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MARKET ANALYSIS

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Partial cointegration and time-varying price integration in the European pig market: The case of Hungary

ABSTRACT

Market events have significantly impacted the European meat industry over the past few decades, potentially altering the underlying dynamics and interrelationships of price movements. Notably, the pig market has experienced drastic changes, primarily due to disease outbreaks and a significant increase in production costs. This study examines both cointegration (CI) and partial cointegration (PCI) between Hungary and major European pig markets from 2010 to 2023. Cointegration (CI) refers to the long-run equilibrium of prices, whereas partial cointegration (PCI) represents a less restrictive framework that allows the cointegrating relationship to be decomposed into a mean-reverting component and a stochastic random walk component. Our findings indicated time-varying price co-movement with Germany, the Netherlands, and Austria, which gradually weakened in the second half of the sample period. The price relationship between Hungary and Germany has changed significantly, with evidence of cointegration disappearing in the second half of the sample period. Standard tests for Austria similarly indicated no evidence of linear cointegration. Instead, a statistically and economically significant PCI relationship appears to have developed. These results imply that important price relationships may have diminished or that their nature has shifted. The findings indicate that price relationships in the European pig market are much more complex than previously assumed, and their time-varying nature amplifies price-related risks for market participants.

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Introduction

Over the past 20 years, pig production has undergone a significant structural transformation, driven by various global and local trends. Domestic markets have become more integrated with international markets, driven by growing information transmission, while market concentration and competition have also increased (Deconinck, 2021). Globally, the Chinese pig sector has strongly influenced the European pig sector through its demand for meat (Kim *et al.,* 2024). The emergence of African swine fever (ASF) in both China and Europe (Bellini, 2021, Jongeneel *et al.,* 2021) and the COVID-19 pandemic led to a disruption of the market (Padilla et al., 2023), further exacerbating the already significant market price volatility (Assefa *et al.,* 2017). Price developments were also disturbed by the outbreak of the Russian-Ukrainian war in 2022 in a way never experienced in the previous decade. The European pig industry has been in turmoil ever since (Lin *et al.,* 2023)>.

These tendencies were critical in the case of Hungary, which has only about 2% market share in European pigmeat production (Eurostat, 2024), resulting in a price-taker market role. The connection to Germany remains strong regarding retail price settings; however, recent research has highlighted that pricing based on benchmark markets, which has traditionally been used in Hungary, has become inefficient in recent years (Szabó *et al.,* 2023). Additionally, global events have significantly impacted the market, suggesting that stable market relationships may have shifted. As a result of recent events and the underlying structural issues in the industry, the Hungarian pig sector is facing multiple challenges. Time-varying changes have been particularly pronounced in the past, which warrants further price investigation. Short-term market disruptions are often balanced by longer-term stability, but price relationships may not remain stable over time, especially when examining long periods. To investigate price developments in the European pig market, we analysed the co-movements between the Hungarian weekly average pig price and prices of benchmark Member States. We used a linear cointegration and a partial cointegration method to decompose the co-movement into a mean-reverting and a random walk component. As a result, the residual series reflects both transient and permanent shocks. The concept of partial cointegration offers valuable insights into price relationships, providing a more flexible framework than linear cointegration methods. The method was used by Vollmer *et al.* (2020) to test wheat prices. Previous research has also suggested that using alternative co-movement metrics in pig price-related analysis would be beneficial (Fousekis and Grigoriadis, 2019).

We consider these models for two main reasons: first, in a highly turbulent international market that has been evident in recent years, market stakeholders are more likely to base their strategic decisions on the local market, especially when international connections are temporarily disrupted or uncertain. In such situations, partial cointegration can provide valuable insights by accounting for permanent shocks in long-term relationships. This may indirectly indicate a temporary disruption in long-term stable relationships. Second, to the best of our knowledge, this is the first application of the partial cointegration method to pig prices, potentially offering a novel insight into the price development process.

These findings may help policymakers and professionals better understand the relationships between prices. First, we discuss the market developments between 2010 and 2024. Then, the method and data are described. Finally, we offer policy recommendations based on the cointegration results.

Market developments after 2010

Globally, China was the leading pigmeat producer in 2023, with more than 56 million tonnes, or approximately 46% of global production. The European Union ranked second with more than 22 million tonnes (18%), ahead of the US (10%), Brazil (4%), and the Russian Federation (4%). Pigmeat production was highly concentrated, with seven countries accounting for 87% of total global output (European Commission, 2024). In the EU, Spain had a 23% share of the total production volume by product weight, while Germany and France contributed 20% and 10%, respectively. In fact, just seven Member States accounted for 82% of the total EU production (European Commission, 2024). A notable shift in market power has been observed in Europe since 2010. Germany had long been the leading producer of pig meat, but in 2015 Spain surpassed Germany in herd size and has maintained its leading position since. Over the past few decades, the pig sector has been characterised by high demand, particularly in developing countries, as well as high input costs, notably in the cases of feed, energy, and labour. Additionally, intense competition with poultry meat is now evident (Szűcs and Vida, 2017).

The EU pork meat markets exhibited increasing integration and complexity, with price co-movements strongly linked to the physical proximity of markets. The largest producing Member States exert greater influence on overall price formation (Fousekis and Grigoriadis, 2019). Although pig markets in the EU are geographically separated, the law of one price (LOP) is expected to hold, given the high level of market integration. However, these price relationships are often characterised by nonlinearity, as indicated by various empirical studies (Emmanouilides and Fousekis, 2012). While price convergence has been observed across European pig markets (Tluczak, 2022), prices also display marked seasonal and cyclical fluctuations, as well as significant spatial variation (Utnik-Banaś *et al.,* 2022). Drastic price fluctuations have occurred in response to major shocks such as COVID-19 (Bellini, 2021) or the ASF epidemic (Niemi, 2020).

