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Volatility Modelling – What Drives CEE Currency Option Prices?

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Abstract:
This paper investigates the drivers of foreign exchange implied volatility in Central and Eastern European (CEE) countries. Currencies in non-euro EU countries are particularly sensitive to changes in market sentiment. Risk aversion significantly impacts the implied volatility surface for FX options, making these options crucial for managing skew risk. By analysing option prices, this study identifies co-movements between spot rates, interest rates, and volatilities for specific option strategies. Empirical evidence reveals robust determinants of volatility levels, volatility smiles, and volatility term structures. Applying error correction models and the directional quality measure across a long time span (2010–2025), we find that spot rate movements and mean reversion play significant roles in shaping implied volatilities in CEE markets, with patterns distinct from those in developed markets. The data suggests that the spot price rise is positively correlated with the pricing of both straddles and risk reversals. Our findings provide new insights into the behaviour of FX volatility in semi-liquid markets and have practical implications for pricing, hedging, and policy signalling in the CEE region.

Keywords: currency options, directional quality measure, error correction models, volatility surface

JEL: C53, C58, G15, G17

1. Introduction

Volatility plays a critical role in the pricing and risk management of FX derivatives. While volatility dynamics in developed markets like EUR/USD are well-documented, the behaviour of volatility in Central and Eastern European (CEE) FX options markets remains underexplored. These markets, although growing in sophistication, often reflect unique economic structures, market frictions, and institutional factors. This paper addresses a fundamental question: what drives the pricing of FX options in CEE markets? We analyse the implied volatility surfaces of three major CEE currency pairs—EUR/PLN, EUR/HUF, and EUR/CZK[1]—and benchmark them against EUR/USD. We study how various option strategies, such as straddles, risk reversals, and calendar spreads, react to underlying market variables including spot returns, interest rate differentials, and historical volatility. Our work contributes to the literature by shedding light on volatility drivers in relatively illiquid markets, using an extensive empirical framework grounded in econometric modelling.

Managing foreign exchange risk involves two main aspects: level terms and volatility terms. The latter is managed through options. FX options are the dominant non-linear derivatives in small open economies with their own currencies, such as the CEE countries: Poland, Czechia, and Hungary. The price of options is determined by implied volatility. The standard model used for premium calculations of European vanilla currency options is the Garman-Kohlhagen formula (1983), a modification of the classic Black-Scholes (1973) and Merton models (1976). Volatility is quoted by market makers and traded via option contracts. Each option has its own volatility, dependent on strike (delta) and expiry date (maturity). This specific volatility is implied from the so-called volatility surface, a 3D function of delta and maturity of the option (Cont et al., 2002). Forecasting volatility is a crucial aspect of risk modelling (Engle and Patton, 2001; Fullwood et al., 2021).

Contrary to market model assumptions, the real market is significantly different. Market prices exhibit non-normal log returns with unstable volatility and shrinking liquidity, which increases transaction costs and hampers smooth hedging of exposures. Consequently, as Rebonato (2004, p. 169) notes: "Implied volatility is the wrong number to put in the wrong formula to get the right price of plain-vanilla options." This means that volatility is not an estimator of future standard deviation but rather a parameter encompassing the shape of a non-normal density function of daily returns.

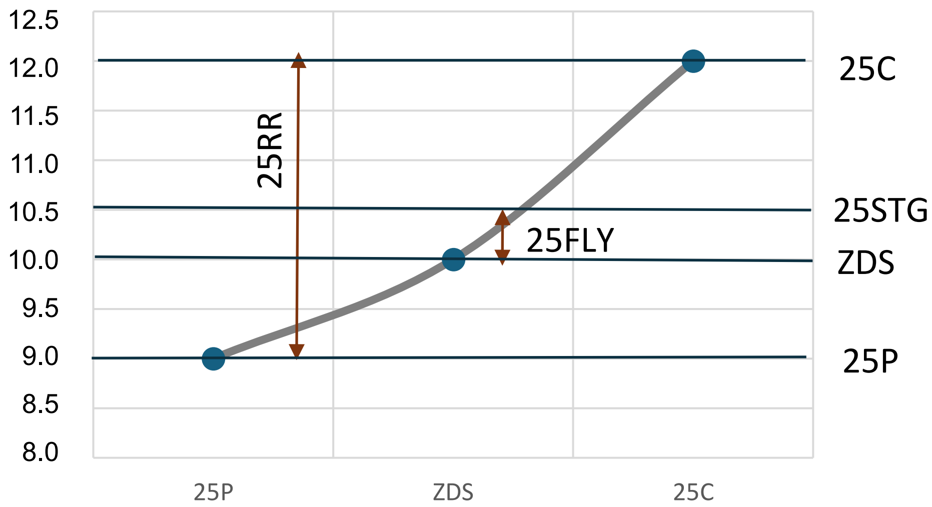
In practice, on the wholesale market options are traded through basic option strategies: zero-delta straddles, 25-delta risk reversals and 25-delta butterflies[2] with standard maturities from 1 day to 1 year (Ahoniemi, 2009). These strategies are quoted in volatility terms, and their prices allow the construction of an online volatility surface. The surfac-

1 All main CEE currency pairs are against the euro, as EUR/CCY for all three countries is the most liquid and has the lowest variance among all local currency pairs.

2 Zero-delta straddle is a connection of call and put with a strike that neutralises the forward premium-adjusted delta, 25-delta risk reversal is a connection of OTM (out-of-the-money) call and put (one bought the other sold) with probability of exercise close to 25% and 25-delta butterfly is a connection of 25-delta strangle (OTM call and put, both bought or both sold) and zero-delta straddle (if the strangle is bought, the straddle is sold).

es can be decomposed to 2D functions in delta and maturity terms. The first is known as the volatility smile, the latter known as the volatility curve (Lee, 2005). The relationship between prices of the strategies and a construction of the volatility smile is presented on figure 1. The paper analyses the dependencies between the prices of these strategies, and therefore the determinants of the volatility smile and volatility curve.

