale=MAD (median centered)
Huber Type I Standard Errors & Covariance

Variable	Coefficient	Std. Error	z-Statistic	Prob.
DLOGNRA	1.018243	5.071076	0.200794	0.8409
NPL	-1.880055	0.847402	-2.218610	0.0265
LOGVIABRANCH	19.42352	2.297181	8.455371	0.0000
EQUITY	2.886317	0.641247	4.501098	0.0000
DLOGTOTALNCRC	-10.33631	5.881487	-1.757432	0.0788
DLOANDEP	-0.773289	0.343163	-2.253414	0.0242
INTINCOME	1.153828	0.108769	10.60803	0.0000
DINT	0.227825	0.148512	1.534052	0.1250
C	-304.2157	31.80358	-9.565456	0.0000

Robust Statistics

R-squared	0.637034	Adjusted R-squared	0.556375
Rw-squared	0.930714	Adjust Rw-squared	0.930714
Akaike info criterion	79.76084	Schwarz criterion	102.0965
Deviance	568.3801	Scale	2.894594
Rn-squared statistic	314.9757	Prob (Rn-squared stat.)	0.000000

Non-robust Statistics

Mean dependent var	17.61051	S.D. dependent var	12.82481
S.E. of regression	7.823295	Sum squared resid	2203.342

Appendix 4. Program Output of the Model 3

Dependent Variable: NPL
Method: Robust Least Squares
Date: 08/26/25 Time: 15:22
Sample (adjusted): 2021M06 2025M02
Included observations: 45 after adjustments
Method: M-estimation
M settings: weight=Bisquare, tuning=4.685, scale=MAD (median centered)
Huber Type I Standard Errors & Covariance

Variable	Coefficient	Std. Error	z-Statistic	Prob.
DLOGNRA	1.937172	0.640993	3.022140	0.0025
LOGVIABRANCH	-0.010965	0.290177	-0.037789	0.9699
EQUITY	0.250280	0.080296	3.116947	0.0018
DLOGTOTALNCRC	-2.092334	0.744051	-2.812085	0.0049
DLOANDEP	-0.050041	0.041934	-1.193319	0.2327
INTINCOME	-0.039450	0.012827	-3.075446	0.0021
DINT	-0.052445	0.018049	-2.905673	0.0037
C	-2.052435	4.013683	-0.511360	0.6091

Robust Statistics

R-squared	0.315435	Adjusted R-squared	0.185923
Rw-squared	0.612184	Adjust Rw-squared	0.612184
Akaike info criterion	77.28212	Schwarz criterion	96.97319
Deviance	8.576080	Scale	0.359061
Rn-squared statistic	38.76951	Prob (Rn-squared stat.)	0.000002

Non-robust Statistics

Mean dependent var	2.193778	S.D. dependent var	0.708302
S.E. of regression	0.742758	Sum squared resid	20.41249

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The Role of Financial Development on Economic Growth in South Africa

Güney Afrika'da Finansal Gelişmenin Ekonomik Büyüme Üzerindeki Rolü

Sevgi SÜMERLİ SARIGÜL
Assoc. Prof. Dr., Kayseri University
ssumerli@kayseri.edu.tr
https://orcid.org/0000-0002-3820-6288

Murat ÇETİN
Prof. Dr., Tekirdağ Namık Kemal University
mcetin@nku.edu.tr
https://orcid.org/0000-0002-7886-4162

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ABSTRACT

South Africa has long been a prominent example of economic growth, unlike other African countries. Therefore, this study investigates the financial development-economic growth link employing time-series techniques over the period 1990-2022. It also incorporates energy efficiency, trade openness, and government spendings into the economic growth model. The study uses the ARDL bounds test to analyze the cointegration relationship and the FMOLS estimator for long-term coefficient estimates. The estimates suggest that financial development accelerates economic growth. Therefore, the "financial development-driven economic growth" hypothesis is proven for the South African economy. The estimates also suggest that energy efficiency, trade openness, and government spendings support economic growth. These results may offer important recommendations for growth policies in the South African economy.

