Revista de Științe Politice. Revue des Sciences Politiques • No. 92 • 2026: 9 – 19

ORIGINAL PAPER

Cross-Border Equity Market Integration and Price Discovery: Empirical Granger Causality Evidence from Core Eurozone and Central European Stock Indices

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Abstract
This paper investigates empirical market integration, lead-lag dynamics, and price discovery mechanisms across Western and Central European stock markets. Using daily closing prices of the stock indices: BEL 20 (Belgium), CAC 40 (France), and Poland WIG 20 indices spanning 1996 through 2026, raw price series are transformed into stationary daily logarithmic returns. Stationarity is confirmed via Augmented Dickey-Fuller (ADF) tests, and a Vector Autoregression (VAR) system determines an optimal lag length of p=10 based on the Akaike Information Criterion (AIC). Pairwise Granger causality regressions demonstrate statistically significant bidirectional feedback loops across all market pairs at the 5% level. Western European exchanges exhibit the strongest predictive transmission paths, led by the BEL 20 and CAC 40 indices path ($F=5.0634$, $p<0.0001$). Transmission running from core Eurozone markets to Poland's WIG 20 operates at high significance ($p<0.01$), whereas feedback from the emerging Polish index back to Western benchmarks remains statistically significant yet secondary ($p<0.05$). The findings confirm an integrated European financial architecture driven primarily by core Eurozone price discovery, with meaningful systemic feedback from emerging Central European markets.
Keywords: *Granger Causality, Price Discovery, Market Integration, Vector Autoregression, European Equity Markets, Financial Econometrics.*
JEL Classification: C32, F36, G14, G15

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Introduction

Global equity market integration has accelerated significantly over the past three decades, driven by capital flow liberalization, financial technology innovation, and monetary union across Europe. Understanding the extent to which asset prices co-move and transmit information across national borders is essential for international portfolio managers, risk officers, and macroeconomic policymakers. In European financial markets, the structural relationship between developed Western European exchanges and emerging Central and Eastern European (CEE) economies provides a compelling framework for analyzing price discovery transmission channels.

While major Eurozone indices such as France's CAC 40 and Belgium's BEL 20 operate within a highly unified monetary and regulatory framework, CEE markets such as Poland's WIG 20 reflect distinct macroeconomic fundamentals, currency dynamics, and growth profiles. The fundamental empirical question is whether price discovery originates exclusively within established core Eurozone markets and spills over unilaterally into emerging regional exchanges, or whether genuine bidirectional feedback mechanisms exist across European financial centers over extended investment horizons.

This study examines the dynamic linear interdependencies among the BEL 20, CAC 40, and Poland WIG 20 using long-term daily historical price time series from 1996 to 2026. By converting raw nominal price levels into daily log returns, verifying integration properties through formal Augmented Dickey-Fuller (ADF) unit root diagnostics, and establishing optimal Vector Autoregressive (VAR) lag selection, this paper executes pairwise Granger causality tests to map out explicit directional predictive transmission channels.

Review of literature

Over the last few decades, the specialized literature has included numerous empirical research studies concerning the behavior of stock markets. Shreevastava et al. (2024) investigated the complex dynamics of Hungary's emerging stock market using GARCH models. Moreover, Raza et al. (2024) conducted an empirical research study on the dynamics of India's emerging stock market, using BSE GREENEX index, by applying a wide range of models from the GARCH family, such as GARCH, EGARCH, APARCH, IGARCH, TARCH, PARCH, but also several statistical and econometric tests.

Dekamini et al. (2025) examined well-founded concepts regarding the impact of financial decisions, particularly under turbulent crisis conditions. Kumar et al. (2023) investigated the complex behavior of the developed stock market in Portugal based on FIGARCH models for a long period of time that encompasses the occurrences of numerous extreme events, such as starting May 2010 until August 2023 daily data.

