MiF 2023: Conference Programme

Monday (24th)		Tuesday (25th)		Wednesday (26th)		Thursday (27th)		Friday (28th)	
Session 1		**Session 5**		**Session 9**		**Session 11**		**Session 15**	
09:00	Plen 1: Obloj	09:00	Plen 3: Guyon	08:30	Plen 5: Tasche	09:00	Plen 6: Schlogl	08:30	Burnecki
10:00	Wiesel	10:00	Grasselli	09:30	Visentin	10:00	Skovmand	09:00	Cvitanic
10:30	Tea	10:30	Tea	10:00	duToit/Schutte	10:30	Tea	09:30	Teichmann
				10:30	Tea			10:00	Cohen
Session 2		**Session 6**				**Session 12**		10:30	Tea
11:00	Krach	11:00	McWalter	**Session 10**		11:00	Rudd		
11:30	Neufeld	11:30	Backwell	11:00	Botha	11:30	van Appel	**Session 16**	
12:00	Sester	12:00	Alfeus	11:30	Obanya	12:00	Sithole	11:00	van Zyl
12:30	Lunch	12:30	Lunch	12:00	Schutte	12:30	Lunch	11:30	Semenova
				12:30	Osler			12:00	Futter
Session 3		**Session 7**		13:00	Close	**Session 13**		12:30	Close
13:30	Acciaio	13:30	Li			13:30	Aidoo		
14:00	Pesenti	14:00	Moro		Free afternoon	14:00	Van Schaik		
14:30	Xiang	14:30	Dube			14:30	Mananga		
15:00	Tea	15:00	Tea			15:00	Tea		
Session 4		**Session 8**				**Session 14**			
15:30	Plen 2: Jaimungal	15:30	Plen 4: Cuchiero			15:30	Plen 7: Tsomocos		
16:30	Macrina	16:30	Primavera			16:30	Close		
17:00	Close	17:00	Close						
	Free evening	19:00	Boma braai		Free evening	16:30	Bush braai		

Sunday (23rd) 19:00 Welcome / Cocktail Event

	Speaker	Title
Session 1		
Plenary 1	Obloj	Optimal Transport methods in Quantitative Finance
1	Wiesel	On Concentration of the Empirical Measure for General Transport Costs
Session 2		
2	Krach	Robust Utility Optimization via a GAN Approach
3	Neufeld	Markov Decision Processes under Model Uncertainty
4	Sester	Robust Q-learning Algorithm for Markov Decision Processes under Wasserstein Uncertainty
Session 3		
5	Acciaio	Quantifying Arbitrage
6	Pesenti	Minimal Kullback-Leibler Divergence for Constrained Levy-Ito Processes
7	Xiang	Model-free Bounds for Multi-asset Options Using Option-implied Information and their Exact Computation
Session 4		
Plenary 2	Jaimungal	Risk Budgeting Allocation for Dynamic Risk Measures
8	Macrina	Arcade Processes for Informed Martingale Interpolation and Transport
Session 5		
Plenary 3	Guyon	Volatility is (Mostly) Path-dependent
9	Grasselli	Sensitivity Analysis of Climate-economic Models
Session 6		
10	McWalter	On Stock-based Loans
11	Backwell	Agency Issues Associated with Contingent Equity
12	Alfeus	Dynamic Roughness in the Term Structure of Oil Markets Volatility
Session 7		
13	Li	Joint SPX-VIX Calibration with Gaussian Polynomial Volatility Models: Deep Pricing with Quantization Hints
14	Moro	Applying Regression and Classification Machine Learning Techniques to Construct Geospatial Price and Liquidity Indices
15	Dube	Supervised Machine Learning for Credit Risk Prediction with Sampling Techniques to Remedy Class Imbalance
Session 8		
Plenary 4	Cuchiero	Signature Methods in Stochastic Portfolio Theory
16	Primavera	Signature SDEs with Jumps and their Connections with Polynomial Processes
Session 9		
Plenary 5	Tasche	Classifier Accuracy and Class Prior Probabilities
17	Visentin	A Non-Markovian Approach to Portfolio Credit Risk
18	duToit	Shapley Values as Interpretability Technique in Credit Scoring

	Speaker	Title
Session 10		
19	Botha	Defining and Comparing SICR-events for Classifying Impaired Loans Under IFRS 9
20	Obanya	Assessing Permuatation Entropy on the Volatility of Financial Markets
21	Schutte	A Sample-size Dependent Measure of Population Correspondence in Banking - Improving the Population Stability Index (PSI)
22	Osler	Investigating the statistical properties of a parametric and non-parametric time series model in the financial markets
Session 11		
Plenary 6	Schlogl	Term Rates, Multicurve Term Structures and Overnight Rate Benchmarks: What We're Losing in the LIBOR Transition & What Changes
23	Skovmand	Scheduled Jumps in the SOFR Term Structure
Session 12		
24	Rudd	Throwing Away a Billion Yuan, Real or Rand: the Cost of Sub-optimal Hedging in High Interest-rate Environments
25	van Appel	Analysing Quantiles in Models of Forward Term Rates
26	Sithole	On a Consistent State-space Bond Markets Model for Pricing Long-maturity Bonds
Session 13		
27	Aidoo	Regression-based Estimation of Heteroscedastic Term Structure Models
28	Van Schaik	Robust Extension of the ACM Model to a Multiple Risk Premium Environment
29	Mananga	A Network Approach to the Interbank Contagion Risk in South Africa
Session 14		
Plenary 7	Tsomocos	The Persistence of Investment Inefficiencies: The Dynamics of Default and Endogenous Leverage
Session 15		
30	Burnecki	Pricing of Insurance-linked Securities: A Multi-peril Approach
31	Cvitanic	Optimal Fund Menus
32	Teichmann	Ergodic Robust Maximization of Asymptotic Growth Under Stochastic Volatility
33	Cohen	Data Driven Models of Individual Algorithms
Session 16		
34	van Zyl	A Minimax Approach to a Duality Result for Linear Distributional Sensitivity Testing
35	Semenova	Social Contagion and Asset Prices: Reddit's Self-organised Bull Runs
36	Futter	Optimal Trading Strategies using Signatures

Quantifying arbitrage

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Abstract

In this talk I will present a way to quantify arbitrage, that allows to deal with model uncertainty without imposing the no-arbitrage condition. In markets that admit "small arbitrage", we can still make sense of the problems of pricing and hedging. The pricing measures here will be such that asset price processes are close to being martingales, and the hedging strategies will need to cover some additional cost. We show a quantitative version of the Fundamental Theorem of Asset Pricing and of the Super-replication theorem. We study robustness of the amount of arbitrage and existence of respective pricing measures, showing stability with respect to a new, strong adapted Wasserstein distance.

