



Project Laboratory Report

Department of Telecommunications and Media Informatics

Author: **Márton Torner**
Neptun: **OZFKFP**
Specialization: **Infocommunication (HIT)**
E-mail address: **torner.marton@gmail.com**
Supervisor: **Bálint Gyires-Tóth, PhD**
E-mail address: **toth.b@tmit.bme.hu**

Title: Financial time series modeling and forecasting with deep neural networks

Task

The task is to collect Limit Order Book data from a chosen cryptocurrency, to analyze and process the gathered records and to develop a neural network based solution to predict the direction of the price movement of the asset-pairs.

In this work, level 100 data (Limit Order Book, depth: 100) is used from Kraken crypto exchange. The live order flow is queried with the help of the provided API and saved on local storage. The aim is to create a Deep Learning powered system which can predict the price movement direction from the given history with better results than the baseline solutions. The first approaches are models based on autoregressive solutions (logistic regression and random forest regression) and then I try to use a deep neural network as the model.

In the future, this work can be used as a base for creating a complex algorithmic trading system.

2018/19 II. semester

1 Theory and previous works

1.1 Introduction

The computerization of financial markets and the availability of the electronic records of different stock exchanges like transactions, order flow and Limit Order Books provide us a great opportunity to analyze and model the dynamics of these markets. Over the last years, a huge number of studies have been done on this field which can serve as a good base for further studies.

With the computerization also came the rapid acceleration of the trading on these financial markets and big companies started to use algorithmic solutions to steal a march on their rivals and gain some higher profits.

The quick development that the field of Deep Learning had in the last decade and the impressive number of successful researches conducted on the topic of time series forecasting opened the door to change the traditional mathematical algorithms with a neural network based solutions. Price forecasting is just a step leading to more complex systems which use the predictions as inputs to deliver a trading strategy with the help of machine learning (reinforcement learning).

These solutions could change the role of financial specialists in the future.

1.2 Theoretical summary

1.2.1 Price formation mechanism

The market price per share of stock (“share price”) is the amount of money an investor is willing to pay to own a company’s single stock. The ‘price formation mechanism’ - given in [Equation 1](#) - is a map which tries to represent the relation between market price and different variables affecting it, e.g. price history, order flow, news about the companies or the market etc.

$$Price(t + \Delta t) = F(Pricehistory(0...t), OrderFlow(0...t), OtherInfo) = F(X_t, \epsilon_t) \quad (1)$$

X_t : set of state variables (e.g. order flow, volatility, price, etc.)

ϵ_t : random noise (represents the arrival of new, unknown information)

Δt : time resoution

It is shown that this relation is universal (not asset-specific) and stationary (stable across time, even at out-of-sample predictions) [\[1\]](#). These two features give us the opportunity to use all collected data points to design and train a universal model which can make predictions for all asset-pairs valid even in the future.

1.2.2 Limit Order Book

In this work, Limit Order Book (LOB) data is used as the input so this section provides a short overview what it is and how it works. It is a record of unexecuted limit orders which can be divided to two main categories: orders to buy shares or to sell the holded ones. They remain in the LOB until being executed or cancelled. It is guaranteed that the top priority order is executed before other orders in the book.

The LOB has two sides, the ask and the bid side, shown on [Figure 1](#). The ask side represents the sell orders (willing to sell the given amount at the given price) and the bid side the buy orders (willing to buy the given amount at the given price).