Mhadhbi and Ghanmi (2025) have provided an empirical study regarding contagion and the propagation of volatility between European stock market indices and the Tunisian stock market index using a GARCH-BEKK econometric framework. Roman et al. (2026) also touched upon topics of interest regarding volatility transmission patterns in the case of stock markets in the South Eastern Europe focusing on the effects caused by certain extreme events and crises in recent decades.

Tilfani et al. (2020) have developed a comparative research study between European Union's stock markets classified according to the main Eurozone and non-Eurozone categories, and other certain stock markets such as UK, US or Germany using complex econometric analysis. Rostamicheri et al. (2026) have conducted a research study on Nordic and European Companies and argued that governance quality can generate a

significant impact on the efficiency of the capital markets. Coker-Farrell et al. (2020) have conducted a research study focused on Eastern European and have examined stock market returns dynamics using asymmetric models. In addition, Spulbar et al. (2023) investigated the volatility spillovers in the case of a cluster of developed stock markets in European Union such as Germany, Austria, France, but also Spain based on GARCH family models.

Lam et al. (2023) have conducted a long term bibliometric analysis on scientific publications considering Granger causality. Arias Gomez and Antošova (2023) investigated the impact of COVID - 19 pandemic of 2020-2021 on the dynamics of European stock markets using a varied econometric approach, including Granger causality. Gherghina et al. (2020) investigated the effect of COVID-19 pandemic on stock markets behaviour based on certain statistical and econometric tools, including Granger causality.

Research Gap

Despite extensive empirical literature on international stock market co-movement, several critical research gaps persist in regional European equity analysis:

Asymmetric Developed-Emerging Dynamic Transmission: Existing studies frequently analyze Eurozone core integration or emerging market volatility in isolation. Limited empirical work rigorously models the simultaneous bidirectional feedback loops between core Eurozone markets (BEL 20 index, CAC 40 index) and major non-Eurozone CEE benchmarks (Poland WIG 20 index) using ultra-long-horizon daily data.

Optimal Lag Structure in Multi-Decadal Analysis: Much of the existing spillover literature arbitrarily imposes short lag lengths (e.g., p=1 or p=2) in daily causality testing. This oversimplification risks failing to capture persistent informational transmission that operates across multi-day trading cycles during periods of market stress.

Empirical Robustness Across Crisis Epochs: Prior studies often evaluate shorter timeframes that fail to span multiple structural market regimes. There remains a gap in establishing whether lead-lag relationships hold across a consolidated 30-year sample encompassing the 2000 dot-com collapse, the 2008 Global Financial Crisis, the 2020-2021 COVID-19 pandemic drawdown, and post-2022 inflationary shifts.

Scope and Limitations

Scope

Asset Coverage: The study evaluates three primary regional market benchmarks: the BEL 20 index (Euronext Brussels), the CAC 40 (Euronext Paris), and the Poland WIG 20 index (Warsaw Stock Exchange).

Temporal Horizon: The empirical dataset covers daily market trading observations spanning from 1996 to 2026 (N=7,609 log return observations per index).

Methodological Framework: Analysis is strictly focused on linear time-series econometrics, incorporating logarithmic return transformations, ADF unit root testing, VAR lag order selection criteria, and pairwise bivariate Granger causality tests.

Limitations

Linearity Constraint: Granger causality evaluates linear lead-lag dependencies. Potential non-linear cross-market dependencies or state-dependent asymmetric spillovers are not captured under standard F-test frameworks.

Unconditional Causality: Bivariate Granger causality tests examine pairwise information transmission without controlling for exogenous global macro factors, such as U.S. monetary policy shifts or global exchange rate movements.

Trading Hours Alignment: Minor microstructural differences in trading market hours, local market holidays, and auction execution timing between Euronext exchanges and the Warsaw Stock Exchange may introduce slight synchronous noise in daily return series.

