IN PARTNERSHIP WITH:
CNRS

Ecole des Ponts ParisTech

Université Paris-Est Marne-la-Vallée

Activity Report 2017

Project-Team MATHRISK

Mathematical Risk handling

IN COLLABORATION WITH: Centre d'Enseignement et de Recherche en Mathématiques et Calcul Scientifique (CERMICS)

RESEARCH CENTER
Paris

THEME
Stochastic approaches

Table of contents

1. **Personnel** **1**
2. **Overall Objectives** **2**
3. **Research Program** **3**
    3.1. Dependence modeling 3
    3.2. Liquidity risk 3
        3.2.1. Long term liquidity risk. 4
        3.2.2. Market microstructure. 4
    3.3. Contagion modeling and systemic risk 5
    3.4. Stochastic analysis and numerical probability 5
        3.4.1. Stochastic control 5
        3.4.2. Optimal stopping 5
        3.4.3. Simulation of stochastic differential equations 5
        3.4.4. Monte-Carlo simulations 6
        3.4.5. Malliavin calculus and applications in finance 6
4. **Application Domains** **7**
5. **New Software and Platforms** **7**
    5.1. PREMIA 7
    5.2. Platforms 8
6. **New Results** **9**
    6.1. Systemic risk 9
    6.2. Optimal stopping for Backward stochastic (partial) differential equations with jumps 9
    6.3. Approximation of Martingale Optimal Transport problems 9
    6.4. Numerical methods for Asset-Liability Management 10
    6.5. American options 10
    6.6. Stochastic Analysis and Malliavin calculus 10
7. **Bilateral Contracts and Grants with Industry** **10**
    7.1. Bilateral Grants with Industry 10
    7.2. Bilateral Contracts with Industry 11
8. **Partnerships and Cooperations** **11**
    8.1. National Initiatives 11
        8.1.1. ANR 11
        8.1.2. Competitivity Clusters 11
    8.2. International Initiatives 11
    8.3. International Research Visitors 11
9. **Dissemination** **12**
    9.1. Promoting Scientific Activities 12
        9.1.1. Scientific Events Organisation 12
        9.1.2. Scientific Events Selection 12
            9.1.2.1. Member of the Conference Program Committees 12
            9.1.2.2. Reviewer 12
        9.1.3. Journal 12
            9.1.3.1. Member of the Editorial Boards 12
            9.1.3.2. Reviewer - Reviewing Activities 12
        9.1.4. Invited Talks 13
        9.1.5. Scientific Expertise 14
        9.1.6. Research Administration 14
    9.2. Teaching - Supervision - Juries 14
        9.2.1. Teaching 14
        9.2.2. Supervision 15

9.2.3. Juries 15
10. Bibliography **16**

Project-Team MATHRISK

Creation of the Team: 2012 January 01, updated into Project-Team: 2013 January 01

Keywords:

Computer Science and Digital Science:

A6. - Modeling, simulation and control
A6.1. - Mathematical Modeling
A6.1.2. - Stochastic Modeling (SPDE, SDE)
A6.2.1. - Numerical analysis of PDE and ODE
A6.2.2. - Numerical probability
A6.2.3. - Probabilistic methods
A6.4.2. - Stochastic control

Other Research Topics and Application Domains:

B3.1. - Sustainable development
B9.5.3. - Economy, Finance
B9.9. - Risk management

1. Personnel

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2. Overall Objectives

2.1. Overall Objectives

MathRisk is a joint Inria project-team with ENPC (CERMICS Laboratory) and the University Paris Est Marne-la-Vallée (UPEMLV, LAMA Laboratory), located in Paris and Marne-la-Vallée.
http://www.inria.fr/en/teams/mathrisk. Mathrisk is based on the former Mathfi project team. Mathfi was founded in 2000, and was devoted to financial mathematics. The project was focused on advanced stochastic analysis and numerical techniques motivated by the development of increasingly complex financial products. Main applications concerned evaluation and hedging of derivative products, dynamic portfolio optimization in incomplete markets, and calibration of financial models.

2.1.1. Crisis, deregulation, and impact on the research in finance

The starting point of the development of modern finance theory is traditionally associated to the publication of the famous paper of Black and Scholes in 1973 [54]. Since then, in spite of sporadic crises, generally well overcome, financial markets have grown in a exponential manner. More and more complex exotic derivative products have appeared, on equities first, then on interest rates, and more recently on credit markets. The period between the end of the eighties and the crisis of 2008 can be qualified as the "golden age of financial mathematics": finance became a quantitative industry, and financial mathematics programs flourished in top universities, involving seminal interplays between the worlds of finance and applied mathematics. During its 12 years existence, the Mathfi project team has extensively contributed to the development of modeling and computational methods for the pricing and hedging of increasingly complex financial products.

Since the crisis of 2008, there has been a critical reorientation of research priorities in quantitative finance with emphasis on risk. In 2008, the "subprime" crisis has questioned the very existence of some derivative products such as CDS (credit default swaps) or CDOs (collateralized debt obligations), which were accused to be responsible for the crisis. The nature of this crisis is profoundly different from the previous ones. It has negatively impacted the activity on the exotic products in general, - even on equity derivative markets-, and the interest in the modeling issues for these products. The perfect replication paradigm, at the origin of the success of the Black and Scholes model became unsound, in particular through the effects of the lack of liquidity. The interest of quantitative finance analysts and mathematicians shifted then to more realistic models taking into account the multidimensional feature and the incompleteness of the markets, but as such getting away from the "lost paradi(gm)" of perfect replication. These models are much more demanding numerically, and require the development of hedging risk measures, and decision procedures taking into account the illiquidity and various defaults.