Figure 1. The relationship between prices of the option strategies and the volatility smile



Note: 25C – call with delta 25, 25P – put with delta 25, 25STG – strangle with delta 25 for both OTM options, 25RR – risk reversal with delta 25 for both OTM options, 25FLY – butterfly with delta 25 for both OTM options, ZDS – zero-delta straddle

Source: own elaboration

CEE economies are still considered emerging markets converging towards the eurozone. Therefore, the basic currency pair is against the EUR. This pair has the best liquidity (highest turnover, lowest bid-ask spread) and lower volatility compared to other currency pairs in the local market. However, being "emerging" implies fragile liquidity and unstable volatility with significant asymmetry of risk. Statistical evidence of this pattern is seen in the skewness and kurtosis of daily returns, which are higher than those of mature markets like EUR/USD (see Table 1). Despite higher volatility, the euro/dollar pair has lower skewness and kurtosis than CEE currencies.

Table 1. Statistical moments of FX rates

	EUR/PLN	EUR/CZK	EUR/HUF	EUR/USD
M1	0.00%	0.00%	0.01%	–0.01%
M2	0.42%	0.30%	0.50%	0.52%
M3	0.20	1.56	0.09	–0.02
M4	4.42	25.18	2.58	1.95

Note: statistics calculated on daily log-returns (October 2010 – January 2025). M1 – average, M2 – daily SD, M3 – skewness, M4 – excess kurtosis.
Source: own calculations.

Non-normality of daily returns and fat tails in the density function have significant consequences for option pricing (Lim et al., 2006; Hood et al., 2009; Simonato and Stentoft, 2015). This results in a significant positive sign for risk reversal and butterfly strategies (Zhang and Xiang, 2008; Santa-Clara and Saretto, 2009). Risk reversals reflect skewness expectations, while butterflies capture kurtosis effects (Dunis and Lequeux, 2001; Hafner and Schmidt, 2005). A risk reversal involves the simultaneous purchase of a low delta call and the sale of a low delta put (or vice versa). For CEE currencies, there is a constant demand for high strikes, covered by a supply of low strikes (Filho da Costa, 2016). This strategy hedges against currency crises, as most investors are long in local currency due to a positive carry. Additionally, higher volatility for high strikes indicates that the market forecasts an increase in volatility following a rise in the underlying price. There is strong evidence of a positive correlation between changes in FX spot rates and implied volatility for CEE currencies (see Table 4 in the appendix). This positive correlation results in a positive sign for the risk reversal price.

In turn, butterflies are primarily quoted to construct the volatility surface. However, the number of actual trades is low (Corrado, 2001). This is due to limited demand for kurtosis bets compared to skewness bets, as the fourth moment is more difficult to model and hedge (Ge et al., 2023). Consequently, bid-ask spreads for butterflies are wide relative to expected price volatility (Rogers & Singh, 2010). Time series of butterfly prices exhibit high inertia and lower sensitivity to economic incentives[3].

3 Butterfly prices are not a subject of this research due to their limited liquidity.

Following these observations, the research verifies the interdependence between spot rates, volatilities, and risk reversals for CEE currency pairs compared to the mature market represented by the EUR/USD currency pair. This research is further enriched by examining the determinants of the shape of the volatility curve. The shape is traded via calendar spreads, which connect straddles referring to different maturities. Prices of calendar spreads account for the mean reversion phenomenon (Bali and Demitras, 2008; Goudarzi, 2013; Ahmed et al., 2018). Short-term volatility is more sensitive than long-term volatility, with the latter being closer to the long-term mean. A normal curve is observed when the general level of volatility is low, and an inverted curve is seen when volatility is high. Consequently, the correlation between changes in the level and changes in the slope is significantly negative (see Table 4 in the appendix).

Volatility modelling is supplemented by analysing the influence of other factors on the level of traded volatility. These factors include historical volatility and interest rates. Historical volatility psychologically influences traders, leading to higher option prices if the past market is more volatile (Plíhal and Lyócsa, 2021). Higher interest rates relate to capital flows, providing stronger incentives for carry trading, which increases the instability of foreign exchange rates.

However, these models are incorporated on an auxiliary basis to examine exogenous factors influencing both emerging and mature currency markets.

2. Literature review

The study of implied volatilities is essential for understanding the dynamics of foreign exchange (FX) options and their role in managing both volatility and skew risk. This section synthesises existing research on exchange rate volatility, option pricing models, and the determinants of volatility surfaces, thereby providing a foundation for the empirical analysis presented in this paper.

The first strand of the literature focuses on the determinants of volatility. Aderemi et al. (2019) examine the relationship between exchange rate volatility and foreign capital inflows using a Vector Error Correction Model (VECM). Their findings underscore the significant influence of exchange rate fluctuations on capital movements—an insight particularly relevant to the CEE context. Ahmed et al. (2018) investigate stock returns and volatility in both emerging and developed markets, with an emphasis on mean reversion. Their work offers valuable perspectives on financial market behaviour that can be extended to the analysis of non-linear derivatives. Ahoniemi (2009) and Altin (2022) focus on modelling and forecasting implied volatility using various approaches, including VECM. These models are instrumental in predicting volatility surfaces and identifying the factors that influence implied volatilities in FX options. This body of research supports the application of error correction mechanisms in volatility modelling.

The second area of scholarly interest concerns the internal behaviour of volatility used in option pricing, as well as its external role in transmitting market shocks. Bali and Demirtas (2008) test for mean reversion in financial market volatility, using evidence from S&P 500 index futures. Their findings enhance our understanding of volatility patterns, which are critical for option pricing. Bauwens et al. (2006) provide a comprehensive survey of multivariate GARCH models, which are widely employed to capture the dynamics of financial market volatility. The GARCH framework has also been applied to examine volatility spillovers in CEE foreign exchange markets, as demonstrated by Hung (2021). Similar spillover effects in equity markets have been studied by Dedi et al. (2016). Cont et al. (2002) and Hafner and Schmid (2005) develop stochastic models of implied volatility surfaces, offering a framework for forecasting volatility movements. These models are particularly useful for analysing the determinants of volatility levels, smiles, and term structures. Krylova et al. (2009) extend this analysis to FX markets. Ding et al. (2021) and Ni et al. (2008) explore risk spillovers and volatility information trading, highlighting the importance of understanding the interdependence between market variables, particularly in the context of volatility trading.

