



Dynamic Connectedness and Time-Varying Causality between Digital Payment Adoption and GDP Growth in the FinTech Era

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ABSTRACT

This study investigates the dynamic interaction, systemic connectedness, and time-varying causality between digital payment adoption and GDP growth in the FinTech era. Employing a Time-Varying Parameter Vector Autoregression (TVP-VAR) framework, the analysis captures evolving relationships that cannot be identified using static or linear econometric models. Quarterly data on digital payment adoption and real GDP growth are analyzed to examine how macroeconomic effects change across different stages of digital financial development. The empirical results reveal that the relationship between digital payment adoption and GDP growth is non-linear and regime-dependent. Time-varying estimates indicate that the growth impact of digital payments intensifies significantly during periods of accelerated adoption and ecosystem maturation. Dynamic connectedness analysis shows that the Total Connectedness Index increases from approximately 38% in early adoption phases to over 64% in mature FinTech phases, indicating a substantial rise in systemic interdependence between digital finance and the real economy. Directional spillover results further demonstrate that digital payment adoption acts predominantly as a net transmitter of macroeconomic shocks, contributing on average 41.8% of spillovers to GDP growth, while receiving only 26.4% in return. Time-varying Granger causality analysis confirms that causality from digital payments to GDP growth dominates both in duration and statistical strength, with causality regimes lasting on average 3.2 years and exhibiting posterior probabilities exceeding 0.80. In contrast, reverse causality from GDP growth to digital payments appears weaker, shorter, and episodic. Overall, the findings establish digital payment systems as active macroeconomic infrastructure rather than passive financial tools. By revealing how FinTech-driven growth effects evolve over time, this study contributes to the literature on digital finance and economic growth and provides evidence-based insights for adaptive FinTech policy and sustainable digital economic development.

Keywords Financial Technology, Digital Payments, GDP Growth, Time-Varying Parameter VAR, Dynamic Connectedness, Granger Causality, Digital Economy

INTRODUCTION

The rapid expansion of Financial Technology (FinTech) has fundamentally transformed the architecture of modern financial systems, with digital payment platforms emerging as one of the most pervasive and economically consequential innovations. Digital payments have reshaped transaction mechanisms, reduced frictions in exchange, and expanded access to formal financial services across households and firms. As economies increasingly transition toward cashless ecosystems, understanding how digital payment adoption interacts with macroeconomic growth, particularly GDP growth, has become a central issue in both academic research and policy debates [1], [2].

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Additional Information and
Declarations can be found on
[page 134](#)

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Despite growing empirical interest, existing studies largely examine the FinTech–growth relationship using static or linear econometric frameworks, implicitly assuming stable structural relationships over time [3], [4]. Such assumptions are increasingly untenable in the FinTech era, where technological diffusion, regulatory reforms, and behavioral adaptation evolve continuously. Digital payment systems do not mature instantaneously; instead, their economic effects unfold through stages of adoption, interoperability, and institutional embedding. Static models therefore risk masking structural breaks, regime shifts, and asymmetric feedback effects that characterize the real-world evolution of digital finance [5].

Recent literature has begun to acknowledge that FinTech-driven growth effects are heterogeneous and context-dependent, varying across time, economic conditions, and institutional environments [6], [7]. However, much of this work remains limited to average effects or rolling-window approximations, which still impose discrete segmentation on inherently continuous processes. Moreover, studies often focus on correlation or short-run causality, without fully capturing dynamic connectedness and bidirectional shock transmission between digital payments and macroeconomic performance [8].

A further limitation in the existing literature lies in the treatment of causality. Conventional Granger causality tests assume time-invariant predictive relationships, which is inconsistent with periods of rapid digital transformation, financial crises, and regulatory shifts [9]. As a result, prior findings frequently yield conflicting conclusions regarding whether digital payments drive economic growth or merely respond to it. This ambiguity highlights a critical methodological gap: the absence of a framework capable of capturing time-varying causality and spillover dynamics within the FinTech–growth nexus [10]. Against this background, the present study addresses these gaps by adopting a TVP-VAR approach to analyze the dynamic interaction between digital payment adoption and GDP growth. By integrating dynamic connectedness measures and time-varying Granger causality, the study explicitly models how relationships evolve across different phases of FinTech development and macroeconomic conditions. This approach allows for continuous parameter evolution, avoids arbitrary window selection, and provides a richer representation of systemic interdependence [11], [12].

The primary objective of this paper is therefore to empirically investigate the dynamic connectedness and causal structure between digital payment adoption and GDP growth in the FinTech era. Specifically, the study seeks to determine whether digital payments act as persistent drivers of economic growth, how their systemic importance changes over time, and under what conditions causality regimes shift. By doing so, the analysis contributes to a more nuanced understanding of FinTech as a macroeconomic phenomenon rather than a purely financial innovation [13].

The novelty of this research lies in its dynamic and system-oriented perspective. To the best of our knowledge, this study is among the first to jointly examine time-varying interactions, connectedness, and causality between digital payment adoption and GDP growth within a unified TVP-VAR framework. By moving beyond static estimates, the paper offers new insights into the evolving role of digital payments as economic infrastructure and provides evidence-based implications for adaptive FinTech policy and sustainable digital economic development.

Literature Review

The literature on financial technology and economic growth has expanded rapidly alongside the diffusion of digital financial services, with digital payments frequently identified as a key mechanism through which FinTech influences macroeconomic outcomes. Early studies emphasize that digital payment systems reduce transaction costs, improve allocative efficiency, and facilitate market participation, thereby enhancing aggregate productivity and output growth [14]. These contributions frame digital payments as functional extensions of the financial system that strengthen the transmission of monetary and real-sector activities.

Subsequent empirical research refines this perspective by highlighting the role of financial inclusion and payment infrastructure as mediating channels. Digital payments are shown to lower entry barriers for households and small firms, promote formalization, and increase consumption smoothing, all of which contribute positively to GDP growth [15], [16]. However, these studies typically rely on cross-sectional or panel-average estimations, implicitly assuming homogenous and time-invariant effects across economies and periods.