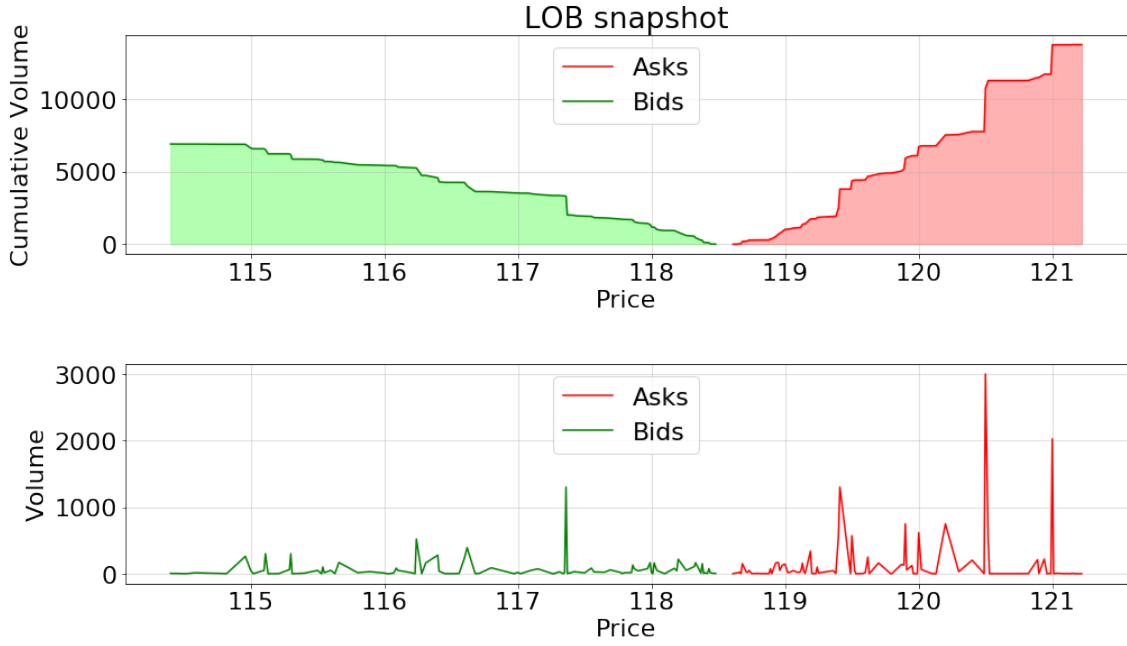


Figure 1: Limit Order Book snapshot (ETH-EUR). Bottom: Volume at each price level. Top: Cumulative volume at price levels.

A tick is the measure of the minimum upward or downward movement in a price of a security this means the price levels in the LOB must be the multiples of this value (so order prices can not differ less than this). The best ask price is the lowest sell order and the best bid price is the highest buy order. These are the prices at which the given number of shares can be bought or sold. The difference between best ask and bid price is called the spread and their average is the mid-price (2). The weighted average mid-price (WAMP) and volume weighted average price (VWAP) can be calculated as given in Equation 3 and Equation 4. The depth of the book is used in this paper as the number of best orders on each side (so depth=100 means the top 100 lowest priced ask- and the top 100 highest priced bid orders).

$$Midprice = \frac{p_{best}^{bid} + p_{best}^{ask}}{2} \quad (2)$$

$$WAMP = \frac{p_{best}^{bid} * v_{best}^{ask} + p_{best}^{ask} * v_{best}^{bid}}{v_{best}^{bid} + v_{best}^{ask}} \quad (3)$$

$$VWAP = \frac{(\sum_{i=1}^{depth} (p_i^b * v_i^b)) * v^a + (\sum_{i=1}^{depth} (p_i^a * v_i^a)) * v^b}{v^a + v^b} \quad (4)$$

p : price

v : volume (without lower index = sum over side)

b : bid

a : ask

Orders are submitted and cancelled continuously which means that the updates arrive in a very high frequency (millisecond) and it is also easy to see that consuming the order flow of stock exchanges leads to Terabytes of data. At crypto exchanges order manipulation is a big problem to be faced at filtering the collected data. So, to process a live order book we have to deal with various problems.

1.2.3 Deep Learning

Deep Learning models are deep neural networks (an example can be seen on [Figure 2](#)) trained on large datasets to uncover complex non-linear relations between the (high-dimensional) inputs and outputs. This can be simplified as it represents a functional relation like $y = f(x)$ where y is the output and x is a typically high-dimensional input vector.

