IN PARTNERSHIP WITH:
**CNRS**

**Ecole des Ponts ParisTech**

**Université Paris-Est Marne-la-Vallée**

# Activity Report 2018

# 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**

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## Project-Team MATHRISK

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

**Keywords:**

**Computer Science and Digital Science:**

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A6.1. - Methods in mathematical modeling
A6.1.2. - Stochastic Modeling
A6.2.1. - Numerical analysis of PDE and ODE
A6.2.2. - Numerical probability
A6.2.3. - Probabilistic methods
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**Other Research Topics and Application Domains:**

B3.1. - Sustainable development
B9.6.3. - Economy, Finance
B9.11. - Risk management

# 1. Team, Visitors, External Collaborators

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Benjamin Jourdain [Ecole Nationale des Ponts et Chaussées, Senior Researcher, HDR]

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# 2. Overall Objectives

## 2.1. Overall Objectives

The Inria project team **MathRisk** team was created in 2013. It is the follow-up of the MathFi project team founded in 2000. MathFi was focused on financial mathematics, in particular on computational methods for pricing and hedging increasingly complex financial products. The 2007 global financial crisis and its "aftermath crisis" has abruptly highlighted the critical importance of a better understanding and management of risk. The project **MathRisk** has been reoriented towards mathematical handling of risk, and addresses broad research topics embracing risk measurement and risk management, modeling and optimization in quantitative finance, but also in other related domains where risk control is paramount. The project team **MathRisk** aims both at producing mathematical tools and models in these domains, and developing collaborations with various institutions involved in risk control. Quantitative finance remains for the project an important source of mathematical problems and applications. Indeed, the pressure of new legislation leads to a massive reorientation of research priorities, and the interest of analysts shifted to risk control preoccupation.

The scientific issues related to quantitative finance we consider include systemic risk and contagion modeling, robust finance, market frictions, counterparty and liquidity risk, assets dependence modeling, market micro-structure modeling and price impact. In this context, models must take into account the multidimensional feature and various market imperfections. They are much more demanding mathematically and numerically, and require the development of risk measures taking into account incompleteness issues, model uncertainties, interplay between information and performance and various defaults.

Besides, financial institutions, submitted to more stringent regulatory legislations such as FRTB or XVA computation, are facing practical implementation challenges which still need to be solved. Research focused on numerical efficiency remains strongly needed in this context, renewing the interest for the numerical platform Premia (http://www.premia.fr) that Mathrisk is developing in collaboration with a consortium of financial institutions.

While these themes arise naturally in the world of quantitative finance, a number of these issues and mathematical tools are also relevant to the treatment of risk in other areas as economy, social insurance and sustainable development, of fundamental importance in today's society. In these contexts, the management of risk appears at different time scales, from high frequency data to long term life insurance management, raising challenging renewed modeling and numerical issues.

The **MathRisk** project is strongly involved in the development of new mathematical methods and numerical algorithms. Mathematical tools include stochastic modeling, stochastic analysis, in particular stochastic (partial) differential equations and various aspects of stochastic control and optimal stopping of these equations, nonlinear expectations, Malliavin calculus, stochastic optimization, dynamic game theory, random graphs, martingale optimal transport (especially in relation to numerical considerations), long time behavior of Markov processes (with applications to Monte-Carlo methods) and generally advanced numerical methods for effective solutions.

# 3. Research Program

## 3.1. Risk management: modeling and optimization

### 3.1.1. Contagion modeling and systemic risk

After the recent financial crisis, systemic risk has emerged as one of the major research topics in mathematical finance. Interconnected systems are subject to contagion in time of distress. 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.

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. [40] and A. Minca [79]) or mean field interaction models (Garnier-Papanicolaou-Yang [70]).