Based on joint work with Julio Backhoff and Gudmund Pammer.

Regression-based estimation of heteroscedastic term structure models

Mansa Aidoo

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Abstract

Affine term structure models have been used to analyse the relationship between interest rates and observable factors, such as bond prices, to understand the drivers of changes in interest rates and provide insights into the term structure. These models are typically parameterised using complex maximum likelihood estimation techniques, which have been found to be computationally intensive and inefficient. The need for simpler, yet effective, modelling techniques led to the development of a popular method of no-arbitrage term structure estimation named the ACM method, after its originators. The method estimates the parameters of the term structure, given a set of observable pricing factors, using ordinary least squares regression, thus simplifying the estimation process.

This paper aims to explore an extension to the ACM method of estimating a no-arbitrage term-structure model. The ACM method assumes that the evolution of the pricing factors is underpinned by constant volatility through time. While this is highly tractable, it is not entirely plausible as there are periods of time where the yield curve exhibits unusually higher volatility, particularly during periods around announcements by the monetary policy committee (MPC) about rate change decisions. The extension therefore is heteroscedasticity, in which we intend to model jumps in the short-term interest rate, to better understand the effect of jumps on the term structure. Crucially, we aim to show that the ability to estimate via regression is maintained.

This is joint work with Alex Backwell and Joshua Hayes.

Dynamic roughness in the term structure of oil markets volatility

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Abstract

This paper analyses the attributes and the significance of the roughness of oil market volatility. We employ unspanned stochastic volatility models driven by rough Brownian motions that yield semi-analytic prices for futures options entailing efficient calibration applications. We calibrate option prices written on oil futures and provide empirical evidence of the dynamic nature of the roughness in oil volatility. The calibrated option-implied Hurst parameter varies over time, and rough stochastic volatility models provide a better fit to the term structure of implied oil volatility compared to classical stochastic volatility. Furthermore, including the Hurst parameter into the set of implied parameters benefits the stability of the calibrated parameters and improves pricing performance. These results underscore the importance to model the time dependency of the roughness of oil market volatility for future directions.

This is joint work with Christina S. Nikitopoulos and Ludger Overbeck.

Agency issues associated with contingent equity

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Abstract

We model a firm with contingent equity on its balance sheet. Contingent equity refers to warrants, employee options, convertible bonds, and other firm-issued claims whose exercise triggers an issue of shares. We show that the presence of contingent equity has a number of effects on how the ordinary shareholders should control the firm, such as the timing of expansions and bankruptcy. These effects are suboptimal for the value of total equity.

This is joint work with Peter Ritchken and Thomas McWalter.

Defining and comparing SICR-events for classifying impaired loans under IFRS 9

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Abstract

The IFRS 9 accounting standard requires the prediction of credit deterioration in financial instruments, i.e., significant increases in credit risk (SICR). However, the definition of such a SICR-event is inherently ambiguous, given its reliance on comparing two subsequent estimates of default risk against some arbitrary threshold. We examine the shortcomings of this approach and propose an alternative framework for generating SICR-definitions, based on three parameters: delinquency, stickiness, and the outcome period. Having varied these parameters, we obtain 27 unique SICR-definitions and fit logistic regression models accordingly using rich South African mortgage data; itself containing various macroeconomic and obligor-specific input variables. This new SICR-modelling approach is demonstrated by analysing the resulting portfolio-level SICR-rates (of each SICR-definition) on their stability over time and their responsiveness to economic downturns. At the account-level, we compare both the accuracy and flexibility of the SICR-predictions across all SICR-definitions, and discover several interesting trends during this process. These trends form a rudimentary expert system for selecting the three parameters optimally, as demonstrated in our recommendations for defining SICR-events. In summary, our work can guide the formulation, testing, and modelling of any SICR-definition, thereby promoting the timeous recognition of credit losses; the main imperative of IFRS 9.

Pricing of insurance-linked securities: A multi-peril approach

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Abstract

We build a methodology for pricing of insurance-linked securities which are tied to multiple natural catastrophe perils. As a representative example, we construct a multi-peril catastrophe (CAT) bond which can be linked to the industry loss indices or actual losses incurred by an insurer. We provide pricing formulas for such CAT bonds. We illustrate the introduced methodology on the US natural catastrophe data obtained from Property Claim Services (PCS). For the data, we select two risks, namely losses related to wind and thunderstorm, and winter storm events. We identify and validate underlying compound non-homogeneous Poisson processes taking into account the fact that the data are left-truncated. Finally, we visualise the zero-coupon CAT bond prices for the selected best-fitted models

Data driven models of individual algorithms

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Abstract

Modelling of High Frequency traders is a difficult task, given the understandable secrecy surrounding the algorithms used. This causes challenges for our understanding of markets, and for regulation. In this talk, we will outline some recent results on the modelling of algorithms from the perspective of a regulator, who has access to fully identified records of transactions in the limit order book. We will see how this allows stylized models of different algorithm behaviours to be constructed.

Our dataset, which spans sixteen weeks for four shares, contains all messages sent to the exchange and includes algorithm identification and member identification. We obtain reliable out-of-sample predictions and report the top features that predict direction, price, and volume. The coefficients from the fitted models are used to cluster trading behaviour and we find that algorithms registered as Liquidity Providers exhibit the widest range of trading behaviour among dealing capacities. In particular, for the most liquid share in our study, we find that approximately one third of algorithms with dealing capacity Liquidity Providers exhibit directional and position-building behaviour.

Joint work between the Alan Turing Institute and the Autoriteit Financiële Markten.

Signature methods in stochastic portfolio theory

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Abstract

In the context of stochastic portfolio theory we introduce a novel class of portfolios which we call linear path-functional portfolios. These are portfolios which are determined by certain transformations of linear functions of a collection of feature maps that are non-anticipative path functionals of an underlying semimartingale. As main example for such feature maps we consider (random) signature of the (ranked) market weights. We prove that these portfolios are universal in the sense that every continuous, possibly path-dependent, portfolio function of the market weights can be uniformly approximated by signature portfolios. We also show that signature portfolios can approximate the log-optimal portfolio in generic classes of non-Markovian models arbitrarily well and illustrate numerically that the trained signature portfolios are remarkably close to the theoretical log-optimal portfolios. Besides these universality features, the main numerical advantage lies in the fact that several optimization tasks like maximizing expected logarithmic utility or mean-variance optimization within the class of linear path-functional portfolios reduces to a convex quadratic optimization problem, thus making it computationally highly tractable. We apply our method to real market data demonstrating out-performance on out-of-sample data also in the presence of transaction costs.