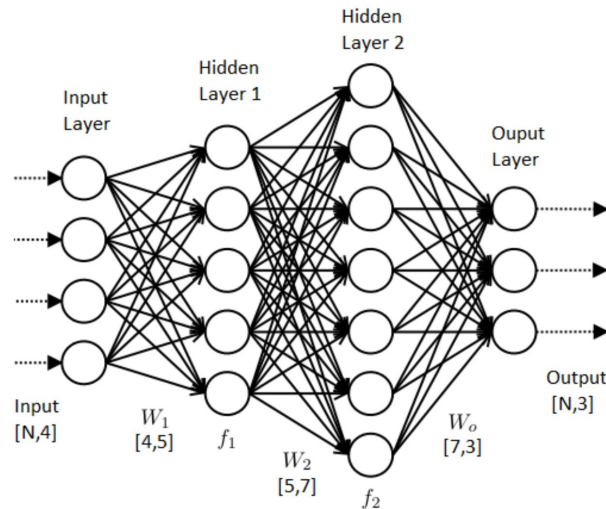


Figure 2: Simple multilayer perceptron.¹

The network iterates the input data through its hidden layer(s) (basically weighted sums are calculated followed by so called ‘activation’ functions). In supervised approaches the weights are modified in the backpropagation process in which a regularized cost function – reflecting the discrepancy between the inputs and the desired output – is tried to be optimized. Depending on the input and output dimensionality and the design of the network it can have millions of parameters which makes these calculations computationally expensive. This problem made the development of this field a standstill until the rapid spread and improvement of GPUs started providing a huge advancement in calculations.

1.2.4 Convolutional Neural Networks

A class of deep neural networks are Convolutional Neural Networks (CNN). The general architecture is the same as any other networks (input, hidden layers, output). General CNNs use a set of convolutional layers followed by fully-connected layers (all neurons in a layer are connected to every neuron in the preceding and following layers as seen on [Figure 2](#)) as hidden layers. Convolutional layers are used for representing small or high features in the data with applying a convolutional operation to their input. [2] It uses filters which are parts of the data with the same or less dimension than the input. Using k filters k feature maps are generated.

Convolutional Neural Networks were introduced as they show a huge advancement at image recognition (2D convolution) and they can be also powerful at time series prediction (1D convolution). [6] They have better results than simple fully-connected architectures but they need more data and computation power to train.

Attention is a mechanism which can be added to reach better results with the cost of more computational expenses [3]. At a high-level attention can be described as giving the network the ability to learn which parts are more important to focus on. Attention mechanism can also be used

¹<https://medium.com/coinmonks/the-artificial-neural-networks-handbook-part-1-f9ceb0e376b4> (Source: VIASAT)

at other types of neural networks (e.g. LSTM). It is commonly and successfully used at Natural Language Processing tasks.

1.2.5 Long Short-Term Memory

Long Short-Term Memory (LSTM) networks [4, 5] are a type of Recurrent Neural Networks (RNNs). The concept is to model the aspect of human thinking that our understanding is not simply based on single samples of the world, rather we take our observations on the past in consideration and based on that our reactions can be completely different. This is achieved with three gates (with trainable parameters): the input-, the output- and the forget gate. The cell states are passed through time and resetted when it is appropriate (exact number of timesteps or rule based, e.g. sentence end). This report does not aim to fully explain the whole architecture, I just wanted to give a small insight.

LSTMs have shown a huge advancement in sequence modeling and became widely used in the following years. However in the recent years several studies stated and have shown that CNNs with attention can outperform these networks in a lot of cases [6, 7].

1.2.6 Generative Adversarial Networks

Generative Adversarial Networks (GAN) are deep neural architectures comprised of a generator and a discriminator network (Figure 3), introduced by Goodfellow et al. [8]. These two networks contest against each other in the following way. The aim of the generator is to produce data indistinguishable of the real data and the discriminator tries to classify whether its input was real data or fake, generated by the opposing network. The losses of the networks are propagated back combined making both networks' reward depending on both of their performance. This means if the generator lacks competence the discriminator's work will be easy thus the system will be incompatible of solving the problem. The design and training of GANs is a complex task, hence in this semester I do not try to use one but they are part of my research which will be conducted later on.

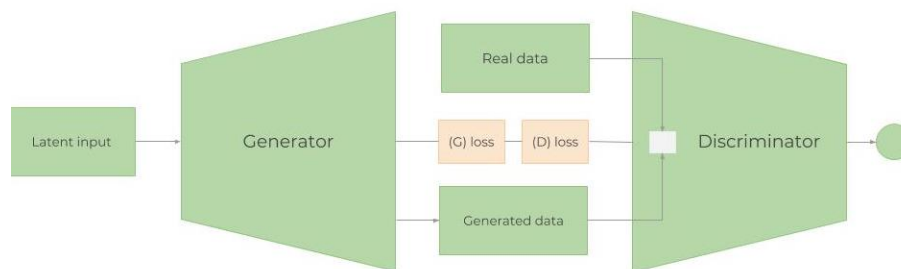


Figure 3: Example of GAN architecture. [9]

1.3 Starting point, previous works on this project

At the start of the project no preceding work was given and did not make any research on this topic before.