Anahtar Kelimeler:
Finansal Gelişme,
Ekonomik Büyüme,
ARDL,
FMOLS,
Güney Afrika

Jel Kodları:
C33, O16, O55

ÖZET

Güney Afrika, uzun süredir diğer Afrika ülkelerinden farklı olarak görece güçlü ekonomik büyüme performansı ile dikkat çekmektedir. Bu çalışmanın amacı, 1990-2022 dönemine ilişkin veriler kullanılarak finansal gelişmenin ekonomik büyüme üzerindeki etkisini zaman serisi yöntemleri aracılığıyla incelemektir. Analize finansal gelişmenin yanı sıra enerji verimliliği, ticari dışa açıklık ve kamu harcamaları da dahil edilmiştir. Eşbütünleşme ilişkisini test etmek amacıyla ARDL sınır testi uygulanmış, uzun dönem katsayılarının tahmininde ise FMOLS yöntemi kullanılmıştır. Ampirik bulgular, finansal gelişmenin ekonomik büyümeyi anlamlı ve pozitif yönde etkilediğini ortaya koymakta; dolayısıyla "finansal gelişme odaklı büyüme" hipotezini Güney Afrika ekonomisi bağlamında doğrulamaktadır. Ayrıca enerji verimliliği, ticari dışa açıklık ve kamu harcamalarının da ekonomik büyümeyi desteklediği sonucuna ulaşılmıştır. Elde edilen bulgular, Güney Afrika ekonomisinin büyüme politikalarına yönelik önemli politika önerileri sunmaktadır.

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1. INTRODUCTION

In every economy, financial development is essential for achieving the desired level of economic progress. From past to present, many scholars have argued that financial development facilitates easier and more affordable access to credit for the real sector, thereby promoting productivity and growth (Kwakwa et al., 2023). Financial development also influences economic growth by facilitating and supporting capital inflows (Nguyen & Lee, 2021). Moreover, financial development can help reduce poverty by facilitating access to financial possibilities for poor people. Developments in the financial sector may also encourage renewable energy investments and projects, thereby escalating the production and use of renewable energy (Horky & Fidrmuc, 2024). Jianguo et al. (2022) suggest that financial sector may influence environmental quality by either increasing or decreasing CO2 emissions and thus influencing environmental pollution.

Undoubtedly, one of the most widely dealt with topics in the literature encompasses the finance-economic development link (Kar et al., 2008; Hasan et al., 2021; Elfaki et al., 2021). The traditional theory of financial development seeks to explain the effects of transaction and information costs in markets, institutions, and financial instruments. The primary aim of the financial system is to ensure the optimal use of resources by enabling their adequate allocation over time and space. When the conditions of financial services are developed and expanded to more efficiently and effectively meet the needs of economic development, economic growth is promoted and supported (Levine, 1997). These theoretical explanations have led to the emergence of the "finance-led growth hypothesis" which has been empirically investigated by numerous researchers over time.

This study tests the aforementioned hypothesis in the example of South Africa. There are several important reasons why this country was selected as the case country for this research. First, the growth figures of South Africa clearly indicate a significant level of development. For example, the country's per capita income increased from $6,381 in 1990 to $8,095 in 2000, $12,637 in 2010, and $15,457 in 2024, demonstrating an upward trend of nearly threefold over the 1990–2024 period. The average annual growth rate of 2.7% between 1960 and 2024 is another key indicator of the country's economic performance (World Bank, 2025). In the first quarter of 2025, while the overall South African economy grew by 0.8%, the agricultural sector expanded by 15.2%, the transportation sector by 2.4%, the trade sector by 0.5%, and the financial sector by 0.2%. During the same period, gross fixed capital increased by 1.7%, and government expenditures rose by 0.1%.

Second, while the financial sectors of many African countries remain fragile, South Africa stands out as a country with a robust financial system in the region. South Africa's financial system appears resilient. The government continues to closely monitor financial risks and develop macroprudential regulations to minimize systemic risks. The capital-to-risk-weighted assets ratio of banks remains above the minimum requirements and is comparable to those in many OECD and G20 economies. Corporate debt has generally remained stable, and at 31%, is lower than the average for developing countries in the OECD and G20 (OECD Report, 2025).

