

Forecasting VIX Futures using Machine Learning and Volatility Surfaces

MAX HARPER

SID: 510471039

Finance Supervisor: Dr Richard Philip
Engineering Supervisor: Dr Clément Canonne

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22 September 2025



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Abstract

This is a concise summary of the entire paper, less than a page. It briefly presents the research problem, methodology, key results, and conclusions. The abstract must be clear and self-contained. This is the recommended structure. 1. Introduction: Provide a basic introduction (1–2 sentences) to the field that is comprehensible to scientists from any discipline, and a more detailed introduction (2 to 3 sentences) that is comprehensible to scientists in the relevant discipline and which introduces the gap in the literature. 2. Aims: State the hypothesis of the study (1 sentence). 3. Methods: Provide a brief description of the experimental design (1–2 sentences). 4. Results: Clearly state the most important finding, in both subjective terms (We found that treatment X resulted in a higher survival rate than treatment Y) and in the form of real data. Explain how this result compares to what was originally thought (i.e. was your hypothesis correct) (3–4 sentences). 5. Conclusions: Explain the implications of your results and why they are important (1–2 sentences).

Acknowledgements

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1. Introduction

Volatility in financial markets has attracted significant attention from investors and academics aiming to mitigate losses from large price deviations [1]. Successful forecasting of volatility would allow fund managers to sell or hedge their positions in advance to reduce risk. The introduction of volatility derivative products has also allowed investors to hedge their portfolios with “long volatility” products and speculators to trade the markets future expectations of volatility [2]. The inclusion of this hedge in a portfolio has been shown to improve risk adjusted returns [3]. However, research has consistently shown that volatility is a complex phenomenon that cannot be easily forecasted [4].

A prominent measure of the market implied volatility is the Chicago Board Option Exchange’s (CBOE) Volatility Index (VIX) which weights 30 day ahead S&P500 options quotes every 15 seconds to form a weighted average of the markets implied volatility [5]. This serves as a “fear gauge” for the market and importantly its value is negatively correlated to down-swings in equity markets as options become more expensive for investors [6].

————— FUTURES —————
 ————— FORECAST HARD —————
 —————
 ————— RESEARCH —————
 ————— QUESTIONS —————
 ————— FINDINGS —————
 —————

TODO

- discuss prev attempt exogenous, dimensionality reduction and ML provide a novel way to feature reduce the IV surface into something analysable compared to network approaches

2. Literature Review

2.1. Volatility, VIX and VIX Futures

Volatility is defined as a measure of the uncertainty of the return realised on an asset [7] however the specifics of how this is calculated and measured have multiple forms. While volatility is often modeled latently using conditional variance, it is measured ex post as “realised volatility” using the standard deviation of returns. Realised volatility is however variable and error prone due to market microstructure fluctuations and varying sampling frequency [8]. There is also “implied volatility”, a forward-looking estimate of realised volatility. This is the one free parameter of options pricing under Black-Sholes [9] which reflects the markets expectation of volatility, calculated by inverting the pricing formula with an option’s market price. The assumptions underlying the calculation of implied volatility have several problematic elements such as the log-normal return distribution and the use of a constant value for volatility, however, it still serves as a useful proxy for risk and uncertainty [1].

The VIX index is a weighted average of implied volatility. It is weighted using the inverse square of an option's strike price to create a payoff independent of underlying index price and proportional to volatility [10]. When markets experience uncertainty, investors pay more for the hedging insurance provided by options, thus increasing the value of the VIX index [11]. This again is why it serves as a prominent "fear gauge" from within the options market [6]. The VIX formula is:

$$\text{VIX} = 100 \times \sqrt{\frac{2}{T} \sum_i \frac{\Delta K_i}{K_i^2} e^{RT} Q(K_i) - \frac{1}{T} \left(\frac{F}{K_0} - 1 \right)^2} \quad (1)$$

Where:

- T is the time to expiration (in years) of the option.
- K_i is the i -th strike price.
- ΔK_i is the interval between strike prices.
- R is the risk-free interest rate to the option's expiration.
- $Q(K_i)$ is the midpoint of the bid-ask spread for the option with strike K_i .
- F is the forward index level, derived from option prices.
- K_0 is the first strike below the forward index level F .

There have been concerns raised with this calculation as CBOE applies a cutoff rule once two consecutive option strikes with no bids and offers are encountered; which can exclude options and produce erratic jumps [12].

The VIX is composed of thousands of S&P500 puts and calls which constantly change. Thus, maintaining a replication of the VIX would involve an impractical amount of transactions in options markets affected by illiquidity. The VIX is therefore not directly tradable, but from 2004, monthly cash-settled VIX futures have been traded on the CBOE futures exchange [5]. This serves as a highly-liquid marketplace for speculators to trade their expectations of volatility, theoretically free from arbitrage with a replicated VIX. It also provides a product for the "long volatility hedge" discussed earlier, with its negative correlation improving portfolio protection in market crashes [13]. It is worth noting that this is not a completely pure market of hedgers and speculators, with significant evidence of attempted manipulation of VIX futures at settlement time via deep out-of-the-money (OTM) put options [14].

Comparing the prices of VIX futures contracts across different maturities yields the futures term structure. Traditional theory suggested that the futures term structure reflected the market's expectations of future prices (the Expectations Hypothesis) [15]. While the shape of this curve fluctuates over time, its long-run average tends to be upward sloping, centered around a long term mean level [16]. This structure is known as contango, where futures prices exceed the spot VIX, and implying that holding a long position in VIX futures typically results losses over time as the futures price converges to spot [17].

More recent literature strongly rejects the Expectations Hypothesis, instead suggesting the existence of a time varying investor risk premium. This is calculated as the difference between realised and implied volatility, and quantifies the premium that sellers charge to compensate for taking downside risk in the event of a market crash [18]. Dew-Becker [19] finds this on average to be negative, implying that there is a premium, and it is largest for near-term futures. Bollerslev, Johnston and Nossman all confirm the existence of this phenomenon and show its predictive ability on index returns, volatility product returns and the VIX index respectively [20][16][21]. Risk premiums have been demonstrated to display counter-intuitive behaviour such as staying constant during risky periods [22].

2.2. Forecasting VIX Futures

Previous research approaches forecasting VIX futures through two techniques: volatility models and machine learning. Traditional volatility models use assumptions about the process of volatility in order to derive pricing formulas; notably using historical volatility models, generalised autoregressive conditional heteroskedasticity (GARCH) models and stochastic volatility models. These parametric forms are not used by the machine learning approaches which instead use explanatory variables to estimate the futures price. Machine learning methods can be distinguished across higher and lower frequency prediction intervals and further by the types of explanatory variables used.

The simplest methods used in past research regress future volatility using the historical volatility series. These include autoregressive (AR) models, autoregressive integrated moving average processes (ARIMA) and Heterogeneous AR models (HAR). These models are oversimplified, constrained by linearity and have been shown to be inconsistent with observed market behavior [23][1]. These are typically used as baseline forecasts in machine learning papers and do not produce notable forecasting accuracy [24][25][26][27].

GARCH and stochastic volatility models utilise different forms and assumptions to model complex behaviour not captured by historical volatility models. GARCH models assume volatility follows a conditional autoregressive process, which is designed to capture more complex processes like volatility clustering [28]. This was used to price VIX futures with a Heston-Nandi GARCH model and extended using a GJR-GARCH model, with both models aimed at incorporating the asymmetrical responses of implied volatility to returns [29][30]. In contrast, stochastic models assume that underlying volatility follows a stochastic process and forecast futures as the conditional expected mean of this volatility. A prominent example of this process is the stochastic square root mean reverting process first explored by Zhang and Zhu [31][32] and later expanded upon by Dotsis et al [33] by adding jumps. Other processes such as the log Ornstein-Uhlenbeck process (diffusion with a mean reverting drift) improved the fit of VIX futures data with the addition of a central tendency component [23].

These models have two main limitations. Firstly, VIX futures pricing models involve several layers of abstraction that can potentially oversimplify the relationship between the VIX index and VIX futures prices. For instance, Zhang and Zhu [31] propose a linear relationship between the squared VIX and instantaneous variance, leading to a futures price derived from a risk-neutral integral. These assumptions

may not always hold in reality and as discussed earlier, VIX futures are influenced by a interplay of market expectations and risk premia, suggesting a more complex relationship. VIX futures move in the opposite direction to the VIX on 26% of trading days, implying that forecasting volatility, implied volatility and futures on the products are distinct tasks [34]. This highlights the value of machine learning models which can be directly fit to VIX futures price without any abstraction or assumptions.

Furthermore, these models are restricted by the rigidity of their assumptions. Small alterations to the underlying process for volatility constantly yield small improvements between papers however there is no consensus about the underlying dynamics [33][23]. The success of multiple underlying processes suggests that each simplifies a more complex underlying pricing mechanism. Poon surveys 93 papers and found GARCH models don't show significant improvement in volatility forecasts compared to more simplistic historical volatility methods [1]. This inherent rigidity in model structure indicates a clear need for more flexible and adaptable forecasting techniques, such as those offered by machine learning algorithms.