Moreover, this crisis, and in particular the Lehman Brothers bankruptcy and its consequences, has underlined a systemic risk due to the strong interdependencies of financial institutions. The failure of one of them can cause a cascade of failures, thus affecting the global stability of the system. Better understanding of these interlinkage phenomena becomes crucial.

At the same time, independently from the subprime crisis, another phenomenon has appeared: deregulation in the organization of stock markets themselves. This has been encouraged by the Markets in Financial Instruments Directive (MIFID) which is effective since November, 1st 2007. This, together with the progress of the networks, and the fact that all the computers have now a high computation power, have induced arbitrage opportunities on the markets, by very short term trading, often performed by automatic trading. Using these high frequency trading possibilities, some speculating operators benefit from the large volatility of the markets. For example, the flash crash of May, 6 2010 has exhibited some perverse effects of these automatic speculating trading strategies. These phenomena are not well understood and the theme of high frequency trading needs to be explored.

To summarize, financial mathematics is facing the following new evolutions:

- the complete market modeling has become unsatisfactory to provide a realistic picture of the market and is replaced by incomplete and multidimensional models which lead to new modeling and numerical challenges.
- quantitative measures of risk coming from the markets, the hedging procedures, and the lack of liquidity are crucial for banks,
- uncontrolled systemic risks may cause planetary economic disasters, and require better understanding,
- deregulation of stock markets and its consequences lead to study high frequency trading.

The project team MathRisk is designed to address these new issues, in particular dependence modeling, systemic risk, market microstructure modeling and risk measures. The research in modeling and numerical analysis remain active in this new context, motivated by new issues.

The MathRisk project team develops the software Premia dedicated to pricing and hedging options and calibration of financial models, in collaboration with a consortium of financial institutions. https://www.rocq.inria.fr/mathfi/Premia/index.html.

The MathRisk project is part of the Université Paris-Est **"Labex" BÉZOUT**.

3. Research Program

3.1. Dependence modeling

Participants: Aurélien Alfonsi, Benjamin Jourdain, Damien Lamberton, Bernard Lapeyre.

The volatility is a key concept in modern mathematical finance, and an indicator of the market stability. Risk management and associated instruments depend strongly on the volatility, and volatility modeling has thus become a crucial issue in the finance industry. Of particular importance is the assets *dependence* modeling. The calibration of models for a single asset can now be well managed by banks but modeling of dependence is the bottleneck to efficiently aggregate such models. A typical issue is how to go from the individual evolution of each stock belonging to an index to the joint modeling of these stocks. In this perspective, we want to model stochastic volatility in a *multidimensional* framework. To handle these questions mathematically, we have to deal with stochastic differential equations that are defined on matrices in order to model either the instantaneous covariance or the instantaneous correlation between the assets. From a numerical point of view, such models are very demanding since the main indexes include generally more than thirty assets. It is therefore necessary to develop efficient numerical methods for pricing options and calibrating such models to market data. As a first application, modeling the dependence between assets allows us to better handle derivatives products on a basket. It would give also a way to price and hedge consistensly single-asset and basket products. Besides, it can be a way to capture how the market estimates the dependence between assets. This could give some insights on how the market anticipates the systemic risk.

3.2. Liquidity risk

Participants: Aurélien Alfonsi, Agnès Sulem, Antonino Zanette.

The financial crisis has caused an increased interest in mathematical finance studies which take into account the market incompleteness issue and the liquidity risk. Loosely speaking, liquidity risk is the risk that comes from the difficulty of selling (or buying) an asset. At the extreme, this may be the impossibility to sell an asset, which occurred for “junk assets” during the subprime crisis. Hopefully, it is in general possible to sell assets, but this may have some cost. Let us be more precise. Usually, assets are quoted on a market with a Limit Order Book (LOB) that registers all the waiting limit buy and sell orders for this asset. The bid (resp. ask) price is the most expensive (resp. cheapest) waiting buy or sell order. If a trader wants to sell a single asset, he will sell it at the bid price. Instead, if he wants to sell a large quantity of assets, he will have to sell them at a lower price in order to match further waiting buy orders. This creates an extra cost, and raises important issues. From a short-term perspective (from few minutes to some days), this may be interesting to split the selling order and to focus on finding optimal selling strategies. This requires to model the market microstructure, i.e. how the market reacts in a short time-scale to execution orders. From a long-term perspective (typically, one month or more), one has to understand how this cost modifies portfolio managing strategies (especially delta-hedging or optimal investment strategies). At this time-scale, there is no need to model precisely the market microstructure, but one has to specify how the liquidity costs aggregate.

3.2.1. Long term liquidity risk.

On a long-term perspective, illiquidity can be approached via various ways: transactions costs [46], [47], [53], [58], [61], [73], [70], delay in the execution of the trading orders [74], [72], [55], trading constraints or restriction on the observation times (see e.g. [60] and references herein). As far as derivative products are concerned, one has to understand how delta-hedging strategies have to be modified. This has been considered for example by Cetin, Jarrow and Protter [71]. We plan to contribute on these various aspects of liquidity risk modeling and associated stochastic optimization problems. Let us mention here that the price impact generated by the trades of the investor is often neglected with a long-term perspective. This seems acceptable since the investor has time enough to trade slowly in order to eliminate its market impact. Instead, when the investor wants to make significant trades on a very short time horizon, it is crucial to take into account and to model how prices are modified by these trades. This question is addressed in the next paragraph on market microstructure.