We have contributed in the last years to the research on the control of contagion in financial systems in the framework of random graph models : In [41], [80], [5], A. Sulem with A. Minca and H. Amini consider a financial network described as a weighted directed graph, in which nodes represent financial institutions and edges the exposures between them. The distress propagation is modeled as an epidemics on this graph. They study the optimal intervention of a lender of last resort who seeks to make equity infusions in a banking system prone to insolvency and to bank runs, under complete and incomplete information of the failure cluster, in order to minimize the contagion effects. The paper [5] provides in particular important insight on the relation between the value of a financial system, connectivity and optimal intervention.

The results show that up to a certain connectivity, the value of the financial system increases with connectivity. However, this is no longer the case if connectivity becomes too large. The natural question remains how to create incentives for the banks to attain an optimal level of connectivity. This is studied in [54], where network formation for a large set of financial institutions represented as nodes is investigated. Linkages are source of income, and at the same time they bear the risk of contagion, which is endogeneous and depends on the strategies of all nodes in the system. The optimal connectivity of the nodes results from a game. Existence of an equilibrium in the system and stability properties is studied. The results suggest that financial stability is best described in terms of the mechanism of network formation than in terms of simple statistics of the network topology like the average connectivity.

### 3.1.2. Liquidity risk and Market Microstructure

Liquidity risk is the risk arising from the difficulty of selling (or buying) an asset. 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, but 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), it 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.

For rather liquid assets, liquidity risk is usually taken into account via price impact models which describe how a (large) trader influences the asset prices. Then, one is typically interested in the optimal execution problem: how to buy/sell a given amount of assets optimally within a given deadline. This issue is directly related to the existence of statistical arbitrage or Price Manipulation Strategies (PMS). Most of price impact models deal with single assets. A. Alfonsi, F. Klöck and A. Schied [39] have proposed a multi-assets price impact model that extends previous works. Price impact models are usually relevant when trading at an intermediary frequency (say every hour). At a lower frequency, price impact is usually ignored while at a high frequency (every minute or second), one has to take into account the other traders and the price jumps, tick by tick. Midpoint price models are thus usually preferred at this time scale. With P. Blanc, Alfonsi [3] has proposed a model that makes a bridge between these two types of model: they have considered an (Obizhaeva and Wang) price impact model, in which the flow of market orders generated by the other traders is given by an exogeneous process. They have shown that Price Manipulation Strategies exist when the flow of order is a compound Poisson process. However, modeling this flow by a mutually exciting Hawkes process with a particular parametrization allows them to exclude these PMS. Besides, the optimal execution strategy is explicit in this model. A practical implementation is given in [35].

### 3.1.3. Dependence modeling

**- Calibration of stochastic and local volatility models.** The volatility is a key concept in modern mathematical finance, and an indicator of market stability. Risk management and associated instruments depend strongly on the volatility, and volatility modeling is a crucial issue in the finance industry. Of particular importance is the assets *dependence* modeling.

By Gyongy's theorem, a local and stochastic volatility model is calibrated to the market prices of all call options with positive maturities and strikes if its local volatility function is equal to the ratio of the Dupire local volatility function over the root conditional mean square of the stochastic volatility factor given the spot value. This leads to a SDE nonlinear in the sense of McKean. Particle methods based on a kernel approximation of the conditional expectation, as presented by Guyon and Henry-Labordère [71], provide an efficient calibration procedure even if some calibration errors may appear when the range of the stochastic volatility factor is very large. But so far, no existence result is available for the SDE nonlinear in the sense of McKean. In the particular case when the local volatility function is equal to the inverse of the root conditional mean square of the stochastic volatility factor multiplied by the spot value given this value and the interest rate is zero, the solution to the SDE is a fake Brownian motion. When the stochastic volatility factor is a constant (over time) random variable taking finitely many values and the range of its square is not too large, B. Jourdain and A. Zhou proved existence to the associated Fokker-Planck equation [77]. Thanks to results obtained by Figalli in [63], they deduced existence of a new class of fake Brownian motions. They extended these results to the special case of the LSV model called Regime Switching Local Volatility, when the stochastic volatility factor is a jump process taking finitely many values and with jump intensities depending on the spot level.

