



RESEARCH ARTICLE

Robust Portfolio Optimization using LSTM-based Stock and Cryptocurrency Price Prediction: An Application of Algorithmic Trading Strategies

Mehrdad Heydarpour, Hossein Ghanbari, Emran Mohammadi*, Saeed Shavvalpour

School of Industrial Engineering, Iran University of Science and Technology, Tehran, Iran

How to cite this article:

Heydarpour, M. , Ghanbari, H. , Mohammadi, E. and Shavvalpour, S. (2025). Robust Portfolio Optimization using LSTM-based Stock and Cryptocurrency Price Prediction: An Application of Algorithmic Trading Strategies. Iranian Journal of Accounting, Auditing and Finance, 9(3), 151-169. doi: 10.22067/ijaaf.2025.46039.1466
https://ijaaf.um.ac.ir/article_46039.html

ARTICLE INFO

Article History

Received: 2024-05-27

Accepted: 2024-11-20

Published online: 2025-07-18

Abstract

Algorithmic trading (AT) has become widely used recently because of its high speed and accuracy in implementing diverse and complex strategies. Using algorithms also allows traders to execute their trading strategies in a high volume and numerous transactions without involving human emotions. While AT has many advantages, it also carries some risks due to the uncertain stock market conditions and the impact of news and political, social, and other events. Therefore, forming a stock portfolio and stabilizing against uncertainties, in conjunction with accurate market predictions, can significantly reduce risk. In this paper, for the first time, we proposed a robust portfolio optimization model based on LSTM prediction using the AT strategies based on short-term moving average (MA) techniques. First, we implement the strategies derived from the VLMA, FLMA, EMA, and SMA algorithms based on the LSTM's predicted price. Secondly, we develop a robust portfolio optimization model using the abovementioned algorithms. The results show that moving average strategies will perform better in both stock and crypto portfolios than the benchmark strategy (Buy-and-hold). Also, when the model parameters are deterministic, the robust portfolio constructed stocks and crypto will perform better than Buy-and-hold for all algorithms. However, when the variance from specific models increases, VLMA and FLMA (15-day holding) for stocks and FLMA (30-day holding) for the crypto will not be a suitable investment option. Additionally, portfolios constructed using all AT strategies and all assets outperform the benchmark portfolio in specific and non-certain markets.

Keywords:

Robust portfolio optimization,
Algorithmic trading, Price
prediction, LSTM

<https://doi.org/10.22067/ijaaf.2025.46039.1466>



NUMBER OF REFERENCES
53



NUMBER OF FIGURES
4



NUMBER OF TABLES
4

Homepage: <https://ijaaf.um.ac.ir>
E-Issn: 2717-4131
P-Issn: 2588-6142

*Corresponding Author: Emran Mohammadi
Email: e_mohammadi@iust.ac.ir
Tel: 09124304053
ORCID:

1. Introduction

In the past few years, the financial industry has experienced significant progress and growth thanks to the rapid development of computer technology. This has paved the way for exciting and valuable opportunities for market participants, with algorithmic trading (AT) emerging as a prominent tool. AT, or algo-trading or automated trading, is a computerized trading system that executes trades based on pre-programmed instructions. Furthermore, it has reduced trading costs, minimized the impact of human emotions on trading decisions, and increased market liquidity, which has made AT popular with many investors and researchers.

Providing a situation with an accurate stock market prediction with the help of machine learning (ML) and deep learning (DL) algorithms is one of the other advantages of developing computer technologies in finance. These advanced algorithms analyze vast amounts of historical data to identify patterns and trends and help predict future market movements. This can be a precious tool for investors and financial professionals looking to make informed decisions about their investments. By leveraging the power of ML and DL Methods, finance professionals can gain a deeper understanding of market trends and make more accurate stock market predictions.

While the stock market offers investors access to innovative investment tools and methods that can yield significant benefits, it is susceptible to fluctuations triggered by dynamic variables such as breaking news, economic developments, and socio-political events like the COVID-19 pandemic and the Russia-Ukraine conflict. These fluctuations increase the risk associated with investments. Thus, forming a well-diversified portfolio that is robust enough is essential to mitigate these risks and improve investment return. For the first time, Markowitz (1952) combined the risk and return concepts in the mean-variance model.

One particularly well-regarded method that has captured the attention of researchers is the LSTM method, known for its accurate forecasting and other associated benefits (Graves and Schmidhuber, 2005; Ta et al., 2020; Rather, 2021; Cipiloglu et al., 2022). Moreover, adopting technical analysis strategies in algorithmic and applied trading has become attractive for researchers and investors (Frattini et al., 2022; Aycel and Santur, 2022; Kalariya et al., 2022). It is worth noting, however, that the implementation of AT strategies based on predicted prices with LSTM has not been widely observed, potentially leading to significant losses. Another critical issue is the underutilization of uncertainty layers to manage uncertainties in portfolios based on LSTM.

The principal objective of this study is to propose a robust portfolio optimization model grounded in prediction established through the algorithmic trading approach. To address the research inquiries, this investigation introduces a three-phase model. The process begins with using the LSTM model to predict stock prices. Then, algorithmic trading techniques are used to implement strategies based on moving averages (MA). After that, each trading algorithm's minimum and maximum return values are determined. In the final stage, a strong portfolio is created for each trading algorithm, and then a diversified, robust portfolio is formed based on all the algorithms. The results show that this approach delivers better performance in stock and crypto portfolios than the benchmark strategy. Additionally, the combined robust portfolio outperforms the buy-and-hold strategy across all levels of uncertainty. The remainder of this paper is organized as follows. Section 2 concisely overviews recent AT methods through a literature review. Section 3 is devoted to mathematical models and strategies. Section 4 presents the experiments performed and the computational results. Section 5 is devoted to the discussion and managerial insights, and Section 6 concludes the paper and provides suggestions for possible future research.

2. Literature review

2.1 Prediction

Price prediction plays a significant role in asset allocation, risk management, and asset valuation (Dai and Zhu, 2020). Therefore, many researchers have focused on this topic in recent years. In this article, we will analyze a few of them. Ariyo et al. (2014) presented a process for building an ARIMA model for forecasting NYSE and Nigeria Stock Exchange (NSE) stock prices. Furthermore, the article asserts that the mentioned model provides better prediction power in the short term than existing methods. Siami-Namini et al. (2019) compare the behavior of LSTM and BILST to discover how useful additional layers of trained data are for adjusting the involved parameters. Finally, they conclude that BILST-based models have better forecasting performance than ARIMA and LSTM-based models due to additional data training. Shahvaroughi Farahani (2021) attempted to forecast interest rates by employing Artificial Neural Networks (ANN) and enhancing the network's performance by utilizing innovative heuristic algorithms such as MFO, CHOA, and TVAC-PSO. Sapankevych and Sankar (2009) use the SVM model to predict stock prices as this method is highly effective in predicting nonlinear, non-stationary, and undefined a priori time series. Mondal et al. (2014) Analyzed the predictive power of the ARIMA model on 56 stocks from different industries in the Indian stock market. The Akaike Information Criterion (AIC) was used in this research to compare and parameterize the ARIMA model. Chen et al. (2021) introduced a novel portfolio construction approach that uses a hybrid ML and mean-variance model. As part of the hybrid model, stock prices are predicted using Extreme Gradient Boosting and IFA, and portfolios are selected using the MV model, which selects stocks with higher potential returns. According to a study on the Shanghai Stock Exchange, the method outperforms traditional methods and benchmarks regarding returns and risks. Sen et al. (2021) present the creation of optimal risk and portfolios in India's four economic sectors using ten significant stocks from web-extracted prices between 2016 and 2020. The paper also evaluates the performance of an LSTM model in forecasting stock prices. It compares the predicted and actual returns six months after the portfolios were constructed. LSTM model performs accurately, demonstrating its capability to forecast stock prices in the Indian market. Imajo et al. (2021) presented two techniques for improving financial prediction algorithms. The first is a technique for efficiently extracting information that can be combined with different prediction models. Second, a novel neural network architecture incorporates biases associated with financial induction, such as fractal dimensions and time scale invariance. U.S. and Japanese stock market data are used to demonstrate their effectiveness. Experimental ablation confirms their contributions. Fu and Wang (2020) developed a multi-period portfolio model that utilizes predictive data to allocate resources efficiently. To optimize resource allocation and predict future stock prices, they employ LSTM neural networks and particle swarm optimization algorithms. The approach they have developed has been validated by empirical research. Ferdiansyah et al. (2019) studied using LSTM modules for Bitcoin forecasting. These modules have gained popularity among researchers and have the same recurrent properties as RNNs. Based on the research, Bitcoin on Yahoo Finance will surpass USD 12600 in the days following the prediction. In Schöneburg (1990), neural networks were used to predict short-term stock prices for three randomly selected German stocks (BASF, COMMERZBANK, and MERCEDES). Within a 10-day prediction period, the researcher achieved promising results with accuracy rates up to 90% using PERCEPTRON, ADALINE, MADALINE, and BACK-PROPAGATION networks. The BACK-PROPAGATION network demonstrated behavior similar to exponential smoothing. These findings suggest that neural networks could enhance stock price prediction. Obthong et al. (2020) examined the challenges associated with stock price forecasting