Machine learning's flexibility and generalisation capabilities have led to impressive results in volatility forecasting. Deep learning and ensemble methods, in particular, have demonstrated superior performance over traditional models in predicting realised variance across various studies, with similarly promising outcomes for implied volatility forecasts [35][36].

One focus of current machine learning research into the VIX specifically is high frequency pricing using deep learning. Hirta and Osterrieder [37][38] use recurrent neural networks and long-short term memory (LSTM) models to process S&P500 options quotes and predict the VIX index on a minute to minute basis, while Hirta extends this to also price VIX futures. This highlights the predictive efficacy of options, however the minutely time scale has limited applicability for investors looking to hedge. Both papers also don't quantify or elaborate on any trading strategies based on their forecasts and the deep learning approaches offer limited economic insights as to how these S&P500 options affect prices.

More research has been devoted to "mid-frequency" prediction intervals, characterised by mixed independent variables and predictive success. Early attempts by Konstantinidi [25][27] used exogenous macro-economic factors such as oil price and bond curve slopes to forecast VIX and VIX futures, concluding that the index and its futures have limited predictability. In contrast to this, macro-economic predictors were however shown to produce profitable returns on a longer month-to-month time scale by Vrontos [39]. The returns and volatility of related financial markets have exhibited more success as predictors however experience significant drawdowns and variability when used in trading strategies [24][40]. Finally, a comparison of the trading strategies shown in these papers highlights the need for more complexity with option straddles outperforming simplistic trading strategies, such as taking a long position if VIX forecasts are positive [27][24].

In contrast to exogenous factors, VIX derivative products show notable predictive value across multiple studies. Johnston [16] shows that the second component of the VIX futures term structure (known as slope) is a statistically and economically significant predictor of VIX futures returns. Hosker [26] also uses spreads between

VIX futures and options as predictors to predict 3 and 5 day-ahead VIX futures returns with the best results emerging from deep learning models. These studies broadly highlight the predictive merit of volatility derivative market sentiment and curve structure.

The machine learning attempts at forecasting VIX futures reveal a marked contrast between "black box" deep learning models and more interpretable linear approaches. While deep learning techniques [37][38] often achieve strong predictive performance, they tend to provide limited economic insight. In contrast, explainable models allow for a clearer assessment of variable significance and predictive value which is increasingly valued within the machine learning and finance communities [41][35]. Notably, the most robust studies extend their evaluation beyond traditional error metrics such as RMSE and MAE by incorporating economic performance measures like the Sharpe ratio to quantify trading strategy efficacy [16].

Machine learning offers a viable framework to both forecast VIX futures and assess variable efficacy. Directly forecasting futures prices using machine learning bypasses the multiple layers of abstraction required of traditional modeling approaches. This enables models to more effectively capture the complex interplay of expectations and risk premia present in the VIX futures markets. As discussed, medium-frequency prediction remains largely dominated by models using exogenous variables and VIX derivative data. While the option quote surface has been employed in high-frequency forecasting of VIX futures, there is also notable gap in the current literature regarding the predictive efficacy of the S&P 500 option-implied volatility surface for forecasting VIX futures in the medium frequency.

2.3. The SPX Implied Volatility Surface

A consistent finding in volatility literature is the strong predictive power of option implied volatility (IV). Latane [42] found this to be a better predictor of future realised volatility than historical volatility and is corroborated by Poon [1], who observed implied volatility outperforming historical volatility models in a significant majority (76%) of reviewed studies. Interestingly, it has been shown that the VIX index itself, as a measure of implied volatility, forecasted future realised volatility more accurately than other models [43].

By comparing implied volatilities of same-maturity options across strikes, one observes the well-documented "smirk" or "skew," wherein deep out-of-the-money (OTM) puts carry higher implied volatilities as compensation for downside insurance [44][7]. The shape and slope of this surface has been shown to predict equity returns [45][46] and histogram-based measures of skew were found to be significant predictors of the probability of market crashes [47].

Short-dated OTM puts, in particular, provide a sensitive gauge of market risk sentiment. Their convex payoff structure makes them attractive to informed traders ahead of downturns, leading to price and volatility spikes that may act as early warning signals [46][48]. Options markets more broadly have been found to lead equity price discovery, often reflecting non-public information before it becomes evident in spot prices [49]. A striking historical case occurred before the 1987 crash, when S&P 500 OTM puts were priced at a 25% premium over theoretical values, anticipating the subsequent 23% market decline [50].

Given the high dimensionality of the IV surface, PCA has previously been used to study the dynamics of implied volatility surfaces [51][52], yielding the traditional ‘level and slope’ interpretations for the first two components [53]. These studies largely employ PCA descriptively rather than as forecasting input as this research explores. This research addresses that gap by applying PCA to the IV surface specifically for forecasting VIX futures, leveraging dimensionality reduction to extract predictive signals from complex data.

3. Data

3.1. Data Sources

Daily close and last price data for VIX futures was obtained from LSEG’s Datascope platform from June 2004 (product inception) to June 2025. Specifically this contained rows of quote dates, contract identifiers, last price and universal close price which was used for significance testing. This platform automatically performs contract rolling hence this was not required during pre-processing. The validity of this data was also cross-checked with other data sources such as CBOE for deviations which yielded only small variation.

Daily closing SPX option quote and implied volatility data was collected from OptionMetrics. This contained quote date, expiry date, strike price, price, implied volatility and option greek metrics from Jan 1996 to Feb 2023 and forms the basis of the implied volatility surface predictive features. Due to data availability limitations, the SPX options dataset was truncated at February 2023.

Finally, daily S&P500 close data was collected from Yahoo Finance which was used to standardise and discretise option strike prices into "percentage moneyness" as is discussed during Data Preparation and Feature Engineering. Spot VIX data was also collected from Yahoo Finance for Exploratory Data Analysis.

3.2. Data Preparation

The VIX futures dataset was truncated at January 2006 to avoid the higher incidence of missing values around the product’s introduction. After this cutoff, rows with missing price data were removed, representing 0.75% of trading days.

Compared to the VIX futures, more substantial processing was necessary to construct the implied volatility surface. Option quote dates were first aligned temporally with S&P 500 closing prices to calculate a "moneyness" measure. This was defined as the strike price divided by the index level in order to standardise strike prices across time as used in multiple studies [26][54]. This measure was then discretised into 10% moneyness buckets ranging from 80% to 110% to categorise options into groups ranging from out-of-the-money puts to at-the-money calls. Similarly, time-to-expiry was calculated in days and grouped into four buckets: less than 30 days, 60 days, 90 days, and 180 days. Finally, to aid data completeness, missing values were filled with their rows mean value. By aggregating quotes within each two-dimensional bucket and averaging their implied volatilities, disparate option contracts were transformed into a discretised implied volatility surface, forming the base of the predictive features.

This discretised surface was temporally joined to the VIX futures data which formed a combined daily dataset from January 2006 to February 2023.

3.3. Exploratory Data Analysis

The purpose of this exploratory data analysis is to characterize the statistical properties of the VIX futures and SPX implied volatility surface. This will identify features such as contango in the term structure and the volatility smirk, which will later inform feature engineering and model design.

VIX Futures and VIX

Examining the mean term structure of VIX futures reveals the contango structure from the front month mean of 19.517 to the 8th month mean of 22.250 as described by Johnston [16]. This long-term contract mean value is the markets long-term expected mean of volatility. A higher standard deviation of 7.836 is also observed in the front month compared to the 4.971 of the 8th contract given its higher sensitivity and reactivity to spot movements. This is also reflected in the inter-quartile range and maximum values, which are higher for near-term contracts compared to longer-term as these contracts don't adjust as much with spikes. It also worth noting the high standard deviation representing 40% of the mean value.