**- Interest rates modeling.** Affine term structure models have been popularized by Dai and Singleton [55], Duffie, Filipovic and Schachermayer [56]. They consider vector affine diffusions (the coordinates are usually called factors) and assume that the short interest rate is a linear combination of these factors. A model of this kind is the Linear Gaussian Model (LGM) that considers a vector Ornstein-Uhlenbeck diffusions for the factors, see El Karoui and Lacoste [62]. A. Alfonsi et al. [33] have proposed an extension of this model, when the instantaneous covariation between the factors is given by a Wishart process. Doing so, the model keeps its affine structure and tractability while generating smiles for option prices. A price expansion around the LGM is obtained for Caplet and Swaption prices.

### 3.1.4. Robust finance

**- Numerical Methods for Martingale Optimal Transport problems.**

The Martingale Optimal Transport (MOT) problem introduced in [53] has received a recent attention in finance since it gives model-free hedges and bounds on the prices of exotic options. The market prices of liquid call and put options give the marginal distributions of the underlying asset at each traded maturity. Under the simplifying assumption that the risk-free rate is zero, these probability measures are in increasing convex order, since by Strassen's theorem this property is equivalent to the existence of a martingale measure with the right marginal distributions. For an exotic payoff function of the values of the underlying on the time-grid given by these maturities, the model-free upper-bound (resp. lower-bound) for the price consistent with these marginal distributions is given by the following martingale optimal transport problem : maximize (resp. minimize) the integral of the payoff with respect to the martingale measure over all martingale measures with the right marginal distributions. Super-hedging (resp. sub-hedging) strategies are obtained by solving the dual problem. With J. Corbetta, A. Alfonsi and B. Jourdain [36] have studied sampling methods preserving the convex order for two probability measures $\mu$ and $\nu$ on $\mathbf{R}^d$, with $\nu$ dominating $\mu$.

Their method is the first generic approach to tackle the martingale optimal transport problem numerically and can also be applied to several marginals.

**- Robust option pricing in financial markets with imperfections.**

A. Sulem, M.C. Quenez and R. Dumitrescu have studied robust pricing in an imperfect financial market with default. The market imperfections are taken into account via the nonlinearity of the wealth dynamics. In this setting, the pricing system is expressed as a nonlinear g-expectation $\mathcal{E}^g$ induced by a nonlinear BSDE with nonlinear driver $g$ and default jump (see [24]). A large class of imperfect market models can fit in this framework, including imperfections coming from different borrowing and lending interest rates, taxes on profits from risky investments, or from the trading impact of a large investor seller on the market prices and the default probability. Pricing and superhedging issues for American and game options in this context and their links with optimal stopping problems and Dynkin games with nonlinear expectation have been studied. These issues have also been addressed in the case of model uncertainty, in particular uncertainty on the default probability. The seller's robust price of a game option has been characterized as the value function of a Dynkin game under $\mathcal{E}^g$ expectation as well as the solution of a nonlinear doubly reflected BSDE in [9]. Existence of robust superhedging strategies has been studied. The buyer's point of view and arbitrage issues have also been studied in this context.

In a Markovian framework, the results of the paper [8] on combined optimal stopping/stochastic control with $\mathcal{E}^g$ expectation allows us to address American nonlinear option pricing when the payoff function is only Borelian and when there is ambiguity both on the drift and the volatility of the underlying asset price process. Robust optimal stopping of dynamic risk measures induced by BSDEs with jumps with model ambiguity is studied in [82].