3.2.2. Market microstructure.

The European directive MIFID has increased the competition between markets (NYSE-Euronext, Nasdaq, LSE and new competitors). As a consequence, the cost of posting buy or sell orders on markets has decreased, which has stimulated the growth of market makers. Market makers are posting simultaneously bid and ask orders on a same stock, and their profit comes from the bid-ask spread. Basically, their strategy is a “round-trip” (i.e. their position is unchanged between the beginning and the end of the day) that has generated a positive cash flow.

These new rules have also greatly stimulated research on market microstructure modeling. From a practitioner point of view, the main issue is to solve the so-called “optimal execution problem”: given a deadline T, what is the optimal strategy to buy (or sell) a given amount of shares that achieves the minimal expected cost? For large amounts, it may be optimal to split the order into smaller ones. This is of course a crucial issue for brokers, but also market makers that are looking for the optimal round-trip.

Solving the optimal execution problem is not only an interesting mathematical challenge. It is also a mean to better understand market viability, high frequency arbitrage strategies and consequences of the competition between markets. For example when modeling the market microstructure, one would like to find conditions that allow or exclude round trips. Beyond this, even if round trips are excluded, it can happen that an optimal selling strategy is made with large intermediate buy trades, which is unlikely and may lead to market instability.

We are interested in finding synthetic market models in which we can describe and solve the optimal execution problem. A. Alfonsi and A. Schied (Mannheim University) [48] have already proposed a simple Limit Order Book model (LOB) in which an explicit solution can be found for the optimal execution problem. We are now interested in considering more sophisticated models that take into account realistic features of the market such as short memory or stochastic LOB. This is mid term objective. At a long term perspective one would like to bridge these models to the different agent behaviors, in order to understand the effect of the different quotation mechanisms (transaction costs for limit orders, tick size, etc.) on the market stability.

3.3. Contagion modeling and systemic risk

Participants: Benjamin Jourdain, Agnès Sulem.

After the recent financial crisis, systemic risk has emerged as one of the major research topics in mathematical finance. The scope is to understand and model how the bankruptcy of a bank (or a large company) may or not induce other bankruptcies. By contrast with the traditional approach in risk management, the focus is no longer on modeling the risks faced by a single financial institution, but on modeling the complex interrelations between financial institutions and the mechanisms of distress propagation among these. Ideally, one would like to be able to find capital requirements (such as the one proposed by the Basel committee) that ensure that the probability of multiple defaults is below some level.

The mathematical modeling of default contagion, by which an economic shock causing initial losses and default of a few institutions is amplified due to complex linkages, leading to large scale defaults, can be addressed by various techniques, such as network approaches (see in particular R. Cont et al. [49] and A. Minca [65]) or mean field interaction models (Garnier-Papanicolaou-Yang [59]). The recent approach in [49] seems very promising. It describes the financial network approach as a weighted directed graph, in which nodes represent financial institutions and edges the exposures between them. Distress propagation in a financial system may be modeled as an epidemics on this graph. In the case of incomplete information on the structure of the interbank network, cascade dynamics may be reduced to the evolution of a multi-dimensional Markov chain that corresponds to a sequential discovery of exposures and determines at any time the size of contagion. Little has been done so far on the *control* of such systems in order to reduce the systemic risk and we aim to contribute to this domain.

3.4. Stochastic analysis and numerical probability

3.4.1. Stochastic control

Participants: Vlad Bally, Jean-Philippe Chancelier, Marie-Claire Quenez, Agnès Sulem.

The financial crisis has caused an increased interest in mathematical finance studies which take into account the market incompleteness issue and the default risk modeling, the interplay between information and performance, the model uncertainty and the associated robustness questions, and various nonlinearities. We address these questions by further developing the theory of stochastic control in a broad sense, including stochastic optimization, nonlinear expectations, Malliavin calculus, stochastic differential games and various aspects of optimal stopping.

3.4.2. Optimal stopping

Participants: Aurélien Alfonsi, Benjamin Jourdain, Damien Lamberton, Agnès Sulem, Marie-Claire Quenez.

The theory of American option pricing has been an incite for a number of research articles about optimal stopping. Our recent contributions in this field concern optimal stopping in models with jumps, irregular obstacles, free boundary analysis, reflected BSDEs.

3.4.3. Simulation of stochastic differential equations

Participants: Benjamin Jourdain, Aurélien Alfonsi, Vlad Bally, Damien Lamberton, Bernard Lapeyre, Jérôme Lelong, Céline Labart.

Effective numerical methods are crucial in the pricing and hedging of derivative securities. The need for more complex models leads to stochastic differential equations which cannot be solved explicitly, and the development of discretization techniques is essential in the treatment of these models. The project MathRisk addresses fundamental mathematical questions as well as numerical issues in the following (non exhaustive) list of topics: Multidimensional stochastic differential equations, High order discretization schemes, Singular stochastic differential equations, Backward stochastic differential equations.

3.4.4. Monte-Carlo simulations

Participants: Benjamin Jourdain, Aurélien Alfonsi, Damien Lamberton, Vlad Bally, Bernard Lapeyre, Ahmed Kebaier, Céline Labart, Jérôme Lelong, Antonino Zanette.