The talk is based on joint work with Janka Moeller.

Optimal fund menus

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Abstract

We study the optimal design of a menu of funds by a manager who is required to use linear pricing and does not observe the beliefs of investors regarding one of the risky assets. The optimal menu involves bundling of assets and can be explicitly constructed from the solution to a calculus of variations problem that optimizes over the indirect utility that each type of investor receives. We provide a complete characterization of the optimal menu and show that the need to maintain incentive compatibility leads the manager to offer funds that are inefficiently tilted towards the asset that is not subject to the information friction.

Supervised machine learning for credit risk prediction with sampling techniques to remedy class imbalance

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Abstract

This research aims to investigate the performance of various machine learning algorithms in credit risk prediction, including decision tree, extreme gradient boosting (XGBoost), naïve Bayesian, K-nearest neighbour (kNN), linear discriminant analysis (LDA), Multivariate Adaptive Regression Spline (MARS), BlackBoost, logistic regression, random forest, and neural networks. The study also evaluates the effectiveness of different sampling techniques, including under-sampling technique (UNDER), over-sampling technique (OVER), a combination of both under-sampling and under-sampling technique (BOTH) and random oversampling examples (ROSE), in addressing the class imbalance problem. The results show that kNN and Random Forest are the best performing algorithms, while OVER sampling technique is the best sampling technique in terms of overall performance. The findings of this research provide valuable insights for practitioners in the financial industry and can inform the development of more effective credit risk prediction models.

This is joint work with Tanja Verster and Temesgen Zewotir.

Shapley values as interpretability technique in credit scoring

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Abstract

The use of machine learning algorithms in credit scoring can be enhanced by an improved understanding of the reasoning behind model decisions. Although machine learning algorithms are widely regarded as highly accurate, the use of these algorithms in settings that require explanation of model decisions, have been limited due to the lack of transparency. Especially, in the banking sector, the model risk frameworks of banks frequently require a significant level of model interpretability.

In this paper, the Shapley value is evaluated as a machine learning interpretability technique in credit scoring. The Shapley value is a model agnostic machine learning interpretability technique that quantifies the contribution of each feature in the prediction of a specific observation. The effectiveness of this technique is tested on various simulated datasets with covariates from different underlying distributions that are linearly and nonlinearly related to the outcome. Traditional models (for example, logistic and linear regression) and machine learning algorithms are trained on the data and the Shapley values are generated. The paper then further illustrates the differences between traditional and machine learning model risk frameworks and identifies potential use cases where this technique can be utilised to validate non-traditional machine learning models.

Our results show that Shapley values are a related measure to Weights of Evidence (a well-known measure in scorecard literature) that can be used to explain the direction of relationships between explanatory variables and the outcome. The paper proposes the use of this technique as a suitable approach when validating machine learning models in the banking industry, especially where explainability is of high importance or a regulatory requirement.

This is joint work with Willem Daniël Schutte, Helgard Raubenheimer.

Optimal trading strategies using signatures

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Abstract

Asset allocation for trading strategies is a fundamental aspect of finance and so has subsequently been researched extensively in the past decades. Classical methods often consist of a predict-then-optimise approach, of which the optimisation is subject to heavy modelling assumptions that do not reflect stylised facts in practice such as non-stationarity, heavy tails and volatility clustering, this leaves the result exposed to asymmetric errors. While well studied parametric models provide a useful benchmark for practitioners, this has led to approaches that are independent of model choice and are inherently data-driven by previous price paths.

In this work, we utilise rough path theory, extending the work of Perez et. al by approximating a trading strategy as a linear functional on the signature of a path, which requires no explicit prediction of future returns. We derive an analytic representation of the mean-variance criterion and provide a closed form solution that is determined by the expected signature of the previous price paths, of which uniquely determines the law of the stochastic process. We then extend this solution to be robust to uncertainty with respect to the expected signature using the maximum mean discrepancy metric between all possible measures on path space. "Sig-trading" encompasses traditional trend following and statistical arbitrage opportunities whilst ensuring to be free from overfitting to past time series data.

Finally, we alleviate the dimensionality bottleneck presented in our previous work, by instead shifting the focus from computing the signature directly, but instead derive a representor theorem when representing the trading strategy as a linear functional on the signature kernel. Our approaches are model-free, data-driven and capture such stylised facts exhibited by financial data, while still being easy to implement and do not require any heavy machinery in comparison to many machine learning alternatives.

Sensitivity analysis of climate-economic models

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Abstract

Assessing the economic impacts of climate change, as well as the effects of economic activity on the climate, requires the use of complex models with high computational costs and a very large number of parameters. In this talk, I will apply global sensitivity analysis techniques from statistics (such as Sobol indices) and machine learning (such as random forests) to representative climate-economic models in order to identify and rank the most important parameters and quantify their effect on select output variables. This will then be followed by both backtesting and exploration of forward scenarios under these models, taking parameter uncertainty into account. In particular, I will describe the effect of uncertainty on the expected result of policiers such as carbon taxes, green financing, and green investment.

Volatility is (mostly) path-dependent

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Abstract

We learn from data that volatility is mostly path-dependent: up to 90% of the variance of the implied volatility of equity indexes is explained endogenously by past index returns, and up to 65% for (noisy estimates of) future daily realized volatility. The path-dependency that we uncover is remarkably simple: a linear combination of a weighted sum of past daily returns and the square root of a weighted sum of past daily squared returns

with different time-shifted power-law weights capturing both short and long memory. This simple model, which is homogeneous in volatility, is shown to consistently outperform existing models across equity indexes and train/test sets for both implied and realized volatility. It suggests a simple continuous-time path-dependent volatility (PDV) model that may be fed historical or risk-neutral parameters. The weights can be approximated by superpositions of exponential kernels to produce Markovian models. In particular, we propose a 4-factor Markovian PDV model which captures all the important stylized facts of volatility, produces very realistic price and (rough-like) volatility paths, and jointly fits SPX and VIX smiles remarkably well. We thus show that a continuous-time Markovian parametric stochastic volatility (actually, PDV) model can practically solve the joint SPX/VIX smile calibration problem.