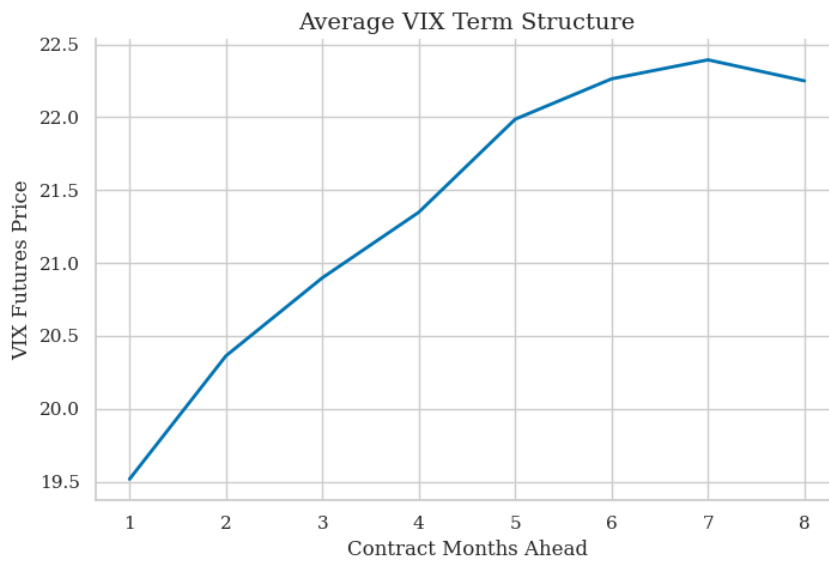


FIGURE 1: Mean VIX Futures Term Structure

TABLE 1: Summary statistics of VIX Futures Contracts One to Eight Months Ahead (VXc1–VXc8)

	VXc1	VXc2	VXc3	VXc4	VXc5	VXc6	VXc7	VXc8
Mean	19.517	20.363	20.899	21.348	21.987	22.264	22.394	22.250
Std	7.836	7.057	6.490	6.082	5.851	5.576	5.319	4.971
Min	9.600	11.300	12.200	12.990	13.470	13.900	14.300	14.690
Median	17.205	18.250	18.800	19.300	20.105	20.385	20.700	20.485
Max	81.950	70.800	60.080	51.680	47.760	45.990	44.500	44.000

This temporal variance in correlation to the underlying spot can be quantified as seen in Table 2. Since the front month contract is the nearest to expiry it has the highest correlation at 98.1% compared to 77.5% for the 8th contract. The front month contract’s high correlation with spot VIX can be seen over time in the overlaid time series in Figure 2, which also underscores its role as a “fear index,” with pronounced spikes observed during the Global Financial Crisis reaching 67.9 and 81.95 during the COVID-19 pandemic. The front-month contract’s strong correlation with the VIX, combined with its superior liquidity, makes it the most suitable instrument for trading directional views on volatility and thus the primary focus of the subsequent analysis.

TABLE 2: Correlation coefficients of VIX futures contracts with the spot VIX

Contract	Correlation (%)
VXc1	0.981
VXc2	0.941
VXc3	0.905
VXc4	0.875
VXc5	0.843
VXc6	0.815
VXc7	0.793
VXc8	0.775

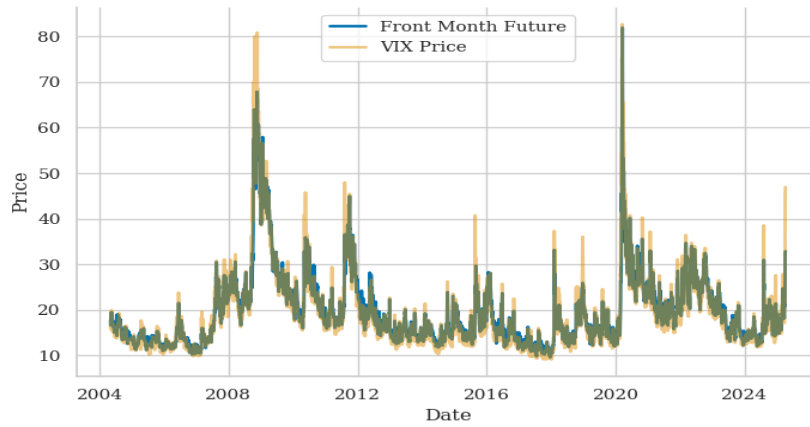


FIGURE 2: VIX Front Month Future Price and VIX over Time

Examining the distribution of the front-month VIX futures contract highlights distinctive properties of volatility. The skewness of 2.28 and the corresponding histogram reveal a pronounced right tail, indicating that large upward moves in volatility are more frequent than large downward moves. In addition, the kurtosis of 7.65 reflects a strongly leptokurtic distribution, with a much higher probability of extreme outcomes than a Gaussian benchmark. These features are consistent with the presence of volatility shocks, a phenomenon often incorporated into econometric models through explicit jump components [23][45][55].

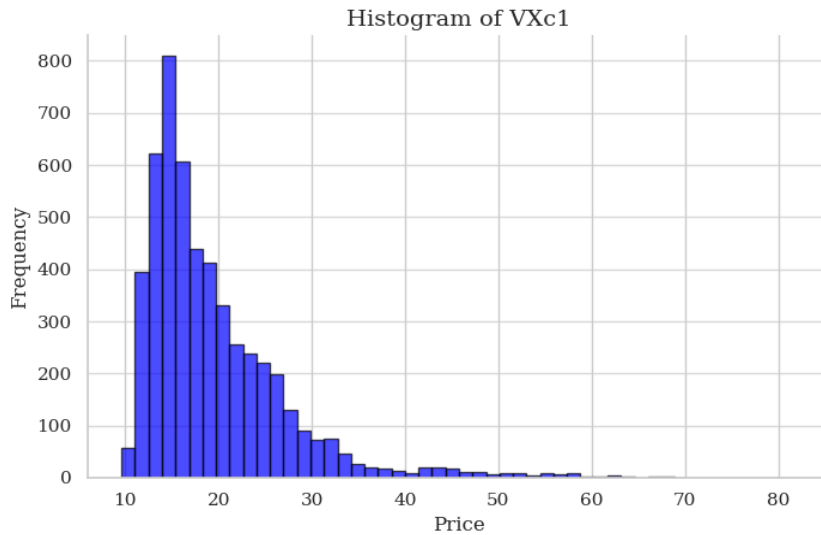


FIGURE 3: VIX Front Month Future Price Histogram

SPX Implied Volatility Surface

Plotting the mean implied volatility against moneyness reveals the well-documented volatility smirk, consistent with previous studies, as option issuers demand higher compensation for highly leveraged risk insurance (tail risk pricing) [44]. This is evident in the 80% moneyness bucket, which exhibits a mean implied volatility of 0.283 compared to 0.154 for at-the-money (ATM) options. Examining the surface across the term structure shows mixed results: implied volatility for 80% moneyness options declines notably across longer expiries, whereas ATM options maintain a near-constant volatility around the mean of 0.154.

Interestingly, the highest mean, maximum, and variance of implied volatility are observed for the 0-day expiry 80% moneyness options, representing short-dated out-of-the-money puts. This highlights the region of the surface that is most pronounced in risk sentiment signaling [50]. Nevertheless, valuable information is embedded across the entire surface. To capture these broader patterns, the subsequent analysis applies Principal Component Analysis, providing a more holistic and dimension-reduced representation of the volatility surface.

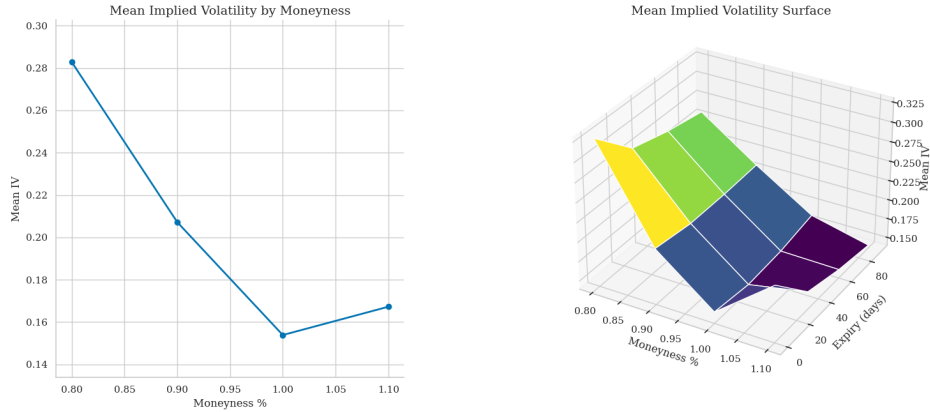


FIGURE 4: Volatility Smirk and Mean SPX Implied Volatility Surface

TABLE 3: Mean implied volatility by moneyness buckets

Moneyness	Mean IV
80%	0.283
90%	0.207
100%	0.154
110%	0.167

TABLE 4: Summary statistics of implied volatility by expiry and moneyness

Expiry / Moneyness	Mean	Std. Dev.	Min	Max
0 days, 80%	0.327	0.080	0.184	0.976
0 days, 90%	0.212	0.085	0.107	0.897
0 days, 100%	0.154	0.076	0.066	0.785
0 days, 110%	0.212	0.063	0.109	0.664
30 days, 80%	0.280	0.075	0.156	0.834
30 days, 90%	0.205	0.077	0.109	0.775
30 days, 100%	0.148	0.072	0.070	0.699
30 days, 110%	0.163	0.053	0.095	0.624
60 days, 80%	0.267	0.071	0.149	0.773
60 days, 90%	0.205	0.072	0.113	0.700
60 days, 100%	0.152	0.069	0.070	0.633
60 days, 110%	0.151	0.053	0.080	0.563
90 days, 80%	0.258	0.067	0.156	0.688
90 days, 90%	0.207	0.067	0.119	0.624
90 days, 100%	0.161	0.066	0.078	0.581
90 days, 110%	0.143	0.057	0.075	0.535

4. Methodology

4.1. Feature Engineering

To extract informative features from the discretised SPX implied volatility surface, Principal Component Analysis (PCA) was applied. PCA generates latent factors that are linear combinations of the original variables, chosen to maximise the variance explained. Each successive component is constructed to be orthogonal to those that precede it. PCA thus reduces dimensionality while capturing the dominant and unique modes of variation. This provides both parsimonious inputs for machine learning models and an alternative perspective on the surface’s dynamics [56][57].