Monte-Carlo methods is a very useful tool to evaluate prices especially for complex models or options. We carry on research on *adaptive variance reduction methods* and to use *Monte-Carlo methods for calibration* of advanced models.

This activity in the MathRisk team is strongly related to the development of the Premia software.

3.4.5. Malliavin calculus and applications in finance

Participants: Vlad Bally, Arturo Kohatsu-Higa, Agnès Sulem, Antonino Zanette.

The original Stochastic Calculus of Variations, now called the Malliavin calculus, was developed by Paul Malliavin in 1976 [63]. It was originally designed to study the smoothness of the densities of solutions of stochastic differential equations. One of its striking features is that it provides a probabilistic proof of the celebrated Hörmander theorem, which gives a condition for a partial differential operator to be hypoelliptic. This illustrates the power of this calculus. In the following years a lot of probabilists worked on this topic and the theory was developed further either as analysis on the Wiener space or in a white noise setting. Many applications in the field of stochastic calculus followed. Several monographs and lecture notes (for example D. Nualart [66], D. Bell [52] D. Ocone [68], B. Øksendal [75]) give expositions of the subject. See also V. Bally [50] for an introduction to Malliavin calculus.

From the beginning of the nineties, applications of the Malliavin calculus in finance have appeared : In 1991 Karatzas and Ocone showed how the Malliavin calculus, as further developed by Ocone and others, could be used in the computation of hedging portfolios in complete markets [67].

Since then, the Malliavin calculus has raised increasing interest and subsequently many other applications to finance have been found [64], such as minimal variance hedging and Monte Carlo methods for option pricing. More recently, the Malliavin calculus has also become a useful tool for studying insider trading models and some extended market models driven by Lévy processes or fractional Brownian motion.

We give below an idea why Malliavin calculus may be a useful instrument for probabilistic numerical methods.

We recall that the theory is based on an integration by parts formula of the form $E(f'(X)) = E(f(X)Q)$. Here X is a random variable which is supposed to be "smooth" in a certain sense and non-degenerated. A basic example is to take $X = \sigma\Delta$ where Δ is a standard normally distributed random variable and σ is a strictly positive number. Note that an integration by parts formula may be obtained just by using the usual integration by parts in the presence of the Gaussian density. But we may go further and take X to be an aggregate of Gaussian random variables (think for example of the Euler scheme for a diffusion process) or the limit of such simple functionals.

An important feature is that one has a relatively explicit expression for the weight Q which appears in the integration by parts formula, and this expression is given in terms of some Malliavin-derivative operators.

Let us now look at one of the main consequences of the integration by parts formula. If one considers the *Dirac* function $\delta_x(y)$, then $\delta_x(y) = H'(y-x)$ where H is the *Heaviside* function and the above integration by parts formula reads $E(\delta_x(X)) = E(H(X-x)Q)$, where $E(\delta_x(X))$ can be interpreted as the density of the random variable X. We thus obtain an integral representation of the density of the law of X. This is the starting point of the approach to the density of the law of a diffusion process: the above integral representation allows us to prove that under appropriate hypothesis the density of X is smooth and also to derive upper and lower bounds for it. Concerning simulation by Monte Carlo methods, suppose that you want to compute $E(\delta_x(y)) \sim \frac{1}{M}\sum_{i=1}^{M}\delta_x(X^i)$ where $X^1, ..., X^M$ is a sample of X. As X has a law which is absolutely continuous with respect to the Lebesgue measure, this will fail because no X^i hits exactly x. But if you are able to simulate the weight Q as well (and this is the case in many applications because of the explicit form mentioned above) then you may try to compute $E(\delta_x(X)) = E(H(X-x)Q) \sim \frac{1}{M}\sum_{i=1}^{M}E(H(X^i-x)Q^i)$. This basic remark formula leads to efficient methods to compute by a Monte Carlo method some irregular quantities as derivatives of option prices with respect to some parameters (the *Greeks*) or conditional expectations, which appear in the pricing of American options by the dynamic programming). See the papers by Fournié et al [57] and [56] and the papers by Bally et al., Benhamou, Bermin et al., Bernis et al., Cvitanic et al., Talay and Zheng and Temam in [62].

L. Caramellino, A. Zanette and V. Bally have been concerned with the computation of conditional expectations using Integration by Parts formulas and applications to the numerical computation of the price and the Greeks (sensitivities) of American or Bermudean options. The aim of this research was to extend a paper of Reigner and Lions who treated the problem in dimension one to higher dimension - which represent the real challenge in this field. Significant results have been obtained up to dimension 5 [51] and the corresponding algorithms have been implemented in the Premia software.

Moreover, there is an increasing interest in considering jump components in the financial models, especially motivated by calibration reasons. Algorithms based on the integration by parts formulas have been developed in order to compute Greeks for options with discontinuous payoff (e.g. digital options). Several papers and two theses (M. Messaoud and M. Bavouzet defended in 2006) have been published on this topic and the corresponding algorithms have been implemented in Premia. Malliavin Calculus for jump type diffusions - and more general for random variables with locally smooth law - represents a large field of research, also for applications to credit risk problems.

The Malliavin calculus is also used in models of insider trading. The "enlargement of filtration" technique plays an important role in the modeling of such problems and the Malliavin calculus can be used to obtain general results about when and how such filtration enlargement is possible. See the paper by P. Imkeller in [62]). Moreover, in the case when the additional information of the insider is generated by adding the information about the value of one extra random variable, the Malliavin calculus can be used to find explicitly the optimal portfolio of an insider for a utility optimization problem with logarithmic utility. See the paper by J.A. León, R. Navarro and D. Nualart in [62]).