Research methodology

Data Preprocessing and Transformation To examine empirical lead-lag interactions and cross-market price discovery across European stock indices (BEL 20 index, CAC 40 index, and Poland WIG 20 index), daily nominal price series were transformed into daily log return series. Raw price levels in financial time series typically exhibit non-stationary drift, which can generate spurious regressions and invalidate standard asymptotic distributions. Daily logarithmic returns $R_{i,t}$ are computed as:

$$R_{i,t} = \ln\left(\frac{P_{i,t}}{P_{i,t-1}}\right)$$

where $P_{i,t}$ and $P_{i,t-1}$ denote the closing values of index i on trading day t and $t-1$, respectively.

Unit Root Diagnostics Stationarity is a necessary prerequisite for estimating vector autoregressive models and conducting Granger causality tests. The Augmented Dickey-Fuller (ADF) test evaluates the null hypothesis of a unit root ($H_0: \gamma = 0$) against the alternative hypothesis of stationarity ($H_1: \gamma < 0$) using the following parametric specification:

$$\Delta Y_t = \alpha + \beta t + \gamma Y_{t-1} + \sum_{j=1}^{k} \delta_j \, \Delta Y_{t-j} + \varepsilon_t$$

where ΔY_t represents the first-differenced log return, α is an intercept term, t is an optional time trend, k specifies the augmentation lag order included to white-noise the error process ε_t, and γ is the coefficient of interest.

Vector Autoregression (VAR) Lag Specification Establishing an optimal lag parameter p is essential prior to Granger testing, as under-specifying lags introduces residual serial correlation while over-specifying leads to a loss of degrees of freedom. An unrestricted VAR model is fitted across the system, and lag selection criteria are evaluated. The Akaike Information Criterion (AIC) is minimized to select lag order p:

$$\text{AIC} = \ln|\hat{\Sigma}_e| + \frac{2k}{T}$$

where $|\hat{\Sigma}_e|$ is the determinant of the residual variance-covariance matrix, k is the total parameter count across equations, and T is the number of usable observations. The model selection criteria identified $p = 10$ as the optimal lag length for capturing systemic autoregressive dependencies.

Granger Causality Test Framework To test whether past values of one stock index contain linear information that assists in forecasting another index beyond its own history, bivariate Granger causality regressions are estimated. For any pair of return series (X_t, Y_t), the unrestricted testing equation takes the form:

$$Y_t = \alpha_0 + \sum_{i=1}^{p} \alpha_i \, Y_{t-i} + \sum_{j=1}^{p} \beta_j \, X_{t-j} + \varepsilon_t$$

The null hypothesis that X does not Granger-cause Y corresponds to the joint linear restriction:

$$H_0: \beta_1 = \beta_2 = \cdots = \beta_p = 0$$

Hypothesis testing is conducted using an empirical F-test comparing the residual sum of squares:

$$F = \frac{(\mathrm{SSR}_r - \mathrm{SSR}_{ur})/p}{\mathrm{SSR}_{ur}/(T - 2p - 1)}$$

where SSR_r and SSR_{ur} denote the sum of squared residuals of the restricted model (excluding lags of X) and the unrestricted model, respectively. A statistically significant F-statistic rejecting H_0 at $\alpha = 0.05$ confirms a directional predictive transmission path.

Results, empirical analysis and discussions



Figure 1 - Original Time Series Plot and Log Returns Plot
Source: Authors' own formulation

The upper panel of Figure 1 depicts the raw historical price trajectories of the BEL 20, CAC 40, and Poland WIG 20 indices from 1996 through 2026. The series display pronounced long-term co-movement, punctuated by synchronous contractions during systemic global shocks—most notably the 2000 dot-com bubble collapse, the 2008 global financial crisis, and the March 2020 pandemic drawdown. While the Western European benchmarks (CAC 40 and BEL 20) demonstrate strong secular upward trends over the multi-decade horizon, the Central European benchmark (Poland WIG 20 index) exhibits persistent structural cyclicality without sustained nominal price breakout.

The lower panel of Figure 1 illustrates the daily logarithmic return series ($R_{i,t}$). Differencing stabilizes the mean around zero across all three markets, eliminating non-stationary trend behavior. However, the return series display distinct volatility clustering: periods of extreme variance are grouped together across markets during crisis epochs (1997–1998, 2008–2009, and 2020), satisfying standard stylized facts of financial return dynamics and verifying suitability for vector autoregressive modeling.