The ASF epidemic in China, which led to significant destruction in 2018, fundamentally reorganised the global pork market and disrupted international trade (Zhou *et al.,* 2023). The resulting price increases were substantial, and unbalanced demand has also increased the price of other meat products (Mason-D'Croz *et al.,* 2020). Similar developments unfolded in the European market. Supply chain disruptions, ASF outbreaks, China's rapid recovery in pig production, regulatory pressure, high production costs, environmental concerns, and labour force issues related to generational change have significantly impacted the sector's development (Mateos *et al.,* 2024). Moreover, the intensive production systems in the EU are expected to face further societal criticism (European Commission, 2023), as climate change is an increasingly pressing issue (Renaudeau and Dourmad, 2022). The declining export opportunities and stringent environmental laws are likely to result in reduced production, while consumption is also expected to decline due to dietary changes and concerns about environmental and societal impacts (European Commission, 2023).

The pig market in Hungary

In 2023, pig meat production in slaughterhouses reached 420 thousand tonnes in Hungary (~2% of total EU production), an almost 25% increase compared to a decade before. Nevertheless, Hungary's production remains considerably lower than that of several Western European countries, including Spain (4.87 million tonnes), Germany (4.20 million tonnes), France (2.06 million tonnes), and Poland (1.76 million tonnes) (Eurostat, 2024). The Hungarian pig sector has been characterised by a competitive disadvantage in pork meat production (Tluczak, 2019). Concentration processes have been particularly pronounced, leading to significant clustering effects (Csonka *et al.,* 2021, Csonka and Fertő, 2020). However, becoming more competitive internationally has remained challenging largely due to productivity issues over the past decade (Baráth *et al.,* 2021).

Industry stakeholders have often cited Danish and German pig farming as benchmarks for good practice (Udovecz *et al.,* 2017). However, Hungary has been slow to adopt the advanced breeding and production practices that characterise leading European producers, and the sector continues to operate at a relatively low level of organisation (Pércsi and Nagy, 2017). This has resulted in a low number of modern, European-standard pork production farms (Szűcs *et al.,* 2020). These structural challenges were further exacerbated by sector-specific shocks, most notably the spread of ASF in wild boar, first detected in 2018 (USDA, 2020), which caused severe market disruptions. The considerable economic and social disturbances that occurred after 2018 highlighted the sector's vulnerabilities, which were evident in volatile price developments.

In Hungary, pricing of the processors is almost exclusively based on a pre-fixed price or price formulas based on the wholesale prices of valuable meat parts. Conversely, producer price is usually determined based on the largest pig producer in European countries. In recent years, local variations have had a more substantial impact on Hungarian prices, despite international price movements – most notably those in Germany – being an important factor in the general contractual price formation among Hungarian stakeholders (Szabó *et al.,* 2023). These tendencies underscore Hungary's high exposure to external market shocks, which are likely to be transmitted directly into domestic price developments. Our analysis reveals that the long-run price equilibria between the Hungarian and key European pig markets have a time-varying nature. Major market events have shaped these dynamics, highlighting the structural complexity and evolving nature of this sector.

Methodology

Linear ("Johansen-type") and partial cointegration methods were used in this study to estimate the relationship between Hungarian and European pig prices. Cointegration allows two or more non-stationary time series to have a stationary linear combination (Engle and Granger, 1987; Johansen, 1988; Johansen, 1995; Hamilton, 1994), thereby forming a long-run equilibrium. Therefore, it provides valuable information about the long-run co-movement of prices. Partial cointegration is less restrictive than regular cointegration, and allows for the residual series to be decomposed as a partial autoregressive (PAR) process (Clegg and Krauss, 2018). This implies that shocks are allowed to have a permanent component. PAR and PCI were developed by Clegg (2015) and Clegg and Krauss (2018), although similar models were considered earlier in the literature by others. The PAR model has the following form (1):

$$X_t = M_t + R_t \quad (1)$$

The series X_t is a sum of a transient mean-reverting component M_t and a permanent random walk component R_t. In addition, M_t and R_t have the usual autoregressive (2 and 4) and random walk form (3 and 5):

$$M_t = \rho M_{t-1} + \varepsilon_{M,t} \quad (2)$$

$$R_t = R_{t-1} + \varepsilon_{R,t} \quad (3)$$

$$\varepsilon_{M,t} \sim NID(0, \sigma_M^2) \quad (4)$$

$$\varepsilon_{R,t} \sim NID(0, \sigma_R^2) \quad (5)$$

The mean reversion coefficient is denoted by $\rho \in (-1,+1)$. In addition, the proportion of variance attributable to mean reversion, R_{MR}^2, is calculated as follows (6):

$$R_{MR}^2 = \frac{Var[(1-B)M_t]}{Var[(1-B)R_t]} = \frac{2\sigma_M^2}{2\sigma_M^2 + (1+\rho)\sigma_R^2} \quad (6)$$

The operator B is the lag operator. The value R_{MR}^2 is always between zero and one, where zero means that X_t is a pure random walk, and one means that X_t is pure AR(1) without a random walk component. The parameters can be estimated using maximum likelihood methods (Clegg, 2015). In the case of PCI, the model is assumed to follow the following process (7):

$$R_{MR}^2 = \frac{Var[(1-B)M_t]}{Var[(1-B)R_t]} = \frac{2\sigma_M^2}{2\sigma_M^2 + (1+\rho)\sigma_R^2} \quad (7)$$

Where $p_{HUN,t}$ is the Hungarian price series and $p_{i,t}$ is the price series of other Member States, where $i = GER, NLD, ESP, DNK, POL, AUT$. An alternative two-step likelihood ratio test (LRT) can be used to test the two PCI scenarios since the random walk component is not stationary. The residual series could be a pure random walk (H_0^R) or a pure mean-reverting AR(1) process (H_0^M), which are assumed to be the two null hypotheses. The testing procedure is the following:

1. (H_0^R): The null hypothesis is tested to determine if the residual series is a pure random walk process. If this null hypothesis is rejected, the residual series may represent an AR process (indicating linear cointegration) or a PAR process (indicating partial cointegration).
2. (H_0^M): In the second step, we test the null hypothesis that the residual series follows a pure AR(1) process.