## 3.2. Perspectives in Stochastic Analysis

### 3.2.1. Optimal transport and longtime behavior of Markov processes

The dissipation of general convex entropies for continuous time Markov processes can be described in terms of backward martingales with respect to the tail filtration. The relative entropy is the expected value of a backward submartingale. In the case of (non necessarily reversible) Markov diffusion processes, J. Fontbona and B. Jourdain [65] used Girsanov theory to explicit the Doob-Meyer decomposition of this submartingale. They deduced a stochastic analogue of the well known entropy dissipation formula, which is valid for general convex entropies, including the total variation distance. Under additional regularity assumptions, and using Itô's calculus and ideas of Arnold, Carlen and Ju [42], they obtained a new Bakry-Emery criterion which ensures exponential convergence of the entropy to 0. This criterion is non-intrinsic since it depends on the square root of the diffusion matrix, and cannot be written only in terms of the diffusion matrix itself. They provided examples where the classic Bakry Emery criterion fails, but their non-intrinsic criterion applies without modifying the law of the diffusion process.

With J. Corbetta, A. Alfonsi and B. Jourdain have studied the time derivative of the Wasserstein distance between the marginals of two Markov processes. The Kantorovich duality leads to a natural candidate for this derivative. Up to the sign, it is the sum of the integrals with respect to each of the two marginals of the corresponding generator applied to the corresponding Kantorovich potential. For pure jump processes with bounded intensity of jumps, J. Corbetta, A. Alfonsi and B. Jourdain [15] proved that the evolution of the Wasserstein distance is actually given by this candidate. In dimension one, they showed that this remains true for Piecewise Deterministic Markov Processes. They applied the formula to estimate the exponential decrease rate of the Wasserstein distance between the marginals of two birth and death processes with the same generator in terms of the Wasserstein curvature.

### 3.2.2. Mean-field systems: modeling and control

**- Mean-field limits of systems of interacting particles.** In [75], B. Jourdain and his former PhD student J. Reygner have studied a mean-field version of rank-based models of equity markets such as the Atlas model introduced by Fernholz in the framework of Stochastic Portfolio Theory. They obtained an asymptotic description of the market when the number of companies grows to infinity. Then, they discussed the long-term capital distribution, recovering the Pareto-like shape of capital distribution curves usually derived from empirical studies, and providing a new description of the phase transition phenomenon observed by Chatterjee and Pal. They have also studied multitype sticky particle systems which can be obtained as vanishing noise limits of multitype rank-based diffusions (see [74]). Under a uniform strict hyperbolicity assumption on the characteristic fields, they constructed a multitype version of the sticky particle dynamics. In [76], they obtain the optimal rate of convergence as the number of particles grows to infinity of the approximate solutions to the diagonal hyperbolic system based on multitype sticky particles and on easy to compute time discretizations of these dynamics.

In [69], N. Fournier and B. Jourdain are interested in the two-dimensional Keller-Segel partial differential equation. This equation is a model for chemotaxis (and for Newtonian gravitational interaction).

**- Mean field control and Stochastic Differential Games (SDGs).**To handle situations where controls are chosen by several agents who interact in various ways, one may use the theory of Stochastic Differential Games (SDGs). Forward–Backward SDG and stochastic control under Model Uncertainty are studied in [83] by A. Sulem and B. Øksendal. Also of interest are large population games, where each player interacts with the average effect of the others and individually has negligible effect on the overall population. Such an interaction pattern may be modeled by mean field coupling and this leads to the study of mean-field stochastic control and related SDGs. A. Sulem, Y. Hu and B. Øksendal have studied singular mean field control problems and singular mean field two-players stochastic differential games [72]. Both sufficient and necessary conditions for the optimal controls and for the Nash equilibrium are obtained. Under some assumptions, the optimality conditions for singular mean-field control are reduced to a reflected Skorohod problem. Applications to optimal irreversible investments under uncertainty have been investigated. Predictive mean-field equations as a model for prices influenced by beliefs about the future are studied in [85].