A. Kohatsu Higa and A. Sulem have studied a controlled stochastic system whose state is described by a stochastic differential equation with anticipating coefficients. These SDEs can be interpreted in the sense of *forward integrals*, which are the natural generalization of the semi-martingale integrals, as introduced by Russo and Valois [69]. This methodology has been applied for utility maximization with insiders.

4. Application Domains

4.1. Financial Mathematics, Insurance

The applications domains are quantitative finance and insurance with emphasis on risk modeling and control. In particular, Mathrisk focuses on dependence modeling, systemic risk, market microstructure modeling and risk measures.

5. New Software and Platforms

5.1. PREMIA

KEYWORDS: Financial products - Computational finance - Option pricing
SCIENTIFIC DESCRIPTION: The Premia project keeps track of the most recent advances in the field of computational finance in a well-documented way. It focuses on the implementation of numerical analysis techniques for both probabilistic and deterministic numerical methods. An important feature of the platform Premia is the detailed documentation which provides extended references in option pricing.

Premia is thus a powerful tool to assist Research and Development professional teams in their day-to-day duty. It is also a useful support for academics who wish to perform tests on new algorithms or pricing methods without starting from scratch.

Besides being a single entry point for accessible overviews and basic implementations of various numerical methods, the aim of the Premia project is: 1 - to be a powerful testing platform for comparing different numerical methods between each other, 2 - to build a link between professional financial teams and academic researchers, 3 - to provide a useful teaching support for Master and PhD students in mathematical finance.
FUNCTIONAL DESCRIPTION: Premia is a software designed for option pricing, hedging and financial model calibration.

- Participants: Agnes Sulem, Antonino Zanette, Aurélien Alfonsi, Benjamin Jourdain, Jacques Printems and Jérôme Lelong
- Partners: Inria - Ecole des Ponts ParisTech - Université Paris-Est
- Contact: Agnes Sulem
- URL: http://www.premia.fr

5.2. Platforms

5.2.1. Development of the quantitative platform Premia in 2017

- Premia 18 has been registered at the Agence pour la Protection des Programmes APP (IDDN.FR.001.190010.014.S.C.2001.000.31000)

- Premia 19 has been delivered to the Consortium Premia on March 16th. It contains the following new algorithms : Risk Management, Model Risk, Insurance

- XVA simulation on GPUs using Nested Monte Carlo. L. Abbas Turki
- Model-independent bounds for option prices a mass transport approach. M. Beiglböck, P. H. Labordère, F. Penkner
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Equity Derivatives

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- Efficient unbiased simulation scheme for the SABR stochastic volatility model. B. Chen, C.W. Oosterlee J.A.M van der Weide.
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  The Journal of Computational Finance, Volume 19, Issue 1, 2015.
- Unbiased simulation of stochastic differential equations. P.H. Labordere X. Tan, N. Touzi

We have benefited from the help of the engineer Cedric Doucet, supervised by Jérôme Lelong, for designing non regression tests for Premia.

6. New Results

6.1. Systemic risk

Participants: Agnès Sulem, Andreea Minca [Cornell University], Rui Chen.

We have studied optimal connectivity of a large financial network in presence of growth and contagion [27]. We obtained asymptotic results for the magnitude of default contagion in a large financial system with intrinsic recovery features in the framework of a random network. We have moreover added a game component to the model, allowing institutions to choose their optimal linkages in order to maximize their final profits, given their initial states and estimated survival probabilities.

6.2. Optimal stopping for Backward stochastic (partial) differential equations with jumps

Agnès Sulem, Rui Chen and R. Dumitrescu have addressed the problem of optimal stopping for general mean-field backward stochastic differential equations driven by a Brownian motion and an independent Poisson random measure. Existence, uniqueness, comparison and dual representation results have been obtained. Links with reflected mean-field BSDEs have been established and application to global dynamic risk measure theory has been investigated.

American options in markets with imperfections and default have been studied by Agnès Sulem, M.C. Quenez and R. Dumitrescu [28].

6.3. Approximation of Martingale Optimal Transport problems

With J. Corbetta, A. Alfonsi and B. Jourdain study sampling methods preserving the convex order for two probability measures μ and ν on $\mathbf{R}^d$, with ν dominating μ. When $(X_i)_{1\leq i\leq I}$ (resp. $(Y_j)_{1\leq j\leq J}$) are independent and identically distributed according μ (resp. ν), in general $\mu_I = \frac{1}{I}\sum_{i=1}^{I}\delta_{X_i}$ and $\nu_J = \frac{1}{J}\sum_{j=1}^{J}\delta_{Y_j}$ are not rankable for the convex order. They investigate modifications of μ_I (resp. ν_J) smaller than ν_J (resp. greater than μ_I) in the convex order and weakly converging to μ (resp. ν) as $I, J \to \infty$. They first consider the one dimensional case $d = 1$, where, according to Kertz and Rösler, the set of probability measures with a finite first order moment is a lattice for the increasing and the decreasing convex orders. Given μ and ν in this set, they define $\mu \vee \nu$ (resp. $\mu \wedge \nu$) as the supremum (resp. infimum) of μ and ν for the decreasing convex order when $\int_{\mathbf{R}} x\mu(dx) \leq \int_{\mathbf{R}} x\nu(dx)$ and for the increasing convex order otherwise. This way, $\mu \vee \nu$ (resp. $\mu \wedge \nu$) is greater than μ (resp. smaller than ν) in the convex order. They give efficient algorithms permitting to compute $\mu \vee \nu$ and $\mu \wedge \nu$ (and therefore $\mu_I \vee \nu_J$ and $\mu_I \wedge \nu_J$) when μ and ν are convex combinations of Dirac masses.