The null hypothesis of no PCI is rejected only if (H_0^R) and (H_0^M) are rejected individually. In the partialCI package, the union of these hypotheses is also tested, referred to as the joint or combined p-value (Clegg and Krauss, 2018). Our decisions are based on these joint tests. Simulated critical values were provided by Clegg (2015) since the test statistics follow a non-standard distribution. First, we tested for the presence of cointegrating relationships using the commonly employed multivariate Johansen-type cointegration test (Johansen, 1988, Johansen and Juselius, 1990, Johansen, 2000), and then analysed the PCI results in a static and a 200-week rolling-window framework.

The choice of the time window involves an inherent trade-off between noise and signal. Longer windows tend to yield smoother, more direct approximations of time-varying regimes. In contrast, shorter windows are more responsive to short-term fluctuations and thus more susceptible to noise. Although this noise-signal trade-off can make the choice of time window seem somewhat arbitrary, we conducted robustness checks (not detailed here) using different window lengths. Our findings indicate that the primary results remain unaffected and robust to alternative window lengths.

Data

The data consisted of log-transformed weekly pig producer prices for Hungary, Germany, the Netherlands, Spain, Denmark, Poland, and Austria, denominated in Hungarian Forints (HUF) from Week 1 of 2010 to Week 10 of

2023 (AKI-PÁIR, 2024). General data handling was performed in the *Tidyverse* (Wickham *et al.,* 2019). For the price series of Spain and Poland, significant seasonality was found by the combined method of Ollech and Webel (2019) in the *'seastests'* package in R (Ollech, 2021). The seasonal component was removed from the price series (if it were present) since it can affect the results of the cointegration analysis, and the methods currently used are not designed to handle deterministic seasonal structures. The series was decomposed using an automatic Seasonal-Trend decomposition procedure based on Robust Regression decomposition (STR), which allows for very flexible seasonal components over time (Hyndman *et al.,* 2018, Hyndman and Khandakar, 2008). We selected this method because it is highly flexible and robust for various data specifications. In addition, additive outliers were identified and removed using the method developed by Chen and Liu (1993) with the package *'tsoutliers'*. Additive outliers represent transitory shocks that occur at a specific point in time and, as such, do not have a permanent effect on the price series (López-de-Lacalle, 2024). Removing additive outliers improves efficiency without altering the stochastic structure of the price series. We did not consider level shifts or trend changes, as time-varying models can account for changes in parameters over time. The eliminated additive outliers occurred at different times depending on the country; however, there seems to be a higher frequency during the years 2020-2022. These years were marked by significant economic changes, resulting in considerable weekly price fluctuations (see Appendix Figure 1). The presence of only a moderate number of outlier values and the limited impact of seasonal components have resulted in adjusted and unadjusted results that are nearly identical. Both methods aimed to remove potentially distortive effects and non-informative patterns, such as seasonality, thereby further emphasising the existing relationships and trends in prices.

Hungarian prices closely followed international trends, which have varied widely over the past few decades, and Hungarian pig prices were among the highest in nominal terms between 2014 and 2021. The drastic price movements caused considerable uncertainty in the market, especially after 2014 and 2020 (Figure 1). Descriptive statistics show that the data have fatter tails compared to the normal distribution, as indicated by the kurtosis. This suggests a higher frequency of price drops and spikes (Appendix Table 1).

Figure 1: The weekly average pig price in Hungary and in other EU Member States (HUF/kg, carcass weight).
Source: Authors' calculations

Table 1: The results of the ADF test.

	HUN	GER	NLD	ESP	DNK	POL	AUT	CV
Level series								
test statistics	0.907	0.995	0.799	1.158	1.074	1.026	0.991	−1.95
Return series								
test statistics	−14.334*	−14.560*	−15.924*	−8.784*	−15.878*	−15.199*	−14.510*	−1.95

Note: * Indicates significance at the 0.05 level. CV = critical value at the 0.05 level of significance.
Source: Authors' calculations

The price movements were strongly correlated, implying that similar underlying factors were driving them. This is unsurprising, as major industry stakeholders must respond to international price developments. The return series exhibited a slightly positive mean, indicating a greater share of upward price movements, particularly toward the end of the sample period (Appendix Table 1). In the next step, the presence of a unit root was tested using the Augmented Dickey-Fuller (ADF) test (Dickey and Fuller, 1981; Dickey and Fuller, 1979). The testing procedure began with the most general specification (not presented here), which included both a deterministic trend and a constant in the artificial regression of the Augmented Dickey–Fuller test. However, based on the joint F-test, the trend and drift terms were excluded from the model. As expected, the level series were non-stationary, whereas the return series were stationary (Table 1).

In the following section, we applied the Johansen cointegration test and the partial cointegration (PCI) method to evaluate the long-run relationships between the price series. Throughout the analysis, we set a significance level of 0.05. However, we did not consider this value as a strict threshold, given that neither the statistical estimates nor the resulting p-values are ever exact. Consequently, we interpreted statistical estimates that were near this threshold with caution, indicating that there was no evidence to reject the null hypothesis.

Results

According to Table 2, the null hypothesis of $r = 0$ (indicating no cointegration) was tested at the 0.05 significance level. The Johansen method indicates the existence of cointegration between the Hungarian price series and those of the other Member States. Such long-run co-movement is expected, as similar market fundamentals influence these prices. Moreover, trade linkages between Member States can further reinforce these relationships. The static estimates, however, do not reveal the evolving nature of price relationships; therefore, we performed a rolling window analysis to provide deeper insights into their dynamics.

The cointegration relationships were calculated as running test statistics with a window of 200 weeks (Figure 2).

Table 2: The Johansen cointegration between Hungary and other Member States.