This is joint work with Jordan Lekeufack (UC Berkeley).

Risk budgeting allocation for dynamic risk measures

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Abstract

We define and develop an approach for risk budgeting allocation — a risk diversification portfolio strategy — where risk is measured using a dynamic time-consistent risk measure. For this, we introduce a notion of dynamic risk contributions that generalise the classical Euler contributions and which allow us to obtain dynamic risk contributions in a recursive manner. We prove that, for the class of dynamic coherent distortion risk measures, the risk allocation problem may be recast as a sequence of strictly convex optimisation problems. Moreover, we show that any self-financing dynamic risk budgeting strategy with initial wealth of one is a scaled version of the unique solution of the sequence of convex optimisation problems. Furthermore, we develop an actor-critic approach, leveraging the elicitability of dynamic risk measures, to solve for risk budgeting strategy using deep learning.

This is joint work with Silvana Pesenti, Yuri Saporito, and Rodrigo Targino.

Robust utility optimization via a GAN approach

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Abstract

We study the robust expected utility maximisation problem. In this problem, an agent wants to maximise the expected utility of the final wealth X_T under her trading strategy π in an uncertain market environment that chooses the worst case market model $P \in \mathcal{P}$ for the given trading strategy, i.e., $\sup_\pi \inf_{P\in\mathcal{P}} \mathbb{E}_P[U(X_T^\pi)]$. This problem can be understood as a two-player zero-sum game between the agent and the market. We restrict our attention to markets consisting of one risk-free and d risky assets given by Itô processes, where the drift μ and diffusion σ are chosen by the market player out of

a set of admissible candidate functions (using the paths of the portfolio and asset values as inputs). To make this tractable, we consider a penalized version of the robust utility optimization problem, where the market model can choose any such functions that are continuous, but is penalized for deviating from a reference market model via a penalty function F. We suggest an algorithm to solve this problem using two recurrent neural networks (RNNs), one for the agent and one for the market, which are trained iteratively by competing in the zero-sum game

$$\sup_{\theta} \inf_{\omega} \mathbb{E}\left[U(X_T^{\pi_\theta,\mu_\omega,\sigma_\omega}) + F(\mu_\omega, \sigma_\omega, X^{\pi_\theta,\mu_\omega,\sigma_\omega})\right].$$

On a high level, this can be interpreted as a generative adversarial network (GAN) approach, where the generator produces a trading strategy π_θ and the adversarial discriminator tries to find the worst case market model $(\mu_\omega, \sigma_\omega)$. Importantly, the use of RNNs allows both players to learn non-Markovian strategies. The utility function U as well as the penalty function F can be chosen freely. We examine several set-ups to empirically show the quality of our proposed algorithm. At first, we consider log-utility in a frictionless market and instantaneous penalization of the market parameters. In this case, an analytic solution is known to exist which is replicated by our trained model. When introducing friction to the market, or using other utility functions as e.g. isoelastic utilities, or using more realistic path-dependent penalties, an analytic solution no longer exists. Therefore, we construct new evaluation metrics and we observe that our trained model achieves convincing results.

This is joint work with Josef Teichmann and Hanna Wutte.

Joint SPX-VIX calibration with Gaussian polynomial volatility models: Deep pricing with quantization hints

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Abstract

We consider the joint SPX-VIX calibration within a general class of Gaussian polynomial volatility models in which the volatility of the SPX is assumed to be a polynomial function of a Gaussian Volterra process defined as a stochastic convolution between a kernel and a Brownian motion. By performing joint calibration to daily SPX-VIX implied volatility surface data between 2012 and 2022, we compare the empirical performance of different kernels and their associated Markovian and non-Markovian models, such as rough and non-rough path-dependent volatility models. In order to ensure an efficient calibration and a fair comparison between the models, we develop a generic unified method in our class of models for fast and accurate pricing of SPX and VIX derivatives based on functional quantization and Neural Networks. For the first time, we identify a *conventional one-factor Markovian continuous stochastic volatility model* that is able to achieve remarkable fits of the implied volatility surfaces of the SPX and VIX together with the term structure of VIX futures. What is even more remarkable is that our conventional one-factor Markovian continuous stochastic volatility model outperforms, in all market conditions, its rough and non-rough path-dependent counterparts with the same number of parameters.

This is joint work with Eduardo Abi Jaber and Camille Illand.

Arcade processes for informed martingale interpolation and transport

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Abstract

Arcade processes are a class of continuous stochastic processes that interpolate in a strong sense between zeros at fixed pre-specified times. Their additive randomization allows one to match any finite sequence of target random variables, indexed by the given fixed dates, on the whole probability space. The randomized arcade processes can thus be interpreted as a generalization of anticipative stochastic bridges. The filtrations generated by these processes are utilized to construct a class of martingales which interpolate between the given target random variables. These so-called filtered arcade martingales (FAMs) are almost-sure solutions to the martingale interpolation problem and reveal an underlying stochastic filtering structure. In the special case of nearly-Markov randomized arcade processes, the dynamics of FAMs are informed through Bayesian updating. FAMs can be connected to martingale optimal transport (MOT) by considering optimally-coupled target random variables. Moreover, FAMs allow to formulate the information-based martingale optimal transport problem, which enables the introduction of noise in MOT, in a similar fashion to how Schrödinger's problem introduces noise in optimal transport. This information-based transport problem is concerned with selecting an optimal martingale coupling for the target random variables under the influence of the noise that is generated by an arcade process.

This is joint work with Georges Kassis, UCL Mathematics.

A network approach to the interbank contagion risk in South Africa

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Abstract

This paper adopts a dynamic agent-based model to simulate the interbank networks for the South African banking system and introduces DebtRank to capture the losses caused by relative drops in the banking system's equity before the occurrence of a default. In contrast to past research that has mostly concentrated on large banks to the detriment of small and medium-sized banks, we investigate banks' systemic importance and vulnerability and conduct a panel data analysis to explore their respective explanatory power of vulnerability. Our findings imply that a high interbank lending ratio is a key indicator of bank fragility. Our approach is intended to be a tool for identifying vulnerabilities from a top-down perspective, which can lead to a more in-depth sector analysis for policy formation.

This is joint work with Shiqiang Lin and Hairui Zhang.

