

APPLICATIONS IN COMPUTATIONAL FINANCE
WITH A FOCUS ON APPROXIMATION OF
FINANCIAL TIME SERIES BY NEUROCOMPUTING

Der Wirtschaftswissenschaftlichen Fakultät der
GOTTFRIED WILHELM LEIBNIZ UNIVERSITÄT HANNOVER
zur Erlangung des akademischen Grades

Doktor der Wirtschaftswissenschaften
— Doctor rerum politicarum —

vorgelegte Dissertation
von

Diplom-Ökonom CHRISTIAN VON SPRECKELSEN



2013

Betreuer/Gutachter: PROF. DR. MICHAEL H. BREITNER

Zweitgutachter: PROF. DR. DANIEL RÖSCH

Vorsitz Prüfungskommission: JUN.-PROF. DR. HANS-JÖRG VON METTENHEIM

Wissenschaftliche Mitarbeiterin: DR. UTE LOHSE

Dedicated to Sarah and Luisa

ABSTRACT

My dissertation shows how neural networks can be used in order to achieve more accurate approximation as well as better decision making in financial markets. In order to study its approximation ability for computational finance, I perform different empirical investigations. First, neural networks are suitable for approximating price functions of assets. I present empirical results for pricing and hedging FX options. Second, the usage of neural computing for forecasting financial time series is investigated, where neural networks compete with traditional time series models. I show empirical studies about the maritime freight rates market and the Chinese FX market. Above all mentioned techniques remains the question of neuronal computing application in the financial industry. In a last step I thus propose the implementation and design of a financial decision support system with neural networks. Nevertheless, I also expose limitations and further research topics in the area of neural networks, which could improve neural networks applications in computational economics in the future.

ZUSAMMENFASSUNG

Meine Dissertation zeigt, wie Neuronale Netze für eine bessere Entscheidungsfindung an den Finanzmärkten eingesetzt werden können. Um die Approximationsfähigkeit für den Einsatz in Computational Finance zu analysieren, habe ich verschiedene empirische Untersuchungen durchgeführt. Zunächst eignen sich Neuronale Netze für die Approximation der Preisfunktion von Assets. Ich zeige empirische Ergebnisse für die Preisfindung und Absicherung von FX-Optionen. Zweitens wird der Einsatz von Neural Computing für die Prognose finanzieller Zeitreihen untersucht, wo Neuronale Netze mit traditionellen Zeitreihenmodellen konkurrieren. Dazu zeige ich empirische Analysen über den maritimen Frachtratenmarkt und den chinesischen Devisenmarkt. Über allen erwähnten Techniken bleibt die Frage der Anwendung von Neural Computing in der Finanzmarktindustrie. Ich schlage daher in einem letzten Schritt die Umsetzung und das Design eines Financial Decision Support System mit Neuronalen Netzen vor. Dennoch stelle ich auch Einschränkungen und weitere Forschungsthemen für den Einsatz von Neural Computing im Bereich von Computational Economics in Zukunft verbessern könnte.

ACKNOWLEDGMENTS

It would not have been possible to write this dissertation without the help and support of the kind people of my personal environment. It is hardly possible to mention all of them and their individual support in my acknowledgments, but I really like to let all of them know, how important and special they are for me. Above all, I would like to thank my wife Sarah for her unequivocal support throughout, as always, for which my mere expression of thanks likewise does not suffice. I would also thank my parents and brother for their great patience at all times.

Foremost, I would like to express my sincere gratitude to my advisor Prof. Michael H. Breitner and for the continuous support of my PhD study and research, for his patience, motivation, and knowledge. The good advice, support and friendship of my second supervisor, Assistance Prof. Hans-Jörg von Mettenheim, has been invaluable on both an academic and a personal level, for which I am extremely grateful. His guidance helped me in all times of research and writing of this dissertation.

I also thank Prof. Dr. Daniel Rösch, my second referee, for accepting the examination of my dissertation.

