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Research Report

Quantile Methods for Complex Financial Systems - Final Report of the project under the DFG-Individual Research Grants Programme

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Quantile Methods for Complex Financial Systems

Final Report of the project
under the DFG-Individual Research Grants Programme

By Melanie Schienle and Weining Wang

1. General Information

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2. Summary

Financial systems have become increasingly complex. They are characterized by their large dimensional, strong cross-sectional dependence amounting to networks of unknown and time-varying form which appear as main drivers of risk of and within the system. Moreover, in turbulent market times, accurate estimation and prediction of systemic and idiosyncratic risk requires novel econometric and statistical models and techniques that account for the network topology but also for macro- and micro-economic factors and determinants in order to quickly adjust and respond to changing environments.

In this project, we provide innovative techniques to better estimate and predict moderate and extreme risk in complex systems. This is of key interest for financial market participants and for prudential supervisors, but also delivers solutions for a better understanding of other complex systems such as electricity markets. We focus on econometric methodologies for conditional quantiles directly related to the Value-at-Risk (VaR) concept for risk measurement. Though, all presented approaches are readily extendible to further risk measures such as expected shortfall or others. In particular, we have developed statistical concepts for (tail) networks uncovering novel structural risk channels within large dimensional financial systems and for determining suitable tail factors for accurate prediction. Beyond that, we have developed

novel techniques that address further challenges in dynamic networks such as their dynamic evolution, high-dimensionality, nonstationarity and causal effect identification. For the general public, we have graphically illustrated and maintained the practical impact on financial systemic risk measurement of many of our techniques on the companion website <http://frm.wiwi.hu-berlin.de>.

3. Progress Report

3.1 Background, Objectives and Overview of the Project Results

As the structure of financial networks is not known and might also change over time, there is a huge demand for econometric techniques which can detect the topology of tail networks from data without pre-imposing any ex-ante structure. Just before the start of the project there were initial empirical results that enhanced systemic risk measurement by adding a network dimension (Hautsch et al., 2015) to the novel but simple idiosyncratic CoVaR (Adrian and Brunnermeier, 2016) or by extending on the connectedness framework of Diebold and Yilmaz (2014). But these network results were limited to rather low dimensions of networks, could not model, estimate and illicit the dynamics of such networks directly and smoothly over time, could not handle challenges such as nonlinear effects, economic side-effects and factors, nonstationarities, high-dimensionality, common factors and causality of policy measures in networks. Spillovers in the tails were also limited to moderate tails and ignored the worst cases of extreme quantiles. Techniques mostly focused on estimation and to a much lesser extend to (probabilistically) forecasting spillovers and channels.

The main objective of the project was the development of new econometric methodologies for assessing complex financial systems with a particular focus on systemic risk measurement and prediction. This comprised the following milestones:

- I. Development of network models for detection of structural risk channels within large dimensional financial systems with an emphasis on the tails
 - a. Methods advances: Tail networks for dense and nonlinear systems
 - b. Empirical advances in systemic risk measurement
- II. Improved prediction in tail network settings
 - a. Dynamic quantile factor models
 - b. Extreme Multivariate Quantiles in a Dynamic Setting

Within this project we have developed substantial contributions for I.a. and II.a. When empirically studying systemic risk measurement with these novel techniques, however, we encountered additional challenges for which we needed to derive further statistical advancements. These included methods that can deal with nonstationarities or can capture the time evaluation of all individual spillover effects or determine the causal impact of a policy intervention on the

network. In addition to the original plan, we have derived novel fundamental solutions for these challenges which let to improvements in the measurement and understanding of systemic system risk. This has also inspired additional empirical studies that go well beyond systemic risk in financial stock markets. While there was a strong and largely extended focus on I and II.a., we could still derive statistical results for the fundamentally different extreme quantile cases and the main part of II.b. as planned. The intended ultimate extension to dimension reduction and factor model techniques for extreme quantiles, however, requires further research that is ongoing.