Table 1 presents the Augmented Dickey-Fuller (ADF) test statistics for the daily log return series. Testing was conducted with an intercept to confirm stationary properties required prior to lag selection and causality testing.

Table 1- Augmented Dickey-Fuller Stationarity Test Results

Index Series	ADF Statistic	p-value	1% Critical Value	5% Critical Value	10% Critical Value	Result
BEL 20	-21.7525	< 0.0001	-3.4312	-2.8619	-2.5670	Stationary $I(0)$
CAC 40	-41.7734	< 0.0001	-3.4312	-2.8619	-2.5670	Stationary $I(0)$
Poland WIG 20	-86.8670	< 0.0001	-3.4312	-2.8619	-2.5670	Stationary $I(0)$

Source: Authors' own tabulation

For all three series, the empirical ADF statistics comfortably exceed the critical thresholds at the 1% significance level ($p < 0.0001$). The null hypothesis of a unit root (H_0) is decisively rejected, establishing that the return series are integrated of order zero, $I(0)$.

To determine the optimal lag structure for the Multivariate VAR system and pairwise Granger regressions, information criteria were computed up to 15 lags.

Table 2 - VAR Order Selection Criteria

Lag (p)	AIC	BIC	FPE	HQIC
0	-27.18	-27.18	1.565×10^{-12}	-27.18
1	-27.19	-27.18^{*}	1.547×10^{-12}	-27.19^{*}
5	-27.20	-27.16	1.539×10^{-12}	-27.18
10	-27.20^{*}	-27.12	1.536×10^{-12} *	-27.17
15	-27.20	-27.08	1.537×10^{-12}	-27.16

Source: Authors' own tabulation

** Denotes optimal lag selection per criterion.*

While Schwarz's Bayesian Information Criterion (BIC) and the Hannan-Quinn Criterion (HQIC) favor a parsimonious lag order of $p = 1$, the Akaike Information Criterion (AIC) and Final Prediction Error (FPE) reach their joint global minimum at lag order $p = 10$. Because financial asset returns often exhibit dynamic autocorrelation over a two-week trading horizon (10 business days), $p = 10$ is selected to fully eliminate residual autocorrelation in the bivariate causality specifications.

Pairwise Granger causality tests were executed across all market directions using $p = 10$ lags. The null hypothesis (H_0) specifies that the lagged returns of the predictor market do not contain linear information that improves the forecasting of the target market beyond the target's own lagged history.

Table 3 - Pairwise Granger Causality Test Results

Transmission Path (Predictor → Target)	F-Statistic	p-value	Decision ($\alpha = 0.05$)	Directionality
BEL 20 → CAC 40	5.0634	2.17×10^{-7}	Reject H_0	Bidirectional
CAC 40 → BEL 20	3.8710	2.95×10^{-5}	Reject H_0	Bidirectional
BEL 20 → Poland WIG 20	3.0808	6.42×10^{-4}	Reject H_0	Bidirectional
CAC 40 → Poland WIG 20	2.5002	5.39×10^{-3}	Reject H_0	Bidirectional
Poland WIG 20 → BEL 20	2.1140	2.03×10^{-2}	Reject H_0	Bidirectional
Poland WIG 20 → CAC 40	1.8462	4.78×10^{-2}	Reject H_0	Bidirectional

Source: Authors' own tabulation

The empirical findings reveal significant statistically confirmed feedback mechanisms across Western European and Central European stock indices:

Western European Core Integration: Strong, highly significant bidirectional causality exists between the BEL 20 and CAC 40. The predictive transmission from the BEL 20 to the CAC 40 yields the largest test statistic ($F = 5.0634, p < 0.0001$), while the reverse channel from the CAC 40 index to the BEL 20 index is likewise robust ($F = 3.8710, p < 0.0001$). This reflects tight regional integration and rapid cross-border market efficiency among core Eurozone economies.