Furthermore, the financial system in South Africa is large and well-regulated, reflecting a strong commitment to independent auditing and adherence to international standards and best practices (IMF Report, 2022). Scholars such as Abiodun & Temidayo (2022) acknowledge that South Africa's economic development is encouraged by this robust financial structure.

In light of these developments, the study detects the "finance-led growth" hypothesis in the South African economy using time series techniques. This study provides important gains for the literature. Firstly, few studies specifically investigate this link in the South African context; thus, the study is expected to provide a substantial contribution. Secondly, although the study primarily focuses on the financial development-economic growth relation, it also incorporates series such as energy efficiency, trade openness, and government expenditures into the growth model, drawing from the literature. In doing so, it becomes a unique study that examines the relationships among these variables in the South African economy. A notable distinction of this study is its inclusion of energy efficiency and government expenditure variables in the model, which has rarely been done in the literature. Thirdly, by applying the Ng-Perron test, the study conducts stationarity analysis using four different test statistics. The ARDL bounds test is applied as a cointegration approach. FMOLS estimator is employed for coefficient estimations. Finally, the empirical findings offer valuable insights for policy recommendations.

The structure of the study is as follows: Section 2 reports the literature. Section 3 provides the model, data set, and econometric techniques. Section 4 discusses the empirical outcomes. The study ends with a conclusion.

2. LITERATURE REVIEW

The relationship between financial development (FD) and economic growth (EG) has long been one of the most debated topics in the economics literature. Levine (1997) emphasizes that the financial system supports growth by mobilizing savings, allocating capital efficiently, and financing innovative activities, while Arestis & Demetriades (1997) argue that the growth effects of financial deepening are context-specific and dependent on institutional structures. Early empirical studies show a generally positive relationship between FD and EG, though measurement choice plays a crucial role (De Gregorio & Guidotti, 1995). Calderón & Liu (2003), using a large sample of 109 countries, demonstrate that the direction of causality between FD and EG varies across regions and levels of development. A comprehensive meta-analysis by Valickova et al. (2015) further confirms the overall positive and significant impact, but highlights that the magnitude of the relationship is sensitive to sample, indicator choice, and methodological specifications.

Empirical evidence at the country and panel level highlights the heterogeneity of the FD-EG nexus. Hassan et al. (2011) find robust positive effects of FD on growth across panels, though the magnitude is smaller in low-income countries. Bist (2018), focusing on 16 low-income countries, reveals that institutional capacity conditions the strength of the FD-EG relationship. In Sub-Saharan Africa, Ibrahim & Alagidede (2018) argue that financial development contributes to growth particularly when accompanied by financial inclusion. In Ghana, Adu et al. (2013) show that the choice of FD indicator (credit, monetary, or market-based measures) critically shapes empirical outcomes. Caporale et al. (2015) demonstrate that in new EU member states, financial development supports growth but the magnitude is affected by integration pace, regulatory quality, and macroeconomic vulnerabilities.

The Asian experience also offers valuable insights. In China, financial reforms and banking sector deepening have been found to support long-run growth (Liang & Jian-Zhou, 2006; Zhang et al., 2012). In Taiwan and Vietnam, FD positively contributes to growth, though the effects vary across periods and policy structures (Chang & Caudill, 2005; Anwar & Nguyen, 2011). Fung (2009) suggests that the FD-EG relationship may display convergence or divergence dynamics depending on regional integration. In the BRICS context, Guru & Yadav (2019) find a robust positive nexus, while Ohlan (2017) highlights the complementary role of tourism and financial development in supporting growth in India.

Recent contributions have extended the debate by incorporating nonlinearity, asymmetry, and vulnerability to external shocks. Asteriou & Spanos (2019) show that the FD-EG relationship in the EU weakens, or even reverses, during crisis periods. Badeeb and Lean (2017) find that in oil-dependent economies, the FD-EG nexus is highly sensitive to oil price fluctuations. Similarly, Shahbaz et al. (2017) demonstrate that in India, the link between FD, energy consumption, and growth is nonlinear and asymmetric, indicating regime-dependent dynamics. Cheng et al. (2021) emphasize the role of ICT diffusion in enhancing the efficiency of financial intermediation, thereby strengthening the FD-EG channel in the digital era.