and the importance of accurate information for effective decision-making. Various methods and algorithms for improving accuracy in stock price prediction are examined in this review. To optimize the problem of stock price prediction, [Lee \(2001\)](#) proposed a reinforcement learning model as a Markov process. As a result of experimental testing on the Korean stock market, this method demonstrated promising performance in improving accuracy in stock price prediction. Although, investors can gain enormous benefits from the novel investment tools and methods available in the stock market. However, considering its nature and the high effectiveness of news, economic parameters change, and political and social events, such as the dollar's removal from global exchanges, the coronavirus epidemic, the Ukraine-Russia war, etc. Investing in the stock market can be risky. Therefore, it is necessary to form a stock portfolio. Novel mean-variance portfolio optimization model that balances risk and return, presented by Markowitz. By using this model, the investor can create his ideal portfolio based on his risk tolerance. Several studies have been conducted to complete and improve the Markowitz model. A mean-variance portfolio selection model with stochastic parameters published by [Lim and Zhou \(2002\)](#) focuses on the continuous mean-variance portfolio selection model with random interest rate and volatility coefficients in a complete market. This problem is solved using the optimal quadratic linear and backward differential equations. Through this quadratic linear equation, the strategies, as well as the efficient frontier of the average variance, are extracted. [Low et al. \(2016\)](#) attempt to answer why mean-variance models work poorly. In response to this question, first, by sampling the multivariate probability model that explicitly includes distributional asymmetry, it estimates the expected return. The study also demonstrates that marginal models of dynamic characteristics, such as volatility clustering and skewness, are effective in reducing estimation errors compared to historical sampling windows. Finally, several models based on average variance exhibit significant statistical performance even after accounting for transaction costs. Due to its simplicity, accessibility, and robustness, mean-variance portfolio theory is usually used in investments. However, one of the gaps in this theory is ignoring the non-Gaussian returns of higher moments [Lassance \(2022\)](#) Provided the updated mean-variance portfolio using non-Gaussian returns, it optimizes the selected high moment criteria. In multi-objective optimization, convergence and diversity are two essential aspects. Researchers have made numerous attempts to design convergent systems in recent decades.

2.2 Algorithmic trading

[Moldovan et al. \(2011\)](#) proposed a trading algorithm that uses multiple technical indicators to increase the accuracy of trading signals. The indicator parameters can be adjusted quickly and reliably with this solution but can also be used to identify new trading rules. Trading rules discovered automatically and by experts' observations could be combined to create an automated trading system. Risk-return balances must be controlled since everyone has different risk tolerance levels. This may lead to the development of evolutionary trading systems. [Lei et al. \(2020\)](#) improved the efficiency of the traditional MACD algorithm based on residual networks. They believe DL networks can analyze the likelihood of a trading point succeeding based on market behavior. The MACD-KURT strategy was tested on the Chinese market based on Residual Networks predictions and analysis of technical indicators. According to the results, a strategy employing residual network forecasting and indicators analysis together is more effective than a strategy based exclusively on technical analysis. This is both in terms of risk and returns. [Shavandi and Khedmati \(2022\)](#) present an agent-based deep reinforcement learning framework that utilises multiple agents' collective intelligence. It works in a hierarchical structure where knowledge flows from high-timeframe agents to low-timeframe agents. This makes them highly robust to financial

time series noise. Results indicate that the developed multi-agent framework, based on several return-based and risk-adjusted performance measures, outperforms individual agents and benchmark trading strategies in all investigated trading timeframes. Multi-agent frameworks are appropriate for AT in financial markets because of their robust performance. Scholtus et al. (2014) found that news-based trading strategies become significantly less profitable if there is a delay of 300 MS or more in news delivery. The reduction in volatility is more pronounced on days with efficacious news and high levels of volatility. They also examine AT's impact on market quality around the release of macroeconomic news. It was stated in their report that automated activity increases trading volume and depth within one minute of the arrival of macroeconomic news. A real-world setting where prices are interrelated is considered by Iqbal et al. (2019). In this scenario, each price is determined by the price that precedes it. They also derive a lower bound on non-preemptive randomized algorithms. Based on the erroneous and fixed price bounds, they developed an updated model that enhances the bounds. Based on the updated model, they proposed a non-preemptive reservation price algorithm RP^* and analyzed it using a comparative analysis framework. A quantitative analysis of time series data was used to propose trading strategies by Salkar et al. (2021) to achieve high profits on intraday trades, and these strategies were developed. Findings indicate that the strategy combining RSI and MACD provides the highest returns of up to 12%. Chang et al. (2017) assessed the performance of every stock listed on the Taiwan Stock Exchange (TWSE) using variable-length moving averages (VMAs). They calculated the excess returns of technical trading in comparison with BH trading. In addition, the study results indicate that VMAs perform better than BH strategies. Furthermore, the profitability of VMAs is positively correlated with the size and volume of trades. Pradhan et al. (2021) developed the strategy of $SMA(30,100)$ based on the predicted price by LSTM.

Garcia and Schweitzer (2015) analyzed economic and social signals about Bitcoin prices. These signals included exchange volume, technology adoption, Analysis of Bit coin-related tweets for information, word-of-mouth volume, emotional valence, and opinion polarization. The study's findings inform profitable AT strategies for Bitcoin, which leverage the sentiments expressed in social media to generate positive investment returns. Vo and Yost-Bremm's (2020) Applied Design Science Study to develop a high-frequency trading strategy for Bitcoin based on six exchanges as their Information Technology artefact. Their strategy incorporates indicators related to the financial market and algorithms based on ML. Chaboud et al. (2014) examined AT and its effects on the FOREX utilizing extensive high-frequency data. They observe that AT improves price efficiency by reducing triangular arbitrage opportunities and decreasing autocorrelation of high-frequency returns. Hendershott et al. (2011) studied the effect of AT on liquidity by employing the NY Stock Exchange (NYSE) automatic quote dissemination system in 2003 as an external control. AT decreases spreads, minimizes adverse choices, and diminishes trade-related pricing, especially in large firms. The results of this study indicate that AT contributes to improved liquidity and informativeness of quotes. Weller (2018) has challenged the idea that AT can enhance price efficiency. Based on an analysis of stock-quarter data provided by the Securities and Exchange Commission (SEC), researchers found that the amount of information in prices diminished between 9% and 13% per standard deviation of AT activities one month before the planned disclosure. Another innovative tool available to investors, investment funds, and other institutions is the ability to predict market fluctuations with high accuracy through advanced methods and techniques. ML, artificial neural networks, DL, etc., are among the methods and techniques that are involved in these

processes.