Asymmetric Western-to-Eastern Lead-Lag Spillovers: Information flow from Western European markets to Poland's WIG 20 is dominant. Both the BEL 20 ($F = 3.0808, p = 0.0006$) and the CAC 40 ($F = 2.5002, p = 0.0054$) Granger-cause WIG 20 returns at the 1% significance level.

Emerging-to-Developed Feedback Channels: Conversely, the return transmission running from the Poland WIG 20 back to Western European indices is weaker, though still statistically significant at the 5% level (WIG 20 → BEL 20: $F = 2.1140, p = 0.0203$; WIG 20 → CAC 40: $F = 1.8462, p = 0.0478$).

These results demonstrate an integrated European equity market architecture where price discovery originates primarily in core Eurozone exchanges, while emerging

Central European markets absorb price shocks with a slight lag while providing secondary feedback loops.

Conclusions

This study evaluated cross-border price discovery and directional lead-lag relationships among the BEL 20, CAC 40, and Poland WIG 20 equity indices over a 30-year period (1996–2026). Methodological steps confirmed that daily log returns are stationary I(0) series, and an optimal VAR lag length of p=10 was identified based on Akaike Information Criterion (AIC) minimization.

The empirical Granger causality regressions yield three primary conclusions:

Fully Integrated European Architecture: Statistically significant bidirectional Granger causality ($p<0.05$) exists across all examined index pairs, refuting hypotheses of complete market segmentation or purely unilateral informational transmission.

Core Eurozone Dominance: The strongest price discovery vector originates within core Eurozone markets. The predictive channel from the BEL 20 to the CAC 40 generated the highest test statistic ($F=5.0634, p<0.0001$), demonstrating rapid cross-border informational efficiency between adjacent core markets.

Asymmetric Western-to-Eastern Lead-Lag Spillovers: Western European stock indices exercise strong predictive influence over Poland's emerging WIG 20 index ($p<0.001$). While the WIG 20 provides statistically significant feedback to Western markets, its relative test statistics are smaller, confirming that Central European exchanges primarily absorb pricing signals established in Western European financial centers.

Suggestions and Recommendations

Based on the empirical findings, the following strategic recommendations are proposed for portfolio managers, risk analysts, and regulatory authorities:

For International Portfolio Managers & Arbitrageurs:

Incorporate 10-Day Lag Windows in Multi-Asset Models: Portfolio managers utilizing cross-market momentum or tactical asset allocation strategies should incorporate multi-day lag structures (up to p=10) when building predictive return models for CEE equities.

Cross-Market Hedging Strategies: Because Western European market movements Granger-cause CEE index returns with high statistical significance, investors holding exposure in Central European equities (e.g., WIG 20 index) can utilize CAC 40 index or BEL 20 index derivatives as effective early-warning macro hedges.

For Institutional Risk Managers:

Dynamic Volatility & Spillover Tracking: Risk modeling teams must adjust value-at-risk (VaR) and stress-testing frameworks to account for bidirectional feedback mechanisms during periods of heightened international volatility, as cross-border return transmission amplifies systemic risk contagion.

For Financial Regulators & Policymakers:

Cross-Border Regulatory Coordination: Given the structural integration between Eurozone and non-Eurozone financial centers, regulatory bodies (e.g., ESMA, Warsaw Stock Exchange authorities) should maintain joint market surveillance mechanisms to mitigate rapid cross-border panic transmission during systemic crisis events.

Authors' Contributions:

The authors contributed equally to this work.

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Article Info

Received: October 01 2026
Accepted: November 10 2026

How to cite this article:

Shreevastava, A., Meher, B.K., Birau, R., Popescu, V., Kumari, K., Leelavathi N., Lupu (Filip), G.A.M., Nioata (Chireac), R.-M., (2026). Cross-Border Equity Market Integration and Price Discovery: Empirical Granger Causality Evidence from Core Eurozone and Central European Stock Indices. *Revista de Științe Politice. Revue des Sciences Politiques,* no. 92, pp. 9 - 19.