The third relevant strand of literature addresses market frictions and liquidity constraints, which are critical for understanding the dynamics of implied volatility. Illiquidity can lead to larger and more discontinuous price movements in the underlying asset (Chiu et al., 2023). Liquidity risk may be priced into options, resulting in a premium that reflects the potential difficulty of trading either the option or its underlying asset (Ludkovski and Shen, 2013; Lin and Yang, 2015). This arises because market makers may encounter challenges in hedging their positions under liquidity constraints, potentially leading to wider bid–ask spreads and increased hedging costs (Deng and Yao, 2024).

The literature confirms that emerging markets exhibit distinct behaviours due to factors like lower liquidity, inconsistent policy responses, and unique sensitivities to global shocks. However, CEE markets are different than other emerging markets due to their constant convergence to eurozone (disregarding a fact of not having strong intention to convert local currencies to euro).

Bubak and Žikeš (2009) and Lyocsa et al (2016) analyse high frequency data from CZK, HUF and PLN markets to density forecast of short-term future volatility. Dömötör and Havran (2011) or Dumitrescu and Roşca (2015) implement GARCH framework for volatility forecasting. Bubák et al. (2010) perform research of spillover effects between EUR/USD market and CEE currency exchange rates.

The reviewed literature provides a robust foundation for understanding the factors that influence implied volatilities in CEE countries. By synthesising prior research on volatility forecasting, this study contributes to the broader field of financial economics and offers practical insights into managing volatility surface of FX options. However, the relative incompleteness and lower liquidity of CEE markets suggest the need for alternative approaches to pricing and risk management.

3. Methodology and data

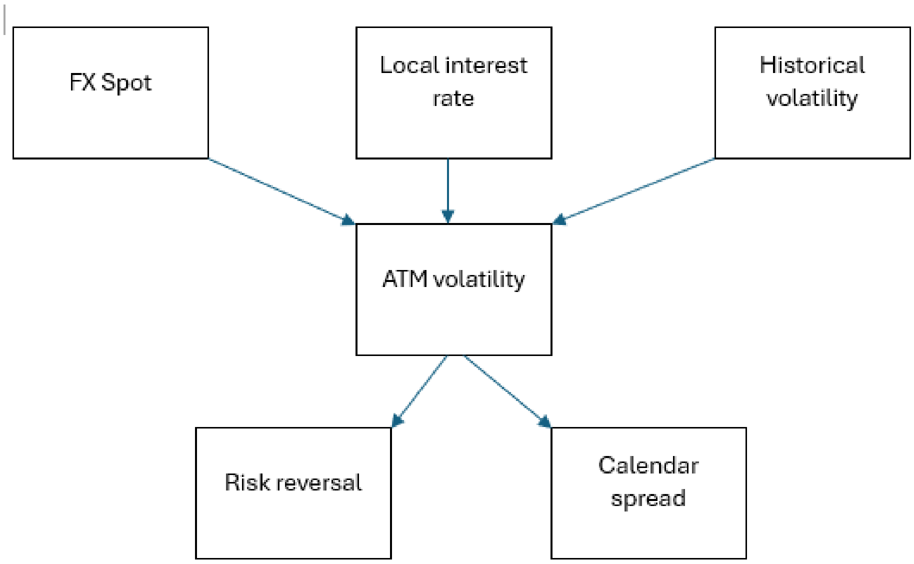
The empirical framework consists of five linear models estimated using daily data over 2010–2025. The models relate implied volatility for the most liquid option strategies (zero-delta straddles, risk reversals, and calendar spreads) to contemporaneous and lagged values of spot exchange rate changes, interest rate differentials, and realized volatility. Stationarity of the time series is evaluated using ADF and KPSS tests. Where evidence of cointegration exists, an error correction model (ECM) is employed to capture short-run dynamics around a long-run equilibrium relationship. Directional accuracy is assessed using the Directional Quality Measure (DQM), which quantifies the percentage of correct directional forecasts

The research considers both correlation and causality checks. Based on the aforementioned considerations, five models are calibrated for all four currency pairs:

1. ATM volatility as a function of the FX spot rate (Model 1)
2. Risk reversal price as a function of the ATM volatility (Model 2)
3. Calendar spread as a function of the ATM volatility (Model 3)
4. ATM volatility as a function of the historical volatility (Model 4)
5. ATM volatility as a function of the long-term interest rate (Model 5)

The scheme of the relationship between the variables is presented in Figure 2.

Figure 2. The relationship between the variables



Source: own elaboration

The research encompasses time series data from the EUR/PLN, EUR/CZK, EUR/HUF, and EUR/USD option markets for the period from October 22, 2010, to January 20, 2025, totalling 3,738 daily observations. The data source is Refinitv. A three-month period for option strategies was selected as the basic maturity due to its adequate liquidity and its position in the geometric middle of the liquid volatility curve. The list of variables is presented in Table 2.

Table 2. Description of variables

variable	description
SPOT	spot exchange rate (EoD)
ZDS	3-month implied volatility for ATM option (represented by zero-delta straddle[1])
RR	3-month implied volatility for 25-delta risk reversal (in euro call terms)
HV	3-month historical volatility (SD on log-returns p.a.)
CS	difference between 1Y and 1M implied volatility for ATM options (calendar spread)
IR	5-year plain vanilla IRS

Source: own elaboration[4]

4 ATM and ZDS terms are commonly used as synonyms in economic contexts, despite their arithmetic differences. ZDS strike is not equal to forward because forward premium-adjusted delta is neutralized. Due to embedded premium paid in the fore-currency the strike decreases in comparison to the forward rate as the option becomes longer and more in-the-money. Therefore, ATMF options do not have a 50% delta in trading terms, contrary to common assumptions.