I would like to acknowledge the support of my employer, the Norddeutsche Landesbank Girozentrale, particularly for giving me the opportunity to combine both my work and my dissertation. I firmly believe that it arises useful synergy effects from my dissertation. Many people contributed in different ways to my dissertation. It is impossible to name them all. Without making a claim of completeness I mention some of them. In particular, I thank Christoph Wegener and Tobias Basse for useful comments and discussions in the field of time series analysis. I am most grateful to Jana Wiegrefe and my wife Sarah for proofreading this dissertation.

CONTENTS

LIST OF FIGURES	xi
LIST OF TABLES	xiii
ACRONYMS	xv
SYMBOLS	xvii
PUBLICATIONS	xviii
EXECUTIVE SUMMARY	xxi
I A SURVEY AND CRITICAL REVIEW	1
1 INTRODUCTION	2
1.1 Synthesis, Forecasting and Decision Making	2
1.2 Approximation by Neural Computing	4
1.2.1 Universal Approximation Theorem	4
1.2.2 Multilayer Feedforward Networks	7
1.2.3 Merits of Neural Computing for this Dissertation	8
1.3 Research Design and Organisation of My Dissertation	9
1.4 Empirical Studies at a Glance	11
2 MARKET PRICE SYNTHESIS	14
2.1 Approximation of Price Functions and Their Derivatives	14
2.2 Modelling FX Options by Neural Computation	16
2.2.1 Literature Review	16
2.2.2 Methodology and Implementation	18
2.3 Empirical Findings	21
3 FORECASTING FINANCIAL TIME SERIES	23
3.1 Time Series Modeling by Neural Computing	23
3.2 Forecasting Shipping Freight Rates by Neural Computation	26
3.2.1 The Shipping Freight Rates Market	26
3.2.2 Literature Review	29
3.2.3 Methodology and Implementation	32
3.2.4 Empirical Findings	34
3.3 Forecasting the Chinese FX Market by Neural Computation	35

3.3.1	The Chinese FX Market	35
3.3.2	Literature Review	37
3.3.3	Methodology and Implementation	38
3.3.4	Empirical Findings	39
4	DECISION MAKING TECHNIQUES	41
4.1	Model-driven Decision Support Systems for Trading	41
4.2	High-frequency Trading Systems with Neural Computation	43
4.2.1	Literature Review	43
4.2.2	Methodology and Implementation	44
4.3	Empirical Findings	45
5	CRITICAL ASSESSMENT AND LIMITATIONS	46
6	CONCLUSION	52
II APPENDED PAPERS		55
A	THE »GREEKS APPROXIMATION« PAPER	56
1	Introduction	57
2	Approximation Capabilities of Feedforward Neural Networks	59
2.1	Approximation of Functions by the Multilayer Perceptron	59
2.2	Numerical Approximation of Partial Derivatives	61
3	Price Derivatives of American Call Options	62
4	Learning Greeks – A Simulation Experiment	64
4.1	Calibrating the Simulation	64
4.2	Training Option Prices	65
4.3	Numerical Results	67
4.4	Discussion	70
5	Conclusion	71
B	THE »PRICING AND HEDGING OPTIONS« PAPER	72
1	Introduction	73
2	Methodology	75
3	Data	78
4	Option Pricing Models	80
4.1	Closed-form Option Pricing Formula	80
4.2	Empirical Option Pricing Based on Neural Networks	82
4.3	Empirical Option Pricing Based on Hybrid Neural Networks	83
5	Results	84
5.1	Simulation Strategy and Training the Networks	84

5.2	Out-of-sample Pricing Accuracy	85
5.3	Out-of-sample Hedging Performance	88
6	Conclusion	93
C	THE »FORECASTING RENMINBI QUOTES« PAPER	95
1	Introduction	96
2	RMB Onshore and Offshore Forward Exchange Market	97
3	Methodology	99
4	Description of Data	100
5	Forecasting Results	103
6	Conclusions and Recommendations	105
D	THE »FINANCIAL DECISION SUPPORT SYSTEM« PAPER	107
1	Motivation and Research Formulation	108
2	Methodology	110
3	Implementation of a High-frequency FDSS to Pricing Options on Currency Futures	112
3.1	Proposed FDSS Architecture	112
3.2	Neural Network Topology	114
4	Experimental Design: Pricing of Options on Currency Futures	117
4.1	Description and Preparation of Tick Data	117
4.2	Simulation Results	119
4.3	Evaluation and Limitations	121
5	Conclusions and Management Recommendations	121
E	THE »PRICING OPTIONS« PAPER	124
1	Introduction	125
2	Methodology	128
3	Option Pricing Models	130
3.1	Closed-form Option Pricing Formula	130
3.2	Empirical Option Pricing based on Neural Networks	132
3.3	Empirical Option Pricing based on Hybrid Neural Networks	133
4	Data	133
5	Results	137
5.1	Optimal Network Topologies	137
5.2	Out-of-sample Pricing Accuracy	137
5.3	A brief Outlook on further Research	140
6	Conclusions	141
F	THE »FORECASTING FREIGHT RATES I« PAPER	143
1	Introduction	144
2	Forecasting Models	146