### 3.2.3. Stochastic control and optimal stopping (games) under nonlinear expectation

M.C. Quenez and A. Sulem have studied optimal stopping with nonlinear expectation $\mathcal{E}^g$ induced by a BSDE with jumps with nonlinear driver $g$ and irregular obstacle/payoff (see [82]). In particular, they characterize the value function as the solution of a reflected BSDE. This property is used in [19] to address American option pricing in markets with imperfections. The Markovian case is treated in [59] when the payoff function is continuous.

In [8], M.C. Quenez, A. Sulem and R. Dumitrescu study a combined optimal control/stopping problem under nonlinear expectation $\mathcal{E}^g$ in a Markovian framework when the terminal reward function is only Borelian. In this case, the value function $u$ associated with this problem is irregular in general. They establish a *weak* dynamic programming principle (DPP), from which they derive that the upper and lower semi-continuous envelopes of $u$ are the sub- and super- *viscosity solution* of an associated nonlinear Hamilton-Jacobi-Bellman variational inequality.

The problem of a generalized Dynkin game problem with nonlinear expectation $\mathcal{E}^g$ is addressed in [60]. Under Mokobodzki's condition, we establish the existence of a value function for this game, and characterize this value as the solution of a doubly reflected BSDE. The results of this work are used in [9] to solve the problem of game option pricing in markets with imperfections.
A generalized mixed game problem when the players have two actions: continuous control and stopping is studied in a Markovian framework in [61]. In this work, dynamic programming principles (DPP) are established: a strong DPP is proved in the case of a regular obstacle and a weak one in the irregular case. Using these DPPs, links with parabolic partial integro-differential Hamilton-Jacobi- Bellman variational inequalities with two obstacles are obtained.

With B. Øksendal and C. Fontana, A. Sulem has contributed on the issues of robust utility maximization [84], [85], and relations between information and performance [64].

### 3.2.4. Generalized Malliavin calculus

Vlad Bally has extended the stochastic differential calculus built by P. Malliavin which allows one to obtain integration by parts and associated regularity probability laws. In collaboration with L. Caramellino (Tor Vegata University, Roma), V. Bally has developed an abstract version of Malliavin calculus based on a splitting method (see [44]). It concerns random variables with law locally lower bounded by the Lebesgue measure (the so-called Doeblin's condition). Such random variables may be represented as a sum of a "smooth" random variable plus a rest. Based on this smooth part, he achieves a stochastic calculus which is inspired from Malliavin calculus [6]. An interesting application of such a calculus is to prove convergence for irregular test functions (total variation distance and more generally, distribution distance) in some more or less classical frameworks as the Central Limit Theorem, local versions of the CLT and moreover, general stochastic polynomials [48]. An exciting application concerns the number of roots of trigonometric polynomials with random coefficients [49]. Using Kac Rice lemma in this framework one comes back to a multidimensional CLT and employs Edgeworth expansions of order three for irregular test functions in order to study the mean and the variance of the number of roots. Another application concerns U statistics associated to polynomial functions. The techniques of generalized Malliavin calculus developed in [44] are applied in for the approximation of Markov processes (see [52] and [51]). On the other hand, using the classical Malliavin calculus, V. Bally in collaboration with L. Caramellino and P. Pigato studied some subtle phenomena related to diffusion processes, as short time behavior and estimates of tubes probabilities (see [46], [47], [45]).

## 3.3. Numerical Probability

Our project team is very much involved in numerical probability, aiming at pushing numerical methods towards the effective implementation. This numerical orientation is supported by a mathematical expertise which permits a rigorous analysis of the algorithms and provides theoretical support for the study of rates of convergence and the introduction of new tools for the improvement of numerical methods. This activity in the MathRisk team is strongly related to the development of the Premia software.

### 3.3.1. Simulation of stochastic differential equations

#### 3.3.1.1. - *Weak convergence of the Euler scheme in optimal transport distances.*

With A. Kohatsu-Higa, A. Alfonsi and B. Jourdain [4] have proved using optimal transport tools that the Wasserstein distance between the time marginals of an elliptic SDE and its Euler discretization with $N$ steps is not larger than $C\sqrt{\log(N)}/N$. The logarithmic factor may is removed when the uniform time-grid is replaced by a grid still counting $N$ points but refined near the origin of times.