I started learning the theory of Deep Learning as part of the university course VITMAV45 and gained a well based knowledge on the subject to start with.

2 Own work on project

2.1 Data

The project's first task was to find or collect a database to work with. On financial field the big and high frequency raw datasets which are precise enough can cost a lot of money (3000 USD+). There was no funding available so I collected my own raw data from Kraken (www.kraken.com) which is a US based cryptocurrency exchange. Kraken gives the opportunity to access live order book (and of course other) data through a REST- and a WebSocket based API.

In the training and evaluation process only ETH-EUR² snapshots are used but for further research on universality and stationarity [1] I save 25 asset-pairs' data in aggregate. For each currency 1 snapshot is queried every minute through REST API calls and the real-time order flow is recorded through the previously mentioned WebSocket API.

The saved data is stored in CSV file format, Table 1 and Table 2 show the structure. Every asset-pair is saved to a separate folder and at the end of each day all buffer files (updates and snapshots) are compressed (I chose gzip compression) and saved into a separate file this way saving space and ensuring that the unexpected corruption of a file causes minimal data loss. The saving method also makes parallel datapreparation on multiple CPUs possible. The dataset contains entries from 15th March 2019.

| Field | Description |
|--------------------|--|
| L1 Ask Price | The price of the ask order at 1st level (best ask) |
| L1 Ask Volume | The volume of the ask order at 1st level |
| L1 Ask Timestamp | The last modification time of the ask order at 1st level |
| ... | |
| L100 Ask Price | The price of the ask order at 100th level |
| L100 Ask Volume | The volume of the ask order at 100th level |
| L100 Ask Timestamp | The last modification time of the ask order at 100th level |
| L1 Bid Price | The price of the bid order at 1st level (best bid) |
| L1 Bid Volume | The volume of the bid order at 1st level |
| L1 Bid Timestamp | The last modification time of the bid order at 1st level |
| ... | |
| L100 Bid Price | The price of the bid order at 100th level |
| L100 Bid Volume | The volume of the bid order at 100th level |
| L100 Bid Timestamp | The last modification time of the bid order at 100th level |
| Timestamp | The timestamp of the snapshot |

Table 1: One snapshot (one row in snapshot files).

| Field | Description |
|-----------|---|
| AskOrBid | The update type: 0 = ask, 1 = bid |
| Price | The price of the order |
| Volume | The volume of the order (0 means that the level is deleted) |
| Timestamp | The last modification time |

Table 2: One update (one row in update files).

²Ethereum - Euro: Ethereum is an open-source, public, blockchain-based distributed computing platform and operating system featuring smart contract (scripting) functionality. - *Wikipedia*

2.1.1 Data preparation

I wrote a parameterizable Python script to do the whole preprocessing. The following section explains the steps executed by the generator.

The first step of the preprocessing is to clean and reorder the update records to put them into an ascending flow. This is required because the WebSocket API not always sends the packets in the right order or a short loss of the network connection can also cause some problems. At visualizing the data I also noticed that the API sometimes forwards updates with timestamps from few days ago. Although I could not explain this behavior I had to remove these entries. The next task was to process the saved snapshots and create a full dataset which is saved to a single gzipped file. One parameter is which depth to use and it is important to emphasize that this is the first operation as we calculate every metrics for the following steps from the snapshots.

These are followed by labelling and scaling operations which are explained in the next two sections of this paper. Before feeding the consumed data into the used models the last step is to split it into training, validation and test sets. By definition these sets must not have any intersections but since I use time series data it was important to make one more constraint which is the datapoints in the train set must be prior to the ones in validation and the same applies for validation and test. This guaranties that the models learn to generalize without seeing into the future.

For training my models I used 30 days of ETH-EUR Limit Order Book snapshots data which was divided into 80% training and 20% test sets, in case of baseline models and 72% training, 18% validation and 10% test data in case of neural networks. I collected price aggregated LOB snapshots with the depth of 100 but for my models I used only the best 30 levels in this work to limit the number of parameters at first approaches.

To use it as an input each snapshot is needed to be converted to a one dimensional array. I use the prices and the cumulative volumes from each level (the timesteps are dropped) in the ascending order of the price values (so basically like on the top diagram of [Figure 1](#)).