In general dimension, when μ and ν have finite moments of order $\rho \geq 1$, they define the projection $\mu \curlywedge_\rho \nu$ (resp. $\mu \curlyvee_\rho \nu$) of μ (resp. ν) on the set of probability measures dominated by ν (resp. larger than μ) in the convex order for the Wasserstein distance with index ρ. When $\rho = 2$, $\mu_I \curlywedge_2 \nu_J$ can be computed efficiently by solving a quadratic optimization problem with linear constraints. It turns out that, in dimension $d = 1$, the projections do not depend on ρ and their quantile functions are explicit in terms of those of μ and ν, which leads to efficient algorithms for convex combinations of Dirac masses. Last, they illustrate by numerical experiments the resulting sampling methods that preserve the convex order and their application to approximate Martingale Optimal Transport problems.

With V. Ehrlacher, D. Lombardi and R. Coyaud, A. Alfonsi has started to develop and analyze numerical methods to approximate the optimal transport between two probability measures.

6.4. Numerical methods for Asset-Liability Management

With A. Cherchali, A. Alfonsi is working on obtaining a model for the Asset-Liability Management (ALM) of insurance companies. The purpose is to use this model to develop Monte-Carlo methods to approximate the SCR (Solvency Capital Requirement).

6.5. American options

With Giulia Terenzi, D. Lamberton has been working on American options in Heston's model. Some results about existence and uniqueness for the associated variational inequality, in suitable weighted Sobolev spaces (see Feehan and co-authors for recent results on elliptic problems) have been obtained, as well as some results on monotonicity and regularity properties of the price function. A paper on this topic has just been submitted.

6.6. Stochastic Analysis and Malliavin calculus

- Invariance principles for stochastic polynomials [40].

  With L. Caramellino (Roma), V. Bally has studied invariance principles for stochastic polynomials. This is a generalization of the classical invariance principle from the Central Limit Theorem, of interest in U-statistics. The main contribution concerns convergence in total variation distance, using an abstract variant of Malliavin calculus for general random variables which verify a Doeblin type condition.

- Convergence in distribution norms in the Central Limit Theorem and Edgworth expansions [39] (V. Bally, L. Caramellino and G. Poly).

  The convergence in "distribution norms" represents an extension of the convergence in total variation distance which permits to take into account some singular phenomenons. The main tool is the abstract Malliavin calculus mentioned above. Several examples are given in the paper and an outstanding application concerns the estimates of the number of roots of trigonometric polynomials. considered in a second paper; see [40].

- Bolzmann equation and Piecewise Deterministic Markov Processes. (see [41], [37]). In collaboration with D. Goreac and V. Rabiet, V. Bally has studied the regularity of the semigroup of $PDMP's$ and, as an application estimates of the distance between two such semigroups. An interesting example is given by the two dimensional homogeneous Bolzmann equation. Furthermore, V. Bally obtained some exponential estimates for the function solution of this equation.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Grants with Industry

- Consortium PREMIA, Natixis - Inria

- Consortium PREMIA, Crédit Agricole CIB - Inria

7.2. Bilateral Contracts with Industry

- Chair Ecole Polytechnique-ENPC-UPMC-Société Générale "Financial Risks" of the Risk fondation . Participants: A. Alfonsi, B. Jourdain, B. Lapeyre
- AXA Joint Research Initiative on Numerical methods for the ALM, from September 2017 to August 2020, Participant: A. Alfonsi.

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. ANR

- ANR Cosmos 2015-2018, Participant: B. Jourdain ; Partners : Ecole des Ponts, Telecom, Inria Rennes and IBPC

8.1.2. Competitivity Clusters

Pôle Finance Innovation.

8.2. International Initiatives

8.2.1. Informal International Partners

- Center of Excellence program in Mathematics and Life Sciences at the Department of Mathematics, University of Oslo, Norway, (B. Øksendal).
- Kings College, London (R. Dumitrescu)
- Department of Mathematics, University of Manchester (Tusheng Zhang, currently in charge of an EU-ITN program on BSDEs and Applications).
- Kensas University (Yaozhong Hu)
- Cornell University, ORIE department (Andreea Minca)
- Mannheim University (Alexander Schied, Chair of Mathematics in Business and Economics, Department of Mathematics)
- Roma Tor Vergata University (Lucia Caramellino)
- Ritsumeikan University (A. Kohatsu-Higa).

8.3. International Research Visitors

- Oleg Kudryavtsev, Rostov University (Russia)
- Martino Grasselli, Padova University,

8.3.1. Visits of International Scientists

8.3.1.1. Internships

- Adel Cherchali (June to August 2017): Multilevel Monte-Carlo methods for nested expectations. Supervisor: A. Alfonsi.

- Zeqi Chen (ENSTA), May -July , Supervisor: A. Zanette

- Mohamed Homed, April-September, Supervisor: A. Zanette

- Xinglong Tian (ENSTA), May-July 2017, Supervisor: A. Zanette

- Sebastien Villette, April-October, Supervisor: A. Zanette

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. Member of the Organizing Committees

- A. Alfonsi:

  - Co-organizer of the conference ”Advances in Financial Mathematics”, 10-13 January 2017, https://fin-risks2017.sciencesconf.org/.