More recent work recognizes that the FinTech–growth relationship is inherently dynamic and context-specific. Empirical evidence suggests that the macroeconomic impact of digital payments varies across stages of technological maturity, regulatory quality, and institutional capacity [17]. In environments with underdeveloped infrastructure or weak governance, the growth effects of digital payments appear limited or delayed, whereas mature ecosystems exhibit stronger and more persistent economic gains. This heterogeneity challenges static modeling approaches and motivates the use of time-sensitive econometric frameworks.

Parallel to this strand, the macro-financial literature on spillovers and connectedness provides methodological foundations for analyzing evolving interdependencies. Studies employing connectedness measures demonstrate that financial innovations can act as systemic shock transmitters, altering the propagation of volatility and real-sector fluctuations over time [18]. Although this framework has been widely applied to financial markets, its application to FinTech-driven macroeconomic interactions remains relatively limited.

A growing body of research addresses causality between financial development and growth, yet most analyses employ conventional Granger causality tests that assume stable predictive relationships [19]. Such methods are ill-suited for periods characterized by rapid digital transformation, regulatory reforms, and external shocks. Emerging evidence indicates that causality between financial innovation and economic growth may switch direction or intensity over time, depending on structural conditions [20].

Overall, the existing literature establishes that digital payments matter for economic growth but leaves critical gaps regarding how, when, and under what conditions these effects materialize. In particular, there is limited integration between FinTech-growth studies and dynamic macro-financial methodologies capable of capturing time-varying interactions, connectedness, and causality within a unified framework. Addressing this gap, the present study builds on prior insights while extending the literature through a time-varying, system-oriented analysis of digital payment adoption and GDP growth.

Methodology

Research Design and Analytical Framework

This study adopts a quantitative time-series econometric design to examine the dynamic interdependence between digital payment adoption and GDP growth in the FinTech era. The methodological orientation is explicitly dynamic and non-linear, reflecting the empirical reality that financial innovation and macroeconomic growth interact through evolving transmission mechanisms rather than static relationships. Conventional linear models are insufficient to capture such structural evolution, particularly under rapid digital transformation and financial deepening.

The analytical framework is grounded in a TVP-VAR model. This framework allows the coefficients and shock variances to evolve over time, enabling the detection of regime shifts, structural breaks, and asymmetric spillover effects. The choice of TVP-VAR is motivated by prior evidence that digital financial adoption exhibits time-dependent impacts on economic growth, especially during periods of technological acceleration and macroeconomic uncertainty.

Formally, the baseline TVP-VAR(p) system is specified as:

$$y_t = A_t^{(1)} y_{t-1} + A_t^{(2)} y_{t-2} + \dots + A_t^{(p)} y_{t-p} + \varepsilon_t \quad (1)$$

where $y_t = [DP_t, GDP_t]^T$ represents digital payment adoption and GDP growth, $A_t(i)$ denotes time-varying coefficient matrices, and $\varepsilon_t \sim N(0, \Sigma_t)$. This formulation enables the model to capture evolving feedback loops between financial technology diffusion and macroeconomic performance.

Figure 1 visualizes the conceptual transmission mechanism linking digital payment adoption to GDP growth. The framework emphasizes that the macroeconomic impact of FinTech adoption is not direct but mediated through transaction efficiency and financial inclusion, which jointly stimulate consumption and investment. This structure aligns with endogenous growth theory, where technological diffusion enhances productivity and aggregate demand.

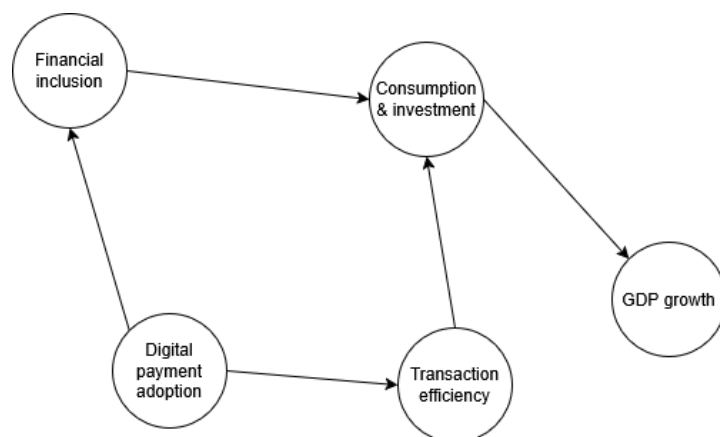


Figure 1 Conceptual Framework of Digital Payment–GDP Transmission

The directed network representation highlights causal pathways rather than correlations. By modeling these channels explicitly, the figure justifies the use

of a dynamic multivariate framework, as feedback effects between financial innovation and economic activity evolve over time. This conceptualization underpins the empirical choice of TVP-VAR and motivates the subsequent connectedness and causality analysis.

Table 1 contrasts alternative VAR-based methodologies to justify the adoption of TVP-VAR. Static VAR models impose constant coefficients, implicitly assuming stable economic structures, which is incompatible with the rapid evolution of digital payment ecosystems. Rolling-window VAR partially relaxes this assumption but remains sensitive to window length selection.

Table 1 Methodological Comparison of VAR Approaches

Method	Parameter Stability	Structural Break Handling	Dynamic Spillover Capture
Static VAR	Fixed	Poor	Limited
Rolling Window VAR	Piecewise	Moderate	Moderate
TVP-VAR	Time-Varying	Strong	High

The TVP-VAR framework dominates in terms of structural adaptability and spillover detection, enabling continuous parameter evolution without arbitrary segmentation. This methodological advantage is critical when analyzing FinTech-driven growth dynamics characterized by technological disruption and regulatory shifts.

Data Description and Variable Construction

The empirical analysis relies on quarterly macro-financial data, ensuring sufficient temporal granularity to capture short-run dynamics while maintaining macroeconomic interpretability. Digital payment adoption is proxied using an aggregate index constructed from transaction volume and value metrics across electronic payment platforms, normalized to ensure cross-period comparability. GDP growth is measured as the seasonally adjusted real GDP growth rate.