As this analysis is purely conducted on the discretised IV surface, each principle component can be represented as:

$$PC_n = \alpha_1 IV_{0,0.8} + \alpha_2 IV_{0,0.9} \dots \alpha_{16} IV_{180,1.1}.$$

The sign and magnitude of the loading coefficients (α_i) can highlight the dominant sources of variation and can be examined across the surface to associate principal components with underlying economic factors. The first three principal components accounted for 96.1% of the explained variance, with subsequent components contributing negligibly (Figure 5). Given this, only the first three were retained for analysis.

Furthermore, preliminary statistical tests supported the suitability of applying principal component analysis. Bartlett’s Test of Sphericity yielded a p-value of 0.000,

indicating significant correlations among features, while the Kaiser–Meyer–Olkin measure returned a value of 0.927, demonstrating a high degree of shared variance.

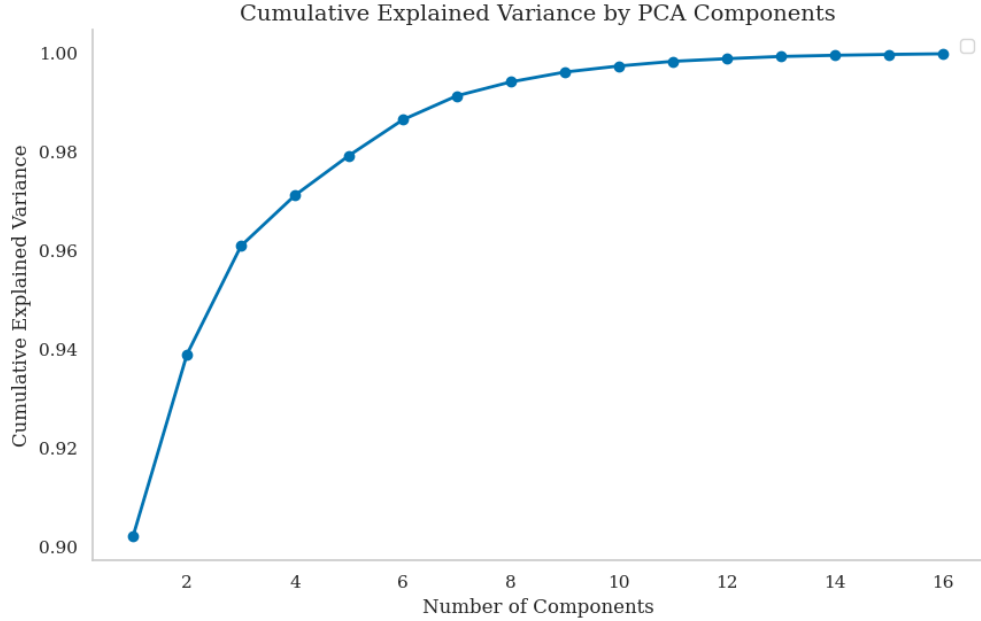


FIGURE 5: Explained Variance of Principle Components

4.2. Models

A wide variety of machine learning models ranging from linear regressions to random forests and neural networks were tested and considered. Baseline controls were also included using traditional forecasting approaches, such as ARIMA, commonly employed in machine learning studies [24][26][27].

Hyperparameter optimisation was performed using a grid search over key parameters, with a validation subset spanning November 2016 to July 2019. The first three principal components of the implied volatility surface were used as predictors to forecast front-month VIX futures prices at the 1-day horizon. Final model parameters were selected based on the validation root mean squared error (RMSE), reported in Table 5.

Most machine learning models showed comparable performance on the validation set, with ARIMA having the highest validation RMSE. The low shrinkage parameters selected for Ridge and Lasso indicate that regularisation was not strongly required for the regression coefficients. In contrast, the relatively shallow maximum depths chosen for Gradient Boosting and Random Forest suggest that these models have some potential to overfit the data.

TABLE 5: Models considered in the study with Hyperparameters and Validation Performance

Model	Key Hyperparameters	Validation RMSE
Machine Learning Models		
Linear Regression	–	1.327
Ridge Regression	Shrinkage parameter $\alpha = 0.1$	1.327
Lasso Regression	Shrinkage parameter $\alpha = 0.001$	1.326
Random Forest	Number of trees $n = 100$, max depth $d = 5$	1.306
Gradient Boosting	Number of trees $n = 125$, max depth $d = 1$, learning rate $l = 0.5$	1.376
Neural Network (MLP)	Hidden layer size $n = 100$, learning rate $l_0 = 1$, max iterations = 50	1.250
Long Short-Term Memory	Hidden layer size $n = 50$, learning rate $l_0 = 0.001$, epochs = 250	1.458
K-Nearest Neighbours	Number of neighbours $k = 8$	1.396
Baseline Control		
ARIMA	Orders $(1, 1, 3)$	1.496

4.3. Training and Evaluation Framework

This research will employ a multi-faceted testing approach to evaluate model performance and practical utility.

Dependent Variable

This study models VIX futures prices rather than returns for several reasons. Returns are highly volatile and heavy-tailed compared to the price series: for example, a move from \$15 to \$18 represents a 20% change but only a \$3 absolute shift. This is further demonstrated by the front-month return series having a standard deviation around 40% of its mean. Logarithmic transformations can reduce this volatility but at the cost of intuitive meaning and added analytical complexity. In contrast, modeling raw prices provides a more stable and interpretable framework for assessing predictive performance, facilitates comparison with other studies that mainly use price, and generally yields a higher proportion of explained variance, as shown in Table 6.

TABLE 6: Full Sample Fit Metrics Across Dependent Variables with Linear Regression of PC1, PC2 and PC3

Dependent Variable	R^2
One Day Return	0.030
One Week Return	0.104
One Month Return	0.295
Vxc1 T+1	0.957
Vxc1 T+3	0.920
Vxc1 T+5	0.885

Machine Learning Evaluation Framework

First, a standard 80:20 train-test split will be implemented by withholding the final 20% of the time series data for out-of-sample testing, spanning July 2019 to February 2023. To mitigate the risk of overfitting to a specific time period and improve generalisation, this will be complemented by a 5 fold expanding time series cross validation averaging metrics across all folds as per Hosker’s paper [26]. See Figure 6 for the dates of each period.

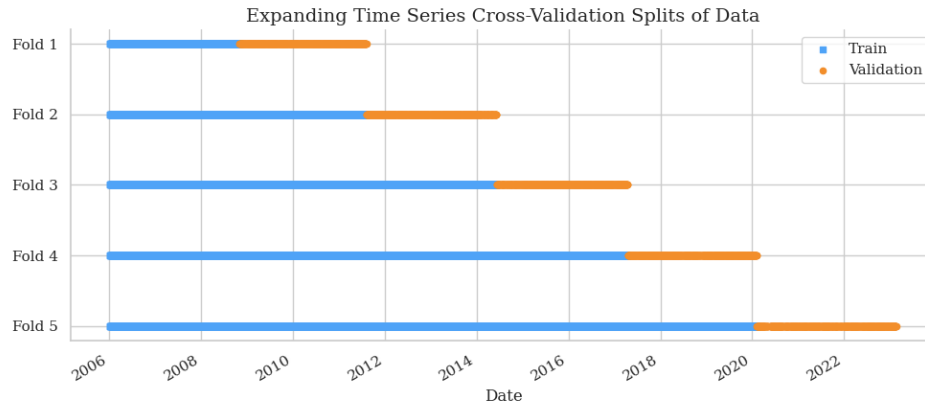


FIGURE 6: Expanding Time Series Cross Validation

To strengthen the robustness and practical relevance of the results, multiple forecast horizons will be examined. These include a 1-day-ahead forecast, consistent with multiple studies [16][24][25], as well as 3 and 5 day horizons used by Hosker [26]. These forecasts will be for the price of the front month contract: $VXc1 = f(PC_1, PC_2, PC_3)$, with tests collecting Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and explained variance (R^2) to evaluate model performance.

A modified version of these tests was used for the traditional forecasting baselines as these operate on time series data. ARIMA models were trained on the VXc1

training series, and forecasts were generated one step at a time. After each step, the model's internal state was updated with the new observation, but the model parameters were not retrained. This allows a more accurate comparison with the machine learning models.

Economic Significance Evaluation Framework

Economic significance will be assessed using a trading strategy simulation. The models will be trained on the first 50% of the dataset, with the remaining data divided into three expanding folds for evaluation. Trading costs and the a historical median spread of 5 cents, are incorporated to approximate realistic conditions. The trading simulation will be constructed the following trading rules:

If $\hat{y}_{t+1} - y_t > \text{threshold}$; go long and hold until $\hat{y}_{t+1} - y_t < \text{threshold}$.