The econometric analysis is based on error correction models (ECM) using the Engle-Granger cointegration approach. The ECM is based on cointegration tests that estimate an error correction component. To build an ECM, the following procedure is performed:

1. Granger causality analysis (see Table 5 in Appendix)
2. stationarity assessment of variables (see Table 6 in Appendix)
3. construction of cointegration equations and evaluation of the stationarity of their residuals (see Table 7 in Appendix)
4. estimation of error correction models (see Table 8 below)

The procedure is based on Engle-Granger cointegration test (1987) and the method described by Charemza and Deadman (1997).

The ECM has the following construction:

$$\Delta y_t = \alpha_1 \times \Delta x_t + \alpha_2 \times uhat_{t-1} + \varepsilon_t$$

where:

$uhat_{t-1} = y_{t-1} - \beta_0 - \beta_1 \times x_{t-1}$
$y_t \sim \mathrm{I}(1)$
$x_t \sim \mathrm{I}(1)$
$uhat_t \sim \mathrm{I}(0)$

The univariate model was chosen to identify clear and easily identifiable long-term relationships between variables. Stationary and lagged residuals from a regression OLS model allow to stabilize deviations from the mean in the final model.

4. Results and discussion

The Pearson matrix and Granger causality suggest a long-term directional co-dependence between the time series in line with the scheme presented in Figure 1. The cointegration model can be constructed if both time series are I(1) and the residual time series is I(0). The stationarity tests provide ambiguous results (see Tables 6 and 7 in Appendix). Such situation is common in literature related to emerging markets modelling (see: Pasaribu 2002; Kipkoech, 2015; Aderemi et al., 2019). Barnhart & Szakmary (1991) noticed that results of unit root tests are sensitive to adequate model specification. It may affect the calibration of error correction models for the non-stationary and cointegrated series.

However, the models have significant parameters, and the sign for the error correction component α_2 is always negative indicating that the error correction component decreases divergence from the long-term mean. Table 8 presents estimated coefficients and their statistical significance. All coefficients except for four (5%) are significant at the 1% confidence level.

Table 8. Error correction models

		β_0	p-val(β_0)	β_1	p-val(β_1)	α_1	p-val(α_1)	α_2	p-val(α_2)
EUR/PLN	**Model 1**	5.1849	<0.0001***	0.3267	0.0647*	15.2262	<0.0001***	−0.0047	0.0023***
	Model 2	−0.6926	<0.0001***	0.2687	<0.0001***	0.1774	<0.0001***	−0.0375	<0.0001***
	Model 3	1.1850	<0.0001***	−0.0694	<0.0001***	−0.6426	<0.0001***	−0.0220	<0.0001***
	Model 4	1.8798	<0.0001***	0.7516	<0.0001***	0.1935	<0.0001***	−0.0099	0.0017***
	Model 5	4.4229	<0.0001***	0.6693	<0.0001***	0.3488	<0.0001***	−0.0066	0.0006***
EUR/CZK	**Model 1**	17.5041	<0.0001***	−0.5118	<0.0001***	7.6524	<0.0001***	−0.0067	0.0009***
	Model 2	−2.0573	<0.0001***	0.5368	<0.0001***	0.1122	<0.0001***	−0.0394	<0.0001***
	Model 3	1.5124	<0.0001***	−0.2302	<0.0001***	−0.5573	<0.0001***	−0.0263	<0.0001***
	Model 4	2.1907	<0.0001***	0.5174	<0.0001***	0.0289	0.0747*	−0.0120	<0.0001***
	Model 5	3.9379	<0.0001***	0.1965	<0.0001***	−0.1572	0.0076***	−0.0067	0.0005***
EUR/HUF	**Model 1**	4.7933	<0.0001***	0.0084	<0.0001***	13.1799	<0.0001***	−0.0026	0.0345**
	Model 2	−0.7553	<0.0001***	0.2882	<0.0001***	0.1498	<0.0001***	−0.0623	<0.0001***
	Model 3	1.3758	<0.0001***	−0.0828	<0.0001***	−0.5839	<0.0001***	−0.0254	0.0072***
	Model 4	1.3795	<0.0001***	0.8527	<0.0001***	0.2148	<0.0001***	−0.0110	0.0004***
	Model 5	4.1862	<0.0001***	0.8561	<0.0001***	0.5468	<0.0001***	−0.0087	0.0001***
EUR/USD	**Model 1**	1.5121	0.0002***	5.5985	<0.0001***	−18.7271	<0.0001***	−0.0068	<0.0001***
	Model 2	1.5764	<0.0001***	−0.3264	<0.0001***	−0.2272	<0.0001***	−0.0319	<0.0001***
	Model 3	1.0521	<0.0001***	−0.0739	<0.0001***	−0.6939	<0.0001***	−0.0280	<0.0001***
	Model 4	1.4245	<0.0001***	0.8695	<0.0001***	0.1522	<0.0001***	−0.0176	<0.0001***
	Model 5	8.0623	<0.0001***	0.1101	0.0002***	0.4180	0.2250	−0.0064	0.0003***

Note:

Model 1 = SPOT → ATM, Model 2 = ATM → RR, Model 3 = ATM → CS, Model 4 = HV → ATM, Model 5 = IR → ATM
Source: own calculations

Interpretation of the results in Table 8 is as follows:

- α_2 is consistently negative, indicating the strength of the error correction mechanism. This suggests that when the dependent variable deviates above the explanatory variable, there is a corrective tendency—driven by a form of mean reversion—to reduce this divergence. In essence, the model "observes" the residuals (errors) from the previous period (t−1) and "corrects" the deviation in the current period (t).