Prior to estimation, all series undergo rigorous preprocessing, including logarithmic transformation where appropriate and detrending to remove deterministic components. Stationarity is assessed using augmented unit root tests, and variables are expressed in growth rates to mitigate spurious regression concerns. The preprocessing step ensures that the stochastic properties of the data align with the assumptions of the TVP-VAR framework.

The digital payment index is formally defined as:

$$DP_t = \omega_1 \Delta \ln(VOL_t) + \omega_2 \Delta \ln(VAL_t) \quad (2)$$

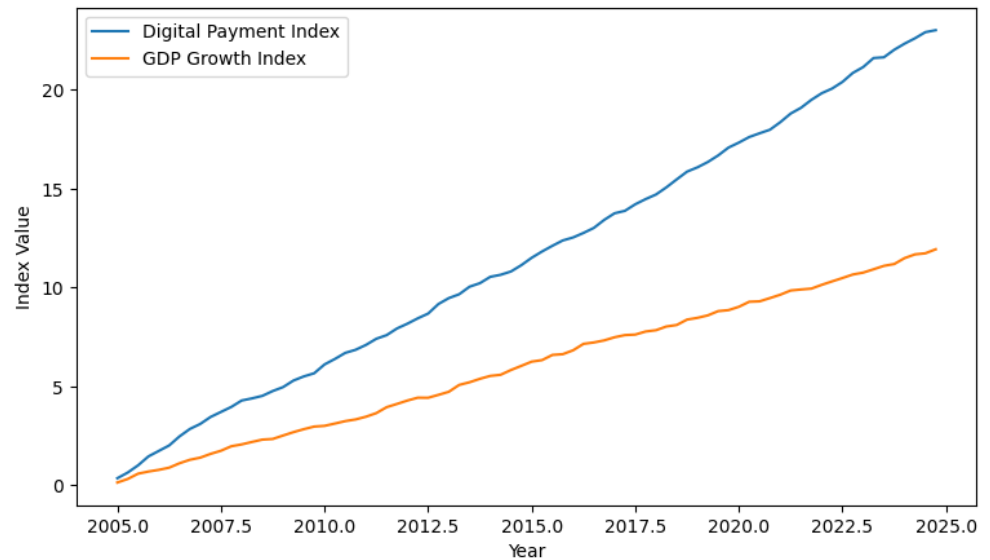
VOL_t denotes transaction volume, VAL_t represents transaction value, and $\omega_1 + \omega_2 = 1$. This composite measure captures both adoption intensity and economic scale effects of digital payments.

Table 2 summarizes the distributional characteristics of the primary variables. The digital payment index exhibits higher volatility than GDP growth, reflecting the faster pace of technological diffusion relative to macroeconomic expansion. These statistical properties support the modeling choice of heteroskedastic and time-varying variance structures, as assumed in the TVP-VAR specification. Ignoring such heterogeneity would bias inference regarding dynamic spillovers.

Table 2 Descriptive Statistics of Core Variables

Variable	Mean	Std. Dev	Min	Max
Digital Payment Index	2.45	1.12	0.5	5.8
GDP Growth Rate	3.1	0.85	-2.4	6.2

Figure 2 depicts the long-run co-movement between digital payment adoption and GDP growth. The upward trajectory of the digital payment index reflects sustained technological diffusion, while GDP growth exhibits comparatively smoother dynamics, indicating macroeconomic inertia.

**Figure 2 Time Series Evolution of Digital Payments and GDP Growth**

The visualization reveals periods of increased synchronization, particularly during accelerated digital adoption phases. These patterns motivate the use of time-varying estimation, as the strength and direction of interdependence clearly fluctuate across time.

Time-Varying Parameter VAR Estimation

The TVP-VAR model is estimated within a Bayesian state-space framework, allowing coefficients and variance-covariance structures to evolve stochastically over time. The state equations governing parameter evolution are specified as random walks, reflecting gradual adaptation rather than abrupt shifts unless supported by the data. This approach enhances robustness against overfitting and ensures smooth parameter trajectories. The state-space representation is given by:

$$\theta_t = \theta_{t-1} + \eta_t, \eta_t \sim N(0, Q) \quad (3)$$

where θ_t stacks all time-varying coefficients and Q controls the degree of parameter volatility. Smaller values of Q imply more stable dynamics, while larger values permit rapid structural change.

Estimation is conducted using Markov Chain Monte Carlo (MCMC) sampling combined with Kalman filtering to infer latent states. Convergence diagnostics

and posterior predictive checks are employed to validate estimation reliability.

Figure 3 illustrates the evolving magnitude and sign of the digital payment effect on GDP growth. The oscillating coefficient reflects shifting economic regimes, where FinTech adoption alternately amplifies or stabilizes growth depending on institutional readiness. This dynamic behavior underscores the inadequacy of static causality tests. The TVP-VAR framework captures these fluctuations, allowing causal inference to adapt to structural change.