3.2 Details on Project-Specific Results and Findings

I. Advancements in Modelling, Estimation and Inference of Dynamic (Tail) Networks and Systemic Risk

a. Methodology

(i) Dense /high-dimensional networks: In **Betz et al. (2016)** we have extended the analysis from pure banking tail networks to bank/sovereign interlinkages which cause the financial network to be rather dense. In particular, we included sovereign controls in the banks' equity network but also include them as components of a comprehensive sovereign-bank network in credit default swaps (CDS). For the analysis of such dense networks previously existing methods require some crucial robustification to yield reliable results. Therefore, we have extended the original LASSO selection procedure of Hautsch et al. (2015) to allow for differing penalization levels in banks and sovereigns. We provide new evidence on how banking sector fragmentation and sovereign-bank linkages evolved over the European sovereign debt crisis, and how they are reflected in estimated network statistics and systemic risk measures. Finally, our results indicate that the fragmentation of the European financial system had peaked by 2016. In **Buse and Schienle (2019)** we focus on the eurozone sovereign only part of the system for analyzing spillovers during the sovereign crisis in a forecast errors variance set-up building on Diebold and Yilmaz (2014). We introduce a method for measuring the default risk connectedness of euro zone sovereign states based on an out-of-sample variance decomposition of model forecast errors. Due to its predictive nature, it can respond to crisis occurrences more quickly than common in-sample techniques. With the new technique we study underlying factors that drive the differences between CDS and bond movements in the system. In **Chernozhukov et al. (2021)** we develop the respective statistical theory for estimation and inference in a high-dimensional CoVaR set-up allowing for temporal and cross-sectional dependence in covariates and error processes, covering rather general forms of weak temporal dependence. A sequence of regressions with many regressors using LASSO (Least Absolute Shrinkage and Selection Operator) is applied for variable selection purpose, and an overall penalty level is carefully chosen by a block multiplier bootstrap procedure to account for

multiplicity of the equations and dependencies in the data. Correspondingly, oracle properties with a jointly selected tuning parameter are derived. We further provide high-quality de-biased simultaneous inference on the many target parameters of the system. We provide bootstrap consistency results of the test procedure, which are based on a general Bahadur representation for the Z-estimators with dependent data. Here the LASSO penalization parameter λ is data-driven and time varying. Serving as an indicator to the system noise level and the degree of collinearity among covariates, it conveys important information on the systemic risk level.

(ii) Nonlinearities: We have also developed techniques tackling potential nonlinear linkages in highdimensional quantile systems. The latter was one of the key problems in modeling the systemic risk when only relying on linear LASSO of Adrian and Brunnermeier (2016) and Hautsch et al. (2015). For studying financial contagion and risk spillover effects, it is important to consider a more flexible (nonlinear) conditional quantile framework that allows for stronger dependencies among financial institutions in “bad” states (when all assets prices are low) than within those in “normal” states. In **Fan et al (2018)** we provide a single-index-based model determination technique for CoVaR with very high-dimensional covariates. We use a projection-based single-index model specification to allow for ultra high-dimensional regressors. This combination of semiparametric ideas with variable selection techniques, allows to balance precision in model determination and estimation versus dimensionality challenge. This approach is used for practical CoVaR estimates with a systemically chosen indicator. The application to the U.S. financial sector shows improved model performance due to the nonlinearity and indicates market contagion before the crisis period.

The developed techniques in (i) and (ii) have let to substantial advances in financial risk measurement (see also I.b below). But further challenges emerged when enlarging systems in systemic risk measurement, e.g., by including the credit market in addition to equity markets in the analysis or when considering different currencies of sovereign players. These included: nonstationarities in CDS and FX rates, the dynamic evolution of all individual spillover channels and the causal impact of closely policy measures during crisis periods.