2.3 Robust portfolio optimization

A robust portfolio optimization process considers the worst-case scenario and performs optimization based on that scenario. Robust optimization for the first time was presented by Soyster (1973) in the form of a linear optimization model that provides the best-justified solution regardless of the duration of the input data. This approach produces conservative results in practice. To ensure robustness, we move away from the optimality of the nominal problem. This field has been the subject of numerous research studies. Bertsimas and Sim (2004) presented a model that can be adjusted to resolve high conservatism. This can only be done by setting one parameter to this model's linearity and ability to solve integer models quickly. Following, we will briefly review some examples of robust portfolio optimization models. In this section, we will review a few examples. Goldfarb and Iyengar (2003) Formulated and solved a robust portfolio selection problem (allocation). This study analyses an optimal portfolio to determine its sensitivity to errors and optimize the relevant market parameters. According to the study's findings, uncertainty structures are related to statistical confidence regions used to evaluate parameters. Eskorouchi et al. (2024) conducted a bibliometric analysis to investigate recent progress in the robustness of portfolio optimization in light of the current global economic instability impacting financial markets. Kim et al. (2018) described recent developments in the classification of robust optimization models, the allocation of assets according to asset classes, and the selection of portfolios based on private assets. Additionally, robust portfolio selection methods suitable for each asset category were separated. A hierarchical model for robust investment between two risky assets has been proposed by Lin et al. (2022). The model consists of two steps. First, it chooses a relatively safe asset, and then it decides how much to invest in the relatively risky asset to avoid uncertainty in the relatively safe asset. A robust portfolio optimization model based on evidence theory was presented by Eskorouchi et al. (2022); using the Dempster-Shaffer model, they determined each share's range. Following this, the Bertsimas model was applied to calculate stock portfolio returns at different levels of uncertainty. The literature review indicates that there are two gaps in algorithm trading studies. First is the lack of integration between AT studies and robust portfolio optimization models. Secondly, a study that combined the VLMA, FLMA, EMA, and SMA algorithms with the predicted price using LSTM in a short-term period was not observed.

Therefore, to cover the gaps mentioned in this paper, we developed a robust portfolio optimization model based on LSTM prediction using the AT algorithm for the first time. First, we predicted daily price fluctuations using the LSTM model. In the next step, we developed a robust portfolio optimization model for each VLMA, FLMA, EMA, and SMA algorithm based on the predicted price. This study was conducted between January 2018 and July 2023 on ten assets, including five shares of the American stock market and five cryptocurrencies.

3. Research methodology

3.1 Model

In this section, we present the methodology employed in our study, which consists of three key subsections: portfolio optimization model, LSTM prediction model, and algorithmic trading strategies. Each subsection focuses on a specific aspect of our research and contributes to our robust

portfolio optimization framework using LSTM-based stock and cryptocurrency price prediction.

3.1.1 Mean-variance portfolio optimization model (MV)

Mean-variance Portfolio optimization was introduced by (Markowitz, 1952). The objective of this model is to balance profit and risk. The first objective function in Eq (1) focuses on minimizing portfolio risk, whereas Eq (2) is geared towards maximizing returns. Eq (3) is a budget constraint, indicating that the sum of all stock weights must equal 1. It is also possible to define restrictions based on different conditions. Markowitz's model takes the general form shown below:

$$\min \sum_{i,j=1}^n x_i \times x_j \times cov_{i,j} \quad (1)$$

$$\max \sum_{i,j=1}^n r_i \times x_j \quad (2)$$

$$S.T. \sum_{i=1}^n x_i = 1 \quad (3)$$

$$x_i \geq 0, \quad \forall i \in (1, \dots, n) \quad (4)$$

The variable x denotes the allocated budget for each stock, while n represents the total number of stocks in the portfolio and r is the stock's historical return. Eq (4) explicitly dictates the prohibition of short selling.

3.1.2 MVF model.

To develop the Markowitz Mean-Variance model (MV), Yu et al. (2020) developed a model called MVF. Unlike MV which relies on historical data, the MVF model uses the predicted rate of return for its calculations (Ma et al., 2021). In addition to minimizing risk and maximizing return, it provides a novel objective function for reducing prediction error Eq (7).

$$\min \sum_{i,j=1}^n x_i \times x_j \times cov_{i,j} \quad (5)$$

$$\max \sum_{i=1}^n x_i \times \hat{r}_i \quad (6)$$

$$\max \sum_{i=1}^n x_i \times \varepsilon_i \quad (7)$$

$$S.T. \sum_{i=1}^n x_i = 1 \quad (8)$$

$$x_i \geq 0, \quad \forall i \in (1, \dots, n) \quad (9)$$

The above model uses $\hat{r}_i$ instead r_i that is predicted return, and also $\varepsilon_i = r_i - \hat{r}_i$ calculates prediction errors.

3.1.3 case study: robust MVF model

This analysis, similar to the MVF, computes the rate of return using forecast data. However, it employs an uncertainty interval return based on algorithmic trading strategies. Therefore, this paper assumes that the return is an interval uncertainty parameter and utilizes Bertsimas' robust optimization to address these uncertainties. *eq* (10) Shows a uniform interval of changes of predicted return ($\tilde{r}$).

$$\tilde{r} \sim (\tilde{r} - \hat{\alpha}_i, \tilde{r} + \hat{\alpha}_i) \quad (10)$$

In this study, to maintain the linearity of the model, we focus on the first part of the objective function of the model and run the robust model. It specifies the level of conservatism and determines how many parameters can have their maximum value. *eq* (15) specifies that the maximum weight assigned to each AT strategy in the portfolio should be 40% of the total budget and improves portfolio diversification

$$\text{Max } U \quad (11)$$

Subjected to:

$$U - \sum_{i=1}^n \hat{r}_{i,k} \times x_{i,k} + z_j \Gamma_j + \sum_i p_{ij} \leq 0 \quad \forall j \quad (12)$$

$$z_j + p_{ij} \geq a_{ij} y_i, \quad \forall i, j \in j_j \quad (13)$$

$$-y_i \leq x_{i,k} \leq y_i \quad \forall i, k \quad (14)$$

$$x_{i,k} \leq 0.4 \quad \forall i, k \quad (15)$$

$$x_{i,k} \geq 0 \quad \forall i, k$$

$$p_{ij} \geq 0, \quad \forall i, j \in j_j \quad (16)$$

$$y_i \geq 0, \quad \forall i \quad (17)$$

$$z_j \geq 0, \quad \forall j \quad (18)$$

In this study, i denotes the index associated with each asset. Furthermore, k is the implemented AT strategies index on each asset, including FLMA (15), SMA, FLMA (30), EMA, and VLMA. $\hat{r}_{i,k}$ is the uncertainty parameter of the model, it shows the expected return for implementing each AT strategy on each asset. $x_{i,k}$ shows the dedicated weight when applying each AT strategy on each asset. Γ specifies the uncertainty level, and $\hat{\alpha}_{i,k}$ shows the maximum possible variance from $\hat{r}_{i,k}$.

3.2. LSTM prediction model

As the name suggests, LSTM stands for Long-Short-Term-Memory. It is a type of RNN network. However, it has long-term memory, while RNN does not have this possibility. There are generally three layers in an LSTM neural network: the input layer, the hidden layer, and the output layer.

3.3. Algorithm trading strategies

Buy and hold strategy

Buy and hold is the oldest and simplest trading strategy. Likewise, many researchers have used this article as a benchmark strategy, including [Mohr et al. \(2014\)](#) and [Chang et al. \(2017\)](#). This strategy generates the buy signal on the first day of the study period and the sell signal on the last day.

Simple Moving Average (SMA)

MA is considered one of the oldest and most popular technical analysis tools and has different types. According to Table 1, as the name suggests, the Simple Moving Average (SMA) is the simplest type of the MA family. If $MA_{short} > MA_{long}$, a buy signal is issued. And when $MA_{short} < MA_{long}$ a sell signal is issued. Algorithm 1 presents a formal description of the algorithm.