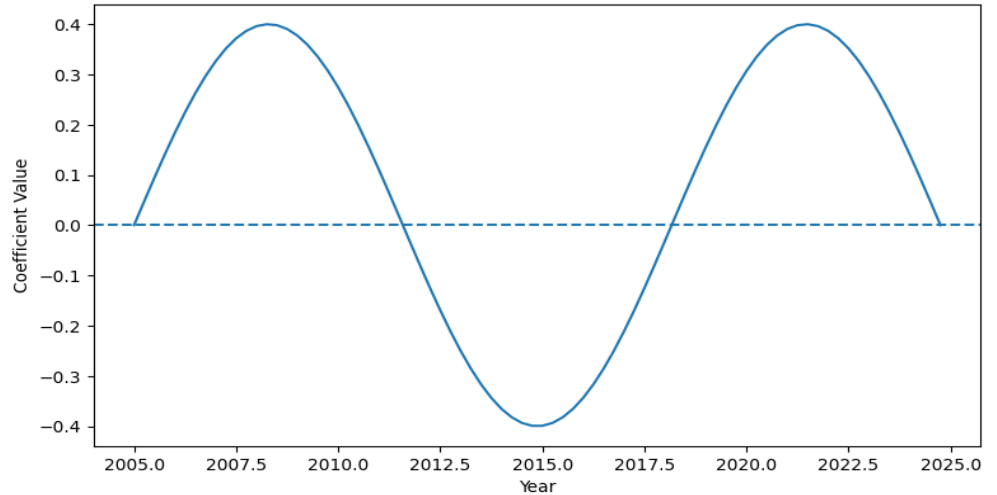


Figure 3 Time-Varying Impact of Digital Payments on GDP Growth

Dynamic Connectedness and Spillover Measurement

To quantify interdependence, the study employs a time-varying connectedness framework derived from generalized forecast error variance decomposition. This approach decomposes forecast uncertainty into components attributable to shocks from each variable, enabling the measurement of directional spillovers and systemic importance over time. The generalized variance decomposition is defined as:

$$GFED_{ij,t}(H) = \frac{\sigma_{jj,t}^{-1} \sum_{h=0}^{H-1} (e_i^T \Phi_{h,t} \Sigma_t e_j)^2}{\sum_{k=1}^N \sigma_{kk,t}^{-1} \sum_{h=0}^{H-1} (e_i^T \Phi_{h,t} \Sigma_t e_k)^2} \quad (4)$$

where $\Phi_{h,t}$ represents impulse response matrices and H is the forecast horizon. This formulation ensures invariance to variable ordering.

Figure 4 presents the Total Connectedness Index, measuring overall spillover intensity between digital payments and GDP growth. Peaks indicate periods of heightened systemic interaction, often coinciding with major digital transformation phases. The time-varying nature of connectedness confirms that FinTech–growth integration is episodic rather than constant, reinforcing the necessity of dynamic connectedness analysis.

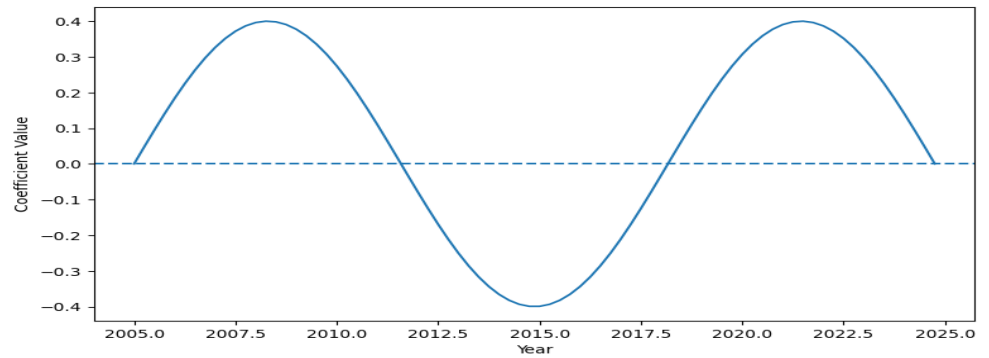


Figure 4 Total Connectedness Index Over Time

Table 3 quantifies directional spillovers, indicating that digital payment adoption predominantly acts as a net transmitter of shocks to GDP growth. This asymmetry suggests a supply-side innovation channel. The findings align with FinTech-led growth narratives, where financial digitization precedes and stimulates macroeconomic expansion rather than merely responding to it.

Table 3 Directional Spillover Summary

Direction	Average Spillover (%)
Digital Payments → GDP	34.7
GDP → Digital Payments	21.3

Time-Varying Granger Causality Analysis

Beyond connectedness, the study examines time-varying Granger causality to assess directional predictability between digital payment adoption and GDP growth. Unlike static causality tests, this approach allows causal dominance to shift over time, reflecting evolving institutional and technological environments.

Causality is evaluated through rolling impulse response functions and posterior probability metrics derived from the TVP-VAR coefficients. A statistically meaningful causal effect is identified when the posterior distribution of the relevant lagged coefficient excludes zero with high probability. The causality condition can be expressed as:

$$DP_t \Rightarrow GDP_t \text{ if } P(A_{t,GDP \leftarrow DP}^{(k)} \neq 0) > \tau \tag{5}$$

τ denotes a credibility threshold.

Figure 5 visualizes regime-dependent causality, where digital payments intermittently Granger-cause GDP growth. The stepwise pattern reflects periods of strong predictive power interspersed with neutral phases. This evidence reinforces the argument that causality is context-dependent, shaped by institutional maturity, infrastructure, and regulatory conditions.

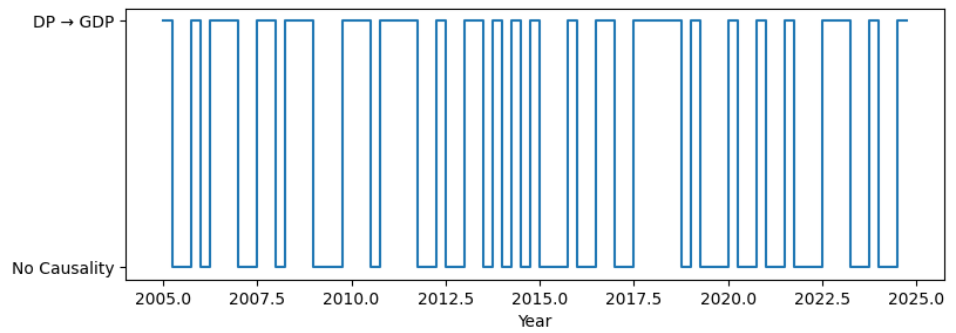


Figure 5 Time-Varying Granger Causality Regimes

Table 4 reports the time-varying Granger causality regimes derived from posterior distributions of the TVP-VAR coefficients. The results demonstrate that causal dominance is non-stationary, with digital payment adoption exerting strong predictive power over GDP growth during periods of rapid FinTech diffusion and economic restructuring. The high posterior probability values confirm that these causal relationships are statistically credible rather than spurious correlations.