If $\hat{y}_{t+1} - y_t < -\text{threshold}$; go short and hold until $\hat{y}_{t+1} - y_t > -\text{threshold}$.

Where y_t is the current VIX front month price on day t , and \hat{y}_{t+1} is the forecast for tomorrows.

The trading rule acts directionally on the forecasted price change $\hat{y}_{t+1} - y_t$, however positions are only entered when the predicted move has sufficient value relative to the current price, regulated by the threshold. This again uses $\hat{y}_{t+1} = f(PC_1, PC_2, PC_3)$ to forecast.

Comparisons across studies can then be made using common metrics when the time scales are broadly comparable. Normalised measures, such as the annualised Sharpe ratio and annualised compound return, will be collected and are the preferred metrics for cross-study evaluation. Adjustments to features, feature subsets, and trading strategy parameters will also be explored to enhance performance metrics and provide separate analysis.

5. Results and Discussion

5.1. Principle Components

Principle Component One

The first principal component (PC1) of the implied volatility surface closely tracks the VIX front-month futures price (VXc1). These variables exhibit a linear correlation of 98.34%, and a regression of VXc1 on PC1 produces an R^2 of 0.967. This relationship is evident in the scatter plot (Figure 8) and in the time series of PC1 (Figure 9), which captures the characteristic VIX peaks during the Global Financial Crisis and the COVID-19 pandemic. Further statistical testing through a Johansen test confirmed rank one co-integration at a 95% confidence level, implying a stable relationship between these two variables, see Table 17.

The loadings heatmap shows minimal variation, with all values ranging from 0.16 to 0.31, indicating that PC1 functions as a weighted average of implied volatility, similar to the VIX index (Figure 7). This observation is consistent with prior PCA analyses of financial curves, where the first principal component is typically interpreted as the "level" of the curve [53]. Similarly, cross-sectional PCA of the implied volatility surface has also identified a dominant "level" factor [52].

TABLE 7: OLS Regression of VXc1 on PC1

Variable	Coefficient	Std. Error	t-statistic	p-value
Intercept	20.364	0.023	878.570	0.000
PC1	30.055	0.229	131.418	0.000
R-squared	0.967			
Adjusted R-squared	0.967			
F-statistic	1.727e+04			
Prob (F-statistic)	0.000			

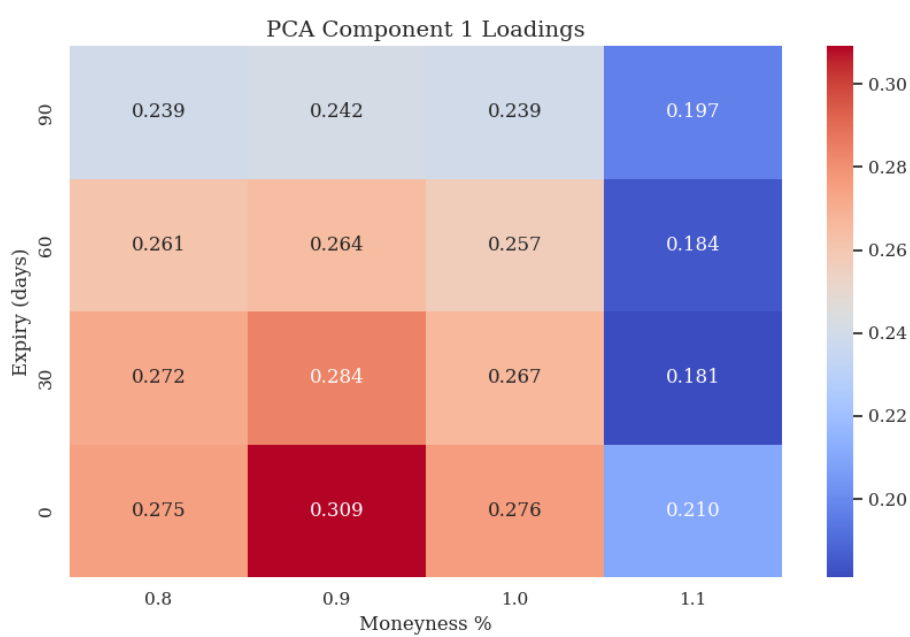


FIGURE 7: Loadings of PC1 by Moneyiness and Expiry

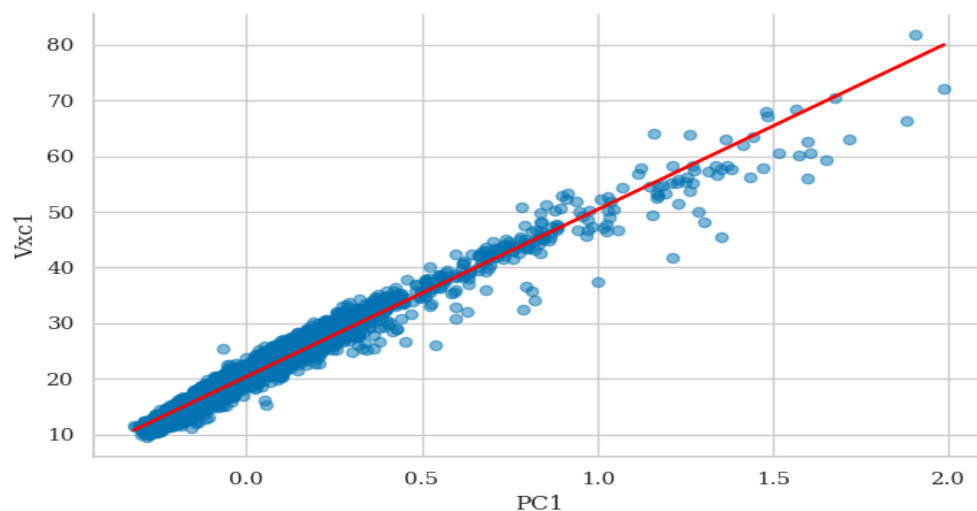


FIGURE 8: PC1 scattered against VIX front month

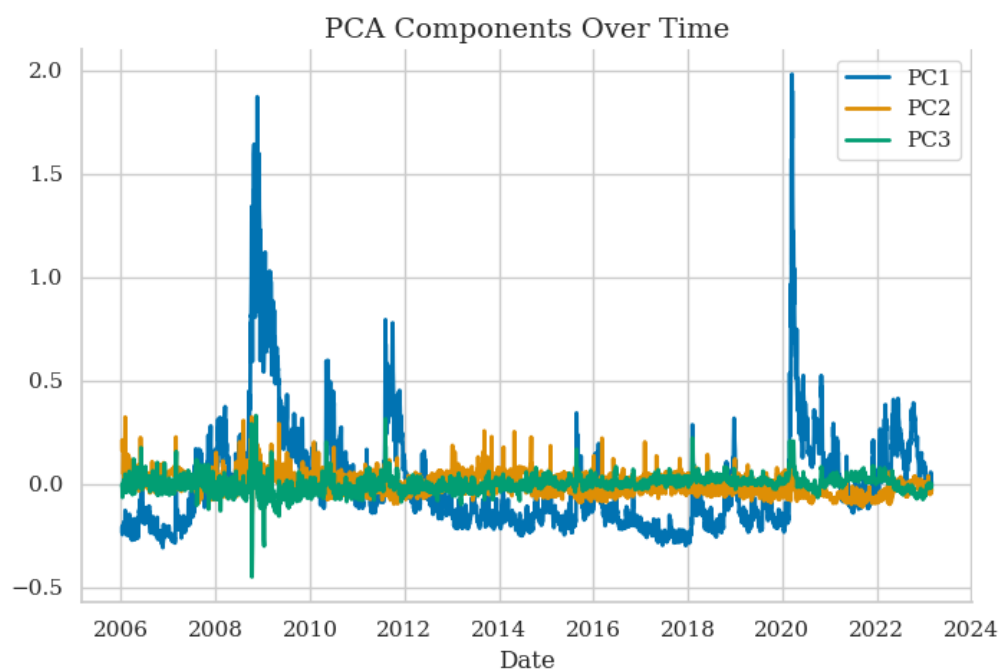


FIGURE 9: Principle Components over Time

Principle Component Two

The second principal component (PC2) is associated the skew of the option smirk. Previous work has shown the second component typically represents skew or slope of the surface [51][53] and this can clearly be seen in the loadings heatmap 10.

Other studies have linked this skew factor to VIX returns [16], and to investigate this, PC2 was regressed on VIX front-month returns over one-day, one-week, and one-month horizons. All regressions produced low R^2 values indicating that PC2 captures variation in the surface largely independent of short-term VIX returns.