Table 1. Structure of SMA

Algorithm 1: SMA Algorithm

REQUIRE: MA_{long} , MA_{short}

1. if $MA_{short} > MA_{long}$
 2. A buy signal should be generated
 3. end if
 4. if $MA_{short} < MA_{long}$
 5. A sell should be generated
 6. end if
 7. Issue a sell signal on the last trading day, regardless of the open position
-

Exponential moving average (EMA)

An exponential EMA is based on generating buy and sell signals like a simple SMA in Algorithm 1. But in the roll's calculations $eq(19)$, act differently. In this technique, more weight is given to the value of the recent day.

$$EMA_{t1} = price_{t1} * \left(\frac{smoothing}{1 + days} \right) + EMA_{t0} * \left(1 - \left(\frac{smoothing}{1 + days} \right) \right) \quad (19)$$

Variable and fixed length MA: (VLMA) & (FLMA)

To prevent multiple signals from being generated in SMA, (Brock et al., 1992) introduced a new model that was used by Ahmad et al. (2021), Zhu et al. (2015) and Ming-Ming and Siok-Hwa (2006). this algorithm generates a buy signal when $MA_{short} > (1 + \beta) * MA_{long}$ and the sell signal when if $MA_{short} < (1 - \beta) * MA_{long}$. The FLMA model can also be operated similarly, except that in this case, we also have a maintenance period. In other words, once a signal has been generated, the position must be held for a fixed period. For example, if the holding time is 30 days, the current open position will be maintained for those 30 days, regardless of the type of new signal issued (Table 2).

Table 2. Structure of (VLMA) & (FLMA)

Algorithm 2: Variable Moving Average Algorithm (VLMA) & Fixed Moving Average Algorithm (FLMA)

REQUIRE: $Band(\beta)$ MA_{long} , MA_{short}

1. if $MA_{short} > (1 + \beta) * MA_{long}$
 2. A buy signal should be generated
 3. end if
 4. if $MA_{short} < (1 - \beta) * MA_{long}$
 5. A sell should be generated
 6. end if
 7. Issue a sell signal on the last trading day, regardless of the open position
-

4. Experimental results

$$\text{MSE} = \frac{1}{n} \sum_{i=1}^n \left(\frac{\hat{r}_i - r_i}{r_i} \right)^2 \quad (20)$$

$$\text{MAE} = \frac{1}{n} \sum_{i=1}^n |\hat{r}_i - r_i| \quad (21)$$

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n \left(\frac{\hat{r}_i - r_i}{r_i} \right)^2} \quad (22)$$

First, we extracted daily price data for the five largest shares of the American stock market, including APLE, TSLA, AMD, GOOG, SONY, and five cryptocurrencies from the crypto market, BITCOIN, Dodge, ADA, BNB and ETH, from the finance.yahoo.com, From January 2018 to June 2023. The data from 2018 to November 2022 are considered training data, and then using the LSTM neural network model ([kaggle.com](https://www.kaggle.com)), we predicted each asset's six months of December 2022 to June 2023. Table 3 displays the mean squared error (MS), the root mean squared error (RMSE), and mean absolute error (MAE) metrics for LSTM based on the change in return percentage over the past 45 trading days.

(20), (21), and (22) equations are MSE, RMSE, and MAE metrics calculations.

The effectiveness of the LSTM model in ranking is demonstrated using the Rank Graduation Accuracy (RGA) measure, as shown in Equation (23), and Spearman's Rank Correlation Coefficient (ρ) in Equation (24), with the results presented in Table 3. In these equations, $Y_{\hat{r}}(Y)$ denotes the actual price reordered by the predicted ranks, Y represents the actual price of assets, and $F(Y)$ is the cumulative distribution function based on the actual price, (Raffinetti, 2023). Additionally, d_i represents the squared difference between the predicted and actual ranks, and q is for days in the test period, (Spearman, 1961). According to the results in Table 3, the MSE and RMSE criteria indicate that Apple and Sony have the lowest prediction errors. Additionally, Apple shows the smallest variance from the actual value based on the MAE criterion, with an error of 1.19E-02. The LSTM model demonstrates high predictive accuracy, with errors below 4% across all three criteria and for all assets studied.

$$\text{RGA} = \frac{\text{cov}(Y_{\hat{r}}(Y), F(Y)) + \text{cov}(Y, F(Y))}{\text{cov}(Y, F(Y)) * 2} \quad (23) \quad \rho = \frac{6 * \sum_{i=1}^n d_i^2}{q(q^2 - 1)} \quad (24)$$

The RGA criterion, which evaluates the model's effectiveness in predicting the relative ranking of assets, achieves the highest accuracy for ADA, with a value of 0.95. In contrast, the model's accuracy in ranking assets such as SONY (0.57) and APLE (70.61%) is comparatively lower. Additionally, the LSTM model exhibits a strong positive rank correlation (ρ) between actual and predicted values across most assets.

Table 3. Comparing prediction accuracy with various measurements

Metrics	Stock					Cryptocurrency				
	tesla	aple	sony	amd	goog	btc	ada	bnb	eth	doge
MSE	8.270	2.300	3.530	1.460	3.210	1.090	8.390	8.450	6.130	8.890
RMSE	2.880	1.520	1.880	3.830	1.790	3.300	2.900	2.910	2.480	2.980
MAE	2.170	1.190	1.420	2.880	1.390	2.420	3.470	2.080	1.920	2.090
RGA	86.96%	70.61%	57.69%	91.03%	81.92%	80.08%	95.03%	71.28%	78.53%	79.01%
ρ	95.66%	88.73%	95.02%	96.29%	94.80%	97.61%	97.45%	93.21%	96.50%	95.23%

BTC shows a particularly high correlation of 97.61%, while ETH achieves a correlation of 96.50%, indicating a strong alignment with actual values. The RGA and ρ criteria results indicate that the LSTM model demonstrates a strong ability to detect the general direction of asset movements. This capability can aid in identifying suitable strategies for algorithmic trading and enhance the model's robustness against future market fluctuations. Then, we implemented short-

term trading strategies derived from FLMA (15) FLMA (30), VLMA, EMA, and SMA algorithms on predicted prices. Table 4 shows the results of each strategy.

4.1 Which strategy is most profitable?

In this study, as well as in (Schmidt et al., 2010), returns have been calculated utilizing the geometric average trading period return (GPR) in equation (25).

$$GPR = \left(\prod_{i=1}^n r_i \right)^{1/n} \quad (25)$$

Table 4. AT Strategies geometric rate of return

<i>sstrategy</i>	<i>Hold time</i>	<i>stock portfolio</i>	<i>crypto portfolio</i>	<i>(stock + crypto)</i>
<i>FLMA (5,15,0.01)</i>		1.086	1.081	1.083
<i>FLMA (6,18,0.01)</i>		1.061	1.094	1.078
<i>FLMA (10,30,0.01)</i>		1.024	1.078	1.051
<i>FLMA (15,45,0.01)</i>		0.995	0.988	0.991
<i>FLMA (5,15,0.02)</i>	15	1.057	1.103	1.080
<i>FLMA (6,18,0.02)</i>		1.030	1.085	1.057
<i>FLMA (10,30,0.02)</i>	days	1.042	1.033	1.038
<i>FLMA (15,45,0.02)</i>		0.961	1.026	0.993
<i>VLMA (5,15,0.01)</i>		1.085	1.0439	1.064
<i>VLMA (6,18,0.01)</i>		1.063	1.0408	1.052
<i>VLMA (10,30,0.01)</i>		1.031	1.0549	1.043
<i>VLMA (15,45,0.01)</i>	0	0.987	0.9881	0.988
<i>VLMA (5,15,0.02)</i>		1.059	1.0472	1.053
<i>VLMA (6,18,0.02)</i>		1.039	1.0316	1.035
<i>VLMA (10,30,0.02)</i>	day	1.042	1.0335	1.038
<i>VLMA (15,45,0.02)</i>		0.961	1.0254	0.993
<i>FLMA (5,15,0.01)</i>		1.117	1.124	1.120
<i>FLMA (6,18,0.01)</i>		1.098	1.126	1.112
<i>FLMA (10,30,0.01)</i>		1.054	1.062	1.058
<i>FLMA (15,45,0.01)</i>	30	0.991	0.980	0.986
<i>FLMA (5,15,0.02)</i>		1.100	1.110	1.105
<i>FLMA (6,18,0.02)</i>		1.079	1.090	1.085
<i>FLMA (10,30,0.02)</i>	days	1.046	1.020	1.033
<i>FLMA (15,45,0.02)</i>		0.967	1.019	0.993
<i>SMA (5,15)</i>		1.119	1.036	1.077
<i>SMA (6,18)</i>		1.094	1.047	1.071
<i>SMA (10,30)</i>	**	1.014	1.042	1.028
<i>SMA (15,45)</i>		1.003	1.017	1.010
<i>EMA (5,15)</i>		1.085	1.045	1.065
<i>EMA (6,18)</i>	**	1.066	1.043	1.054
<i>EMA (10,30)</i>		1.058	1.071	1.065
<i>EMA (15,45)</i>		0.945	1.100	1.039
<i>B&H (5)</i>		1.007	1.001	1.004
<i>B&H (15)</i>		1.017	1.010	1.014
<i>B&H (30)</i>	**	1.033	1.032	1.033
<i>B&H (45)</i>		1.030	1.038	1.034
<i>GPR</i>		1.039	1.045	1.044