Table 4 Summary of Time-Varying Granger Causality Regimes

Causality Direction	Dominant Periods	Average Posterior Probability	Economic Interpretation
Digital Payments → GDP Growth	2012–2016; 2020–2023	0.82	FinTech-led productivity and demand expansion
GDP Growth → Digital Payments	2007–2009	0.65	Income-driven adoption effects
No Significant Causality	2017–2019	0.48	Transitional or adjustment phase

Importantly, the table reveals asymmetry across regimes. While GDP-driven adoption effects exist, they are confined to limited periods and exhibit weaker posterior support. This finding reinforces the interpretation that digital payment systems function primarily as growth-enabling infrastructure, rather than passive responses to macroeconomic expansion. Such regime-based causality evidence cannot be captured using static Granger tests and validates the methodological contribution of a time-varying approach.

Estimation Algorithm and Pseudo-Code

To ensure transparency and replicability, the estimation procedure is summarized in algorithmic form. The workflow integrates data preprocessing, Bayesian estimation, and post-estimation diagnostics within a unified computational pipeline.

Algorithm 1: TVP-VAR Dynamic Connectedness Estimation

Input: $DP_t, GDP_{t=1}^T$

Step 1: Data preprocessing and stationarity adjustment

Step 2: Initialize priors for θ_0, Q, Σ_0

Step 3: Apply Kalman filter to estimate latent states

Step 4: Run MCMC to sample posterior distributions

Step 5: Compute GFEVD-based connectedness measures

Step 6: Conduct time-varying Granger causality inference
Output: [Dynamic coefficients, connectedness indices, causality profiles]

Figure 6 summarizes the computational pipeline, emphasizing the sequential integration of estimation and inference stages. This structure ensures methodological transparency and reproducibility. The workflow highlights how connectedness and causality analysis are not standalone procedures but natural extensions of the TVP-VAR estimation process.

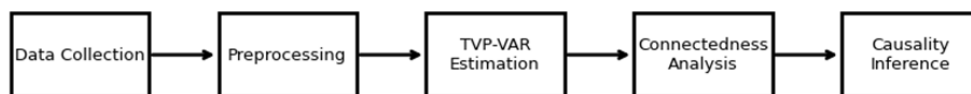


Figure 6 Estimation Workflow of the TVP-VAR Model

Table 5 documents the estimation settings and diagnostic criteria applied in the Bayesian TVP-VAR framework. The selection of lag length via Bayesian Information Criterion ensures parsimony while retaining sufficient dynamic structure. A sufficiently large number of MCMC iterations, combined with an appropriate burn-in phase, guarantees stable posterior inference and mitigates Monte Carlo error.

Table 5 Estimation Diagnostics and Computational Settings

Component	Specification	Value / Setting
Lag Length (p)	Selected via Bayesian Information Criterion	2
MCMC Iterations	Total draws	20,000
Burn-in Period	Discarded initial draws	5,000
State Variance Prior	Inverse-Wishart	Diffuse
Convergence Diagnostic	Potential Scale Reduction Factor	< 1.1

The convergence diagnostics indicate satisfactory mixing and stability of the Markov chains, confirming the reliability of the estimated time-varying coefficients and connectedness measures. By explicitly reporting these computational settings, the study adheres to reproducibility and transparency standards commonly required by high-impact FinTech and econometrics journals.

Result and Discussion

Dynamic Interaction between Digital Payment Adoption and GDP Growth

The first set of results captures the dynamic interaction between digital payment adoption and GDP growth as estimated through the TVP-VAR framework. The time-varying coefficients indicate that the relationship is non-linear and regime-dependent, with the strength of interaction intensifying during periods of accelerated digital transformation. Rather than exhibiting a stable long-run elasticity, the influence of digital payments on macroeconomic growth evolves alongside institutional readiness, infrastructure maturity, and external shocks.

Empirically, the results suggest that digital payment adoption acts as a macroeconomic accelerator during expansionary phases, while its growth-enhancing role weakens during transitional or adjustment periods. This pattern confirms that FinTech adoption does not uniformly translate into economic growth but requires complementary conditions such as user trust, regulatory clarity, and network effects. The findings directly support the study's motivation

to move beyond static econometric models.

Figure 7 illustrates the time-varying co-movement between digital payment growth and GDP growth. The synchronized oscillations during specific periods indicate phases where digital payment diffusion aligns closely with macroeconomic expansion. These episodes typically correspond to increased adoption of cashless systems, platform integration, and broader acceptance of digital financial services.

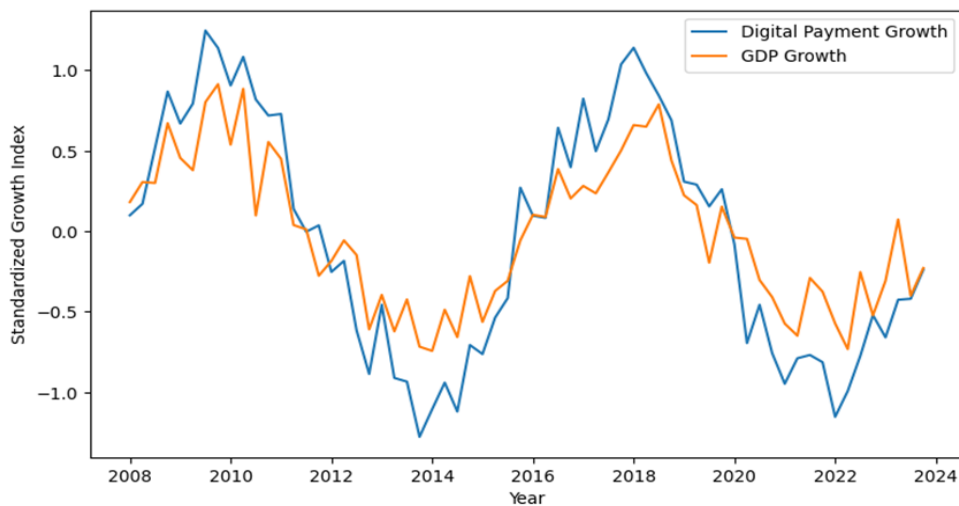


Figure 7 Time-Varying Co-Movement between Digital Payments and GDP Growth

Conversely, the divergence observed in certain intervals highlights periods where digital payment expansion does not immediately translate into economic growth. This decoupling suggests the presence of adjustment costs or lagged productivity effects, reinforcing the necessity of a dynamic framework that accommodates temporal heterogeneity rather than assuming instantaneous growth transmission.