2.1.2 Labels

For each snapshot the WAMP (3) or the VWAP (4) is calculated since these are used in further steps. After this, we create the labels previously mentioned in [1.2.2](#). The research aims to successfully predict the direction of the price movement using 3 categories: UP (1), DOWN (-1), SIDEWAY_MOVE (0). Snapshots are labelled using the following technique, based on the method introduced in the work by Zihao Zhang et al. ([\[10\]](#)). Although trades aren't executed exactly at the WAMP or the VWAP, they are a good estimation since they contain more information than the mid-price with also taking the volumes at the price levels in consideration. As financial time series, especially high frequency Limit Order Book metrics are highly stochastic, the comparison between $WAMP_t$ and $WAMP_{t+1}$ would result noisy labels which are unable to compress bigger trends (here where the updates can happen on the scale of milliseconds this doesn't mean whole days, only minutes). I used a smoothing method which I recall briefly in [Equation 5](#) and [Equation 6](#). The first is the mean of the previous k – including the present one – (history), the second is the following k number of WAMPs (future). So k is the prediction horizon.

$$m_{-}(t) = \frac{1}{k} \sum_{i=0}^k p_{t-i} \quad (5)$$

$$m_{+}(t) = \frac{1}{k} \sum_{i=1}^k p_{t+i} \quad (6)$$

The labels are decided based on a threshold which is calculated as multiplying the volatility – calculated on the full time period (history + future) – by α , a hyperparameter. An example can be

seen on [Figure 4](#). Red color indicates the down, green the up and white the stationary labels.

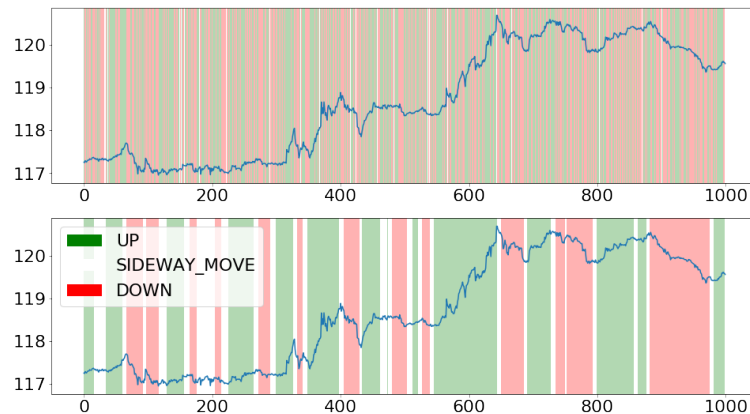


Figure 4: Comparison between basic labeling and using the smoothing technique.

In my research i tried out 10, 20, 30, 50 and 100 as possible values for k and found 30 the ideal one and for α 0.7 but these were selected based on my own opinion only.

2.1.3 Scaling

After the labelling, the next step is to rescale the input (the snapshots as first approach). This is inevitable since there are multiple reasons for it. One is that if we use multiple asset-pairs the numbers can be on different scales e.g. the prices of Bitcoin and Ripple have a huge variance, this means we have to process them separately. The first approach was to use the z-score standardization method. As financial time series have regime shifts a static standardization would be inappropriate for a high frequency database over a considerable period of time, hence the previous 3 day's mean and standard deviation was used to standardize the actual day's prices. As for the volumes my first try was to simply normalize them, but a few tries showed that using the cumulative volumes at price levels boosts performance. This is reasonable, as humans can also see more information from the cumulative volume chart than from the normal diagram (1). This approach also partly solved the problem of the outliers which means that some volumes were on an other scale than the othes in the same snapshot and they grew even bigger during the scaling because they were too rare to effect the standard deviation which stayed a small number this way and enlarged the huge numbers (as they were divided by them).

For neural networks it was an additional task to resample the dataset into small series (e.g. 50 consecutive timesteps).

2.2 Models

In my work I used three methods as a starting-point (baseline) to see how a simple algorithm can solve this complex task and to have some results to which I can compare my future models.

The first model is a very simple one, it uses a similar label calculation method as the labelling script except it only can use the past and present values to make it's prediction. It has two hyperparameters: alpha and k , alpha is used in the same way, k is the horizon. The 'mean baseline' (Model 1) calculates the mean of the VWAPS of the previous k snapshots and compares it to the VWAP of the snapshot in the present.

The following two are logistic regression (Model 2) and random forest classification (Model 3). I used the scikit-learn python library for both of them. Logistic regression is an approach to modelling the relationship between a dependent and one or more independent variables based on

prior observations. It uses a logistic function to predict the target categorical dependent variable which is from the previously mentioned three categories (-1, 0, 1) in this cases.