Recent studies on emerging markets further underline these complexities. Durusu-Ciftci et al. (2017) highlight that FD generally supports growth but may be unstable in the long run due to crises, institutional weaknesses, or external shocks. Abu-Bader & Abu-Qarn (2008) show that while FD supports growth in Egypt, fiscal imbalances and macroeconomic distortions weaken this effect. Choong & Chan (2011) argue that the FD-EG relationship is not universal but context-dependent across different regions. Nguyen et al. (2022), examining emerging markets, confirm that FD matters for growth, though the size and persistence of the effect vary across countries.

Taken together, the literature broadly supports a positive FD-EG relationship, but the evidence consistently reveals heterogeneity depending on measurement choices (Adu et al., 2013; Valickova et al., 2015), institutional and structural conditions (Bist, 2018; Caporale et al., 2015), and vulnerability to crises and external shocks (Asteriou & Spanos, 2019; Badeeb & Lean, 2017). Sectoral linkages (Ohlan, 2017), energy dependence (Shahbaz et al., 2017), and the diffusion of digital and ICT technologies (Cheng et al., 2021) further shape the magnitude and direction of the nexus. Overall, the findings underscore that the FD-EG relationship is not uniform, but rather context-specific, highlighting the need for differentiated policy approaches tailored to levels of development, institutional quality, and structural vulnerabilities.

3. MODEL and DATASET

The study investigates the relationship between financial development and economic growth in South Africa. In this analysis, economic growth is treated as the dependent variable, whereas all other factors serve as explanatory variables. The models used by Islam et al. (2013), Elfaki et al. (2021), Tekbaş (2022), Doğan et al. (2022), Ullah

et al. (2023), Jóźwik et al. (2023), Saadaoui et al. (2024) and Jozwik et al. (2025) effective in determining our model. The model of the study can be expressed through the following closed-form equation:

$$GDP = f\,(FIN, EN, TR, EXP) \tag{1}$$

In this equation, GDP represents real per capita income, FIN denotes financial development, EN indicates energy efficiency, TR refers to trade openness, and EXP represents government expenditures. The energy efficiency data were obtained from the OECD database, while the data for all other series were taken from the World Bank database. Since the elasticities of the series are to be interpreted, all series were transformed into their natural logarithms before being included in the analyses. Accordingly, the explicit form of our model, which was represented in a closed form in Equation 1, is provided below:

$$LNGDP_t = \alpha + \theta_1 LNFIN_t + \theta_2 LNEN_t + \theta_3 LNTR_t + \theta_4 LNEXP_t + \varepsilon_t \tag{2}$$

In this equation, α, t and ε_t represent the intercept term, the time dimension, and the error term, respectively. Each coefficient measures and estimates the elasticity of economic growth with respect to financial development, energy efficiency, trade openness, and government expenditures, respectively. Table 1 provides detailed descriptions of each variable, while Figure 1 summarizes the temporal evolution of the series over the period 1990-2022.

Table 1. Data Set and Descriptive Statistics

Variables	Symbol	Measurement	Source	Expected value
Economic Growth	GDP	Real GDP per capita (constant 2015 USD)	WB	(–)
Financial Development	FIN	Domestic credit provided by banking sector (% of GDP)	WB	(+)
Energy Efficiency	EN	GDP per TPES unit	OECD	(+)
Trade Openness	TR	Total foreign trade (% of GDP)	WB	(–) (+)
Government Expenditures	EXP	Government final consumption expenditure (% of GDP)	WB	(–) (+)

The study follows a three-step econometric strategy. In the first step, the stationarity analysis is examined using the Ng-Perron (2001) test. Monte-Carlo simulations demonstrate that this approach can produce more robust results than other unit root tests. This is primarily due to the ability to apply four different tests simultaneously, as outlined below:

$$MZ_a = ((T^{-1}y_t)^2 - f_0)/2k \tag{3}$$

$$MZ_t = MZ_a * MSB \tag{4}$$

$$MSB = (k/f_0)^{1/2} \tag{5}$$

$$MPT = (c^2 k - cT^{-1}{y_t}^2/f_0) \tag{6}$$

The second step encompasses the cointegration among the series. This is detected using the ARDL bounds test of Pesaran et al. (2001). The most important distinguishing feature of this test is that it allows variables to be stationary at the level or first difference. Its second distinguishing feature is its ability to predict both short- and long-term dynamics. Its third feature is its ability to yield more reliable results in shorter samples. The presence of cointegration in this test is demonstrated by comparing the calculated F-statistic with the upper and lower critical values.