On stock-based loans

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Abstract

We investigate the equilibrium interest rate charges on non-recourse and recourse loans secured by stock. In such loans, the client retains the option to prepay and recover the collateral stock. We adopt a structural model of the firm where debt levels, with endogenous bankruptcy, affect equity dynamics. Complicating matters, the link between total equity and the price of a share of stock that forms the collateral depends on the extent of dilutions and buybacks that occur. For levered firms, due to dilution in bad states of nature, stock prices typically fall faster than equity values; and for firms that engage in buybacks in good states of nature, stock prices will rise faster than equity values. Banks that ignore these features underestimate the equilibrium interest rate charge on stock-based loans. We provide an analysis of individual stock-based loans and their portfolio characteristics, the latter of which can be used by banks to ascertain capital requirements.

This is joint work with Peter Ritchken.

Geospatial price and liquidity real estate indices and their properties

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Abstract

Residential houses represent a low liquidity market with heterogeneous assets differentiated by their geographical location and characteristics. It can be compared to financial OTC markets, except that it is standardised in terms of the set of characteristics, and it is endowed with the geographical feature. This allows estimating price indices for individual geographical areas by applying a model controlling for the heterogeneity of characteristics. Additionally, we propose to proxy market liquidity by the estimated probability of a transaction within a certain time horizon. By merging comprehensive data sets comprising all the transaction prices in the last fifteen years and more than one hundred characteristics of residential houses in Greater London, and applying regression and classification ML techniques, we construct geospatial price and liquidity indices at the postcode level. The statistical properties of these indices, their evolution in time and geographical distribution are subsequently analysed. Finally, we demonstrate how the indices can be used for establishing geospatial price and liquidity relationships and for forecasting expected prices and demand for individual houses.

Markov decision processes under model uncertainty

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Abstract

In this talk we introduce a general framework for *Markov decision problems* under model uncertainty in a discrete-time infinite horizon setting.

To solve the robust optimization problem we establish a dynamic programming principle that involves only a one time-step optimization problem. Via Berge's maximum theorem we obtain the existence of both an optimal action and a worst case transition kernel of this *local* one time-step problem. It turns out that the optimal action that solves this one time-step optimization problem determines also the *global* optimal policy of the infinite time horizon robust stochastic optimal control problem by repeatedly executing this *local* solution. Similarly, the *global* worst case measure can be determined as a product measure given by the infinite product of the worst case transition kernel of the *local* one time-step optimization problem.

Eventually we show how the discussed robust stochastic optimal control framework can be applied to portfolio optimization with real data. To that end, we show how, based on a time series of realized returns of multiple assets of the $S\&P$ 500, a data-driven ambiguity set of probability measures can be derived in two cases. The first case is an entirely data-driven approach where ambiguity is described by a Wasserstein-ball around the empirical measure. In the second case a multivariate normal distribution of the considered returns is assumed while the set of parameters for the multivariate normal distribution is estimated from observed data. Hence, this approach can be considered as a semi data-driven approach. We then train neural networks to solve the (semi) data-driven robust optimization problem based on the local-to-global paradigm obtained from our dynamic programming principle and compare the trading performance of the two approaches with non-robust approaches. It turns out that under adverse market scenarios both robust approaches outperform comparable non-robust approaches. These results emphasize the importance of taking into account model uncertainty when making decisions that rely on financial assets.

This is joint work with Julian Sester and Mario Šikić (see also arXiv:2206.06109).

Assessing permutation entropy on the volatility of financial markets

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Abstract

In this paper, permutation entropy (PE) is employed to analyze Cryptocurrency Market prices and volatility for 2015-2022. In order to determine the implied volatility fluctuations for the time period, GARCH models are developed. The PE of the market prices

and the implied volatility obtained using the GARCH models are estimated to check for the ability of PE in predicting crashes. The dynamics of the market during periods of low and high volatility are also investigated using PE. The results are compared to earlier studies of market crash dynamics in order to determine the ability of PE to predict these events.

This is joint work with Modisane Seitshiro, Carel Olivier and Tanja Verster.

Optimal transport methods in quantitative finance

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Abstract

Quantitative finance is concerned with computing financially relevant outputs: prices, hedging strategies, investment strategies, risk measures etc. It does so by building models which create pathways from inputs to outputs. These models can often be identified with probability measures – as simple as a distribution on R if we only want to price a European option, or as complex as a distribution on a multidimensional pathspace. The theory of Optimal Transport (OT) offers powerful fully non-parametric tools to measure distances between probability measures, trace geodesics in the space of probability measures, project onto its subsets. In this talk, I will survey some recent advancements that leverage the OT tools to describe and manage the space of financial models, helping with selecting/calibrating models and quantifying model uncertainty. In particular, I will discuss robust pricing and hedging and its link to Martingale-OT, non-parametric calibration via Semimartingale-OT, and Wasserstein distributionally robust optimization and the resulting non-parametric Greeks and risk measurements. I will also mention some applications in statistics and data-driven robust risk estimation. I will aim to provide a general overview of the field, while pointing out the ongoing research and future challenges.

The talk is based on works done with many collaborators, including: D. Bartl, S. Drapeau, S. Eckstein, G. Guo, I. Guo, B. Joseph, T. Lim, G. Loeper, S. Wang and J. Wiesel.

Investigating the statistical properties of a parametric and non-parametric time series model in the financial markets

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Abstract

Nowadays traditional financial models are overtaken by state-of-the-art machine learning models. However, the properties of these non-parametric models are neglected and not well documented. This paper aims to analyse the statistical properties and Box-Jenkins framework of the time series in a non-parametric environment using AR-NN (Autoregressive neural network) as a case study applied to a financial index. The forecast performance

errors are compared between an autoregressive integrated moving average (ARIMA) and an AR-NN model. The findings of this research provide valuable insights for statisticians in the financial industry and can inform the development of more effective parsimonious traditional and machine learning time series models.

This is joint work with Modisane Seitshiro and Tanja Verster.