Results indicate that the crypto portfolio with GPR 1.045 will profit more than the stock portfolio with GPR 1.039.

In the *first portfolio (stocks)*, *SMA (5,15)* with 1.119 and *FLMA(5,15,0.01)* with 1.117 will have the highest *GPR*. As compared to the FLMA algorithm with a holding period of 15 days,

FLMA (5,15,0.01) has the highest return of 1.086. Also, for the *VLMA* algorithm, *VLMA* (5,15,0.01) has the highest return. Additionally, *FLMA* (5,15,0.01) is the best strategy for the *FLMA* algorithm with a 30-day holding period and *GPR* 1.117. According to the *SMA* algorithm, *SMA* (5,15) is the most profitable, while *EMA*(5,15) will be the best strategy with *GPR* 1.085.

For the *second portfolio (cryptocurrencies)*, *FLMA*(6,18,0.01) in 30 days is the best strategy with a *GPR* of 1.126. Based on the *FLMA* algorithm with a 15-day holding time, *FLMA* (6,18,0.02) exhibits the highest performance. Among the *VLMA* algorithms, *VLMA*(10,30,0.01) will have the highest *GPR* at 1.054. Also, *SMA*(6,18) strategy with *GPR* 1.047 for the *SMA* algorithm and *EMA*(15,45) will have the greatest performance in the *EMA* algorithm for the second portfolio with a *GPR* value of 1.1.

4.2 Develop a robust portfolio optimization model

Considering that the *GPR* calculated in Table 4 is based on the predicted price, and the prediction will always include some errors, it is impossible to formulate definitive conclusions about the market. Therefore, we developed a robust portfolio optimization model for each portfolio to manage these uncertainties. Figure 1 presents the performance of the different algorithms for Uncertainty levels in the robust portfolio. Based on the results shown in this figure, when we are in stable conditions, the *FLMA* algorithm with a 30-day holding time will be the most suitable algorithm for investment in a stock portfolio. Also, by increasing variance from the central limit (a highly volatile situation) for the first portfolio, the *EMA* algorithm will perform better than all the other algorithms. In addition, the crypto portfolio *EMA* algorithm performs better than the others for certain uncertainty conditions.

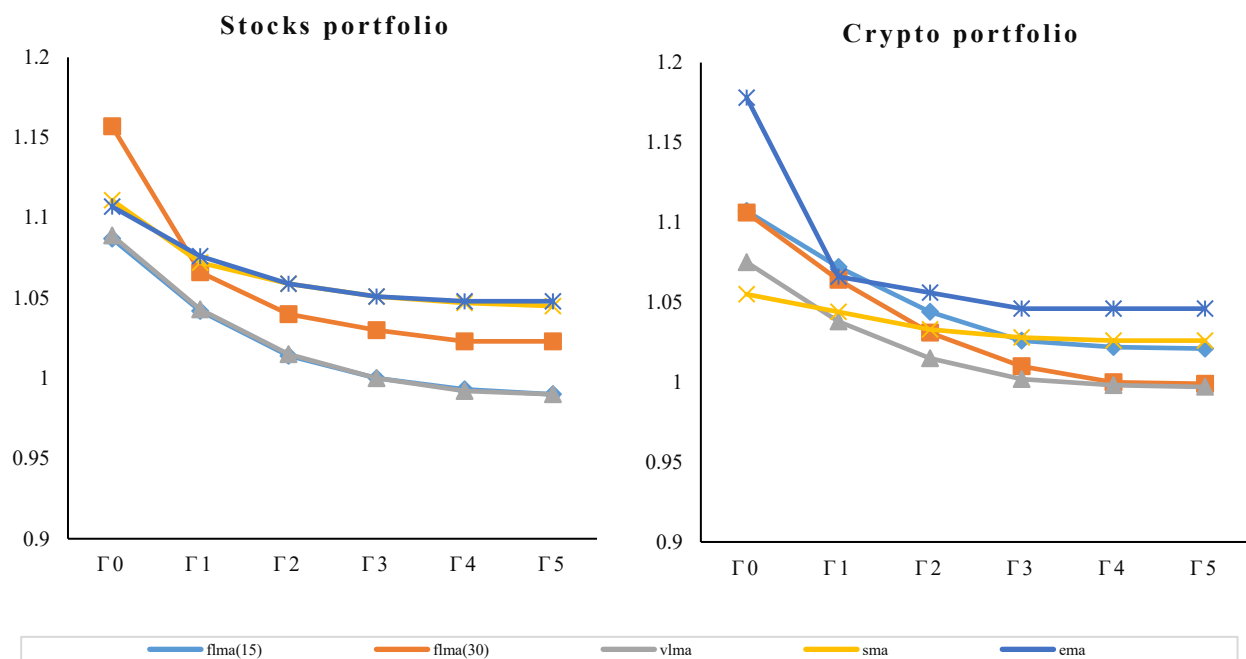


Figure 1. Analyzing the performance of algorithms in stock and cryptocurrency portfolios

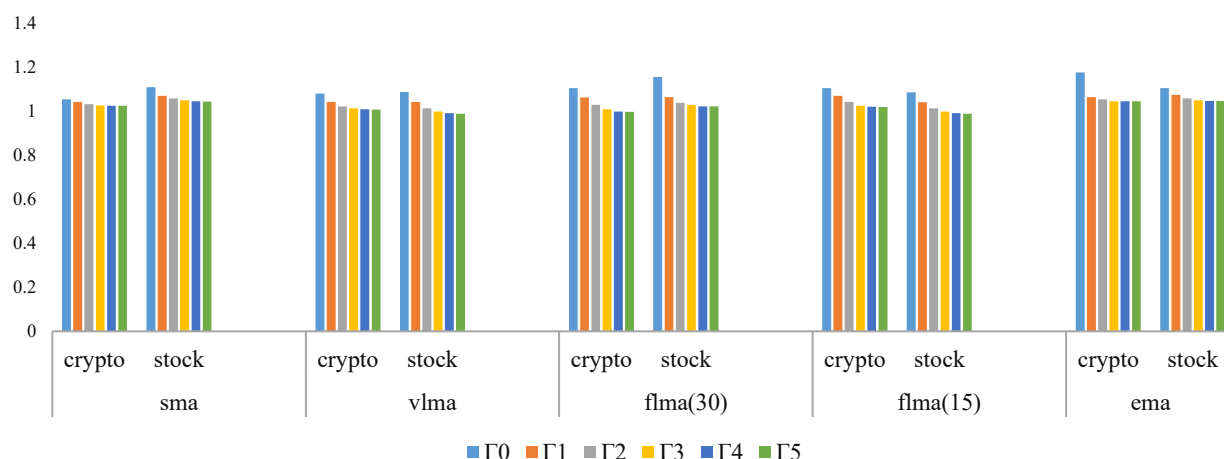


Figure 2. Comparing the profitability of stock and crypto portfolios using different algorithms.