2.1	Linear Time Series Models	146
2.2	Non-linear Neural Network Model	148
3	Description of Data and Forecasting Strategy	149
4	Estimation Results and Model Specification	153
5	Forecasting Performance Results	155
6	Forecasting Performance Evaluation by Economic Criteria	157
6.1	Trading Strategy and Experiment	157
6.2	Results and Analysis	158
7	Conclusions and Recommendations	161
G	THE »TRADING TANKER FREIGHT RATES« PAPER	163
1	Introduction	164
2	Methodology of Neural Networks	165
3	Description of Data and Data Preparation	167
4	Forecasting and Trading Performance Test	168
4.1	Statistical Forecasting Performance Results	169
4.2	Trading Strategy and Experiment	170
4.3	Trading Results and Analysis	171
5	Conclusions and Recommendations	173
H	THE »FORECASTING FREIGHT RATES II« PAPER	174
1	Introduction and Methodology	175
2	Description of Data and Data Preparation	176
3	Forecasting and Trading Performance Test	177
3.1	Statistical Forecasting Performance Results	177
3.2	Trading Simulation and Performance Results	178
4	Conclusions and Recommendations	180
J	THE »NOMADIC COMPUTING« PAPER	181
1	Einleitung	182
2	Konzeptuelle Ausgestaltung des Nomadic Computing	183
2.1	Nomadic Computing als neues Paradigma	183
2.2	Wissenschaftliche Pilotprojekte im Nomadic Computing	185
2.3	Aktuelle Fragestellungen	188
3	Prozessoptimierung in der Wertschöpfungskette	189
3.1	Kritische Erfolgsfaktoren für die Kommerzialisierung	190
3.2	Typische Prozessstrukturen für mobile IT-Unternehmungen	192
4	Analyse und Bewertung der Potentiale für Netzwerke in dynamischen Wertschöpfungsketten und mobile IT-Infrastrukturen	194
4.1	Konzeption eines Referenzmodells	195
4.2	Prozessstrukturanalyse	196

4.3	Analyse und Bewertung der Nutzenpotentiale	197
4.4	Anwendungsszenarien des Nomadic Computing	203
5	Zusammenfassung und Ausblick	207
III BIBLIOGRAPHY		210
PRIMARY BIBLIOGRAPHY		211
SECONDARY BIBLIOGRAPHY		222
INDEX		227

EXECUTIVE SUMMARY

Estimating an underlying relationship from a given finite input-output data set - or more precisely: function approximation involves - has been the fundamental problem for a variety of applications in financial engineering. Nowadays, feedforward neural networks such as [Multilayer perceptron \(MLP\)](#) have been widely used as an alternative approach to function approximation since they provide a generic functional representation. They have been shown to be capable of approximating any continuous function with arbitrary accuracy.