- α_1 represents the primary coefficient indicating the direction of dependence. A positive value implies that an increase in the explanatory variable leads to a subsequent rise in the dependent variable. A negative coefficient is observed across all Model 3 specifications, as an increase in volatility typically results in a flattening or inversion of the volatility curve—consistent with the mean reversion phenomenon in high-volatility environments. Negative α_1 values are also recorded for EUR/CZK Model 5 and EUR/USD Models 1 and 2. The anomaly in the EUR/CZK case may be attributed to the limited role of carry trading in the Czech koruna market, historically characterised by low interest rates relative to the euro.
- In contrast, the negative α_1 coefficients for EUR/USD likely reflect the differing dynamics of developed versus emerging markets. The EUR/USD market does not exhibit pronounced risk asymmetry, as both currencies possess similar credit ratings and risk perceptions. Nevertheless, this symmetry would typically suggest a coefficient close to zero, rather than negative. The negative sign in Model 1 implies that volatility risk is associated with euro depreciation. Consequently, Model 2 also exhibits a negative sign, as rising volatility leads to a decline in risk reversal prices (which tend to become more negative in absolute terms due to the underlying asset exhibiting negative skewness). In the EUR/USD market, jump risk has historically been perceived on the side of dollar appreciation, with the USD often acting as a safe-haven currency during financial crises—more so than the euro.

The forecasting efficiency of the models was estimated using the directional quality measure (DQM) (see Table 9). DQM is a practical tool to assess the model's ability to forecast the direction of the following price change. It belongs to classification binominal metrics that estimate the accuracy of directional forecast according to the following formula:

$$DQM = \frac{\sum_{i=1}^{N} n}{N}$$

$n = 1$, *if* $sgn(F) = sgn\ (E)$
$n = 0$, *if* $sgn(F) \neq sgn\ (E)$

where:
N – number of observations
$sgn(\ )$ – sign of the return (positive of negative)
F – forecast value
E – empirical value

Table 9. Quality measures of the models

		MSE	DQM	min error	max error	R2	DW
EUR/PLN	Model 1	0.0377	52%	–2.13	1.02	0.10	2.14
	Model 2	0.0134	43%	–1.42	1.12	0.11	2.50
	Model 3	0.0350	62%	–1.24	1.40	0.34	2.52
	Model 4	0.0412	48%	–2.30	1.33	0.02	2.05
	Model 5	0.0417	45%	–2.33	1.13	0.01	2.01
EUR/CZK	Model 1	0.0328	45%	–1.85	2.20	0.02	2.30
	Model 2	0.0948	27%	–3.57	3.03	0.02	2.51
	Model 3	0.0365	55%	–1.71	1.54	0.23	2.53
	Model 4	0.0333	44%	–1.78	2.32	0.00	2.26
	Model 5	0.0332	43%	–1.76	2.28	0.00	2.27
EUR/HUF	Model 1	0.0477	52%	–2.11	1.56	0.01	2.16
	Model 2	0.0205	40%	–1.44	1.35	0.08	2.60
	Model 3	0.0417	62%	–1.12	1.22	0.31	2.51
	Model 4	0.0512	50%	–2.24	1.87	0.02	2.06
	Model 5	0.0501	48%	–2.00	1.82	0.05	2.08
EUR/USD	Model 1	0.0576	58%	–2.18	1.83	0.14	1.97
	Model 2	0.0137	56%	–1.31	1.44	0.21	2.00
	Model 3	0.0534	70%	–2.08	2.69	0.29	2.53
	Model 4	0.0661	52%	–2.47	2.11	0.01	1.91
	Model 5	0.0667	50%	–2.43	2.08	0.00	1.91

Note:

Model 1 = SPOT → ATM, Model 2 = ATM → RR, Model 3 = ATM → CS, Model 4 = HV → ATM, Model 5 = IR → ATM

MSE – mean square error, DQM – directional quality measure, R2 – goodness of the model, DW – Durbin-Watson test

Source: own calculations

According to Levich (2001), the quality of the forecast in financial markets can be related to direction rather than the size of the change. Consequently, DQM is a robust alternative to measures like MSE and R2 (Chan-Lau and Mendez-Morales 2003; Campbell et al. 2014; Vrontos et al. 2021). DQM values over 50% indicate better-than-random forecasting power. The DQM is positive for all EUR/USD models and only some CEE models, suggesting that volatility assessment for mature markets is easier than for emerging markets.

Model 1 (underlying asset impact on volatility) and model 3 (volatility impact on the slope of the volatility curve) have good statistical features for all currency pairs and outperform random directional guesses. It is in line with observation in literature referring to equity markets what proofs its suitability also for emerging currency markets.

Except EUR/USD market, risk reversal models underperform, what can be explained by instable skewness expectations and lower liquidity of out-of-the-money options.

Historical volatility exhibits only a weak, psychologically driven influence. Its effects are scarce and short-lived, resulting in modest statistical significance (as observed for stock markets by Christensen & Prabhala, 1998; Li & Yang, 2009; Chen & Li, 2021).

The weakest models refer to interest rates, suggesting a divergent pace of capital flow movements to the instability of the currency rate. Interest rate effects are distorted by sentiment shifts and variability in cross-border capital flows. Notably, non-residents often finance their emerging market investments via currency swaps (Živkov et al., 2015; Cerutti & Zhou, 2024). Unfortunately, currency swap prices are influenced by numerous factors shaping the currency basis spread. For example, an increase in short-term interest rates may result from both bond buyers hedging FX risk and local currency short-sellers. Moreover, during periods of stress, some capital flows may become insensitive to yield curve levels (Pagliari & Hannan, 2017; Matschke et al., 2023).

Among CEE currency pairs, EUR/CZK has the weakest statistical performance. The unique characteristics of the CZK market have been evident since the introduction of free-floating regimes in CEE countries (1997–2001). Rapid convergence of Czech yield curves to the eurozone and the maintenance of the local currency without a currency board created persistent pressure on monetary policy (Stavárek, 2007; Kołodziejczyk, 2020). Evidence of "overconvergence" was reflected in negative carry and shifted currency basis swaps. Consequently, the local FX rate and its implied volatility have exhibited high leptokurtosis, making time-series analysis less efficient than for normally distributed data. This distorts statistical evidence. On the other hand, CZK is perceived as a stabilizing anchor in the region (Aliu et al., 2024).