	GER	NLD	ESP	DNK	POL	AUT
Lag	2	2	3	3	4	2
Trace statistics r = 0	50.300*	38.214*	20.265*	20.841*	48.511*	22.241*
CV	19.960	19.960	19.960	19.960	19.960	19.960
Trace statistics r <= 1	3.946	4.734	2.542	4.881	3.345	5.297
CV	9.240	9.240	9.240	9.240	9.240	9.240
Eigenvalues (λ)	0.066	0.048	0.026	0.023	0.064	0.024

Note: * Indicates significance at the 0.05 level. CV = critical value at the 0.05 level of significance.
Source: Authors' calculations

The rolling-window results should be interpreted with a focus on the broader dynamic pattern over time, rather than on the specific statistical estimates obtained in individual windows. According to the running Trace test statistics, rejecting the null hypothesis of zero cointegration vector (*r=0*) was considerably time-dependent. This implied that the pairwise systems were cointegrating in most cases, although in a substantially time-varying manner. Other studies also support the convergence hypothesis, which suggests that long-run price co-movements are expected on the market; however, they also emphasise that not all national market prices co-move (Tluczak, 2022, Fousekis and Grigoriadis, 2019). Interestingly, Hungarian pig prices moved in tandem with German prices in the long run for most of the time windows, but this relationship was gradually disrupted in the second half of the sample. Remarkably similar tendencies could be observed in the case of the Netherlands. Both cointegrating relationships were also interrupted around the same time. There was no long-run co-movement with Spain in most cases, and similarly, the relationship was cyclical with Denmark. The Hungarian and Polish pig prices began to co-move in the second half of the sample, despite no significant relationship prior to that. The opposite was essentially the case with Austria. Long-term co-movements gradually diminished over time, and towards the end of the sample, the co-movement of prices effectively disappeared (Figure 2).

For partial cointegration, we first analysed the entire sample. The cointegration relationship can be decomposed

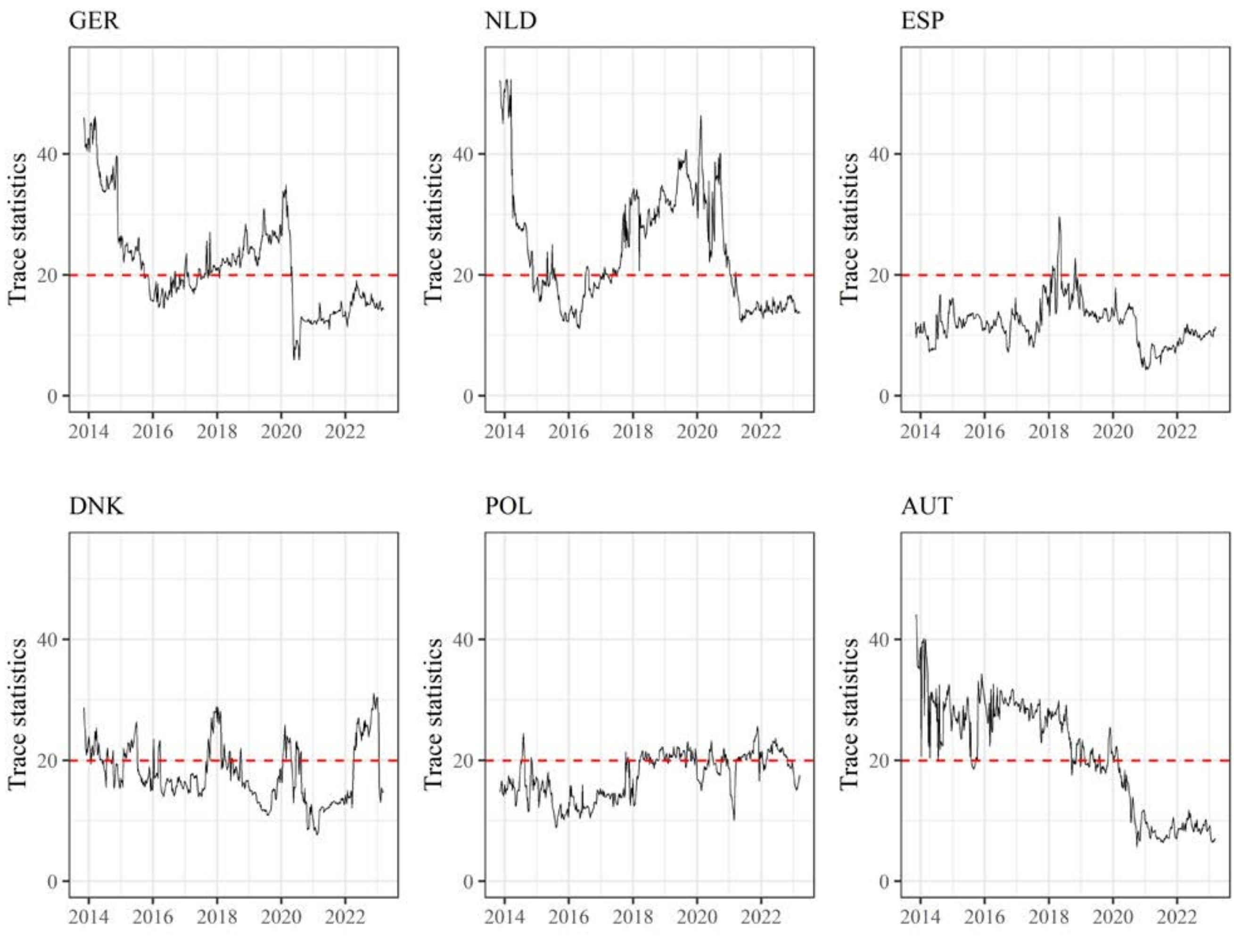

Figure 2: The running Johansen cointegration between Hungary and the other Member States.

Note: Window = 200 weeks. The dark grey line illustrates the trace statistics from the Johansen cointegration test over a specified time window. Each point corresponds to a distinct 200-week time frame; therefore, when evaluating a given test statistic, it is important to note that it refers to the preceding 200-week period. The dashed red line for the trace statistics indicates significance at the 0.05 level.
Source: Authors' calculations

Table 3: Pairwise partial cointegration between Hungary and the other Member States (2010 – 2023).