(iii) Nonstationarity: In **Chen and Schienle (2022)** we develop a vector error correction framework for constructing large consistent spillover networks of nonstationary systems grounded in the network theory of Diebold and Yilmaz (2014). We provide a tailored methodology for large but fixed-dimensional nonstationary (macro)economic and financial system application settings avoiding technical and often hard to verify assumptions for general statistical high-dimensional cases. To achieve this, we propose an elementwise Lasso-type technique for consistent and numerically efficient model selection of Vector Error Correction Models (VECM), and relate the resulting forecast error variance decomposition to the network topology

representation. We also derive the corresponding asymptotic results for model selection and network estimation under standard assumptions. Moreover, we develop a refinement strategy for efficient estimation and show implications and modifications for general dependent innovations. In an application to a system of FX rates, the proposed method leads to novel insights on the connectedness and spillover effects in the FX market among the OECD countries. **Liang and Schienle (2019)** complement the theory for the VECM-dynamics by considering the high-dimensional case, where dimensions can increase with sample size. This requires a change in the LASSO procedure requiring row-wise penalization in the Lasso-VECM estimator to derive consistency under very general assumptions on dimension, rank and error terms. We demonstrate the effectiveness of the proposed approach by an empirical application to recent CDS data after the financial crisis.

(iv) Direct network time series models: All existing approaches for modelling dynamic networks in financial econometrics so far, either relied on a rolling window setting with statistic networks within a window, or work in two-steps where the system dynamics is modelled first and the network structure acts on a functional of the residuals. Both lose on modelling the actual time evolution of spillovers and eliciting underlying economic channels. In **Zhu et al. (2019)** we develop a network quantile autoregression model (NQAR), which characterizes the dynamic quantile behavior. Our NQAR model consists of a system of equations, of which we relate a response to its connected nodes and node specific characteristics in a quantile autoregression process. We show the estimation of the NQAR model and the asymptotic properties with assumptions on the network structure. For this propose we develop a network Bahadur representation that gives us direct insight into the parameter asymptotics. Moreover, innovative tail-event driven impulse functions are defined. In **Xu et al. (2022)** we further extend the NQAR model by explicitly allowing the contemporaneous network effects and controlling for the common factors across quantiles. To cope with the endogeneity issue due to simultaneous network spillovers, we adopt the instrumental variable quantile regression (IVQR) estimation and derive the consistency and asymptotic normality of the IVQR estimator using the near epoch dependence property of the network process.

(v) Causal effects in Networks: **Buse et al. (2022)** provided an identification strategy to determine the causal impact of policy interventions in the CDS network of sovereign CDS. It proposes a difference in difference type test strategy to quantify effects and respective uncertainties. It uses timing effects before between and after announcement and implementation of policy regulations and high-frequency data to disentangle effects. For the uncertainties, it proposes a valid bootstrap procedure on the variance spillover-level.

b. Empirical Findings on Systemic Risk and Beyond

The new techniques of I.a. allowed for substantially new insights in the measurement of systemic risk accounting for network effects. First, within different equity markets we could determine substantial nonlinear spillover effects (**Fan et al., 2019**). Moreover, **Keilbar and Wang (2022)** add a forecasting perspective to the documented findings on nonlinear interactions in **Fan et al (2019)**. In the paper, we propose a neural network quantile regression approach for determining the nonlinear effects in CoVaR. For the network of NASDAQ listed financial institutions we find superior out-of sample performance and suggest three network-based measures for systemic risk with the Systemic Network Risk Index (SNRI) as a measure for total systemic risk the Systemic Fragility Index (SFI) and the Systemic Hazard Index (SHI) as firm-specific measures, which allow the identification of systemically relevant firms during the financial crisis. Moreover, we promote the data-driven penalty parameter in **Chernozhukov et al. (2021)** as an indicator for systemic risk measurement. For NASDAQ listed financial institutions respective results have been collected and gradually updated for public information on the website of the Financial risk meter (FRM) <http://frm.wiwi.hu-berlin.de>. Moreover, results on network quantile autoregression in **Zhu et al. (2019)** and **Xu et al. (2022)** derived insights on the time-evolution of spillovers within different equity markets that were overlooked before.