The final step estimates the parameters using the FMOLS estimator. The FMOLS estimator, proposed by Phillips & Hansen (1990), is one of the most important techniques that can be used when there is a cointegration relationship between the series. Providing reliable and robust results in small samples, the FMOLS estimator also has significant advantages in eliminating problems of endogeneity and serial correlation among the variables.

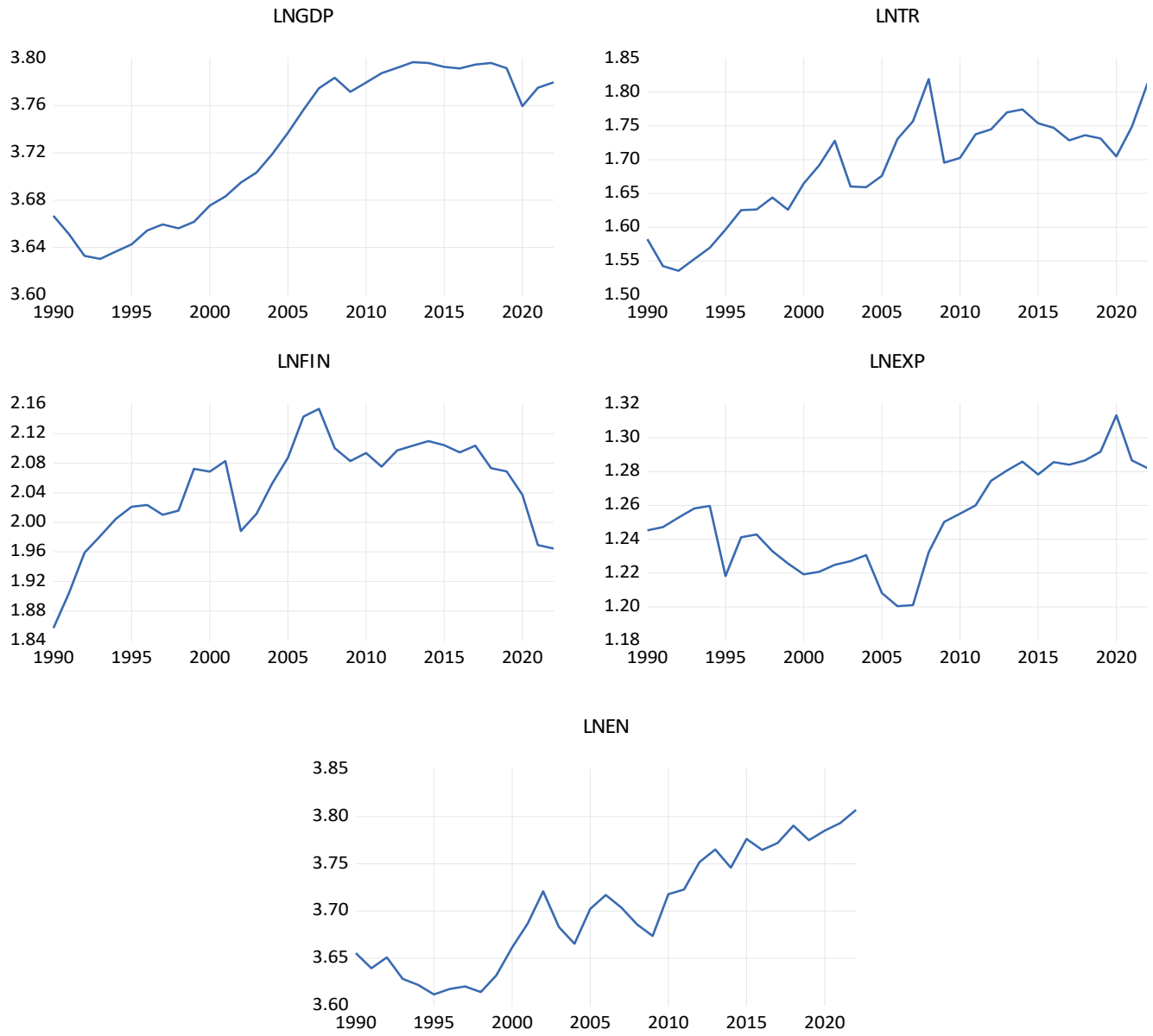

Figure 1. Temporal Trends of the Series Over the Period 1990-2022

4. FINDINGS and DISCUSSION

The empirical analysis begins with a review of the summary statistics (Table 2). Among the series, LNGDP records the highest values for the mean, median, minimum, and maximum, whereas LNEXP exhibits the lowest values across these measures. In terms of variability, LNEXP shows the lowest standard error (0.029), while LNTR displays the highest (0.077). The distributional properties further indicate that LNGDP and LNFIN are negatively skewed, whereas LNEN, LNTR, and LNEXP are positively skewed.

Table 2. Summary Statistics

	LNGDP	LNFIN	LNEN	LNTR	LNEXP
Mean	3.728	1.766	3.701	1.687	1.251
Median	3.756	1.777	3.702	1.702	1.250
Max.	3.796	1.847	3.807	1.819	1.313
Min.	3.630	1.668	3.611	1.535	1.200
Std. Error	0.062	0.045	0.062	0.077	0.029
Skewness	-0.289	-0.389	0.090	0.406	0.074
Kurtosis	1.389	2.435	1.682	2.251	2.025
Observations	33	33	33	33	33

Table 3 presents the correlation matrix, which highlights the relationships among the variables. The results demonstrate a positive correlation between financial development and economic growth, with similar positive associations observed between economic growth and the other explanatory variables. Notably, LNTR exhibits the highest positive correlation with economic growth, with a coefficient of 0.894.

Table 3. Correlation Matrix

	LNGDP	**LNFIN**	**LNEN**	**LNTR**	**LNEXP**
LNGDP	1.000				