Minimal Kullback-Leibler divergence for constrained Lévy-Itô processes

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Abstract

We consider an n-dimensional stochastic processes $(\boldsymbol{X}_t)_{t\in[0,T]}$ that follow Lévy-Itô dynamics under a reference probability measure $\mathbb{P}$ over a finite time horizon. The reference measure, however, does not precisely capture all probabilistic beliefs of a modeller. Here, misspecification can be characterised via (i) expected values of functions applied to the stochastic process at terminal time and (ii) expected running costs of the processes over the entire time horizon. To mitigate model error, the modeller seek over all absolutely continuous probability measures, under which the process satisfies these constraints, the one which is closest to the reference measure $\mathbb{P}$ in the relative entropy. Thus, the key contribution of this work is solving the following constrained optimisation problem:
For functions $f_j, g_i : \mathbb{R}^n \to \mathbb{R}$ and constants $c_j, d_i \in \mathbb{R}$, with $j \in \{1, 2, \dots, r_1\}$, $i \in \{1, 2, \dots, r_2\}$, we consider the optimisation problem

$$\inf_{\mathbb{Q}\ll\mathbb{P}} \mathbb{E}\left[\frac{d\mathbb{Q}}{d\mathbb{P}}\log\left(\frac{d\mathbb{Q}}{d\mathbb{P}}\right)\right] \quad \text{subject to} \quad \mathbb{E}^{\mathbb{Q}}\left[f_j(\boldsymbol{X}_T)\right] = c_j\,, \ \forall\, j\,, \quad \text{and} \quad \mathbb{E}^{\mathbb{Q}}\left[\int_0^T g_i(\boldsymbol{X}_s)\,ds\right] = d_i\,, \ \forall\, i\,. \tag{1}$$

We prove existence and uniqueness of the optimal probability measure, derive an explicit form of the measure change, and characterise the drift and compensator adjustments under the optimal measure.

We illustrate the dynamics of the stochastic process under the optimal measure using multiple examples, including the case of two Value-at-Risk constraints – where we provide an analytical expression for the optimal change of measure –, and show how to perturb a Brownian motion to have zero mean and arbitrary variance. Moreover, we consider infinitesimal perturbations; that is, we solve the problem where the constraints are equal to their $\mathbb{P}$-expectation plus ε multiplied with a direction. In this setting, we prove that the Lagrange multiplier is, up to order ε, the inverse of the $\mathbb{P}$-covariance matrix of the constraint functions multiplied by ε and the direction of the perturbation. Using this result, we define a derivative – termed *entropic derivative* – of a risk functional along constraints in direction of least relative entropy. As examples we show the connection of the entropic derivative to differential sensitivities of risk functionals such as the Tail Value-at-Risk and distortion risk measures.

Finally, we provide an algorithm to simulate under the optimal measure and illustrate our results in a risk management setting, where we seeks to answer the question: what dynamics are induced by a perturbation of the Value-at-Risk and the average time spent below a barrier on the reference process?

This is joint work with Leandro Sánchez-Betancourt and Sebastian Jaimungal.

Signature SDEs with jumps and their connections with polynomial processes

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Abstract

Signature-based models have recently entered the field of stochastic modeling, in particular in Mathematical Finance. The choice of the signature as main building block is mainly explained by a universal approximation theorem (UAT) according to which continuous functions of continuous paths can be approximated by linear functionals of the time-extended signature. This powerful result, however, leaves open the question of approximating continuous functions of the more general set of càdlàg paths. Based on recent advances on the signature of càdlàg paths and by using appropriate topologies thereon, we present a UAT that solves this question. Relying on these approximation results, we then introduce a generic class of jump-diffusion models and recognize them as projections of infinite dimensional polynomial processes. This allows to get power series expansions in terms of the process' initial value for the expected value of analytic functions of the process' marginals. As special cases, we analyze one dimensional jump-diffusions with real-analytic characteristics and the so-called Lévy type-signature models, a new class of signature models that extend the class of continuous signature models for asset prices proposed so far.

This talk is based on joint work with Christa Cuchiero and Sara Svaluto-Ferro.

Throwing away a billion yuan, real or rand: the cost of sub-optimal hedging in high interest-rate environments

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Abstract

Interest-rate volatility is known to be positively level dependent, i.e., to correlate positively with interest-rate levels. However, recent research has provided compelling evidence that as interest rates rise, the amount of level dependence decreases. We advance this line of research by investigating the amount of volatility level dependence in an emerging market with high interest rates, and find no evidence for the positive level dependence implied by the popular log-normal forward-LIBOR market model. This has important consequences for the hedging of interest-rate derivatives: when hedging caps, using the log-normal market model can be worse than not hedging at all and it is significantly outperformed by its normally distributed counterpart, which exhibits no level dependence.

This is joint work with Alex Backwell.

Term rates, multicurve term structures and overnight rate benchmarks: What we're losing in the LIBOR transition and what changes for term structure modelling

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Abstract

In the current LIBOR transition to overnight-rate benchmarks, it is important to understand theoretically and empirically what distinguishes actual term rates from overnight benchmarks or "synthetic" term rates based on such benchmarks. The "multi-curve" phenomenon of tenor basis spreads between term structures associated with different payment frequencies provides key information on this distinction. This information can be extracted using a modelling framework based on the concept of "roll-over risk", i.e., the risk a borrower faces of not being able to refinance a loan at (or at a known spread to) a market benchmark rate. The theoretical modelling and the empirical evidence show that proper term rates based on the new benchmarks remain elusive and that substantial market information will be lost in those jurisdictions where LIBOR-type benchmarks disappear. In addition, overnight rates (and any associated benchmarks) are far more sensitive to changes in monetary policy than term rates (especially for terms of three months and more), meaning that central bank interest rate decisions are much more directly relevant to modelling interest rate dynamics under the new benchmark regime, and term structure models should be modified to reflect this.

A sample-size dependent measure of population correspondence in banking: Improving the Population Stability Index (PSI)

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Abstract

The Population Stability Index (PSI) is a widely-used measure in the banking sector to monitor the degree of correspondence between two discrete probability distributions. The PSI aims to ensure consistency between the current and model development populations by monitoring the evolution of the underlying population. When inconsistencies are detected, model reconstruction is required. Despite its widespread use, the origins and properties of the PSI are not well understood. The term was coined by Lewis (1994) in the textbook "Introduction to Credit Scoring". Other popular texts reference the use of PSI in banking, but make use of arbitrary rule-of-thumb thresholds to decide when model reconstruction is required. To address these concerns, we propose an alternative measure based on the Pearson chi-square statistic and the non-central chi square distribution, which offers statistically well-founded properties. Additionally, we introduce sample size-dependent thresholds and provide simulated and real-world examples to illustrate the efficacy of the new measure.

This is joint work with C. van Zyl and N. Potgieter.