Furthermore, Figure 2 illustrates the portfolio most suitable for each investment algorithm. According to the SAMA algorithm, the first portfolio (stocks) is expected to have a higher profit. Also, the FLMA algorithm with a 15-day holding period for the crypto portfolio and the FLMA algorithm with a 30-day holding period for the stock portfolio would be better investment options. In stable market conditions, VLMA performs better on the stock portfolio. However, this algorithm will be more beneficial to the crypto portfolio when market uncertainty increases. Although the crypto portfolio is more advantageous in a deterministic state, the algorithm produces the same results on both portfolios when uncertainty is high.

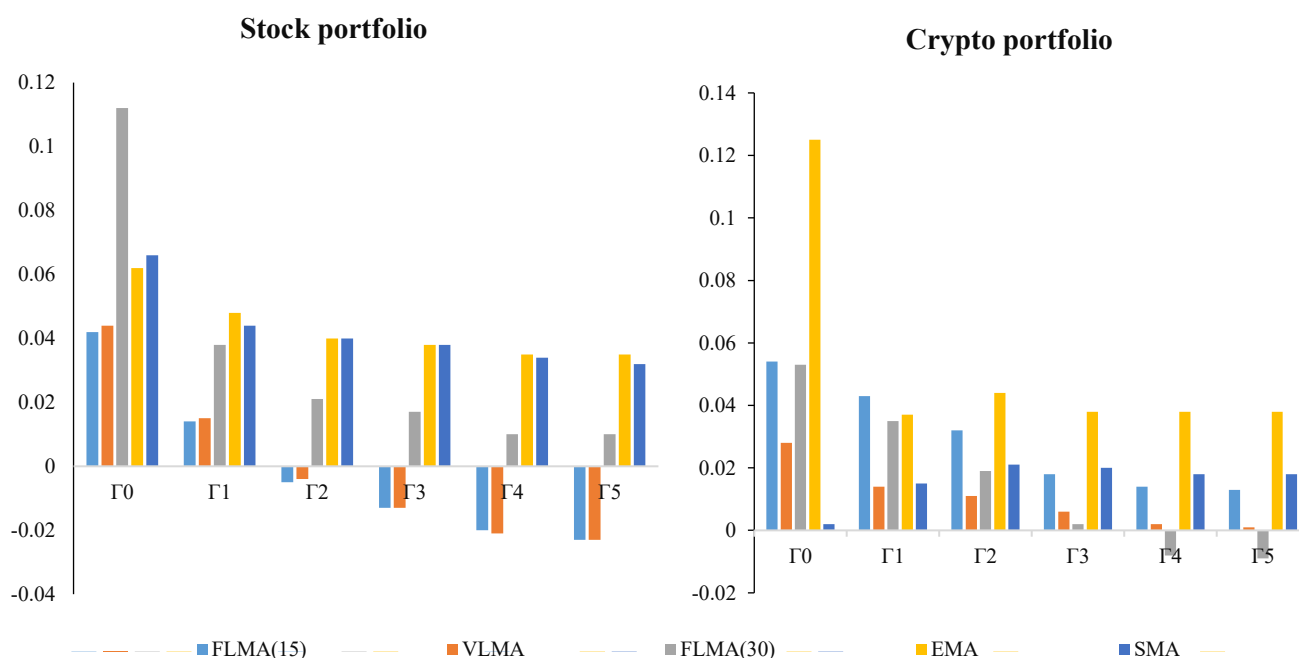


Figure 3. Excess return of each algorithm

According to Figure 3, which shows the excess return of each algorithm over the benchmark

algorithm (B&H) for both portfolios, results show that, for the first portfolio, all the MA algorithms outperform the benchmark algorithm when the model is certain. However, in situations of increased uncertainty (most variance from certain conditions), the VLMA and FLMA (15-day holding) algorithms will not be suitable for a stock portfolio.

4.3 Development of a diversified portfolio

Both portfolios studied have similar assets but are low in diversity, so we combined them for this purpose. The excess return of the newly created portfolio is shown in Figure 4.

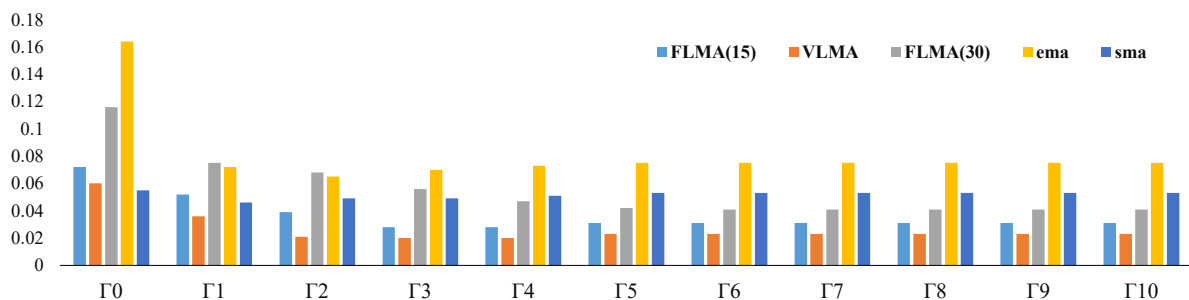


Figure 4. The excess return of the diversified portfolio for each algorithm

The results indicate that the diversified portfolio is a very suitable option for all MA algorithms, regardless of the degree of uncertainty associated with the model parameters.

5. Discussion and managerial insights

This study presents a novel approach to algorithmic trading by integrating LSTM-based price predictions with robust portfolio optimization strategies that leverage various MA, including SMA, EMA, VLMA, and FLMA. The findings reveal that these strategies consistently outperform the traditional buy-and-hold (B&H) method in both stable and uncertain market conditions. Notably, the SMA (5,15) strategy for stocks and the FLMA (6,18,0.01) strategy for cryptocurrencies emerged as top performers, delivering the highest returns over short holding periods. These results highlight the effectiveness of short-term MA in capturing market trends and optimizing portfolio performance. The research further underscores the critical role of diversification in portfolio management. By combining stock and cryptocurrency assets within a robust optimization framework, the study demonstrates that diversified portfolios can maintain strong performance across various market scenarios, including periods of heightened uncertainty. The robust portfolio models, especially those based on SMA and EMA, exhibit remarkable resilience, making them invaluable for investors seeking to balance risk and reward in volatile markets. This approach ensures that the portfolio remains reliable and profitable, even when model parameters are uncertain. Additionally, this study significantly contributes to algorithmic trading by offering practical insights into the real-world application of LSTM-based predictions. The seamless integration of advanced predictive models with robust portfolio optimization provides a powerful strategy for navigating the complexities of contemporary financial markets. Future research could expand on these findings by exploring a broader range of assets, investigating longer-term investment strategies, and incorporating real-time data to further enhance the model's robustness and versatility. Ultimately, this study presents a compelling argument for adopting diversified,

algorithmically optimized portfolios in today's rapidly evolving financial landscape.

5.1. Limitations and future works

This study presents certain limitations that open up avenues for future research. Firstly, while economic forces such as macroeconomic trends and geopolitical events can significantly impact data generation and influence financial markets, the current research focused exclusively on algorithmic trading strategies driven by price predictions. Additionally, due to their simplicity, flexibility, and compatibility with other tools, this study exclusively evaluated the performance of MA-based techniques on an LSTM model, excluding other notable algorithmic trading strategies like MACD, statistical arbitrage, etc. These alternative strategies could provide valuable insights and potentially enhance performance under varied market conditions. Future research could further integrate economic forces to improve prediction accuracy and portfolio resilience. Moreover, incorporating alternative strategies and economic indicators such as arbitrage trading, mean reversion, weighted average price, and statistical arbitrage strategies into the proposed framework could lead to a more comprehensive and robust portfolio optimization approach.