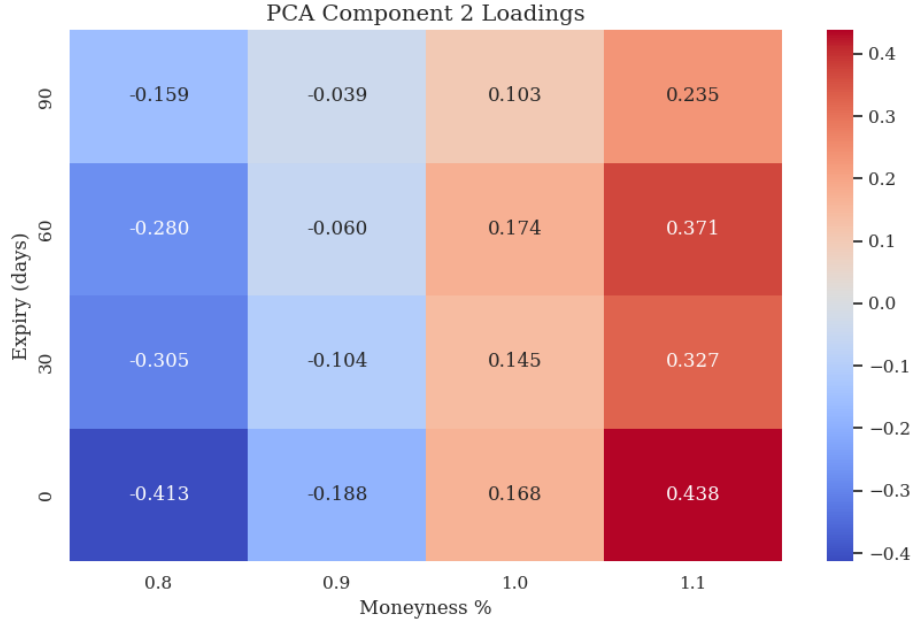


FIGURE 10: Principle Components Two Loadings

TABLE 8: OLS Regression Statistics: PC2 Regressed on Various Predictors

Predictor	R-squared
One-day return	0.015
One-week return	0.039
One-month return	0.052

Principle Component Three

The third principal component (PC3) has less intuitive interpretations than the previous components. The loadings heatmap has negative loadings on longer expiry options and positive loadings on shorter dated options, with notably high loadings on short dated OTM puts and short dated ATM calls. This factor thus seems to capture some term structure dynamics as well as panic spikes in the IV of short-dated puts and calls.

Unlike PC2, PC3 exhibits a clear correlation with VIX returns. This relationship is illustrated in Figure 12, where the regression line of best fit with one-month front-month VIX futures returns is both statistically significant (p -value = 0.000)

and economically meaningful with an R^2 of 0.104, double that of PC2. These results suggest that PC3 functions as a broader panic or stress signal, capturing shifts in demand for short-dated options when markets anticipate sharp moves. This may reflect hedging activity through downside protection, or alternatively speculative demand for leveraged upside exposure, both of which intensify in periods of heightened uncertainty [50]. Its alignment with major market volatility is evident in Figure 13, where extreme values of PC3 consistently coincide with pronounced equity market turbulence.

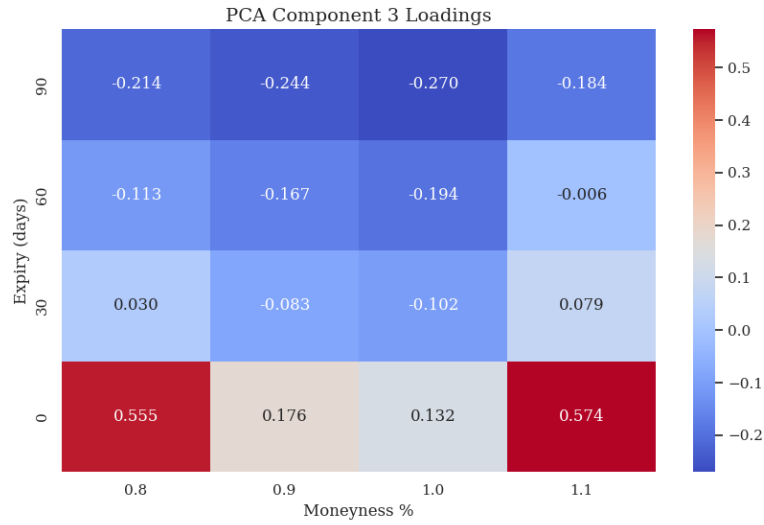


FIGURE 11: Loadings of PC3 by Moneyness and Expiry

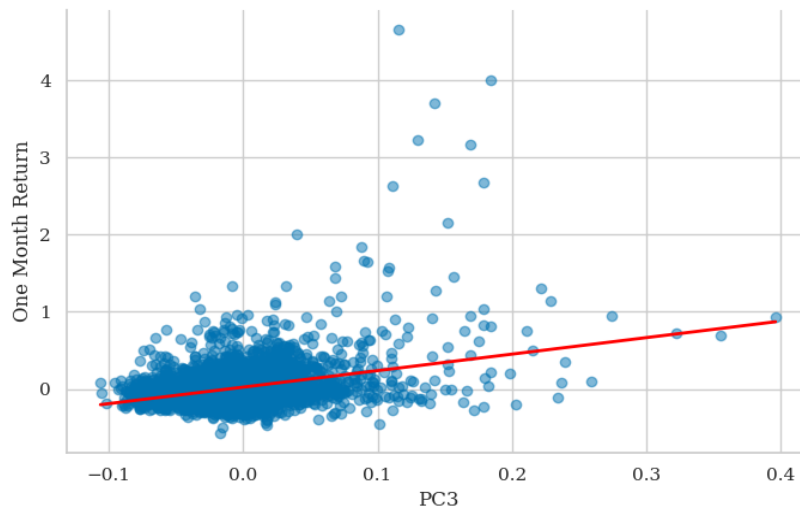


FIGURE 12: PC3 scattered against one month VIX front month Returns

TABLE 9: OLS Regression of One-Month Return on PC3 ³

Variable	Coefficient	Std. Error	z-statistic	p-value
Intercept	0.024	0.004	6.453	0.000
PC3	2.140	0.235	9.117	0.000
R-squared	0.104			
Adjusted R-squared	0.104			
F-statistic	83.12			
Prob (F-statistic)	1.16×10^{-19}			

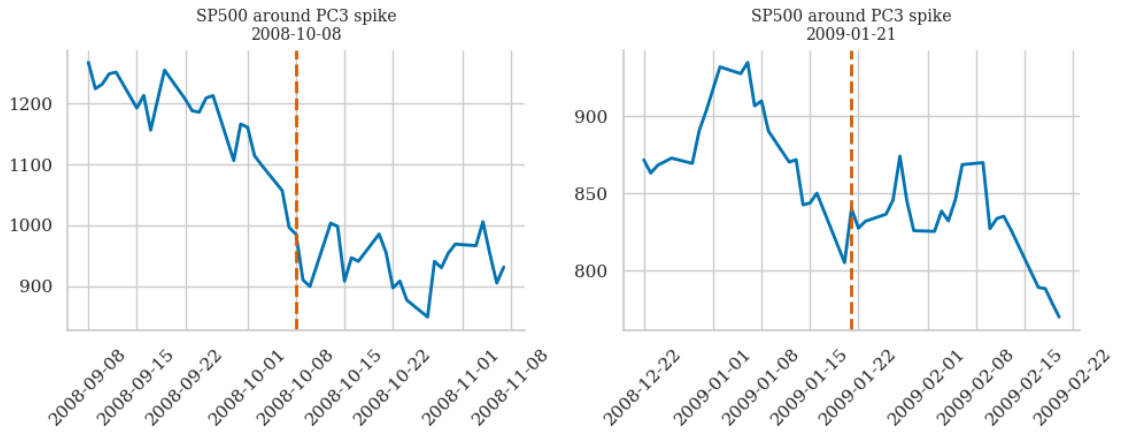


FIGURE 13: S&P500 Performance Around Extreme PC3 Values

5.2. Machine Learning Tests of Significance

TABLE 10: Model Performance Metrics across 80:20 Train Test Split

Model	One-Day Ahead			Three-Day Ahead			Five-Day Ahead		
	RMSE	MAE	R ²	RMSE	MAE	R ²	RMSE	MAE	R ²
Linear Regression	2.118	1.344	0.921	3.140	1.902	0.826	3.910	2.261	0.729
Ridge Regression	2.119	1.345	0.921	3.141	1.903	0.825	3.912	2.262	0.729
Lasso Regression	2.125	1.350	0.920	3.147	1.907	0.825	3.919	2.267	0.728
Random Forest	2.328	1.416	0.904	2.973	1.920	0.844	3.768	2.296	0.748
Gradient Boosting	2.353	1.444	0.902	3.028	1.950	0.838	3.820	2.313	0.741
Neural Network	2.336	1.443	0.904	3.068	1.902	0.833	4.344	2.723	0.666
Nearest Neighbours	2.269	1.476	0.909	3.094	2.075	0.831	3.889	2.518	0.732
LSTM	2.765	1.720	0.865	3.924	2.231	0.727	4.643	2.704	0.617
ARIMA	2.598	1.615	0.881	3.806	2.298	0.744	4.578	2.734	0.628

³This utilises heteroskedasticity-robust p-values based off a residual plot, see Figure 15.