Social contagion and asset prices: Reddit's self-organised bull runs

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Abstract

This paper investigates how social forces can affect asset prices, through an empirical analysis of the beliefs and positions of individuals active on Reddit's WallStreetBets (WSB) forum. The paper proposes a stylized model, incorporating complementarities in asset demand alongside price extrapolation. In doing so, we explain three features of the WSB data: i) users shift their expectations about returns to match those of their peers, ii) returns are predictable and experience reversals, and iii) heterogeneity in investor sentiment can affect markets when popularity is heavy-tailed. We empirically document that sentiments expressed by WSB users about assets' future performances (bullish or bearish) are in part due to sentiments of their peers and past asset returns. The paper also estimates the effect of WSB activity on asset prices, and provides insight into how heterogeneous, idiosyncratic sentiments can impact asset prices. The paper concludes that the unique features of social media, such as its scale and ability to facilitate the spread of information, make it an important driver of market behaviour.

This is joint work with Julian Winkler.

Robust Q-learning algorithm for Markov decision processes under Wasserstein uncertainty

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Abstract

We present a novel Q-learning algorithm to solve distributionally robust Markov decision problems, where the corresponding ambiguity set of transition probabilities for the underlying Markov decision process is a Wasserstein ball around a (possibly estimated) reference measure. We prove convergence of the presented algorithm and provide several examples also using real data to illustrate both the tractability of our algorithm as well as the benefits of considering distributional robustness when solving stochastic optimal control problems, in particular when the estimated distributions turn out to be misspecified in practice.

This is joint work with Ariel Neufeld.

On a consistent state-space bond markets model for pricing long-maturity bonds

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Abstract

In most financial markets, prices for long-maturity derivatives are not readily available due to illiquidity. This reality is particularly common in bond markets, as it is very challenging to model prices consistently—for medium-to-long-term bonds under a single specification of the underlying interest rate process. We develop a bond market state-space model that incorporates uncertainty in the underlying interest rate process parameters. Our state-space representation, coupled with the complementary Kalman filtering, provides a modeling configuration that permits for liquidity risk management and pricing that is designed in a consistent fashion for both medium- and long-term bonds. As an example, we constructed a state-space bond market modeling system formulated on the two-factor Vasicek interest rate model. Wherein, the interest rate model is subject to noise for medium-to-long-term bond maturities and follows an unobservable process. We demonstrate our Kalman filter algorithm using the observed United States (US) 10 year bond yield data.

Scheduled jumps in the SOFR term structure

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Abstract

The London Interbank Offered Rate (LIBOR) is scheduled for discontinuation by the end of June 2023, and the replacement is the Secured Overnight Financing Rate (SOFR). SOFR differs from LIBOR by being an overnight rate and therefore jumps following changes in the target rate by the Federal Reserve. The connection to the policy made by the Federal reserve makes SOFR highly discontinuous around FOMC meeting dates. These discontinuities present challenges when modelling the dynamics of SOFR since classical short-rate models assume continuous dynamics of the short-rate. In order to capture the discontinuous dynamics of SOFR we present an affine model incorporating jumps of unknown size, but at known dates corresponding to the scheduled FOMC meeting dates. Using the historical record of SOFR fixings and SOFR futures prices, we investigate and compare the ability of classical continuous affine models and our jump specification to fit overnight SOFR and the term structure of SOFR futures. The models are estimated jointly under the pricing measure and the historical measure using maximum likelihood in conjunction with the Kalman-Filter. Finally we consider data from the new, but rapidly growing market for options on SOFR futures. We demonstrate how option pricing can be done and document some preliminary stylized facts.

The work is done jointly with Erik Schlögl and Jacob Bjerre Skov.

Classifier accuracy and class prior probabilities

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Abstract

There is no question that it is worthwhile to develop accurate classifiers in order to improve classification performance in typical applications like credit scoring, information retrieval or image recognition. However, the task might not be classification of single instances but estimating the prior probability of a class in a sample, as would for instance be the case for credit loss provisioning. Then it is not obvious that classification accuracy helps improving the performance of the estimator. For binary class prior estimation under prior probability shift, we determine the Cramer-Rao bound for the variance of unbiased estimators and show that it depends on the refinement loss of the related regression problem. This observation suggests that optimising the accuracy of a base classifier, as measured by the Brier score, on the training dataset helps to reduce the variance of the related class prior estimator on the test data set.

Ergodic robust maximization of asymptotic growth under stochastic volatility

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Abstract

We consider an asymptotic robust growth problem under model uncertainty and in the presence of (non-Markovian) stochastic covariance. We fix two inputs representing the instantaneous covariance for the asset process X, which depends on an additional stochastic factor process Y, as well as the invariant density of X together with Y. The stochastic factor process Y has continuous trajectories but is not even required to be a semimartingale. Our setup allows for drift uncertainty in X and model uncertainty for the local dynamics of Y. This work builds upon a recent paper of Kardaras & Robertson, where the authors consider an analogous problem, however, without the additional stochastic factor process. Under suitable, quite weak assumptions we are able to characterize the robust optimal trading strategy and the robust optimal growth rate. The optimal strategy is shown to be functionally generated and, remarkably, does not depend on the factor process Y. Our result provides a comprehensive answer to a question proposed by Fernholz in 2002. Mathematically, we use a combination of partial differential equation (PDE), calculus of variations and generalized Dirichlet form techniques.

This is joint work with David Itkin, Benedikt Koch, and Martin Larsson.

The persistence of investment inefficiencies: The dynamics of default and endogenous leverage

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Abstract

We propose a tractable framework that incorporates endogenous default in a continuous time setting and assesses the interaction of default and leverage. In our heterogeneous agent model, productive experts face leverage constraints and aggregate risk, borrow from less productive households and choose whether to default. We establish a positive correlation between default and borrowing costs, hence a positive default premium. Moreover, higher default generates negative excess returns, lowers experts capital holdings and suppresses investment, thus resulting into constrained inefficient equilibria. Finally, we show how, in environments with low levels of exogenous risk, lower penalties can considerably decrease the time the economy spends in the inefficient region.

This is joint work with Theofanis Papamichalis and Nikolaos Romanidis.