Random forests is a supervised learning algorithm. It can be used both for classification and regression. A forest is comprised of trees. It creates decision trees on randomly selected data samples, gets prediction from each tree and selects the best solution by means of voting [11].

The last approach (the first using neural networks) was a simple LSTM model (Model 4). It's consists of a 1D Convolutional layer (with 32 filters, kernel size and strides both chosen to equal 2) to capture information at each order book level. The next is an LSTM layer with 64 cells and 0.4 dropout. This is followed by the fully connected structure which is a Dense layer with 100 cells ReLU as activation function and 0.2 dropout connected to another Dense layer with 3 cells that does the classification by applying softmax to the output.

2.3 Results

Before showing the results it must be mentioned that predicting stock prices is an exceptionally hard task because of the highly stochastic behavior of the market, hence no good solution was published. The values follow some basic trends and some basic assumptions can be made based on Limit Order Book snapshots but even a small imbalance or a simple news headline can make a great and unpredictable impact on exchanges since the complexity of human- and crowd behavior. At high frequency financial data even a one percent deviation from the 'random guess' or baseline results can mean a huge change in profit.

To visualize my results I use confusion matrixes because I think they are more representative than simply comparing percent values together.

It is clear that the mean baseline (Table 5) gives surprisingly accurate predictions, however as I see it this is only because it uses a similar method as the labeling. Logistic regression (Table 6) and random forest classification (Table 7) can predict upward and downward movement fairly well but are unable to generalize in the stationary case. This can be caused by the fact that stationarity is highly subjective and based on personally chosen hyperparameters. LSTM (Table 8) shows an improvement to all models but the effect of misprediction of down labels needs further investigation.

2.4 Summary

In my work during the semester I successfully managed to collect high frequency financial data with the help of a well scalable system which can handle the everyday problems like loss of internet connection. I could visualize the gathered snapshots to help to get a deeper understanding on a financial topic which previously I was not familiar with. A complex data preparation process was applied to the raw data which made possible to implement or use some basic (mean baseline and regression techniques) and a neural network based model to serve as baseline for my further research on the field.

The results confirmed my assumption on the topic that it is an especially complicated task with limited number of detailed enough publications. This part of the project mainly involved data collection and preparation as an introduction to the financial field of deep learning. I faced a well amount of problems and challenges with regard to hardware and software but with the help of my supervisor I could find a solution to most of them. Because of the short time and my other studies I could not complete all of the planned work but in the future work I would like to try more complex architectures like Deep CNNs as well as GANs which was my original plan to do as I think they are really powerful models and I have only seen one research using them on this field but it was not the same approach (not for LOBs).

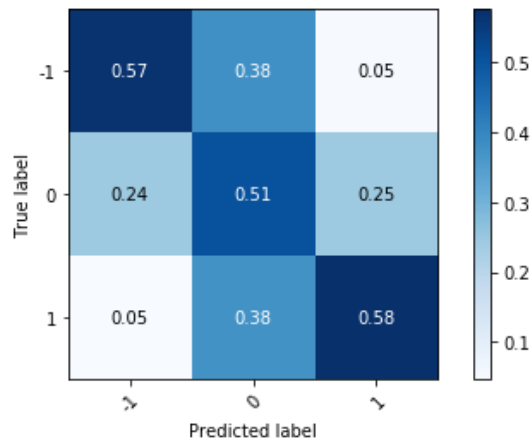


Figure 5: Mean baseline (Model 1)

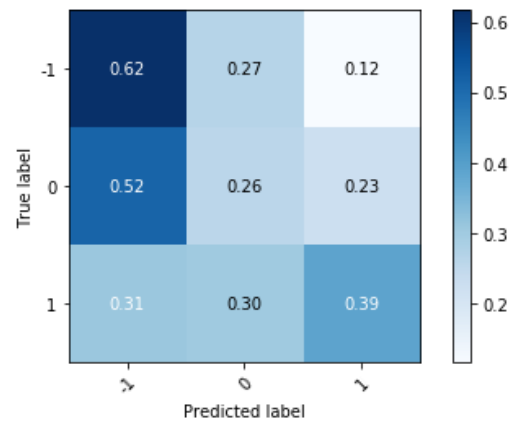


Figure 6: Logistic regression (Model 2)