LNFIN	0.694	1.000			
LNEN	0.869	0.437	1.000		
LNTR	0.894	0.744	0.794	1.000	
LNEXP	0.482	0.013	0.647	0.297	1.000

The study examines the unit root features of the series, specifically their order of stationarity, using the Ng-Perron unit root approach. This method, which involves four test statistics—MZa, MZt, MSB, and MPT—has its application outcomes expressed in Table 4. The relevant table reveals that each series has a unit root at levels but becomes stationary at first differences.

Table 4. Unit Root Analysis

Level	**MZa**	**MZt**	**MSB**	**MPT**
LNGDP	-0.693	-0.435	0.628	22.426
LNFIN	-3.882	-1.361	0.350	6.332
LNEN	-0.104	-0.053	0.509	19.153
LNTR	-1.811	-0.661	0.365	10.041
LNEXP	-2.890	-1.102	0.381	8.208
First difference	**MZa**	**MZt**	**MSB**	**MPT**
LNGDP	-11.127***	-2.342***	0.210***	2.262***
LNFIN	-15.130***	-2.749***	0.181**	1.622***
LNEN	-15.224***	-2.735***	0.179**	1.696***
LNTR	-15.030***	-2.600***	0.173***	2.146**
LNEXP	-15.451***	-2.772***	0.179**	1.612***

Note: *** and ** indicate significance at the 1% and 5% levels, respectively.

The stationarity of the series at their first differences indicates that a cointegration relationship among these series can be investigated. In this context, the ARDL bounds test is utilized to assess the cointegration among the series. A main feature of this cointegration method is its ability to appropriately determine the optimal lag length. The lag length results obtained from the most suitable VAR model established for this purpose are presented in Table 5. As can be seen, the suitable lag length is 1. Therefore, this lag length was preferred for the cointegration analysis.

Table 5. VAR Lag Length

	LR	**FPE**	**AIC**	**SIC**	**HQ**
1	179.326*	2.22e-18*	-26.491	-25.077*	-26.048*
2	21.900	4.36e-18	-25.984	-23.391	-25.172
3	17.794	1.02e-17	-25.628	-21.857	-24.447
4	21.758	1.29e-17	-26.624*	-21.673	-25.074

Note: * indicates the optimal lag length.