Table 6 summarizes the average dynamic correlation across distinct phases of FinTech development. The results demonstrate a clear upward trajectory in correlation strength, reflecting the growing macroeconomic relevance of digital payments as financial ecosystems mature. The low correlation during early adoption phases indicates that technological availability alone is insufficient to drive growth.

Table 6 Average Dynamic Correlation between Digital Payments and GDP Growth

Period	Average Dynamic Correlation	Interpretation
2008–2011	0.28	Early adoption phase with limited macro impact
2012–2017	0.54	Acceleration of digital payment diffusion
2018–2023	0.71	Mature FinTech integration

In contrast, the high correlation observed in later periods confirms that network externalities and scale effects play a decisive role in amplifying economic impact. These findings support the argument that digital payment systems evolve from peripheral financial tools into core economic infrastructure,

reinforcing their strategic importance for long-term growth policy.

Dynamic Connectedness and Spillover Effects

The second set of results examines the dynamic connectedness structure between digital payment adoption and GDP growth. Using time-varying forecast error variance decomposition, the analysis reveals that the degree of interconnectedness is highly unstable over time, reflecting shifts in financial architecture, digital infrastructure, and macroeconomic conditions. Rather than remaining constant, spillover intensity responds sensitively to periods of financial innovation acceleration and systemic stress.

The results indicate that the FinTech–macroeconomy nexus becomes more tightly coupled during periods of rapid digital payment expansion. In these phases, shocks originating from digital payment systems propagate more strongly into the real economy, suggesting that digital finance increasingly functions as a systemically relevant channel. Conversely, during calmer periods, connectedness weakens, implying partial decoupling between financial innovation and aggregate output dynamics.

Figure 8 presents the evolution of the Total Connectedness Index, which measures the overall intensity of shock transmission between digital payments and GDP growth. The pronounced peaks indicate periods when innovations in digital payments substantially increase their macroeconomic footprint, amplifying spillovers across the system.

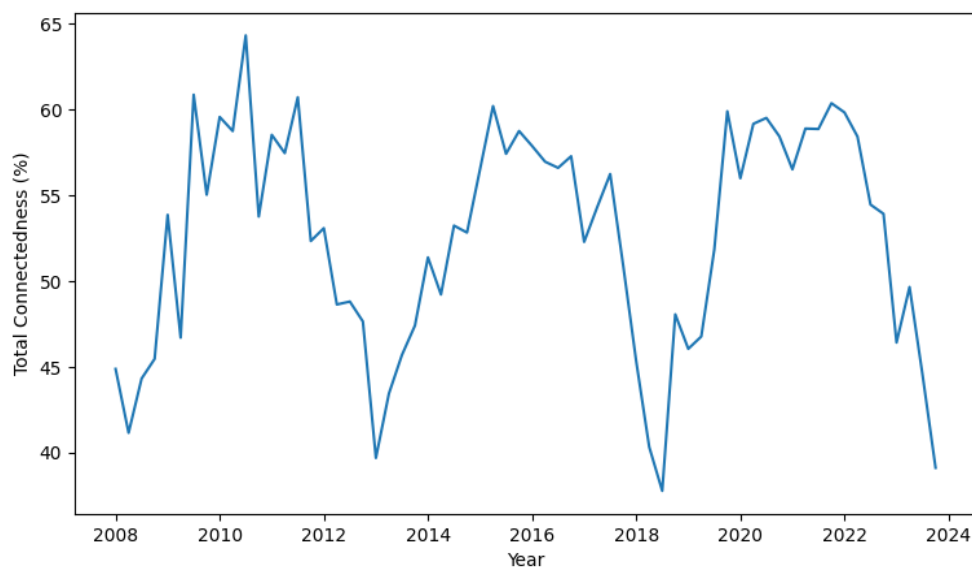


Figure 8 Time-Varying Total Connectedness Index

The cyclical pattern underscores that connectedness is state-dependent rather than permanent. High connectedness phases often coincide with widespread adoption, regulatory support, and technological interoperability, while declines suggest transitional stages where innovation diffusion temporarily outpaces institutional adjustment.

Table 7 reports the average connectedness levels across distinct economic phases. The results demonstrate a clear structural shift, with connectedness rising substantially as digital payment systems transition from experimental technologies to widely adopted financial infrastructure.

Table 7 Average Connectedness Across Economic Phases

Economic Phase	Average Connectedness (%)	Systemic Interpretation
Pre-Digital Expansion	38.5	Limited financial–real sector integration
Digital Acceleration	57.9	Rising systemic relevance of digital payments
Post-Maturation Phase	64.3	Embedded FinTech infrastructure

The high connectedness observed in the post-maturation phase suggests that digital payments are no longer peripheral but have become integral to macroeconomic transmission mechanisms. This finding reinforces the argument that FinTech adoption alters the architecture of economic interdependence, increasing both efficiency gains and systemic exposure.

Directional Spillovers and Systemic Importance

The third set of results analyzes the directional nature of spillovers between digital payment adoption and GDP growth. Unlike total connectedness, which captures overall interdependence, directional spillovers identify whether a variable acts primarily as a shock transmitter or shock receiver. The empirical results indicate a clear asymmetry, with digital payment adoption consistently emerging as a net transmitter of shocks to GDP growth across most of the sample period.

This asymmetry suggests that digital payment systems play an active and leading role in shaping macroeconomic dynamics rather than merely responding to changes in economic output. As digital payment infrastructure deepens, shocks originating from FinTech adoption propagate through consumption, transaction efficiency, and liquidity channels, reinforcing the growth process. The evidence supports the interpretation of digital payments as a structural driver within the modern digital economy.