	GER	NLD	ESP	DNK	POL	AUT
RW statistics	−13.587	−2.836	−1.755	−1.905	−3.010	−5.881
RW p-value	0.010*	0.077	0.189	0.158	0.064	0.010*
AR(1) statistics	−3.049	−1.978	−1.472	−0.201	−1.812	−0.705
AR(1) p-value	0.010*	0.010*	0.010*	0.035*	0.010*	0.020*
Joint p-value	0.010*	0.040*	0.140	0.120	0.030*	0.030*
PCI	YES	YES	NO	NO	YES	YES

Note: *significant at the 0.05 level of significance. RW = Random Walk, AR(1) = first-order autoregressive process.
Source: Authors' calculations

into two components in this case; therefore, we assumed that the change in the relationship can be attributed to a shift in the ratio of these two components. The null hypothesis of no PCI is rejected only if both the RW p-value and the AR(1) p-value indicate rejection (and accordingly if the joint p-value is significant). These results showed partial CI with Germany (p = 0.01), the Netherlands (p = 0.04), Poland (p = 0.03), and Austria (p = 0.03). In some cases, the RW p-value was rejected only at the 0.10 significance level, but the joint p-value was significant at the 0.05 level in all cases. However, no significant relationship was detected with Spain and Denmark (Table 3).

The PCI model was fitted in the next step (Table 4). The parameter β was positive in all cases, indicating a positive relationship between the individual price series. The Hungarian industry stakeholders' pricing method often considers the weighted averages of benchmark international prices, which supports the presence of common trends. The ρ parameter is the AR(1) model parameter associated with the lagged values. It was reasonably close to one, indicating a strong mean-reverting behaviour of the residuals (would indicate pure mean-reverting behaviour, and in this case, the RW component would be zero). The proportion of variance attributable to mean reversion was relatively high (>90%), implying a strong mean-reverting behaviour of the cointegration residuals (Table 4). This implies that even if there is a random walk component, it is relatively moderate over the entire sample. These results indicate linear cointegration rather than a PCI relationship, as the RW component is negligible.

Cointegration intuitively suggests that two (or more) prices move together over the long run and do not drift too far apart. Additionally, any deviations from their long-term trend are gradually corrected over time. In the case of PCI, this self-correction includes a random-walk component that can have a more persistent effect on the price difference. Depending on the relative influence of the random walk and the mean-reverting component, prices may seem unrelated to market participants.

The full sample results may show periods with varying characteristics in a balanced manner. These parameters can be viewed as averages across various sub-periods, which exhibit different characteristics over time. Therefore, it is worth

Table 4: Pairwise partial cointegration between Hungary and other Member States.

	GER	NLD	POL	AUT
β	0.832	0.652	0.681	0.820
s.e.	0.029	0.025	0.031	0.051
ρ	0.822	0.963	0.969	0.957
s.e.	0.043	0.018	0.012	0.022
σ_M	0.015	0.015	0.017	0.015
s.e.	0.001	0.001	0.001	0.000
σ_R	0.004	0.005	0.003	0.001
s.e.	0.002	0.003	0.002	0.002
-LL	−1,888.440	−1,868.730	−1,806.730	−1,919.450
R^2_{MR}	0.932	0.928	0.967	0.991

Note: The parameter β is from the cointegration regression. The estimated ρ denotes the AR(1) parameter, while sigma denotes the error variances for the M and R processes, respectively. The *–LL* denotes the negative log likelihood. s.e. = standard error. R^2_{MR} denotes the proportion of variance attributable to mean reversion.
Source: Authors' calculations

examining a modelling approach that allows parameters to change over time. A rolling-window analysis could provide better insights into price developments, potentially allowing for changing parameters in different sub-periods.

The rolling-window PCI analysis

Although the random walk component was generally not economically significant over the entire sample – except in the case of Germany – there is a strong indication that the partial cointegration (PCI) relationship exhibits substantial time variation. To explore this, a rolling-window analysis with a consistent window size of 200 weeks was conducted, which offers a markedly different perspective on the dynamics. Figure 3 presents these estimates, displaying the proportion of variance attributable to mean reversion, with colour coding indicating the significance of the joint test (periods where ≤ 0.05 are highlighted in red). The following conclusions can be drawn:

- **Germany:** PCI was detected throughout the sample period; however, the value of steadily declined toward the end of the sample. Notably, the Johansen-type cointegration also vanished during the time window of 2016-2020 onwards, suggesting a marked structural change in price relationships. The PCI relationship remained statistically significant, but only with a moderate random walk component. The findings indicate that the long-term price co-movement with the German market has significantly weakened.
- **Netherlands:** The model results were mainly insignificant throughout the sample, with only a few notable exceptions. These findings, along with the Johansen-type cointegration results, point to a cyclical price relationship between the two countries rather than a persistent long-run equilibrium.

- **Spain:** Neither the Johansen cointegration method nor the PCI model provided evidence of long-run co-movement between the prices of Hungary and Spain.
- **Denmark:** Traditionally a strong competitor in the pork market, and its production methods are frequently cited as good practices for Hungary. The relationship between the prices, however, exhibits a cyclical pattern, while the PCI component was not significant except during a few brief intervals.
- **Poland:** The rolling-window PCI estimates were insignificant in every time window. Although this contradicts the full-sample results, the discrepancy is likely due to the shorter sample size of the rolling-window method compared to the static estimations. This interpretation is consistent with the fact that the full-sample PCI results also did not indicate practically meaningful cointegration.
- **Austria:** The relationship with the Austrian market is noteworthy, as the results indicate that the PCI component played a substantial role, with the gradually declining toward the end of the sample and stabilising around 0.6. These results imply a growing random walk component. These findings suggest that the long-term co-movement between the prices of the two countries persisted, and a PCI relationship emerged. *Figure 4* illustrates that the full-sample estimates effectively balance the second half of the sample, which exhibited a noticeable PCI component, with the first half, in which PCI was largely absent.

These findings also help explain the full-sample results, where the share of the random walk component appeared extremely small. Long-term co-movement between the prices has an explicit time-varying nature. Additionally, there may be situations where linear cointegration and the PCI provide the same interpretation. However, PCI can be detected even without the presence of linear cointegration.