TABLE 11: Model Performance Metrics across 5 Fold Expanding Cross Validation

Model	One-Day Ahead			Three-Day Ahead			Five-Day Ahead		
	RMSE	MAE	R^2	RMSE	MAE	R^2	RMSE	MAE	R^2
Linear Regression	1.725	1.188	0.898	2.332	1.576	0.814	2.815	1.880	0.727
Ridge Regression	1.728	1.189	0.898	2.334	1.577	0.814	2.815	1.880	0.727
Lasso Regression	1.727	1.190	0.898	2.334	1.577	0.814	2.817	1.881	0.727
Random Forest	2.015	1.372	0.875	2.533	1.750	0.796	3.105	2.090	0.694
Gradient Boosting	2.145	1.471	0.866	2.598	1.828	0.782	3.219	2.181	0.670
Neural Network	1.942	1.401	0.886	2.436	1.681	0.780	3.277	2.408	0.637
Nearest Neighbours	1.960	1.380	0.876	2.542	1.803	0.787	3.093	2.149	0.681
LSTM	2.231	1.514	0.839	2.848	1.865	0.730	3.648	2.337	0.586
ARIMA	1.892	1.245	0.869	2.569	1.728	0.761	3.043	2.052	0.663

Both the train–test split and the five-fold expanding cross-validation produced consistent and informative results. The most striking pattern is the dominance of linear models: OLS, Ridge, and Lasso repeatedly achieved the lowest RMSE and MAE, and the highest R^2 values across all forecast horizons. This suggests a meaningful degree of linearity between the principal components and VIX futures prices, as highlighted in the previous section.

Models with higher complexity and a tendency to overfit generally underperformed across all forecast horizons and evaluation metrics, with the LSTM model showing the poorest performance. This result is contrasting to other studies where there was an out-performance of more complex models, namely artificial neural network models [35][26].

It is also notable that most models outperformed the traditional ARIMA benchmark, which demonstrated high performance metrics in other studies [26]. As a baseline comparison, this suggests that the principal components capture predictive information beyond what is contained in the VIX futures time series used by ARIMA.

As expected, forecast accuracy deteriorated with longer horizons, reflected in rising errors and falling explained variance. Performance under the simple 80:20 train–test split was also considerably weaker than under cross-validation. This discrepancy can be attributed to the unusually turbulent test period, which encompassed both the COVID-19 shock and the 2022 European bond market crisis.

Direct comparison of error metrics across studies is challenging given differences in test frameworks and time periods. Nevertheless, Hosker’s 10-fold cross-validation over 2006–2018 provides a useful benchmark: their best-performing model achieved an RMSE of 4.73 and an R^2 of 0.43 for three-day-ahead VIX front-month futures [26]. By contrast, this study’s RMSE of 2.332 and R^2 of 0.814 highlight both the stronger predictive accuracy and explanatory power of principal components in modeling VIX futures prices. It is also lower than Guo, Qiao and Konstantinidi’s respective studies reported RMSE however these are on smaller train-test samples, making direct comparison difficult [30][58][27].

TABLE 12: Performance Metrics with Various Feature Subsets using Linear Regression and 5 Fold Expanding Cross Validation

Features	One-Day Ahead			Three-Day Ahead			Five-Day Ahead		
	RMSE	MAE	R ²	RMSE	MAE	R ²	RMSE	MAE	R ²
PC1	1.945	1.376	0.879	2.462	1.698	0.801	2.908	1.970	0.716
PC2	8.482	6.647	-1.409	8.480	6.643	-1.409	8.468	6.641	-1.410
PC3	8.619	6.714	-1.407	8.592	6.700	-1.408	8.560	6.686	-1.412
PC1, PC2	1.824	1.281	0.883	2.395	1.635	0.802	2.869	1.928	0.715
PC1, PC3	1.859	1.292	0.889	2.406	1.638	0.810	2.858	1.923	0.725
PC2, PC3	8.442	6.561	-1.373	8.448	6.573	-1.382	8.439	6.579	-1.390
PC1, PC2, PC3	1.725	1.188	0.898	2.332	1.576	0.814	2.815	1.880	0.727

TABLE 13: OLS Regression of One-Day ahead VIX Front-Month Futures on Principal Components on Full Sample ⁴

Variable	Coefficient	Std. Error	z-statistic	p-value
Intercept	20.369	0.026	770.373	0.000
PC1	29.725	0.249	119.429	0.000
PC2	-10.257	0.784	-13.076	0.000
PC3	-20.188	1.449	-13.936	0.000
R-squared		0.957		
Adjusted R-squared		0.957		
F-statistic		8968		
Prob (F-statistic)		0.000		

A closer examination of the linear regression models yields several notable insights. The cross-validated performance of different principal component (PC) subsets highlights the dominant predictive power of PC1 for VIX futures prices. This result is intuitive, given the structure of PC1 as a weighted average of implied volatility, but it is also economically significant, achieving an out-of-sample R^2 of 0.879 for one-day-ahead front-month VIX futures prices. By contrast, excluding PC1 and relying only on PC2 and PC3 produces negative R^2 values in Table 12, indicating forecasts were worse than the mean VIXc1 value.

Nevertheless, incorporating PC2, PC3, or both alongside PC1 improves RMSE, MAE, and R^2 across all three forecast horizons, suggesting incremental predictive value in these components. Interestingly, Table 13 shows that PC3 enters with a negative coefficient in the price regression, despite its strong positive correlation with VIX returns. This underscores the distinct and separate challenges of forecasting prices versus returns [59]. When all three components are included, the regression achieves an out-of-sample R^2 of 0.898 under five-fold cross-validation and 0.957 over the full sample, demonstrating the strong explanatory power of these features.

⁴This utilises heteroskedasticity-robust standard errors (HC3), see Residual Plot at Figure 17.

5.3. Economic Tests for Significance

TABLE 14: Trading Performance with Various Models

Model	Sharpe Ratio	Sharpe 95% CI	Fixed Trade Return Annualised
Linear Regression	1.821	1.212, 2.419	0.339
Ridge Regression	1.862	1.278, 2.512	0.342
Lasso Regression	1.871	1.246, 2.452	0.342
Random Forest	1.846	1.309, 2.407	0.360
Gradient Boosting	1.677	1.066, 2.266	0.356
Neural Network	0.685	0.292, 1.487	0.366
Nearest Neighbors	1.496	0.855, 2.079	0.321
LSTM	0.726	0.101, 1.425	0.282
ARIMA	-0.155	-0.767, 0.477	-0.139

There are clear distinctions between model fit in machine learning and the ability to generate profitable trading signals. While Linear Regression consistently outperformed all other models across the three forecast horizons in terms of error metrics, it didn't produce the best Sharpe ratios and annual returns. Instead, the strongest performance on these economic measures came from a Ridge and Lasso regression, implying that regularisation can provide valuable guardrails in trading strategies. This does however again emphasise the notable linearity in the data.

Network models, such as LSTM and Neural Networks, performed notably poorly in the trading simulations, mirroring their cross validation performance. The tendency of networks to be over-trained, over-fit, or incorrectly tuned highlights that a strong fitting ability does not necessarily translate into profitable trading models [60][61]. This lower performance and higher variance can be seen in Figure 14, also highlighting the outperformance of the regularised models.

The Sharpe ratios highlight the economic significance of the principle components as predictor, especially when compared with the negative Sharpe ratio from the ARIMA simulation. This again suggests predictive value beyond that embedded in the VIX futures time series. Furthermore, the Sharpe ratios observed here exceed those previously reported in the literature, such as the 0.085 reported by Konstantinidi [25] and the 1.42 reported by Vrontos (based on an assumption of spot VIX tradability) [39]. It is also important to note the wide confidence intervals implying a degree of variability in returns, however this can be partially attributed to the comparatively large 8 year test sample