6. Conclusion

This study presents a new approach to algorithmic trading. Initially, we examined the short-term performance of trading algorithms based on MA, including EMA, SMA, VLMA, FLMA (15), and FLMA (30) on predicted prices using LSM. Then, we formed a robust portfolio optimization model for each algorithm. As a result, when we invest in stocks, the *SMA*(5,15) strategy will have a better return of 1.119, and when we invest in crypto, *FLMA*(6,18,0.01) will have the highest return over a 30-day holding period. When evaluating the performance of strategies for all assets, the *FLMA* (5,15,0.01) strategy with 30 holding times will have the highest GPR with a value of 1.12.

We developed a robust portfolio optimization model for each algorithm to manage uncertainties. The results indicate that robust portfolio models based on SMA and EMA perform better than other algorithms in both determined and uncertain scenarios. A portfolio optimization model utilizing VLMA and FLMA algorithms will outperform benchmark strategy (B&H) under certain conditions and low uncertainty. Also, the FLMA (15-day holding), the VLM for stocks, and the FLMA (30-day holding) for crypto portfolios will not be suitable investment options when uncertain. In our investigation, we have integrated the two portfolios to comply with the key principle of diversity. The results indicate that the proposed portfolio suits all MA algorithms, even when the model parameters are highly uncertain. Therefore, to have a profitable and low-risk investment, using the new diversified-robust portfolio is very suitable.

Despite the promising results, this study faces limitations, notably the reliance on short-term MA strategies, which may restrict the applicability to longer-term investment approaches. Additionally, while the robust portfolio optimization model performs well under certain conditions, its effectiveness in highly volatile or unprecedented market scenarios remains untested.

Future research should explore alternative predictive models, such as reinforcement learning or hybrid approaches that integrate LSTM with other techniques, to improve accuracy and robustness. Expanding the analysis to include a broader range of assets and incorporating real-time data sources like sentiment analysis could enhance the model's adaptability and practical utility in algorithmic trading.

Declaration of generative AI in scientific writing

The authors used the AI system [Chat Gpt] in the writing process to improve the readability and

language of the manuscript. After, the authors reviewed and edited the content as needed and took full responsibility for the content of the published article.

References

1. Ahmad, I., Ahmad, M. O., Alqarni, M. A., Almazroi, A. A. and Khalil, M. I. K. (2021). Using algorithmic trading to analyze short term profitability of Bitcoin. *PeerJ Computer Science*, 7(1), A. e337. <https://doi.org/10.7717/peerj-cs.337>
2. Ariyo, A. A., Adewumi, A. O. and Ayo, C. K. (2014). Stock price prediction using the ARIMA model. In *2014 UKSim-AMSS 16th international conference on computer modelling and simulation*, (pp. 106-112). IEEE. Cambridge, UK
3. Aysel, Ü. and Santur, Y. (2022). A new moving average approach to predict the direction of stock movements in algorithmic trading. *Journal of New Results in Science*, 11(1), pp. 13-25. <https://doi.org/10.54187/jnrs.979836>
4. Bertsimas, D. and Sim, M. (2004). The price of robustness. *Operations Research*, 52(1), pp. 35-53. <https://doi.org/10.1287/opre.1030.0065>
5. Brock, W., Lakonishok, J. and LeBaron, B. (1992). Simple technical trading rules and the stochastic properties of stock returns. *The Journal of Finance*, 47(5), pp. 1731-1764. <https://doi.org/10.1111/j.1540-6261.1992.tb04681.x>
6. Chaboud, A. P., Chiquoine, B., Hjalmarsson, E. and Vega, C. (2014). Rise of the machines: Algorithmic trading in the foreign exchange market. *The Journal of Finance*, 69(5), pp. 2045-2084. <https://doi.org/10.1111/jofi.12186>
7. Chang, Y. H., Jong, C. C. and Wang, S. C. (2017). Size, trading volume, and the profitability of technical trading. *International Journal of Managerial Finance*, 13(4), pp. 475-494. <https://doi.org/10.1108/IJMF-09-2016-0179>
8. Chen, W., Zhang, H., Mehlawat, M. K. and Jia, L. (2021). Mean–variance portfolio optimization using machine learning-based stock price prediction. *Applied Soft Computing*, 100(1), A. 106943. <https://doi.org/10.1016/j.asoc.2020.106943>
9. Cipiloglu Yildiz, Z. and Yildiz, S. B. (2022). A portfolio construction framework using LSTM-based stock markets forecasting. *International Journal of Finance & Economics*, 27(2), pp. 2356-2366. <https://doi.org/10.1002/ijfe.2277>
10. Dai, Z. and Zhu, H. (2020). Stock return predictability from a mixed model perspective. *Pacific-Basin Finance Journal*, 60, A. 101267. <https://doi.org/10.1016/j.pacfin.2020.101267>
11. Eskorouchi, A., Ghanbari, H., & Mohammadi, E. (2024). Exploring the evolution of robust portfolio optimization: a scientometric analysis. *Iranian Journal of Accounting, Auditing and Finance*, 8(3), pp. 75-92. <https://doi.org/10.22067/ijaaf.2024.44518.1402>
12. Eskorouchi, A., Mohammadi, E. and Sadjadi, S. J. (2022). Robust portfolio optimization based on evidence theory. *Scientia Iranica*. Articles in Press (In Persian). <https://doi.org/10.24200/sci.2022.59575.6330>
13. Ferdiansyah, F., Othman, S. H., Radzi, R. Z. R. M., Stiawan, D., Sazaki, Y. and Ependi, U. (2019). A lstm-method for bitcoin price prediction: A case study yahoo finance stock market. In *2019 international conference on electrical engineering and computer science (ICECOS)* (pp. 206-210). IEEE. Cambridge, UK
14. Frattini, A., Bianchini, I., Garzonio, A. and Mercuri, L. (2022). Financial technical indicator and algorithmic trading strategy based on machine learning and alternative data. *Risks*, 10(12), p. 225. <https://www.mdpi.com/2227-9091/10/12/225#>
15. Fu, A. and Wang, B. (2020). Portfolio optimization based on LSTM neural network prediction. In *2020 IEEE International Conference on Networking, Sensing and Control (ICNSC)* (pp. 1-5).