The summary of Pearson correlation, Granger causality, stationarity, model significance, statistical goodness, and forecasting efficiency of all 20 models is presented in Table 10 in the Appendix.

5. Conclusions

The study examines the variables influencing key points on the FX volatility surface in Central and Eastern European (CEE) countries with local currencies. The analysis focuses on the most liquid segments of the surface—namely, the 3-month at-the-money (ATM) and 25-delta points. To identify these relationships, the prices of selected option strategies (zero-delta straddles, risk reversals, and calendar spreads) were collected and analysed. Based on this dataset, five error correction models were constructed, incorporating Pearson correlations, Granger causality tests, and assessments of integration and cointegration within the time series.

Implementation of ECM models to implied volatility quoted for particular option strategies is the added value of the research. Moreover, the comparison to EUR/USD benchmark allows assessment of relative efficiency of the models.

The rationale behind each model is as follows:

- Model 1: In CEE currency markets, local currency depreciation is typically associated with heightened risk, which is reflected in elevated FX option prices. Increased volatility is closely linked to a weakening domestic currency. Accordingly, changes in implied volatility can be explained by movements in spot returns. The volatility surface increases proportionally with the spot exchange rate of the foreign currency against the local currency.
- Model 2: Risk reversals capture the skewness of the volatility smile. Greater skewness is observed in more volatile environments, establishing a link between risk reversal prices and ATM volatility levels. In periods of heightened risk aversion, market participants tend to demand both ATM straddles and risk reversals, as they seek protection against simultaneous increases in spot volatility and directional risk (as described in Model 1).
- Model 3: The mean reversion property of volatility implies that the shape of the volatility curve is influenced by the overall level of volatility. Consequently, changes in the slope of the curve are associated with parallel shifts in volatility levels. A high volatility environment leads to an inverted volatility curve, consequently, calendar spreads exhibit negative prices. Conversely, a low volatility environment yields the opposite effect.

- Model 4: Variations in implied volatility are influenced by changes in historical volatility for comparable maturities. For obvious reasons, a psychological link is often observed between implied (i.e. forecasted) and historical standard deviations, rather than the volatility realised over the life of the option that is not known on the trade date.
- Model 5: The level of domestic interest rates provides incentives for carry trading. A high interest rate differential attracts foreign capital, which may exit rapidly if market sentiment deteriorates. This dynamic implies that elevated interest rates can amplify capital inflows and outflows, thereby increasing the implied volatility of the exchange rate.

All models were calibrated for three CEE currency pairs—Polish zloty, Czech koruna, and Hungarian forint—and benchmarked against the mature EUR/USD market. The results highlight the forecasting utility of several calibrated models, as assessed by the directional quality measure. In general, the EUR/USD models exhibit superior performance relative to their CEE counterparts, likely due to the greater normality of log-returns and higher market liquidity. Among the models, those based on underlying asset performance and focusing calendar spreads demonstrate the strongest statistical properties, consistent with the widespread presence of volatility skew and mean reversion in option markets.

APPENDIX

Table 3. Descriptive statistics

		levels			first differences					
		average	max	min	M1	M2	M3	M4	max	min
EUR/PLN	Spot	4.3127	4.9713	3.8395	0.00%	0.42%	0.20	4.42	3.6%	–3.1%
	ZDS	6.67	14.95	2.92	0.00	0.21	1.83	17.43	2.38	–1.18
	CS	0.74	3.30	–7.19	0.00	0.23	–0.75	8.18	1.58	–1.78
	RR	1.10	3.83	–0.28	0.00	0.12	1.08	25.65	1.68	–1.10
	IR	3.28	7.89	0.43	0.00	0.06	–0.44	7.59	0.39	–0.52
EUR/CZK	Spot	25.733	28.298	23.233	0.00%	0.30%	1.56	25.18	4.6%	–2.0%
	ZDS	4.36	10.48	1.05	0.00	0.19	0.41	18.91	1.80	–2.33
	CS	0.51	3.48	–5.78	0.00	0.22	–0.39	9.56	1.78	–1.55
	RR	0.28	3.35	–5.08	0.00	0.31	0.49	23.88	3.70	–3.00
	IR	1.97	6.38	0.22	0.00	0.05	–0.85	11.67	0.28	–0.60
EUR/HUF	Spot	329.28	430.82	262.20	0.01%	0.50%	0.09	2.58	2.7%	–2.7%
	ZDS	7.65	16.35	3.33	0.00	0.23	1.13	12.00	2.33	–1.75
	CS	0.76	3.70	–7.10	0.00	0.25	–0.85	6.81	1.30	–2.45
	RR	1.46	4.90	–0.13	0.00	0.15	–0.13	17.44	1.28	–1.43
	IR	4.00	12.96	0.45	0.00	0.09	–0.59	15.82	0.67	–1.04
EUR/USD	Spot	1.1835	1.4826	0.9592	–0.01%	0.52%	–0.02	1.95	3.0%	–2.7%
	ZDS	8.19	17.40	4.00	0.00	0.26	0.65	8.15	2.43	–2.10
	CS	0.47	3.22	–4.30	0.00	0.30	–0.01	13.66	3.65	–2.98
	RR	–1.09	2.10	–4.70	0.00	0.13	–1.02	22.18	1.19	–1.70
	IR	0.57	4.00	–0.61	0.00	0.01	–0.61	46.46	0.14	–0.20

Note: log values are taken into account for Spot variable only.