Moreover, we could extend systemic risk measurement to move beyond equity markets to include credit markets that comprise sovereigns as key elements. In particular, in **Betz et al. (2016)** we provide new evidence on how banking sector fragmentation and sovereign-bank linkages evolved over the European sovereign debt crisis, and how they are reflected in estimated network statistics and systemic risk measures. Finally, our evidence provides an indication that the fragmentation of the European financial system has peaked. In **Buse and Schienle (2019)** and **Buse et al. (2022)** we study the impact of changes in regulations and policy interventions on systemic risk among European sovereign entities measured as volatility spillovers in credit risk markets. While the first studies differences in CDS versus bonds on daily data, the unique intraday CDS dataset of the second paper allows assessing the effectiveness of closely subsequent events, and discerning interventions with significant changes in network cross-effects. We show that it was mainly regulatory changes such as the ban of trading naked sovereign CDS in 2012 as well as the new ISDA regulations on sovereign CDS trading in 2014 which were most effective in reducing systemic risk. In comparison, the effect of policy interventions was minor and generally not sustainable. Their impact was only significant when they were implemented for the first time and targeted more than one country. For the volatility spillover channels, we generally find balanced networks with no fragmentation over time. In **Liang and Schienle (2019)** we detect advantages in the predictions for spillovers between corporate CDS and sovereigns when explicitly accounting for nonstationary level effects.

Beyond systemic risk measurement, the developed new techniques have also spurred new insights in further application fields. **Chen et al. (2019)** uses LASSO regulation in determining tail networks within the German power derivative market. The paper profits from results in **Betz et al. (2016)** and **Fan et al. (2019)**. In **Chernozhukov et al. (2021)** we apply the developed method for quantification of spillover effects of textual sentiment indices in a financial market and to test the connectedness among sectors. In **Chen et al (2023)** we employ an adaptation of the techniques of **Chen and Schienle (2022)** and **Liang and Schienle (2019)** for the modelling of high-frequency limit order book (LOB) dynamics within large portfolios. The novel tools allow extracting comprehensive information contained in the LOBs and quantify their impacts on the size and structure of price interdependencies across stocks for a blue-chip NASDAQ portfolio.

II. Advancements in forecasting with tail networks for assessing financial tail risk

a. Dynamic quantile factor models and systemic risk

In **Härdle et al. (2016)** we develop a tail event driven observable nonlinear factor model selecting nodes in the network as “relevant” factors. Methodologically, a variable selection technique in a time series setting is applied in the context of a single-index model for a generalized quantile regression framework. The method extends on the technique in **Fan et al. (2019)** by using a location scale model in the selection step. The suggested three step TENET (Tail Event driven NETWORK technique) selects relevant institutions in a first nonlinear step. In a second step, it calculates the impact of the first-step institution specific value at risk on the system variable in the tail while controlling for relevant network neighbors and economic conditions. Through this, the nonlinear effect of this institution on the system can be identified by various aggregate measures in step 3.

From a large-scale network analysis with TENET we can characterize the role of each financial industry group in the NASDAQ market during 2007–2012. From an additional clustering step, we detect that the depositories received and transmitted more risk among other groups, the insurers were less affected by the financial crisis. Overall, we provide a dynamic ranking for the Systemic Risk Receivers and Systemic Risk Emitters in the US financial market. Our original plans for the development of specific dynamic quantile factor models in the prediction of systemic risk were pursued and published by another team of authors (see Tran et al., 2019).