It is worth noting that the PCI model results do not differ substantially from those obtained with Johansen cointegration when considering the full sample. In contrast, divergence becomes apparent in the analyses of subsamples. Over the full sample, static estimates tend to average time-varying dynamics across periods, potentially masking potential regime changes. This pattern is also evident in the full-

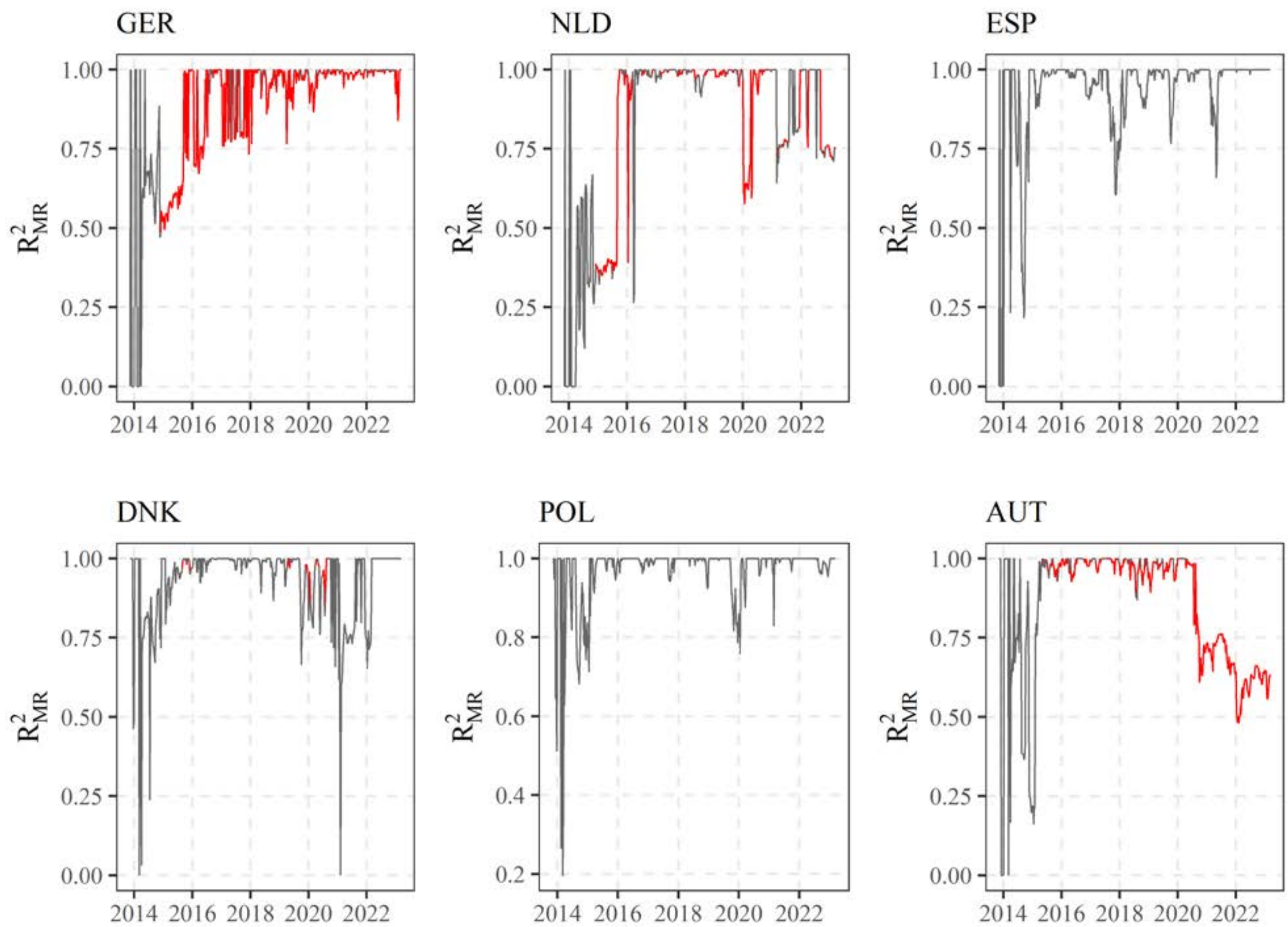

Figure 3: The rolling PCI analysis between Hungary and the other Member States (red = significance at the 0.05 level)

Note: R^2_{MR} denotes the proportion of variance attributable to mean reversion. The grey line represents the R^2_{MR} value for the specified time window. A value of zero indicates a random walk process, suggesting no cointegration. A value of one indicates pure autoregression, suggesting linear cointegration. Window size = 200 weeks. Each test statistic reflects the value estimated for the preceding 200-week period. Red indicates significance at the 0.05 level.
Source: Authors' calculations

sample results of both the PCI and Johansen models, whereas significantly different results can be observed in the specific time windows.

Discussion

The results shed light on two key insights that may influence the strategic position of market stakeholders. First, price relationships showed a strong time-varying tendency. Market risk has not been constant, and the market relationships could be more complex than previously thought. Second, the underlying price relations seem to have changed substantially during the second half of the sample period. Traditional cointegration analysis suggests that these relationships have ceased, but the less restrictive PCI model detected significant co-movements with a random walk component.

Focusing on the main price relationships, the long-standing integration with Germany – traditionally considered a benchmark for Hungary – has gradually weakened. No clear relationships were observed with the Netherlands and Denmark, two Member States often cited as models of good practice for Hungary. In contrast, while there is no linear cointegration with Austria, an emerging partial cointegration relationship suggests a structural shift in market dynamics. The PCI results may reflect evolving stakeholder behaviour, including a more substantial influence of local conditions on price formation and changing business practices. However, the precise drivers of these structural changes remain open to further investigation.

The observed results may be attributed to several interrelated factors. From an econometric perspective, particularly when focusing on the emergence of PCI and the gradual weakening of long-run co-movement, these changes can be linked to structural shocks (Fousekis and Grigoriadis, 2019). In recent years, global shocks – such as outbreaks of animal diseases, extreme weather events, the COVID-19 pandemic, and the Russia–Ukraine conflict – have jointly generated unprecedented disruptions in EU food supply chains and food prices (Matthews, 2023, Nugroho and Masyhuri, 2024).