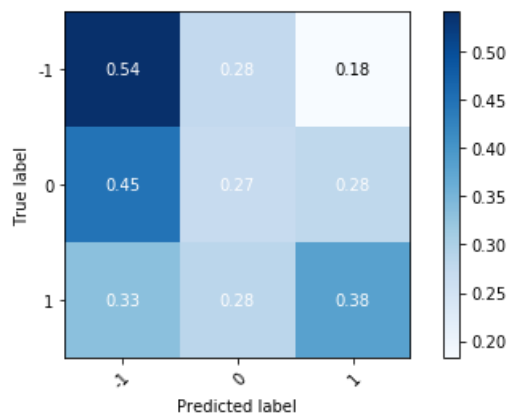


Figure 7: Random forest classification (Model 3)

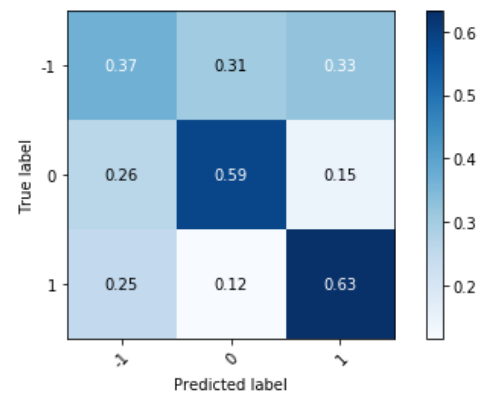


Figure 8: LSTM model (Model 4)

This, along with other studies showed that the topic is worth working on since it not only provides a lot of interesting barriers to overcome (which is not impossible in my opinion) but is promising to help to earn big profits.

3 References

- [1] J. Sirignano and R. Cont, "Universal features of price formation in financial markets: perspectives from Deep Learning", *arXiv preprint arXiv: 1803.06917*, 2018.
- [2] Y. LeCun, B. E. Boser, J. S. Denker, D. Henderson, R. E. Howard, W. E. Hubbard and L. D. Jackel, "Handwritten Digit Recognition with a Back-Propagation Network", *Neural Information Processing Systems*, vol. 2, pp. 396-404, 1989.
- [3] Synced (Medium), "A Brief Overview of Attention Mechanism", URL: <https://medium.com/syncedreview/a-brief-overview-of-attention-mechanism-13c578ba9129>, 2017.
- [4] S. Hochreiter, J. Schmidhuber, "Long Short-Term Memory", *Neural computation*, vol. 9, no. 8, pp. 1735-80, 1997.
- [5] C. Olah, "Understanding LSTM Networks", URL: <https://colah.github.io/posts/2015-08-Understanding-LSTMs/>, 2015.
- [6] S. Bai, J. Z. Kolter, V. Koltun, "An Empirical Evaluation of Generic Convolutional and Recurrent Networks for Sequence Modeling", *arXiv preprint arXiv: 1803.01271*, 2018.
- [7] E. Culurciello, "The fall of RNN / LSTM", URL: <https://towardsdatascience.com/the-fall-of-rnn-lstm-2d1594c74ce0>, 2018.
- [8] I. J. Goodfellow, J. Pouget-Abadie, M. Mirza, B. Xu, D. Warde-Farley, S. Ozair, A. Courville, Y. Bengio, "Generative Adversarial Nets", *Advances in Neural Information Processing Systems* 27, pp. 2672-2680, 2014.
- [9] Boris, "Using the latest advancements in AI to predict stock market movements", URL: <https://github.com/borisbanushev/stockpredictionai/commit/63c59f0c013a1d426d3da1ebaa0d4d80e96a75a3>, 2018.
- [10] Z. Zhang, S. Zohren, and S. Roberts, "DeepLOB: Deep Convolutional Neural Networks for Limit Order Books", *arXiv preprint arXiv: 1808.03668v4*, 2019.
- [11] A. Navlani, "Understanding Random Forests Classifiers in Python", URL: <https://www.datacamp.com/community/tutorials/random-forests-classifier-python>, 2018.

3.1 Source code

The whole project's source code (except the crawler's) can be found on GitHub:

<https://github.com/tornermarton/SemesterProject>

On some topics a deeper insight/longer explanation can be found in the Markdown files under the docs folder.

Most of the images used here can be found in the Jupyter Notebooks which are published also in this repository.

The following library served as a base for the crawler:

<https://github.com/krakenfx/kraken-wsclient-py>