Please also see the forecast results in **Buse and Schienle (2019)** as well as forecast improvements in **Liang and Schienle (2019)** and **Chen and Schienle (2024)** as outlined above in part I. Moreover, results for general probabilistic quantile predictions and their evaluation have been derived in **Gneiting et al. (2023)**.

b. Extreme Multivariate Quantiles in a Dynamic Setting

In **Schaumburg et al (2016)** and **Bormann and Schienle, M. (2020)** we develop techniques for the analysis of extreme risks in multivariate financial systems. Such problems need to be addressed with methods from extreme value theory which statistically account for the rareness of extreme events. This requires a different form of central limit theorem implying non-standard asymptotics and inference. Such techniques are standard in the univariate context for i.i.d. data. The literature on multivariate extensions, however, is small - also the required generalization to dependent data is not straightforward. While results exist for mild dependency, the long-range dependence structure of financial returns requires GARCH-type pre-filtering which impacts the final inference of the tail results. In the applied literature, the standard way to treat multivariate problems on extreme risks was almost exclusively bivariate. In **Schaumburg et al (2016)** we propose a test for detecting situations when such pairwise measures are inadequate and give incomplete results. This occurs when a significant portion of the multivariate dependence structure in the tails is of higher dimension than 2. Our test statistic is based on a decomposition of the stable tail dependence function describing multivariate tail dependence. The asymptotic properties of the test are provided and a bootstrap-based finite sample version of the test is proposed. In an application to stock indices for non-crisis times, pairwise tail models seem appropriate for global markets while the test finds them not admissible for the tightly interconnected European market. From 2007/2008 on, however, higher order dependencies generally increase and require a multivariate tail model in all cases. In **Bormann and Schienle, M. (2020)** we contribute to an accurate assessment of tail inequalities and tail asymmetries of financial returns which is key for risk management and portfolio allocation. We propose a new test procedure for detecting the full extent of such structural differences in the dependence of bivariate extreme returns. We decompose the testing problem into piecewise multiple comparisons of Cramér–von Mises distances of tail copulas. In this way, tail regions that cause differences in extreme dependence can be located and consequently be targeted by financial strategies. We derive the asymptotic properties of the test and provide a bootstrap approximation for finite samples. Moreover, we account for the multiplicity of the piecewise tail copula comparisons by adjusting individual p -values according to multiple testing techniques. During the last 90 years in U.S. stock markets, our test detects up to 20% more tail asymmetries than competing tests. This can be attributed to the presence of nonstandard tail dependence structures. We also find evidence for diminishing tail asymmetries during every major financial crisis, except for the 2007–2009 crisis, reflecting a risk-return trade-off for extreme returns.

3.3 Handling of Research Data, Software and Infrastructures / Scientific Events and Science Communication

As part of our outreach and science communication strategy all methods directly related to quantile network risk have been implemented and showcased by the Financial Risk Meter (FRM) <http://frm.wiwi.hu-berlin.de>. The FRM collected real-time updates on systemic risk measurement based on our technology and developed an elaborate visualization and warning system. The respective software code of all contributed methods is freely available and easily accessible via <https://quantlet.com>. All our empirical studies relied on non-proprietary financial databases that does not allow further publishing or storage of raw data. The small share of funded data access through the project was made available and shared within HU Berlin researchers through the Humboldt Lab for Empirical and Quantitative Research (LEQR). In exchange, LEQR provided access to the full universe of Thomson Reuters and Bloomberg financial data bases.

Both PIs have jointly organized the Workshop “Modern Econometrics faces Machine Learning” (joint with Wolfgang Härdle and Bernd Fitzenberger) at Humboldt University Berlin (07/06/2017) with leading international experts in the field.

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4. Published Project Results

4.1 Publications with scientific quality assurance

(ordered by PI in descending time, limited to the 10 most important ones)

Buse, R.; Schienle, M.; Urban, J. (2022) Assessing the impact of policy and regulation interventions in European sovereign credit risk networks: What worked best?, *Journal of International Economics*, 139, Art.-Nr.: 103673. doi:10.1016/j.jinteco.2022.103673

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