Source: own elaboration

Table 4. Pearson correlation matrix (for daily returns)

	PLN SPOT	PLN ZDS	PLN CS	PLN RR	PLN IRS	CZK SPOT	CZK ZDS	CZK CS	CZK RR	CZK IR	HUF SPOT	HUF ZDS	HUF CS	HUF RR	HUF IR	EUR SPOT	EUR ZDS	EUR CS	EUR RR	EUR IR
PLN SPOT	100%																			
PLN ZDS	32%	100%																		
PLN CS	–25%	–56%	100%																	
PLN RR	14%	30%	–24%	100%																
PLN IRS	7%	10%	–6%	6%	100%															
CZK SPOT	37%	13%	–14%	8%	0%	100%														
CZK ZDS	11%	23%	–18%	10%	–1%	13%	100%													
CZK CS	–9%	–17%	20%	–8%	0%	–14%	–42%	100%												
CZK RR	1%	2%	–4%	7%	1%	2%	6%	–3%	100%											
CZK IR	–3%	–1%	2%	2%	59%	–12%	–4%	3%	1%	100%										
HUF SPOT	52%	22%	–19%	10%	10%	34%	9%	–9%	1%	–2%	100%									
HUF ZDS	25%	53%	–35%	24%	11%	17%	17%	–15%	3%	1%	29%	100%								
HUF CS	–18%	–36%	42%	–21%	–9%	–13%	–13%	21%	–4%	0%	–27%	–54%	100%							
HUF RR	6%	14%	–13%	24%	5%	8%	5%	–7%	12%	2%	11%	23%	–18%	100%						
HUF IR	19%	17%	–13%	10%	52%	9%	3%	–4%	0%	45%	28%	22%	–17%	9%	100%					
EUR SPOT	–25%	–12%	11%	–4%	–7%	–18%	–4%	2%	0%	–1%	–26%	–13%	9%	–2%	–14%	100%				
EUR ZDS	31%	33%	–29%	14%	6%	20%	13%	–10%	–2%	–6%	29%	29%	–24%	7%	15%	–37%	100%			
EUR CS	–16%	–21%	30%	–8%	–1%	–8%	–8%	17%	–2%	8%	–17%	–15%	28%	–5%	–6%	16%	–61%	100%		
EUR RR	–21%	–27%	26%	–11%	–8%	–14%	–12%	10%	2%	0%	–20%	–24%	22%	–4%	–12%	40%	–44%	26%	100%	
EUR IR	0%	–2%	1%	–2%	–1%	1%	–2%	1%	0%	1%	–2%	–1%	0%	1%	0%	–1%	2%	–2%	0%	100%

Source: own calculations

Table 5. Granger causality tests (for daily returns)

PLN	SPOT	ZDS	RR	HV	CS	IR
SPOT		2.3367 (0.0968)*	4.9021 (0.0075)*	0.5441 (0.5804)	2.4168 (0.0893)*	0.8077 (0.4460)
ZDS	92.227 (0.0008)*		8.4177 (0.0002)*	26.4960 (0.0000)*	23.0950 (0.0000)*	1.9008 (0.1496)
RR	60.846 (0.0000)*	10.478 (0.0000)*		15.5420 (0.0000)*	0.9669 (0.3803)	0.8001 (0.4494)
HV	6.9315 (0.0010)*	5.3234 (0.0049)*	4.5133 (0.0110)*		1.4304 (0.2394)	2.4175 (0.0893)*
CS	35.5650 (0.0000)*	24.2730 (0.0000)*	5.2618 (0.0052)*	8.7707 (0.0002)*		0.0786 (0.9244)
IR	0.6923 (0.5005)	0.1596 (0.8525)	0.1459 (0.8643)	0.8626 (0.4222)	0.0925 (0.9116)	

CZK	SPOT	ZDS	RR	HV	CS	IR
SPOT		0.4231 (0.6550)	0.0761 (0.9267)	4.6501 (0.0096)*	0.7811 (0.4580)	2.1614 (0.1153)
ZDS	39.631 (0.0000)*		2.5576 (0.0776)*	2.0445 (0.1296)	8.2868 (0.0003)*	1.7625 (0.1718)
RR	0.5684 (0.5665)	2.9896 (0.0504)*		1.2740 (0.2799)	0.9629 (0.3819)	0.6619 (0.5159)
HV	3.9220 (0.0199)*	8.9375 (0.0001)*	0.4240 (0.6545)		1.9236 (0.1462)	2.3867 (0.0921)*
CS	25.5740 (0.0000)*	16.8540 (0.0000)*	0.2316 (0.7933)	1.9685 (0.1398)		0.5523 (0.5757)
IR	0.1271 (0.8806)	1.2916 (0.2749)	0.0700 (0.9324)	0.6542 (0.5199)	0.0093 (0.9908)	

HUF	SPOT	ZDS	RR	HV	CS	IR
SPOT		2.9819 (0.0508)*	2.3063 (0.0998)*	0.1822 (0.8335)	0.1445 (0.8655)	18.5060 (0.0000)*
ZDS	130.9700 (0.0000)*		4.1831 (0.0000)*	31.6440 (0.0000)*	27.9140 (0.0000)*	9.1754 (0.0000)*
RR	43.3900 (0.0000)*	19.5080 (0.0000)*		2.6696 (0.0000)*	0.7303 (0.8366)	0.0212 (0.0031)*
HV	0.9399 (0.3901)	3.0232 (0.0488)*	0.7113 (0.4911)		0.1784 (0.8366)	5.8013 (0.0031)*
CS	67.6460 (0.0000)*	12.4600 (0.0000)*	1.3050 (0.2713)	9.1512 (0.0001)*		0.0791 (0.9239)
IR	11.4190 (0.0000)*	0.1796 (0.3075)	0.9869 (0.3728)	2.4273 (0.0884)*	0.3398 (0.7119)	

Table 5: Continuation

EUR	SPOT	ZDS	RR	HV	CS	IR
SPOT		0.8128 (0.4437)	2.6477 (0.0709)*	3.3229 (0.0362)*	0.3020 (0.7393)	-
ZDS	5.4545 (0.0043)*		0.6563 (0.5188)	1.9679 (0.1399)	0.0641 (0.9379)	2.3689 (0.0937)*
RR	15.0680 (0.0000)*	16.6650 (0.0000)*		3.3456 (0.0353)*	0.5418 (0.5817)	-
HV	0.2914 (0.7472)	0.1737 (0.8406)	7.4606 (0.0006)*		2.0179 (0.1331)	-
CS	3.5521 (0.0288)*	4.0351 (0.0178)*	1.0235 (0.3595)	0.4430 (0.6421)		-
IR	-	5.3061 (0.0050)*	-	-	-	

* Means rejection of the hypothesis about the lack of causality at 0.10 confidence level

The table presents F-statistics for a test that variables in a left-hand column Granger cause variables in a top row.