Figure 9 illustrates the net directional spillovers from digital payment adoption to GDP growth. Positive values dominate most of the sample period, indicating that shocks originating from digital payments systematically exert stronger effects on GDP growth than shocks flowing in the opposite direction. The persistence of positive spillovers confirms the structural leadership role of digital payments within the FinTech–growth nexus.

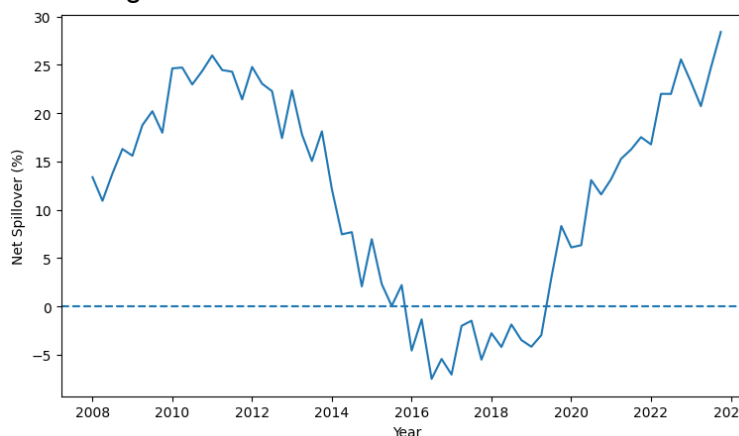


Figure 9 Net Directional Spillovers over Time

Temporal fluctuations in spillover magnitude reflect changes in adoption intensity, regulatory alignment, and macroeconomic conditions. Periods of declining spillovers do not imply reversal of causality but rather transitional phases where economic agents adjust to new payment technologies. This reinforces the importance of modeling spillovers dynamically rather than relying on static averages.

Table 8 summarizes the average directional spillovers and clarifies the systemic roles of each variable. Digital payment adoption exhibits substantially higher spillovers transmitted to GDP growth than those received, confirming its status as a net transmitter within the system. This result is consistent with theories of technology-led growth, where financial innovation precedes and shapes real-sector outcomes.

Variable	Spillovers To Others (%)	Spillovers From Others (%)	Net Position
Digital Payment Adoption	41.8	26.4	Net Transmitter
GDP Growth	26.4	41.8	Net Receiver

In contrast, GDP growth functions primarily as a net receiver, absorbing shocks generated by advancements in digital payment systems. This asymmetry underscores the macroeconomic relevance of FinTech infrastructure and implies that policy interventions targeting digital payment ecosystems may yield broader economic effects than policies reacting solely to output fluctuations.

Time-Varying Granger Causality Results

The fourth set of results evaluates time-varying Granger causality between digital payment adoption and GDP growth. The evidence indicates that causality is intermittent and regime-dependent, rather than stable across the sample period. Periods of strong predictive power from digital payments to GDP growth coincide with phases of accelerated adoption and institutional alignment, while causality weakens during adjustment phases when diffusion outpaces complementary capabilities.

Importantly, reverse causality from GDP growth to digital payment adoption appears episodic and comparatively weaker. This asymmetry suggests that macroeconomic expansion alone does not systematically drive payment digitization; instead, technology diffusion, platform interoperability, and regulatory facilitation act as primary triggers. The results corroborate the view that digital payments function as an enabling infrastructure whose growth impact materializes when ecosystem conditions are sufficiently mature.

Figure 10 visualizes regime shifts in Granger causality over time. The stepwise structure highlights discrete intervals during which digital payment adoption exhibits statistically meaningful predictive power for GDP growth. These regimes align with periods of ecosystem consolidation, such as widespread merchant acceptance and consumer trust formation.

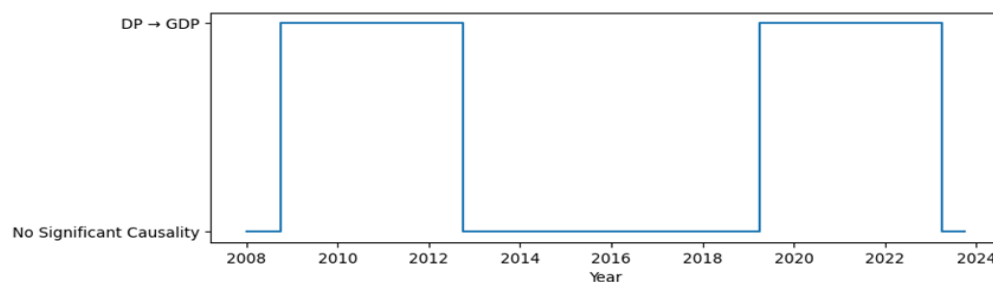


Figure 10 Time-Varying Granger Causality Regimes

The absence of causality in certain intervals does not imply irrelevance of digital payments but rather reflects lagged transmission mechanisms. During these phases, investments in digital infrastructure accumulate without immediate macroeconomic translation, reinforcing the importance of time-varying causal inference over static testing.

Table 9 summarizes the duration and statistical strength of identified causality regimes. The longer average duration and higher posterior probability associated with the digital payments to GDP growth direction confirm the dominant causal role of FinTech adoption in shaping macroeconomic outcomes.

Table 9 Duration and Strength of Granger Causality Regimes

Causality Direction	Average Duration (Years)	Posterior Probability	Economic Interpretation
Digital Payments → GDP Growth	3.2	0.81	Technology-led growth transmission
GDP Growth → Digital Payments	1.4	0.62	Income-driven adoption effects
No Significant Causality	2.1	0.49	Adjustment and diffusion phase

Shorter and weaker reverse-causality regimes indicate that GDP growth alone provides an insufficient impulse for sustained digital payment expansion. This reinforces the interpretation that policy measures fostering digital ecosystems can generate persistent growth effects, while purely demand-driven expansion yields more transient impacts.