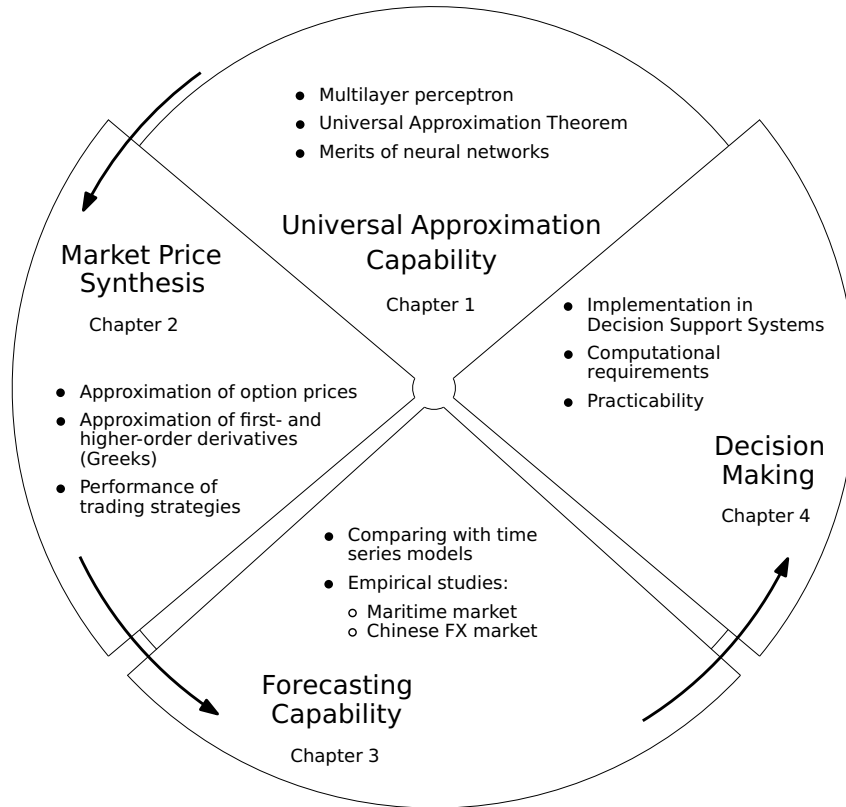
This dissertation shows how neural networks can be used in order to achieve more accurate approximation as well as better decision making in financial markets. The importance of better market price approximation or synthesis, forecasting, and the relationship between spot and derivative markets for better decision making, in the light of increasing financial market volatility and internationalized capital flows, cannot be over exaggerated. In order to study its approximation ability for computational economics, I perform different empirical investigations. [Figure 0.1](#) summarizes the organization of my dissertation.

NETWORK APPROXIMATION BY THEORY

The universal approximation theorem of [Cybenko \(1989\)](#) and [Hornik \(1989\)](#) provides the latent basis of my empirical studies. Artificial neural networks can be mathematically shown to be universal function approximators. This means that NNs can automatically approximate whatever functional form characterizes the data best. Since it is my goal to extract an alternative option pricing function by market observations, I focus on MLP that are applicable to non-linear regression problems. I follow the argumentation of [Hornik \(1989\)](#), that feedforward networks with only one hidden layer and a linear output unit are able to approximate simultaneously its unknown derivatives up to an arbitrary degree of accuracy. This characteristic is substantial since the partial derivatives of a pricing formula are needed for the hedging of option positions.

I perform my network training with the [Fast Approximation with Universal Neural Networks \(FAUN\)](#) neurosimulator. As described in [Mettenheim and Breitner \(2010\)](#) two reasons make FAUN suitable for HFT. First, the FAUN neurosimulator uses fine-grained parallelization. This allows easily achieved speedups on dual and quad core CPUs. FAUN also features coarse-grained parallelization using an easy to install grid computing client. It is possible to use clusters of heterogeneous

Figure 0.1: Overview



workstations. Second, using reverse accumulation and matrix algorithms allow a very efficient computation.

MARKET PRICE SYNTHESIS

Neural networks are information processing tools commonly used for function approximation and classification. They offer an alternative way of developing option pricing and hedging models. Their particular strength lies in their ability to approximate highly non-linear and multivariate relationships without the restrictive assumptions implicit in parametric approaches. This property of neural networks makes them attractive for problems such as pricing and hedging options. Moreover, they are adaptive and respond to structural changes in the financial markets. The drawback of this approach is that it is highly data driven, requiring large quantities of historical prices.

I present empirical results for pricing and hedging FX options. The empirical results confirm the ability of neural networks for universal approximation. Subsequent studies mostly investigated daily equity index options data for option

pricing approximations. Despite the high liquidity of FX options markets, there is no noticeable investigation about pricing FX options with neural networks in a HFT-context.