One key factor behind the observed shift and the weakening of the benchmark role was the export restriction imposed following the outbreak of ASF, which particularly affected Germany's exports to China and third-country markets (Jongeneel *et al.,* 2021). The substantial decline in exports led to excess supply, distorting price formation and thereby reducing Germany's role as an international reference market. At the same time, the continuously strengthening position of the Spanish pig sector contributed to a rebalancing of market power within the EU (Mateos *et al.,* 2024).

From a price transmission perspective, increasing concentration, changing procurement patterns, and processor pricing in the processing sector also help explain our findings. Deconinck (2021) notes that, compared to earlier market conditions, slaughterhouses and integrators now hold significantly stronger bargaining positions. This development is further reinforced by a "domino effect," whereby higher upstream (producer-level) costs are transmitted to processing and retail prices only with a time lag (Matthews, 2023). The growing prevalence of fixed-price contracts and pricing strategies based on revised corporate considerations – rather than spot-market mechanisms – has weakened benchmark-based price-following. Moreover, Emmanouilides and Fousekis (2012) demonstrate the presence of nonlinear price adjustment in EU pork markets, which helps explain why prices do not respond uniformly to all market shocks.

Baráth *et al.* (2021) identify similar patterns at the regional level. They argue that one of the main drivers of Central and Eastern European restructuring has been the improved competitiveness of the Polish pig sector, which has altered the traditional west–east price leadership pattern, shifting it towards the East-Central European region. Tluczak (2022) also documents this trend, and it explains the strengthening co-movement between the Polish and Hungarian markets observed in the current study. In addition, Holst and von Cramon-Taubdel (2014) emphasise that regional interdependence reinforces price transmission between Austria and Hungary, which is likewise identified in our analysis.

Regarding the Hungarian market, previous research confirms a decline in German dominance (Szabó *et al.,* 2023). It is important to note that recent strong macroeconomic shocks have further decoupled domestic price formation from the German benchmark, as Hungary experienced exceptionally high food price inflation within the EU. The rapid depreciation of the Hungarian forint – intensified by balance-of-payments deficits and fiscal expansion – contributed significantly to domestic food inflation (Matthews, 2023). Furthermore, the literature suggests that fluctuations in the real effective exchange rate (REER) constitute one of the most critical global shocks affecting food prices in the EU27, as currency depreciation increases the cost of imported food products and inputs, thereby exerting substantial pressure on domestic consumer prices (Nugroho and Masyhuri, 2024). As a result, price formation in the Hungarian pig sector has increasingly reflected multi-market dynamics and country-specific macroeconomic and exchange rate factors. Although the long-run relationship has not disappeared, the presence of partial cointegration indicates a growing role of permanent shocks.

How can producers address challenges regarding price-related uncertainties? Price volatility has become a common feature in the market in recent years, highlighting the need for competitiveness and adaptability. Pig producers in Hungary are currently falling behind in both of these areas. Establishing stable, long-term partnerships is gaining importance in uncertain market conditions with time-varying price relationships, which could create a potential safety net against price-related uncertainties. This could involve medium- and long-term contracts within the sector or strengthening the role of producer organisations. Producer organisations can facilitate market access, enhance bargaining power, and reduce transaction costs. However, long-term contractual agreements often lack flexibility, resulting in fewer market stakeholders entering such conditions (Alho, 2015). Limited evidence suggests a higher share of cooperatives may enhance price stability at the national level (Müller *et al.,* 2017). There have been decades of efforts in Hungary to promote sectoral cooperation; however, the current situation remains inadequate. In addition, several additional factors are expected to shape the industry, such as the sustainable food system initiatives (Renaudeau and Dourmad, 2022, Galli *et al.,* 2020), digitalisation (Fróna, 2024, Metta *et al.,* 2022), or the increased risk of diseases and zoonoses (UNEP and ILRI, 2020, Dixon *et al.,* 2020). These factors may significantly alter the current price relationships over the long term. Agricultural producers may need to expand their cost- and profit-based business framework to include concepts such as vulnerability, stability, robustness, and resilience (Urruty *et al.,* 2016). These tendencies warrant the importance of regular price analysis.

These results reinforce the view that EU-level food and agricultural policy may need to move away from the implicit assumption of time-invariant price integration across Member States. Long-term co-movements have weakened or disappeared with major markets, and price relationships are considerably time-varying and regime-dependent. While these results were also observed in other commodities, the policy responses remain quite limited. In Hungary, markets that are considered dominant do not necessarily anchor regional prices, and long-run price linkages have weakened substantially. The analysis also revealed incomplete adjustments in the long run, which may increase market uncertainty. Given that price relationships fluctuate episodically, it is crucial to develop prompt and effective policy responses to temporary shocks. Implementing early warning systems and temporary safety nets can assist market stakeholders during challenging times, such as the ASF outbreak or sudden increases in production costs. Although some of these instruments already exist in part or entirely, policymakers should also account for the shifting nature of shocks over time when designing strategies for stable, long-term integration.

These findings suggest that recent events have caused significant structural misalignment in the market. Producers are facing sharply rising costs and changing trade dynamics, while consumers are experiencing considerable inflationary pressures. Implementing multi-benchmark pricing and improving contract structures may help stabilise the market to some extent; however, contractual relationships are often short-term and limited in nature, which may serve gradually to weaken market networks. Historically, market stakeholders have concentrated on individual markets, but establishing a national-level multi-benchmark reference price could alleviate vulnerabilities associated with weak integration. This reference price should be adaptive, accurately reflecting the market environment in a timely manner. When it comes to risk management, higher prices and greater contractual transparency would facilitate the early detection of structural misalignments. Currently, there is a lack of available information regarding such transparency in Hungary. Moreover, policy tools may need to have a broader scope to influence price behaviour effectively. Strengthening Producer Organisations and facilitating vertical conditions would protect producers from price-related uncertainties while reducing the burden of increasing market concentration. Therefore, we believe that addressing sectoral misalignments requires implementing multi-sector policy tools.