  - Co-organizer of the working group seminar of MathRisk “Méthodes stochastiques et finance”.

- J. Lelong :

  - Member of the organizing committee of Les journées de Probabilités, 2017, France, Aussois.

  - Member of the organizing committee of CEMRACS, 2017, Marseille.

  - Member of the organizing committee of Les journées SMAI MODE 2018, Grenoble.

- A. Sulem

  Co-organizer of the seminar Inria-MathRisk /Université Paris 7 LPMA “Numerical probability and mathematical finance”. https://www.lpma-paris.fr/mathfipronum/gt

9.1.2. Scientific Events Selection

9.1.2.1. Member of the Conference Program Committees

B. Jourdain: Member of the scientific committee of the congrès SMAI 2017

9.1.2.2. Reviewer

A. Sulem: Reviewer for *Mathematical Reviews*

9.1.3. Journal

9.1.3.1. Member of the Editorial Boards

- D. Lamberton

  Associate editor of

  – Mathematical Finance,

  – Associate editor of ESAIM Probability & Statistics

- A. Sulem

  Associate editor of

  – 2011- Present: *Journal of Mathematical Analysis and Applications (JMAA)*

  – 2009- Present: *International Journal of Stochastic Analysis (IJSA)*

  – 2008- Present: *SIAM Journal on Financial Mathematics (SIFIN)*

9.1.3.2. Reviewer - Reviewing Activities

The members of the team reviewed numerous papers for many journals in probability, finance, stochastic control, applied mathematics, ...

9.1.4. Invited Talks

- A. Alfonsi

  - "Maximum Likelihood Estimation for Wishart processes", conference on "Mathematics of Quantitative Finance", Oberwolfach, March 1.

  - "Optimal Execution in a Hawkes Price Model and Calibration", Market Microstructure and High Frequency Data June 1-3, The University of Chicago, June 2.

  - "Maximum Likelihood Estimation for Wishart processes", Recent Developments in Numerical Methods with Applications in Statistics and Finance Mannheim, Germany, June 9.

  - "Sampling of probability measures in the convex order and approximation of Martingale Optimal Transport problems." New York, conference in honour of Jim Gatheral, NYU, October 15.

  - "Sampling of probability measures in the convex order and approximation of Martingale Optimal Transport problems." GT CMAP-ENSTA-ENSAE, November 27.

- V. Bally

  - LMS-EPSRC Durham Symposium 10-20 July. Regularity for the solution of jump equations using an interpolation method.

  - Conference of Stochastic Processes and their Applications (SPA2017) 24-28 July. Regularity for the solution of jump equations using an interpolation method.

  - Workshop on Piecewise Deterministic Markov Processes, 29.05-2.06 Gaussian noise versus Poisson Point Measures in PDMP's.

- B. Jourdain:

  - Workshop Stochastic Sampling and Accelerated Time Dynamics on Multidimensional Surfaces, IPAM, Los Angeles, 16-20 October : Convergence and efficiency of adaptive importance sampling techniques with partial biasing

  - Workshop Singular McKean-Vlasov dynamics, Sophia-Antipolis, 14-15 September : Existence to calibrated regime-switching local volatility model

  - Summer school CEMRACS, Marseille, 17-21 July : The Metropolis-Hastings algorithm, introduction and optimal scaling of the transient phase

  - Workshop Stochastic Computation, FOCM 2017, Barcelona, 10-12 July : Strong convergence properties of the Ninomiya-Victoir scheme and applications to multilevel Monte Carlo methods

  - Workshop BSDEs SPDEs, Edinburgh, 3-7 July : Existence to calibrated regime-switching local volatility model

  - Conference PDE/Probability Interactions : Kinetic Equations, Large Time and Propagation of Chaos, Marseille, 18-22 April : On a stochastic particle approximation of the Keller-Segel equation

  - Conference PDE and probability methods for interaction, Sophia-Antipolis, 30-31 March : Evolution of the Wasserstein distance between the marginals of two Markov processes

  - Applied Mathematics seminar of the Collège de France, February 24 : Multitype sticky particles and diagonal hyperbolic systems

  - Conference Advances in Financial Mathematics, Paris, 10-13 January : Existence to a calibrated regime-switching local volatility model

- J. Lelong

  High Performance Computing session during CEMRACS: 4 hours of lectures and 6 hours of hands–on sessions, Marseille.

- A. Sulem

  - Plenary talk at the Congrès SMAI 2017, 8ème biennale française des Mathématiques Appliquées et Industrielles, Ronce-les-bains, June 20017, http://smai.emath.fr/smai2017/index.php

- "Recent advances in financial mathematics", conference organised by "Financial Risks Chair", Paris, Janvier 2017. https://fin-risks2017.sciencesconf.org/program

- Worshop on *Optimal Stopping in Complex environments*, Bielefeld University, December 18-20 2017,
https://sites.google.com/view/imwworkshop17/

- Workshop on "Asymptotics of Stochastic Dynamics", University of Swansea, August, 29-21, 2017

- Simulation of Stochastic graphs and applications symposium, International Conference on Monte Carlo techniques, Paris, July 5-8, 2017 https://montecarlo16.sciencesconf.org

9.1.5. Scientific Expertise

B. Jourdain: Member of the Scientific Advisory Board of the Center for interdisciplinary Research in Biology, Collège de France : March 1st and 2nd 2017

9.1.6. Research Administration

- A. Alfonsi

  - Deputy director of the CERMICS since April 2017.