Hence, I build on prior investigations, but I extend my studies [paper B](#) and [paper E](#) with a run-time trading process in order to uncover special characteristics of high-frequency data. In particular, I pose the following challenge: If option prices were truly determined by the theoretical model exactly, can the closed-form formula be estimated by learning networks with a sufficient degree of accuracy to be of practical use? Furthermore, can both models be implemented in an automatic HFT trading process, in which a signal must be precise enough to trigger trades in a fraction of a second?

To assess the approximation capability I use two big data sets. On the one hand there is a full high-frequency data set of cleared 118,291 quotes of an EUR/USD option on currency futures with various strike prices available. On the other hand I generate more than 20,000 simulated intra-day option prices to get a broader range of data.

To assess the potential value of network pricing formulas in HFT, I implement two different investigations: First, [paper B](#) and [paper E](#) perform a rolling 15 minutes out-of-sample interval for each trading day to assess the models pricing ability. The derived approximation function is then used to perform a delta-hedging examination. All results are benchmarked using a theoretical closed-form model for pricing options on futures. Second, in order to carry out the approximation capability of the network function and its partial derivatives the network in [paper A](#) trains on a simulated data set without any rolling-window technique in order to investigate the numerical approximation of option price functions and their derivatives. I am also interested in the question of whether the data availability is crucial for a better approximation.

FORECASTING CAPABILITY

The usage of neural computing for forecasting financial time series is investigated, where neural networks compete with conventional time series models. Theoretically, the efficient market hypothesis implies that in an efficient market, it is impossible to obtain better predictions using forecasting methods because the observable price already reflects all available information and price fluctuations that will occur in the future randomly. In reality, however, systematic patterns might be found in financial time series.

First, I show empirical studies about the maritime spot and derivatives freight rates market. In [paper F](#), [paper G](#) and [paper H](#) I perform several forecasting techniques in order to examine the forecasting ability of freight rates. I find a lack

of jointly spot and forward forecasting investigations with neural networks. Thus, I extend my study on freight derivatives and a wider range of time series models. The main objective of this paper is to investigate neural networks prediction ability for maritime business forecasting and provide a practical framework for actual forecasting and trading applications of neural computing.

I sample daily prices of the International Maritime Exchange (Imarex) TD3 and TD5 freight forward contracts. These contracts are written on daily spot rates for TD3 and TD5 published by the Baltic Exchange. The spot and [Forward Freight Agreement \(FFA\)](#) data is available from 5 April 2004 to 1 April 2011. I investigate short-term forecasts of spot and FFA prices in the market in order to make inferences about the efficiency and usefulness of FFA rates. The question arises: Are forward rates expectations of spot rates? I consider both univariate and multivariate model specifications fitted with lagged spot freight rates returns $\Delta\hat{S}_t$ and forward rates returns $\Delta\hat{F}_t$.

Another interesting research object is the very unique Chinese FX market, which exhibits a dual characteristic of the market. The uniqueness comes from the two separated markets for the [Renminbi \(RMB\)](#), namely the [onshore Yuan \(CNY\)](#) and [offshore Yuan \(CNH\)](#) market. The main goal of [paper C](#) is to gain insights in the comparatively new market for offshore RMB and to detect first indications for feasible forecasting models for the onshore RMB respectively to improve CNY spot forecasts. I employ a simple GARCH model as well as neural networks. I do also analyze the somewhat older NDF market for which [Ding et al. \(2012\)](#) found a strong relationship with the CNY spot rate. As their work deals with the three RMB markets until June 2011 and since then the CNH market grew quite rapidly and seems to be replacing the NDF market, I lay our main focus on the CNH market.

I collect daily exchange rate data for onshore spot CNY, offshore spot CNH, one-month offshore NDF and CNH forward rates from Bloomberg. The sample period spans 08 September 2010 to 20 March 2013. All forecast models are separated in univariate and multivariate classes: The univariate models consist of single series of CNY, CNH and their spread. I exclusively analyze the CNY in a multivariate way by incorporation of the one-month forward rates NDF and CNH respectively.