Table 6 expresses the estimation outcomes of the cointegration test. The findings show that the F-statistic value (4.642) exceeds the upper critical bound of 4.37 at the 1% significance level, thereby confirming the existence of cointegration among the LNFIN, LNEN, LNTR, LNEXP, and LNGDP series. This also implies a long-run link.

Diagnostic tests for the ARDL model, including tests for autocorrelation, heteroscedasticity, normality, and model specification, indicate that the model is appropriate. Furthermore, the CUSUM and CUSUM^2 test outcomes reveal that the values lie within the relevant bounds, verifying the stability of the parameters.

Table 6. Bounds Test Results

Optimal lag	[1,0,0,1,1]	
F-statistic	4.642***	
Critical values		
Significance level	**Lower bound, *I(0)***	**Upper bound, *I(1)***
1%	3.29	4.37
5%	2.56	3.49
10%	2.20	3.09
Diagnostic tests		
Breusch-Godfrey LM tests	1.007 (0.325)	
ARCH LM tests	0.120 (0.325)	
J-B normality tests	1.400 (0.496)	
Ramsey RESET tests	0.078 (0.782)	
CUSUM	Stable	
CUSUMsq	Stable	
R^2	0.989	
Adj.-R^2	0.986	
F-statistic	321.179***	
Probability	0.000	

Note: ***, indicates significance at the 1% level.

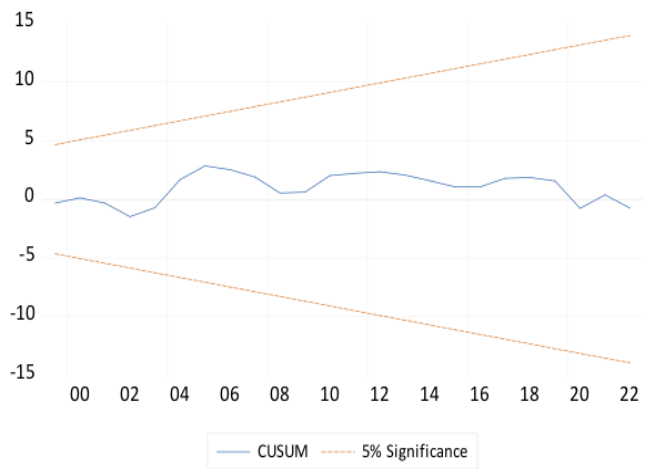

Figure 2. CUSUM Test

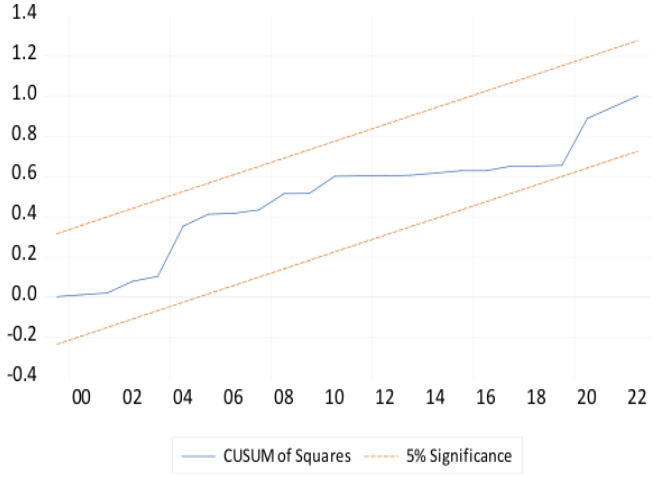

Figure 3. CUSUM^2 Test

In the final stage, the parameters of each explanatory variable are estimated to analyze their impacts on the dependent variable. The outcomes of the FMOLS technique are presented in Table 7.

The first key finding is that the coefficient of LNFIN (0.486) is positive and significant. This indicates that a 1% increase in financial development leads to a 0.486% rise in economic growth, implying that financial development accelerates economic growth. This outcome is in line with the outcomes of Kalaycı & Özden (2020) proving the financial development-supported growth hypothesis. This outcome differs from the findings of Ayad et al. (2017), who tested MENA countries and did not support the financial development-driven growth hypothesis. Additionally, the findings of Elfaki et al. (2021) differ from our study. In other words, this study provides evidence that financial development hinders economic growth.