  - In charge of the Master "Finance and Application" at the Ecole des Ponts.

- D. Lamberton

  Vice-president for research at Université Paris-Est Marne-la-Vallée

- B. Jourdain

  - Head of the doctoral school MSTIC, University Paris-Est

- A. Sulem

  - Member of the Committee for technology development, Inria Paris

  - Corresponding member of the comité opérationel d'évaluation des risques légaux et éthniques (COERLE) at Inria Paris research center

  - Member of the Committee for Inria international Chairs

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Licence :

- A. Alfonsi

  'Probabilités", first year course at the Ecole des Ponts.

- B. Jourdain

  - "Introduction to probability theory", 1st year, Ecole Polytechnique

  - "Mathematical finance", 2nd year ENPC

- V. Bally

  Hilbertien Analysis L3 (36h)

Master

- A. Alfonsi:

  - "Traitement des données de marché : aspects statistiques et calibration", lecture for the Master at UPEMLV.

  - "Mesures de risque", Master course of UPEMLV and Paris VI.

  - Professeur chargé de cours at Ecole Polytechnique.

- V. Bally

  - Interest rates (20h) M2 filière finance

  - Malliavin calculus and applications in finance (30h) M2 filière finance

  - "Risk analysis " M2 filière actuariat (45h)
- B. Jourdain, B. Lapeyre ; course "Monte-Carlo methods", 3rd year ENPC and Master Recherche Mathématiques et Application, University of Marne-la-Vallée
- J.-F. Delmas, B.Jourdain : course "Jump processes with applications to energy markets", 3rd year ENPC and Master Recherche Mathématiques et Application, University of Marne-la-Vallée
- B. Lapeyre: Monte-Carlo methods in quantitative finance, Master of Mathematics, University of Luxembourg,
- D. Lamberton: Calcul stochastique pour la finance, master 1 course, Université Paris-Est Marne-la-Vallée
- A. Sulem :

  - "Finite difference for PDEs in Finance", Master 2 MASEF, Université Paris IX-Dauphine, Département Mathématiques et Informatique de la Décision et des Organisations (MIDO), 27 h.

  - "PDE methods in Finance", Master of Mathematics, University of Luxembourg, 22 h lectures and responsible of the module "Numerical Methods in Finance".

Doctorat :

A. Sulem : "Stochastic Control with Applications to Mathematical Finance", International summer school in "Financial Mathematics and Actuarial Science", **Doctoral lectures**, (30 heures), Atlantic Association for Research in the Mathematical Sciences, University of Prince Edward Island (UPEI), Canada, July https://aarms.math.ca/summer-school

9.2.2. Supervision

HdR : J. Lelong, Quelques contributions aux méthodes numériques probabilistes et à la modélisation stochastique, Université Grenoble-Alpes, September 2017.

- PhD in progress :

  - Adel Cherchali, “Numerical methods for the ALM”, funded by Fondation AXA, starting from September 2017, Supervisor: A. Alfonsi

  - Rafaël Coyaud, “Deterministic and stochastic numerical methods for multimarginal and martingale constraint optimal transport problems”, starting from October 2017, Supervisor: A. Alfonsi

  - Rui Chen (Fondation Sciences Mathématiques de Paris grant), "Stochastic Control of mean field systems and applications to systemic risk, from September 2014, Université Paris-Dauphine, Supervisor: A. Sulem.

  - Marouen Iben Taarit , “ On CVA and XVA computations ”, CIFRE Natixis/ENPC, Supervisor: Bernard Lapeyre

  - Giulia Terenzi , "American options in complex financial models", Université Paris-Est Marne-la-Vallée, Supervisors: Damien Lamberton and Lucia Caramellino, from University Tor Vergata, Rome

  - Alexandre Zhou (started November 2015) "Analysis of stochastic particle methods applied to finance", Supervisor: B.Jourdain

  - Oumaima Bencheikh (started November 2017) "Acceleration of probabilistic particle methods", Supervisor: B. Jourdain

9.2.3. Juries

- Damien Lamberton

  "Opponent" for the PhD thesis defense of Hannah Dyrssen (student of Erik Ekstrom) at Uppsala University (Sweden), May 2017.
- Benjamin Jourdain

  Referee for the PhD thesis and participation to the jury for the defense of the PhD thesis of

  - Victor Reutenauer, defended on March 22, University Côte d'Azur

  - Daphné Giorgy, defended on June 2, University Pierre and Marie Curie

  - Radu Maftei, defended on December 14, University Côte d'Azur
- Agnès Sulem

  - Participation to the committee for the recrutment of a Professeur in "applied mathematics, finance and numerical probability", Laboratoire de probabilités (LPMA), Université Paris VI, 2017
  - Participation to the committee for the recrutment of a Assistant professor in "économy, finance et game theory", Université Paris-Dauphine, 2017.

  - Participation to the jury (Chair) for the defense of the PhD thesis of Amine Ismail, *Robust modeling of volatility and application to derivatives pricing and portfolio optimization*, December 15 2017, Université Paris-Diderot - Paris 7.

  - Participation to the jury (Chair) for the defense of the PhD thesis of Jiang Pu, *Contrôle optimal et applications en finance: exécution optimale, couverture d'options et choix de portefeuille*, September 25 2017, Université Paris-Diderot - Paris 7.

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Major publications by the team in recent years

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Articles in International Peer-Reviewed Journals

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Other Publications

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