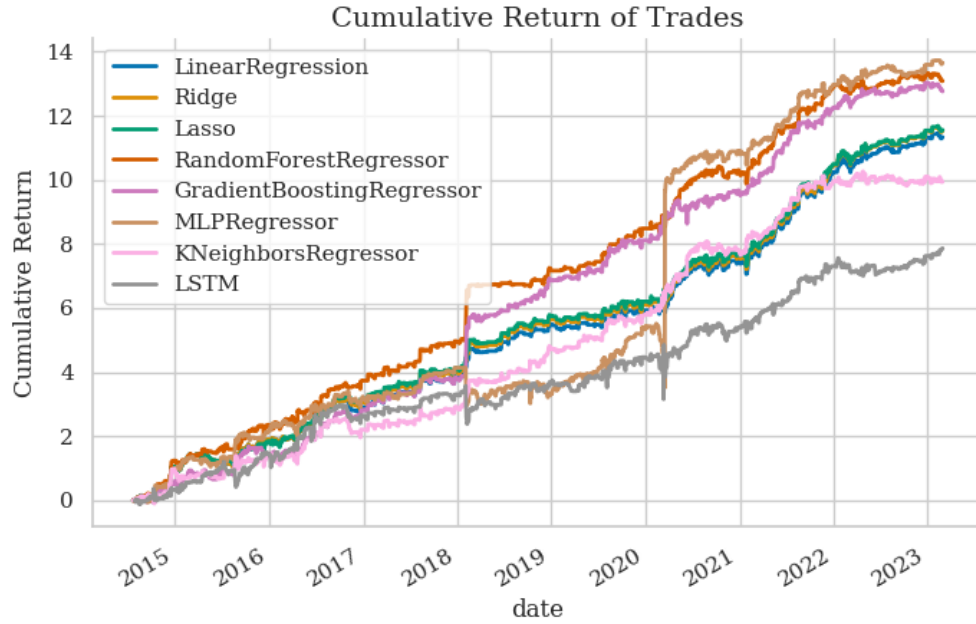


FIGURE 14: Trading Strategy Returns by Models

Hedging

To address the variance in trading strategy performance, a hedge was tested by taking an offsetting position in the second-month futures contract against the front-month trade. Several static weighting schemes were considered, such as an 50/50 split and weights calibrated to be neutral with respect to spot VIX. However, the highest sharpe was consistently achieved allocating 100% to the front month. This suggests that the core strategy was effective, while the hedge merely diluted returns. Alternative approaches such as variance-minimization would overweight the less volatile second-month contract (similarly to the spot VIX neutral hedge), further lowering Sharpe ratios.

The residual plot in Figure 17 highlights the presence of heteroskedasticity in $VXc1$ forecasts, with variance increasing alongside prediction magnitude and hence it was hypothesised that a hedge would be more useful during volatile periods. To test this and retain the stronger performance of the front month under typical conditions; a dynamic hedge weighting scheme was introduced as follows:

If $y_t > 30$; hedge using a [60, 40] weighting.

Else if $y_t < -30$; don't hedge.

Where y_t is the current VIX front month price on day t .

TABLE 15: Trading Performance With Variable Second Month Hedge

Model	Sharpe Ratio Unhedged	Sharpe Ratio Hedged
Linear Regression	1.821	1.977
Ridge Regression	1.862	2.039
Lasso Regression	1.871	2.048
Random Forest	1.846	1.852
Gradient Boosting	1.677	1.806
Neural Network	0.685	1.406
Nearest Neighbors	1.496	1.416
LSTM	0.726	1.087

This demonstrated improvements across the board of ML models and achieved the highest sharpe ratio thus far, again with linear models. This confirms the use of a dynamically increasing hedge can effectively combat heteroskedasticity and increase the risk-reward characteristics of these trading strategies. This finding is consistent with previous work suggesting that dynamic hedging can outperform static hedges [62].

Increasing Surface Granularity

Increasing bins for moneyness and expiry date lead to significant sharpe ratio improvements across more overfit models

TABLE 16: Trading Performance With Improved Surface Resolution

Model	Sharpe Ratio	Sharpe Ratio - More Bins
Linear Regression	1.821	1.838
Ridge Regression	1.862	1.821
Lasso Regression	1.871	1.852
Random Forest	1.846	1.953
Gradient Boosting	1.677	2.136
Neural Network	0.685	0.953
Nearest Neighbors	1.496	1.638
LSTM	0.726	0.595

TODO

- best feature subsets for all models

POINTS TO EMPHASISE

- lin reg beats arima e.g. regressors add information beyond VXc1 price series + ARIMA performance in other papers was good

- better generalised performance from linear models compared to success of networks in other papers
- talk about economic significance of decent sharp etc

6. Conclusion

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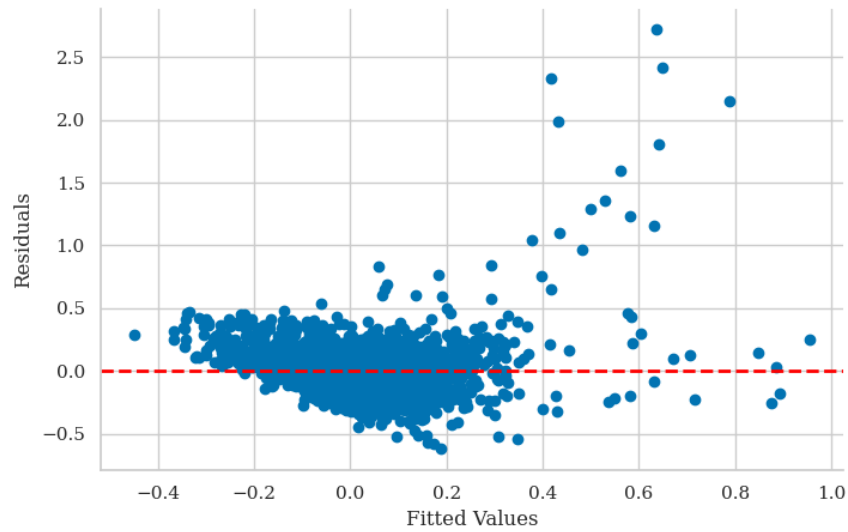


FIGURE 15: Fitted Values and Residuals Plot for PC3 and One Month VXc1 Return

TABLE 17: Johansen Cointegration Test

Rank	Trace Stat	Crit 90%	Crit 95%	Crit 99%
0	32.466	10.474	12.321	16.364
1	1.495	2.976	4.130	6.941

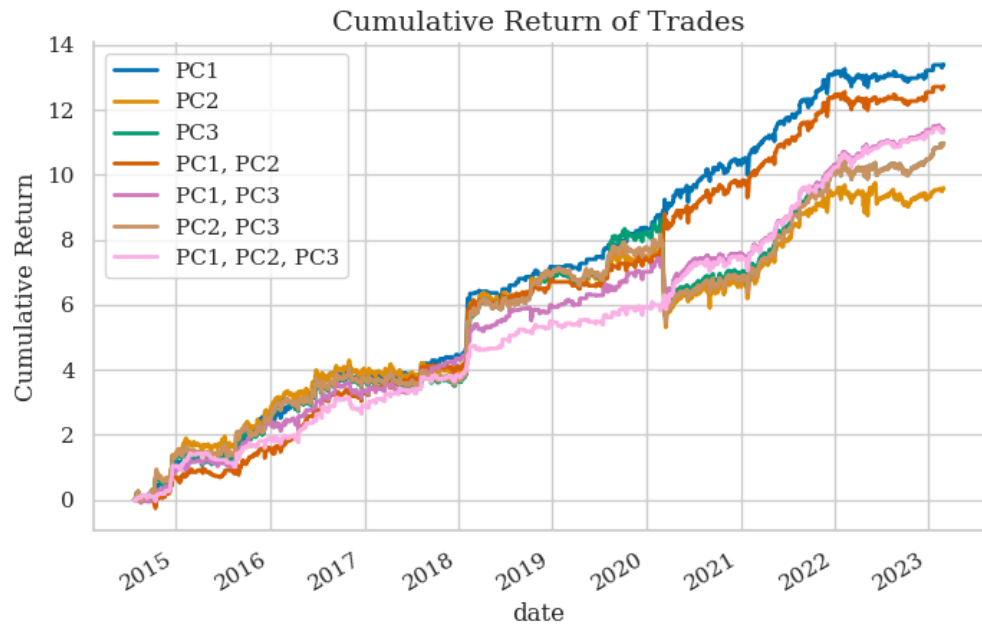


FIGURE 16: Trading Strategy Returns by Feature Subset using Linear Regression

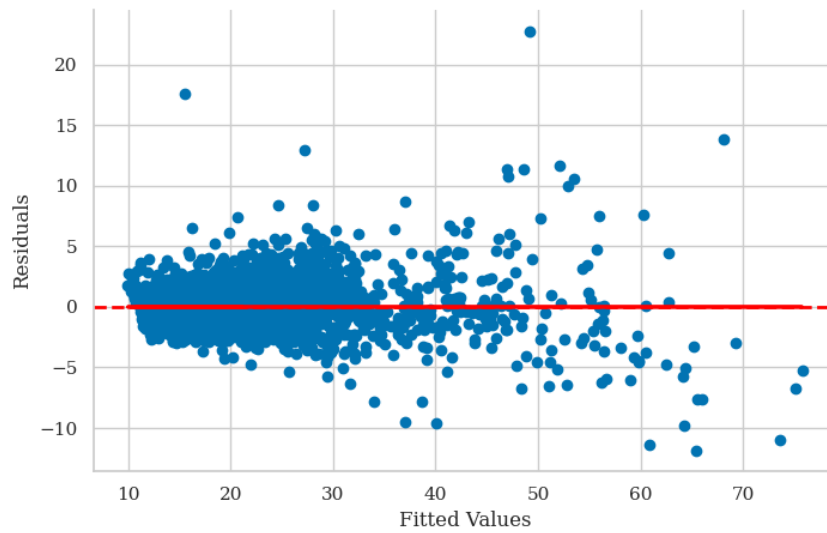


FIGURE 17: Fitted Values and Residuals Plot for PC1, PC2, PC3 and $VXc1_{t+1}$