Secondly, the coefficient of LNEN (0.415) is positive and statistically significant, indicating that a 1% increase in energy efficiency leads to a 0.415% rise in economic growth. This suggests that energy efficiency serves as a growth-enhancing factor. This finding is parallel to the finding of Bayar & Gavriletea (2019).

Thirdly, the coefficient of LNTR (0.244) is also determined to be positive and significant. This reveals that a 1% rise in trade openness increases economic growth by 0.244%, demonstrating that trade openness is a crucial determinant of economic growth. This outcome differs from the empirical outcomes of Menyah et al. (2014), which fail to support the trade-led growth hypothesis. Our finding, unlike this study, is in the same direction as the finding of Khemakhem & Saidi (2024).

Finally, the coefficient of LNEXP is estimated at 0.235, which is again positive and significant. This indicates that a 1% rise in government expenditure contributes to a 0.235% rise in economic growth. Thus, like the other explanatory variables, government expenditure also positively impacts economic growth.

Table 7. FMOLS Estimates

Variables	Coefficients	Std. Error	Prob.
LNFIN	0.486***	0.075	0.000
LNEN	0.415***	0.077	0.000
LNTR	0.244***	0.066	0.000
LNEXP	0.235**	0.101	0.028
Constant	-2.224***	0.205	0.000

Note: *** and ** indicate statistical significance at the 1% and 5% levels, respectively.

5. CONCLUSION

The study econometrically investigates the determinants of economic growth in South Africa, which has witnessed significant economic developments in recent years. Specifically, it examines the link among economic growth and financial development, energy efficiency, trade openness, and government expenditure during the period 1990-2022. The study applies the Ng-Perron technique for stationarity analysis, the ARDL bounds test for cointegration, and the FMOLS estimator for long-run coefficient estimation.

The outcomes indicate a cointegration relationship among all the series. Financial development is found to stimulate economic growth. Additionally, energy efficiency, trade openness, and government spending are also detected to contribute positively to economic growth. Thus, financial development, energy efficiency, trade openness, and government expenditure are empirically confirmed as key derivers of economic growth in South Africa.

These findings offer meaningful insights for policymakers in South Africa. First, the empirical evidence that financial development enhances economic growth suggests that measures aimed at further developing the financial sector could accelerate growth. The financial sector—particularly banks—should continue to support productive projects and investments in the real economy. Moreover, the government should take necessary steps to reduce vulnerabilities within the financial system.

The positive impact of energy efficiency on economic growth reveals that policymakers should prioritize investments and projects aimed at improving energy efficiency. Energy efficiency not only prevents the wastage of existing energy resources but also ensures the optimal use of energy. Both the financial sector and the government should provide financial support for energy efficiency initiatives in the real economy. Such support may include low-interest and long-term loans, as well as tax incentives.

The finding that trade openness enhances economic growth highlights the importance of export and import strategies. In this regard, an export-led growth strategy should be implemented more robustly. Policies that promote high value-added export products should be accelerated. On the import side, priority can be given to the acquisition of technologically advanced capital goods, while imports of consumption goods can be restricted. This finding of our study is similar to the results of Fraihat et al. (2023) and Utkulu & Kahyaoglu (2005).

Finally, another outcome underscores the need for allocating more public resources to productive, efficient, employment-generating, and innovative investments in public and private sectors. Minimizing waste in government expenditures should also be considered as a crucial policy measure. Policy recommendations should not be limited to the variables discussed. Additionally, strengthening institutional structures and accelerating steps toward globalization could also support South Africa's economic growth.

The study's most significant limitations include its single-country nature, its failure to analyze different country groups, and its failure to model variables such as political risk, democracy, and institutional quality, which have recently become popular in economic growth studies. Future studies should be advised to design their studies with these limitations in mind.

AUTHORS' DECLARATION:

There is no need to obtain ethical permission for the current study as per the legislation.

AUTHORS' CONTRIBUTIONS:

Conceptualization, writing-original draft, editing – **SSS** and **MÇ**, data collection, methodology, formal analysis – **SSS** and **MÇ**, Final Approval and Accountability – **SSS** and **MÇ**.

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