Source: own calculations

Table 6. Stationarity tests of variables

variable	*p-value* for ADF test	*p-value* for KPSS test	ADF decision - H0: I(1) at 5% CL	KPSS decision - H0: I(0)
EUR/PLN SPOT	0.7291	value p < .01	I(1)	I(1)
EUR/PLN ZDS	0.1258	value p < .01	I(1)	I(1)
EUR/PLN RR	0.0135	value p < .01	I(0)	I(1)
EUR/PLN HV	0.2135	value p < .01	I(1)	I(1)
EUR/PLN CS	0.0000	value p < .01	I(0)	I(1)
PLN IR	0.4417	value p < .01	I(1)	I(1)
EUR/CZK SPOT	0.6882	value p < .01	I(1)	I(1)
EUR/CZK ZDS	0.1707	value p < .01	I(1)	I(1)
EUR/CZK RR	0.0100	value p < .01	I(0)	I(1)
EUR/CZK HV	0.0920	value p < .01	-	I(1)
EUR/CZK CS	0.0000	value p < .01	I(0)	I(1)
CZK IR	0.5778	value p < .01	I(1)	I(1)
EUR/HUF SPOT	0.9525	value p < .01	I(1)	I(1)
EUR/HUF ZDS	0.2064	value p < .01	I(1)	I(1)
EUR/HUF RR	0.0454	value p < .01	I(0)	I(1)
EUR/HUF HV	0.2646	value p < .01	I(1)	I(1)
EUR/HUF CS	0.0000	value p < .01	I(0)	I(1)
HUF IR	0.4557	value p < .01	I(1)	I(1)
EUR/USD SPOT	0.2270	value p < .01	I(1)	I(1)
EUR/USD ZDS	0.1747	value p < .01	I(1)	I(1)
EUR/USD RR	0.0030	value p < .01	I(0)	I(1)
EUR/USD HV	0.1978	value p < .01	I(1)	I(1)
EUR/USD CS	0.0000	value p < .01	I(0)	I(1)
EUR IR	0.9670	value p < .01	I(1)	I(1)

Source: own calculations

Table 7. Residuals stationarity test

		p-value for ADF test	ADF value for m=4, n=3735	MacKinnon (1994) decision	Blangiewicz-Charemza (1990) decision
EUR/ PLN	**Model 1**	0.0003	-3.5751	I(0)	rejected
	Model 2	0.0000	-5.2006	I(0)	I(0)
	Model 3	0.0000	-5.8038	I(0)	I(0)
	Model 4	0.0000	-7.1084	I(0)	I(0)
	Model 5	0.0000	-3.9432	I(0)	I(0)
EUR/ CZK	**Model 1**	0.0002	-3.7280	I(0)	rejected
	Model 2	0.0004	-3.5377	I(0)	I(0)
	Model 3	0.0000	-4.8328	I(0)	I(0)
	Model 4	0.0000	-5.3141	I(0)	I(0)
	Model 5	0.0015	-3.1660	I(0)	rejected
EUR/ HUF	**Model 1**	0.0111	-2.5297	I(0)	rejected
	Model 2	0.0000	-6.0398	I(0)	I(0)
	Model 3	0.0000	-5.4577	I(0)	I(0)
	Model 4	0.0000	-6.1483	I(0)	I(0)
	Model 5	0.0001	-3.8890	I(0)	rejected
EUR/ USD	**Model 1**	0.0003	-3.6418	I(0)	rejected
	Model 2	0.0000	-7.2869	I(0)	I(0)
	Model 3	0.0000	-6.6566	I(0)	I(0)
	Model 4	0.0000	-6.9160	I(0)	I(0)
	Model 5	0.0005	-3.4916	I(0)	rejected

Extrapolated critical value according to Blangiewicz-Charemza (1990) amounts to 3.94-4.23.
Source: own calculations

Table 10. Summary of the quality of ECM models

		Pearson correlation	Granger causality	I(1) variables	Uhat stationarity	Coefficients significance	R2	DQM
EUR/ PLN	**Model 1**	0.32	yes	yes	uncertain	yes	0.10	52%
	Model 2	0.30	yes	yes	yes	yes	0.11	43%
	Model 3	-0.56	yes	yes	yes	yes	0.34	62%
	Model 4	-	yes	yes	yes	yes	0.02	48%
	Model 5	0.10	no	yes	yes	yes	0.01	45%
EUR/ CZK	**Model 1**	0.13	no	yes	uncertain	yes	0.02	45%
	Model 2	0.06	yes	yes	yes	yes	0.02	27%
	Model 3	-0.42	yes	yes	yes	yes	0.23	55%
	Model 4	-	yes	yes	yes	yes	0.00	44%
	Model 5	-0.04	no	yes	uncertain	yes	0.00	43%
EUR/ HUF	**Model 1**	0.29	yes	yes	uncertain	yes	0.01	52%
	Model 2	0.23	yes	yes	yes	yes	0.08	40%
	Model 3	-0.54	yes	yes	yes	yes	0.31	62%
	Model 4	-	yes	yes	yes	yes	0.02	50%
	Model 5	0.22	no	yes	uncertain	yes	0.05	48%
EUR/ USD	**Model 1**	-0.37	no	yes	uncertain	yes	0.14	58%
	Model 2	-0.44	no	yes	yes	yes	0.21	56%
	Model 3	-0.61	no	yes	yes	yes	0.29	70%
	Model 4	-	no	yes	yes	yes	0.01	52%
	Model 5	0.02	yes	yes	uncertain	no	0.00	50%

Note:
Model 1 = SPOT → ATM, Model 2 = ATM → RR, Model 3 = ATM → CS, Model 4 = HV → ATM, Model 5 = IR → ATM
Source: own calculations

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