Analysing quantiles in models of forward term rates

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Abstract

The class of forward-LIBOR market models can, under certain volatility structures, produce unrealistically high long-dated forward rates, particularly for maturities and tenors beyond the liquid market calibration instruments. We present a diagnostic tool for analysing the quantiles of distributions for forward term rates in a displaced lognormal forward-LIBOR model (DLFM). In particular, we provide a quantile approximation that can be used to assess whether the modelled term rates remain within realistic bounds with a high probability. Applying this diagnostic tool (verified using Quasi-Monte Carlo (QMC) simulations), we show that realised forward term rates for long time horizons may be kept within realistic limits by appropriately damping the tail of the DLFM volatility function.

This is joint work with Thomas McWalter and Erik Schlögl.

Robust extension of the ACM model to a multiple risk premium environment

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Abstract

The proliferation of factor investing strategies in recent years has highlighted the idea that a portfolio can harvest improved risk-adjusted returns through timed exposure to risk factors during times of elevated risk premia. While there is a large body of research on such risk factors and risk premia in equity markets, there has been relatively little research on the topic in fixed income markets. One such fixed income risk factor that has begun to receive interest from practitioners and academics is the term premium, the risk premium associated with duration risk in bonds.

Adrian et al. (ACM) (2013) introduced a sophisticated affine term structure model which is calibrated using ordinary least-squares (OLS) regressions, a faster and more robust approach than the maximum likelihood estimation which is typically used for such models. In addition to its quick and robust calibration method, the ACM model has various properties that make it appealing, including realistic modelling assumptions and, critically, a term premium estimate that is shown to align with various economic indicators that are not used as inputs to the model. As a result, the ACM model has garnered much attention from academics and practitioners alike.

In this paper, we extend the original ACM model on three fronts. Firstly, we extend the set of pricing factors to decompose the term premium into further risk premia such as an inflation risk premium and country risk premium. Secondly, we incorporate regularisation in the OLS regressions to ensure robustness of the term premium estimate. Lastly, we introduce time- and state-dependency in the model through the use of dynamic weightings on the regressors. We evaluate results in both the US Treasury Bond market and the South African Government Bond market.

This is joint work with Emlyn Flint and Florence Chikurunhe.

A minimax approach to a duality result for linear distributional sensitivity testing

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Abstract

Let μ be a probability measure on a complete separable metric space S and f a real-valued function on S satisfying certain mild growth and continuity conditions. Consider the maximum of $\mathbb{E}_\nu[f(X)]$ where ν is allowed to vary over all the probability measures for which $d_c(\mu, \nu) \leq \theta$, where d_c is an optimal transport distance and $\theta \geq 0$. Useful duality results for this problem, reducing the infinite dimensional problem to one of low dimension, have been derived in various ways by Esfahani and Kuhn; Blanchet and Murthy; Gao and

Kleywegt; Feng and Schlögl; Bartl, Drapeau and Tangpi; and others. One of the main approaches relies on Fenchel duality. We present a proof that imposes a further topological assumption to instead use K. Fan's minimax theorem. This allows one to avoid the use of vector spaces of measures, or dual variables other than the Lagrange multiplier.

A Non-Markovian approach to portfolio credit risk

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Abstract

In dynamic credit portfolio models the multivariate default process is usually assumed to be Markov conditionally on a set of exogenous factors (typically macro-economic variables, such as interest rates or inflation). Under this assumption the factors evolve autonomously and are not influenced by the defaults in the portfolio. In reality it is common to observe feedback loops in the economy, especially during financial crises: the default of a systemically important institution may influence macro-economic variables, which in turn impact the default probabilities of the other institutions. In this work we introduce a non-Markovian extension of the classical theory that is able to model this type of phenomena. Our results rely on the theory of enlargements of filtrations and can be used to compute the term structure of default probabilities by recursively solving a system of SDEs. We discuss the model implementation and show numerical results for the pricing of credit derivatives.

This is joint work with Delia Coculescu, University of Zurich.

On concentration of the empirical measure for general transport costs

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Abstract

Let μ be a probability measure on $\mathbb{R}^d$ and μ_N its empirical measure with sample size N. We prove a concentration inequality for the optimal transport cost between μ and μ_N for cost functions with polynomial local growth, that can have superpolynomial global growth. This result generalizes and improves upon estimates of Fournier and Guillin.

The proof combines ideas from empirical process theory with known concentration rates for compactly supported μ. By partitioning $\mathbb{R}^d$ into annuli, we infer a global estimate from local estimates on the annuli and conclude that the global estimate can be expressed as a sum of the local estimate and a mean-deviation probability for which efficient bounds are known.

This talk is based on joint work with Martin Larsson and Jonghwa Park.

Model-free bounds for multi-asset options using option-implied information and their exact computation

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Abstract

In this talk, we consider derivatives written on multiple underlying assets in a one-period financial market, and we are interested in the computation of model-free upper and lower bounds for their arbitrage-free prices. We work in a completely realistic setting, in that we only assume the knowledge of traded prices for other single- and multi-asset derivatives, and even allow for the presence of bid–ask spread in these prices. In other words, we work in a model-free setting in the presence of option-implied information, and make no assumption about the probabilistic evolution of asset prices (*i.e.* their marginal distributions) or their dependence structure. We provide a fundamental theorem of asset pricing for this market model, as well as a superhedging duality result, that allows to transform the abstract maximization problem over probability measures into a more tractable minimization problem over vectors, subject to the super-replication constraints. Then, we recast this problem into a linear semi-infinite optimization problem.

In order to develop algorithms for solving this linear semi-infinite optimization problem, we work under the assumption that the payoff functions of the traded derivatives and the target derivative are continuous piece-wise affine functions. These include many popular payoff functions in finance such as European call and put options, basket call and put options, spread options, call-on-max options, call-on-min options, and best-of-call options. Subsequently, we provide two cutting-plane algorithms for solving the linear semi-infinite optimization problem. These algorithms provide upper and lower bounds for the prices that are ε-optimal, as well as a characterization of the optimal pricing measures. The no-arbitrage gap, *i.e.* the difference between the upper and lower no-arbitrage bounds, directly reflects the model-risk associated to a particular derivative and the information available in the market. These algorithms are efficient and allow the computation of bounds in high-dimensional scenarios (*e.g.* when $d = 60$). Moreover, these algorithms can be used to detect arbitrage opportunities and identify the corresponding arbitrage strategies. Numerical experiments using both synthetic and real market data showcase the efficiency of these algorithms, while they also allow to understand the reduction of model risk by including additional information, in the form of known derivative prices.

This talk is based on joint work with Ariel Neufeld and Antonis Papapantoleon (see also https://doi.org/10.1287/mnsc.2022.4456).