IEEE. Cambridge, UK

16. Garcia, D. and Schweitzer, F. (2015). Social signals and algorithmic trading of Bitcoin. *Royal Society open science*, 2(9), A. 150288. <https://doi.org/10.1098/rsos.150288>
17. Goldfarb, D. and Iyengar, G. (2003). Robust portfolio selection problems. *Mathematics of Operations Research*, 28(1), pp. 1-38. <https://doi.org/10.1287/moor.28.1.1.14260>
18. Graves, A. and Schmidhuber, J. (2005). Framewise phoneme classification with bidirectional LSTM and other neural network architectures. *Neural Networks*, 18(5-6), pp. 602-610. <https://doi.org/10.1016/j.neunet.2005.06.042>
19. Hendershott, T., Jones, C. M. and Menkveld, A. J. (2011). Does algorithmic trading improve liquidity? *The Journal of Finance*, 66(1), pp. 1-33. <https://doi.org/10.1111/j.1540-6261.2010.01624.x>
20. Imajo, K., Minami, K., Ito, K. and Nakagawa, K. (2021). Deep portfolio optimization via distributional prediction of residual factors. In *Proceedings of the AAAI Conference on Artificial Intelligence*, 35(1), pp. 213-222. <https://doi.org/10.1609/aaai.v35i1.16095>
21. Iqbal, J., Ahmad, I. and Shah, A. (2019). Competitive algorithms for online conversion problem with interrelated prices. *International Journal of Advanced Computer Science and Applications*, 10(6), pp. 1-9.
22. Kalariya, V., Parmar, P., Jay, P., Tanwar, S., Raboaca, M. S., Alqahtani, F., ... and Neagu, B. C. (2022). Stochastic neural networks-based algorithmic trading for the cryptocurrency market. *Mathematics*, 10(9), A. 1456. <https://doi.org/10.3390/math10091456>
23. Kim, J. H., Kim, W. C. and Fabozzi, F. J. (2018). Recent advancements in robust optimization for investment management. *Annals of Operations Research*, 266, pp. 183-198. <https://doi.org/10.1007/s10479-017-2573-5>
24. Lassance, N. (2022). Reconciling mean-variance portfolio theory with non-Gaussian returns. *European Journal of Operational Research*, 297(2), pp. 729-740. <https://doi.org/10.1016/j.ejor.2021.06.016>
25. Lee, J. W. (2001). Stock price prediction using reinforcement learning. In *ISIE 2001. 2001 IEEE International Symposium on Industrial Electronics Proceedings* (Cat. No. 01TH8570), 1, pp. 690-695. IEEE. Cambridge, UK
26. Lei, Y., Peng, Q. and Shen, Y. (2020). Deep learning for algorithmic trading: enhancing MACD strategy. In *Proceedings of the 2020 6th International Conference on Computing and Artificial Intelligence*, University of Tsukuba, Tsukuba, Japan (pp. 51-57). <https://doi.org/10.1145/3404555.3404604>
27. Lim, A. E. and Zhou, X. Y. (2002). Mean-variance portfolio selection with random parameters in a complete market. *Mathematics of Operations Research*, 27(1), pp. 101-120. <https://doi.org/10.1287/moor.27.1.101.337>
28. Lin, Q., Luo, Y. and Sun, X. (2022). Robust investment strategies with two risky assets. *Journal of Economic Dynamics and Control*, 134, A. 104275. <https://doi.org/10.1016/j.jedc.2021.104275>
29. Low, R. K. Y., Faff, R. and Aas, K. (2016). Enhancing mean-variance portfolio selection by modeling distributional asymmetries. *Journal of Economics and Business*, 85, pp. 49-72. <https://doi.org/10.1016/j.jeconbus.2016.01.003>
30. Ma, Y., Han, R. and Wang, W. (2021). Portfolio optimization with return prediction using deep learning and machine learning. *Expert Systems with Applications*, 165, A. 113973. <https://doi.org/10.1016/j.eswa.2020.113973>
31. Markowitz, H. (1952). The utility of wealth. *Journal of political Economy*, 60(2), pp. 151-158. <https://doi.org/10.1086/257177>

32. Ming-Ming, L. and Siok-Hwa, L. (2006). The profitability of the simple moving averages and trading range breakout in the Asian stock markets. *Journal of Asian Economics*, 17(1), pp. 144-170. <https://doi.org/10.1016/j.asieco.2005.12.001>
33. Mohr, E., Ahmad, I. and Schmidt, G. (2014). Online algorithms for conversion problems: a survey. *Surveys in Operations Research and Management Science*, 19(2), pp. 87-104. <https://doi.org/10.1016/j.sorms.2014.08.001>
34. Moldovan, D., Moca, M. and Nitchi, S. (2011). A stock trading algorithm model proposal, based on technical indicators signals. *Informatica Economica*, 15(1), p. 183.
35. Mondal, P., Shit, L. and Goswami, S. (2014). Study of effectiveness of time series modeling (ARIMA) in forecasting stock prices. *International Journal of Computer Science, Engineering and Applications*, 4(2), p. 13.
36. Obthong, M., Tantisantiwong, N., Jeamwatthanachai, W. and Wills, G. (2020). A survey on machine learning for stock price prediction: Algorithms and techniques. *2nd International Conference on Finance, Economics, Management and IT Business*, Vienna House Diplomat Prague, Prague, Czech Republic, pp. 63-71. <http://dx.doi.org/10.5220/0009340700630071>
37. Raffinetti, E. (2023). A rank graduation accuracy measure to mitigate artificial intelligence risks. *Quality & Quantity*, 57(Suppl 2), 131-150. <https://doi.org/10.1007/s11135-023-01613-y>
38. Rather, A. M. (2021). Lstm-based deep learning model for stock prediction and predictive optimization model. *EURO Journal on Decision Processes*, 9(1), A. 100001. <https://doi.org/10.1016/j.ejdp.2021.100001>
39. Salkar, T., Shinde, A., Tamhankar, N. and Bhagat, N. (2021). Algorithmic trading using technical indicators. In *2021 International Conference on Communication information and Computing Technology (ICCICT)* (pp. 1-6). IEEE. Cambridge, UK
40. Schmidt, G., Mohr, E. and Kersch, M. (2010). Experimental analysis of an online trading algorithm. *Electronic Notes in Discrete Mathematics*, 36, pp. 519-526. <https://doi.org/10.1016/j.endm.2010.05.066>
41. Scholtus, M., Van Dijk, D. and Frijns, B. (2014). Speed, algorithmic trading, and market quality around macroeconomic news announcements. *Journal of Banking & Finance*, 38, pp. 89-105. <https://doi.org/10.1016/j.jbankfin.2013.09.016>
42. Schöneburg, E. (1990). Stock price prediction using neural networks: A project report. *Neurocomputing*, 2(1), pp. 17-27. [https://doi.org/10.1016/0925-2312\(90\)90013-H](https://doi.org/10.1016/0925-2312(90)90013-H)
43. Sen, J., Mondal, S. and Nath, G. (2021). Robust portfolio design and stock price prediction using an optimized LSTM model. In *2021 IEEE 18th India Council International Conference (INDICON)* (pp. 1-6). IEEE. Cambridge, UK
44. Shahvaroughi Farahani, M. (2021). Prediction of interest rate using artificial neural network and novel meta-heuristic algorithms. *Iranian Journal of Accounting, Auditing and Finance*, 5(1), pp. 1-30 (In Persian). <https://doi.org/10.22067/ijaaf.2021.67957.1017>
45. Shavandi, A. and Khedmati, M. (2022). A multi-agent deep reinforcement learning framework for algorithmic trading in financial markets. *Expert Systems with Applications*, 208, A. 118124. <https://doi.org/10.1016/j.eswa.2022.118124>
46. Siami-Namini, S., Tavakoli, N. and Namin, A. S. (2019). The performance of LSTM and BiLSTM in forecasting time series. In *2019 IEEE International Conference on Big Data (Big Data)* (pp. 3285-3292). IEEE. New York
47. Soyster, A. L. (1973). Convex programming with set-inclusive constraints and applications to inexact linear programming. *Operations Research*, 21(5), pp. 1154-1157. <https://doi.org/10.1287/opre.21.5.1154>
48. Spearman, C. (1961). The proof and measurement of association between two things. *Appleton-*

- Century-Crofts*. (pp. 45–58). <https://psycnet.apa.org/doi/10.1037/11491-005>
49. Ta, V. D., Liu, C. M. and Tadesse, D. A. (2020). Portfolio optimization-based stock prediction using long-short term memory network in quantitative trading. *Applied Sciences*, 10(2), p. 437. <https://doi.org/10.3390/app10020437>
 50. Vo, A. and Yost-Bremm, C. (2020). A high-frequency algorithmic trading strategy for cryptocurrency. *Journal of Computer Information Systems*, 60(6), pp. 555-568. <https://doi.org/10.1080/08874417.2018.1552090>
 51. Weller, B. M. (2018). Does algorithmic trading reduce information acquisition? *The Review of Financial Studies*, 31(6), 2184-2226. <https://doi.org/10.1093/rfs/hhx137>
 52. Yu, J. R., Chiou, W. J. P., Lee, W. Y. and Lin, S. J. (2020). Portfolio models with return forecasting and transaction costs. *International Review of Economics & Finance*, 66, pp. 118-130. <https://doi.org/10.1016/j.iref.2019.11.002>
 53. Zhu, H., Jiang, Z. Q., Li, S. P. and Zhou, W. X. (2015). Profitability of simple technical trading rules of Chinese stock exchange indexes. *Physica A: Statistical Mechanics and its Applications*, 439, pp. 75-84. <https://doi.org/10.1016/j.physa.2015.07.032>