DECISION MAKING

Above all mentioned techniques remains the question of neuronal computing application in the financial industry. In a last step I thus propose the implementation and design of a financial decision support system with neural networks, which is a more business informatics oriented discussion. The merits of neural networks especially for high-dimensional problems are shown.

I present steps towards a model-driven DSS to pricing option on currency futures, which can be embedded in a high-frequency trading process. In order to develop an appropriate DSS, I use the design science methodology of [Hevner et al. \(2004\)](#). Efficient implementation of trading algorithms is crucial, because a vast amount of data has to be processed in very short time.

MAIN CONTRIBUTIONS

In summary, I have attempted to provide empirical evidence for neural networks capability to approximate financial time series. Main contributions are:

- Model option prices derived from NN can synthesize HFT option market prices in a similar manner, but in a simultaneous way and with a more parsimonious input specification. There is e.g. no need of volatility or interest estimation.
- If market liquidity exists, which is equivalent to full data availability in a particular state space, learning networks are capable to approximate first- and higher-order partial derivatives with a sufficient accuracy. But the approximation accuracy decreases with higher-order partial derivatives.
- However, I can not confirm the hypothesis that once a predominant network approximation is found for pricing purposes, the same could be applied for hedging. I have to notice that it is an exhausting balancing act for learning systems to apply the delivered pricing approximation function on unknown hedge parameters.
- In case of forecasting financial time series neural network results are comparable to those of the other models. Some regularities from two different financial markets:
 - Tanker freight rates market: Changes in spot rates are explained by autocorrelation and by changes in the forward rates; but: changes in forward rates are not explained by past changes in spot rates. There is, however, a highly significant autocorrelation in forward rates that is difficult to conciliate with efficient markets. These results imply that the futures prices contain valuable information about future spot rates.
 - Chinese FX market: Our results do not support our assumption of a parity between the CNY and CNH. On the one hand the fact that the used forecasting methods do not outperform the naïve RW forecasts points to the direction that the price movements in the Chinese FX markets are similar to the movements in developed economies' FX markets, which are said to be rather efficient. On

the other hand I found strong evidence that structural breaks do exist in the RMB markets.

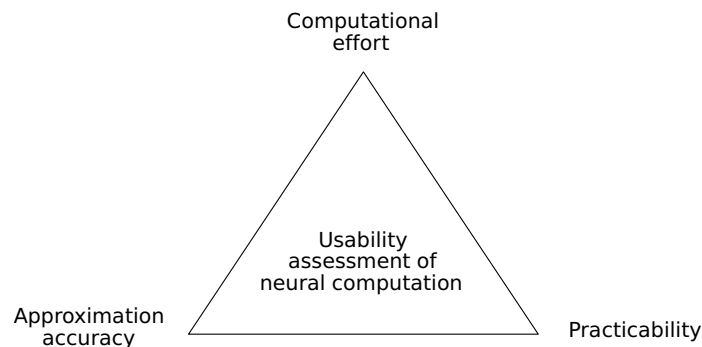
- Neural networks are a suitable core engine for a model-driven DSS embedded in a high-frequency trading process and can support trading decisions.

Hence, this dissertation provides empirical evidence that neural networks may be put to work for more accurate approximation and for better decision making in financial markets.

EVALUATION CRITERIA

In evaluating my empirical studies, there are still some questions left: First, can the empirical results be generalized? Second, are there any restrictions to a practical implementation, which have not been taken into account? For this purpose, I have identified three assessment criteria as shown in figure 0.2. I will give answers in detail to the two questions mentioned above in chapter 5.

Figure 0.2: Assessment criteria



In summary, it can be stated that:

- All empirical investigations in each case refer only to certain time periods and assets. There is a need for further evidence to confirm a generalization or robustness of the models.
- The approximation of neural networks suffer from inhomogeneous data density, in particular when trainable data is rare.
- To implement large and effective software neural networks, much processing and storage resources need to be committed. Neural network systems will often need to simulate the transmission of signals through many of these

connections and their associated neurons - which must often be matched with incredible amounts of CPU processing power and time.

The good news are: I also expose further research topics in doing with neural networks, which could improve neural networks applications in computational economics in future.