Of course, the research is not without limitations. First, only pairwise cointegration was examined, whereas the actual relationships among price series are likely to be more complex. However, previous empirical research and market evidence suggest that a limited number of key market players predominantly influence Hungarian pig prices. Second, the method assumes a first-order autoregressive process and does not account for higher-order dynamics, which may limit its ability to capture the data-generating process fully. Finally, the availability of information regarding the pricing mechanisms used by industry stakeholders is limited, which constrains the interpretation of the results.

Conclusions

In recent decades, animal and human diseases, economic events, structural issues, and geopolitical conflicts have severely affected the European food and agriculture market. These changes could have potentially affected the price relationships. This study examined the cointegration and partial cointegration between Hungary and the leading European pig markets from 2010 to 2023. The partial cointegration allows the cointegration relationships to be decomposed into a mean-reverting and a random walk component. We found that price movements were hectic and showed a strong time-varying tendency. According to the results, cointegration has gradually disappeared with Germany and the Netherlands, somewhat surprisingly, as both Member States are dominant players on the pig market. In contrast, a statistically and economically significant PCI relationship has emerged with Austria during the latter half of the sample period. Meanwhile, with other Member States, such as Denmark and Poland, the relationships appear to be mainly cyclical. Understanding the commodity markets is crucial for developing effective policy responses to global challenges. The findings indicate that price relationships have been much more complex than previously thought, with substantial time-varying characteristics. These results could help researchers and policymakers understand the complex relationship among the market prices by introducing a new dimension of analysis.

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Appendix

Table A1: Descriptive statistics of the level and return series in logarithmic form.

	HUN	GER	NLD	ESP	DNK	POL	AUT	EU
Level data								
mean	6.226	6.225	6.101	6.229	6.142	6.192	6.235	6.208
max	6.798	6.805	6.683	6.823	6.665	6.890	6.834	6.812
min	5.860	5.851	5.739	5.853	5.672	5.811	5.814	5.846
SD	0.185	0.188	0.188	0.196	0.197	0.194	0.202	0.182
skewness	0.972	1.079	0.883	1.026	0.562	1.333	0.890	1.210
kurtosis	4.129	4.188	3.650	4.102	3.064	5.585	4.065	4.822
Return data								
mean	0.126	0.134	0.137	0.132	0.122	0.137	0.147	0.132
max	18.391	16.846	17.637	9.751	19.374	19.056	13.784	24.189
min	–12.389	–10.563	–17.915	–8.056	–15.771	–8.111	–7.763	–17.450
SD	2.308	2.294	2.939	2.090	2.162	2.600	2.204	2.105
skewness	0.675	0.758	0.302	0.095	0.220	1.226	0.554	1.884
kurtosis	11.731	10.577	11.180	4.728	18.332	10.090	6.643	37.153

Notes: SD = standard deviation.
Source: Authors' calculations

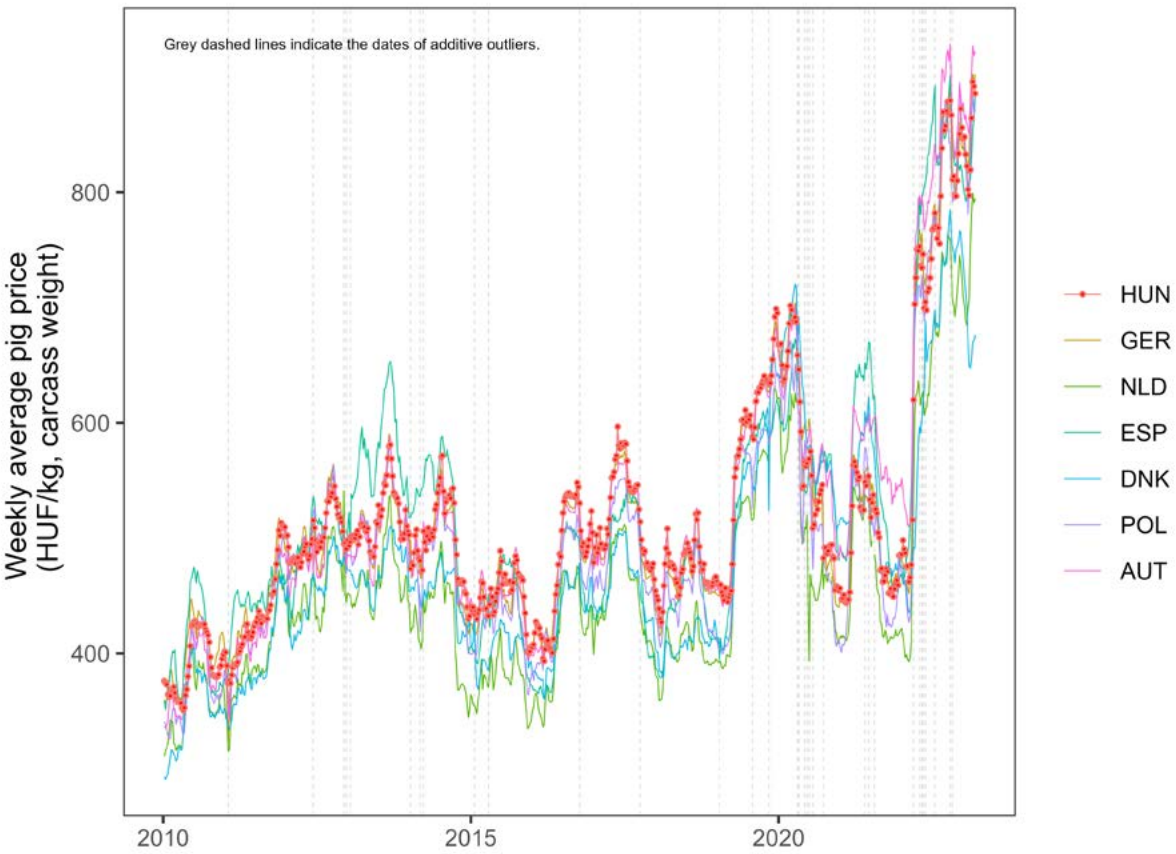

Figure A1: The price developments and the identified outlier values.

Notes: The grey dashed line represents price values identified as additive outliers by the Chen and Liu (1993) process. These values were adjusted to prevent distortion of the estimation procedure.

Source: Authors' calculations