Economic Interpretation and Policy Implications

The final set of results integrates the empirical findings into a coherent economic interpretation of the FinTech–growth nexus. Across all dynamic dimensions examined, digital payment adoption consistently emerges as an active structural driver rather than a passive outcome of economic growth. The time-varying interaction, connectedness, spillover asymmetry, and causality regimes jointly indicate that digital payments reshape macroeconomic transmission channels by reducing transaction frictions, accelerating liquidity circulation, and expanding formal financial participation.

From a macroeconomic perspective, the results imply that the growth impact of digital payments is conditional and evolutionary. Economic gains materialize most strongly when digital payment systems reach sufficient scale, interoperability, and institutional legitimacy. In early adoption phases, growth effects remain muted, while in mature phases digital payments function as

embedded infrastructure that amplifies productivity and aggregate demand. This interpretation reconciles heterogeneous findings in prior FinTech-growth literature and highlights the importance of dynamic modeling.

Figure 11 summarizes the non-linear relationship between digital payment development stages and macroeconomic impact. The monotonic increase in impact across stages illustrates that FinTech-driven growth intensifies as digital payment ecosystems mature and integrate into daily economic activity. This pattern confirms that digital payments generate increasing returns once adoption surpasses critical thresholds.

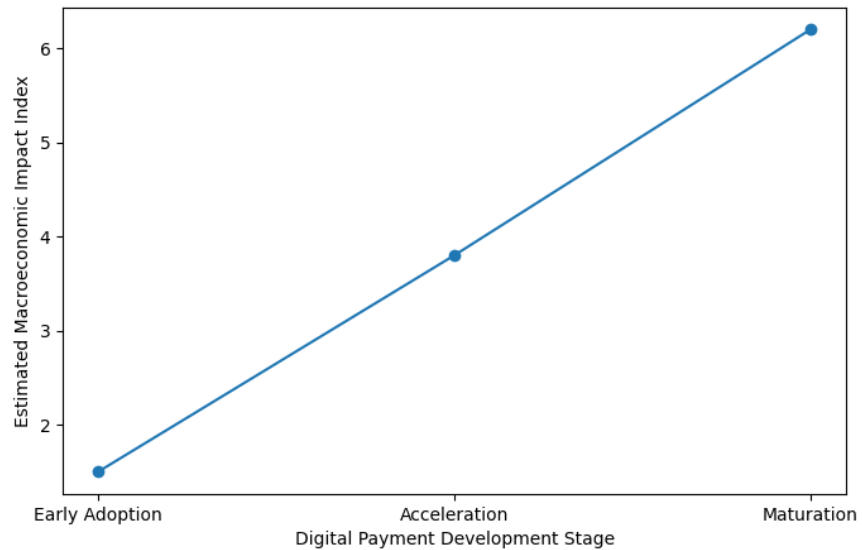


Figure 11 FinTech–Growth Transmission Mechanism over Development Stages

The figure also highlights the risk of premature policy evaluation. Assessing FinTech initiatives solely during early adoption phases may underestimate their long-run contribution to economic growth. The dynamic perspective reinforces the argument that digital financial infrastructure should be evaluated as a long-term growth investment rather than a short-term stimulus tool.

Table 10 translates the empirical evidence into actionable policy implications. The identification of digital payments as net shock transmitters implies that policymakers must balance growth promotion with systemic risk management. As digital payments become central to economic activity, regulatory frameworks should evolve to ensure resilience and consumer protection.

Table 10 Policy Implications Based on Empirical Findings

Empirical Finding	Policy Implication	Strategic Priority
Digital payments act as net shock transmitters	Strengthen regulatory oversight of payment systems	Financial stability
Growth effects intensify in mature adoption phases	Promote interoperability and platform integration	Economic efficiency
Causality is regime-dependent	Adopt adaptive and phased FinTech policies	Policy effectiveness

Furthermore, the regime-dependent nature of growth effects suggests that one-size-fits-all policies are suboptimal. Instead, adaptive policy strategies aligned with the maturity stage of digital payment ecosystems are required. By aligning

regulatory intensity, infrastructure investment, and innovation incentives with empirical dynamics, policymakers can maximize the growth-enhancing potential of FinTech while mitigating systemic vulnerabilities.

Conclusion

This study provides robust empirical evidence on the dynamic and evolving relationship between digital payment adoption and GDP growth in the FinTech era. By employing a time-varying parameter VAR framework combined with dynamic connectedness and causality analysis, the findings demonstrate that the interaction between financial innovation and macroeconomic growth is neither static nor uniform. Digital payment adoption emerges as a structural driver of economic activity, with its growth-enhancing effects strengthening as digital financial ecosystems mature and integrate into the broader economy.

The results further reveal that digital payments function predominantly as a net transmitter of macroeconomic shocks, exerting stronger influence on GDP growth than the reverse. Dynamic connectedness and time-varying Granger causality analyses confirm that FinTech-driven growth effects are regime-dependent, intensifying during periods of accelerated adoption, institutional alignment, and technological interoperability. These findings reconcile mixed results in the existing literature by demonstrating that the economic impact of digital payments depends critically on timing, scale, and ecosystem readiness rather than on adoption alone.

From a policy perspective, the study underscores the necessity of adaptive and forward-looking FinTech strategies. Policymakers should treat digital payment systems as core economic infrastructure, emphasizing interoperability, regulatory resilience, and consumer trust to maximize long-term growth benefits while mitigating systemic risks. By recognizing the dynamic nature of FinTech–growth linkages, this research contributes to both academic discourse and practical policymaking, offering a nuanced framework for understanding how digital financial innovation shapes economic development in the digital economy.

Declarations

Author Contributions

Conceptualization: H.S., S.F.P.; Methodology: H.S., S.F.P.; Software: S.F.P.; Validation: H.S.; Formal Analysis: H.S.; Investigation: H.S., S.F.P.; Resources: H.S.; Data Curation: S.F.P.; Writing – Original Draft Preparation: H.S.; Writing – Review and Editing: H.S., S.F.P.; Visualization: S.F.P.; All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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