#### 3.3.1.2. - *Strong convergence properties of the Ninomiya Victoir scheme and multilevel Monte-Carlo estimators.*

With their former PhD student, A. Al Gerbi, E. Clément and B. Jourdain [1] have proved strong convergence with order $1/2$ of the Ninomiya-Victoir scheme which is known to exhibit order 2 of weak convergence [81]. This study was aimed at analysing the use of this scheme either at each level or only at the finest level of a multilevel Monte Carlo estimator : indeed, the variance of a multilevel Monte Carlo estimator is related to the strong error between the two schemes used in the coarse and fine grids at each level. In [14], they proved that the order of strong convergence of the crude Ninomiya Victoir scheme is improved to 1 when the vector fields corresponding to each Brownian coordinate in the SDE commute, and in [34], they studied the error introduced by discretizing the ordinary differential equations involved in the Ninomiya-Victoir scheme.

#### 3.3.1.3. - *Non-asymptotic error bounds for the multilevel Monte Carlo Euler method.*

A. Kebaier and B. Jourdain are interested in deriving non-asymptotic error bounds for the multilevel Monte Carlo method. As a first step, they dealt in [73] with the explicit Euler discretization of stochastic differential equations with a constant diffusion coefficient. They obtained Gaussian-type concentration. To do so, they used the Clark-Ocone representation formula and derived bounds for the moment generating functions of the squared difference between a crude Euler scheme and a finer one and of the squared difference of their Malliavin derivatives. The estimation of such differences is much more complicated than the one of a single Euler scheme contribution and explains why they suppose the diffusion coefficient to be constant. This assumption ensures boundedness of the Malliavin derivatives of both the SDE and its Euler scheme.

*3.3.1.4. - Computation of sensibilities of integrals with respect to the invariant measure.*

In [43], R. Assaraf, B. Jourdain, T. Lelièvre and R. Roux considered the solution to a stochastic differential equation with constant diffusion coefficient and with a drift function which depends smoothly on some real parameter $\lambda$, and admitting a unique invariant measure for any value of $\lambda$ around $\lambda = 0$. Their aim was to compute the derivative with respect to $\lambda$ of averages with respect to the invariant measure, at $\lambda = 0$. They analyzed a numerical method which consists in simulating the process at $\lambda = 0$ together with its derivative with respect to $\lambda$ on a long time horizon. They gave sufficient conditions implying uniform-in-time square integrability of this derivative. This allows in particular to compute efficiently the derivative with respect to $\lambda$ of the mean of an observable through Monte Carlo simulations.

*3.3.1.5. - Approximation of doubly reflected Backward stochastic differential equations.*

R. Dumitrescu and C. Labart have studied the discrete time approximation scheme for the solution of a doubly reflected Backward Stochastic Differential Equation with jumps, driven by a Brownian motion and an independent compensated Poisson process [58], [57].

*3.3.1.6. - Parametrix methods.*

V. Bally and A. Kohatsu-Higa have recently proposed an unbiased estimator based on the parametrix method to compute expectations of functions of a given SDE ( [50]). This method is very general, and A. Alfonsi, A. Kohastu-Higa and M. Hayashi [37] have applied it to the case of one-dimensional reflected diffusions. In this case, the estimator can be obtained explicitly by using the scheme of Lépingle [78] and is quite simple to implement. It is compared to other simulation methods for reflected SDEs.

### *3.3.2. Estimation of the parameters of a Wishart process*

A. Alfonsi, A. Kebaier and C. Rey [38] have computed the Maximum Likelihood Estimator for the Wishart process and studied its convergence in the ergodic and in some non ergodic cases. In the ergodic case, which is the most relevant for applications, they obtain the standard square-root convergence. In the non ergodic case, the analysis rely on refined results for the Laplace transform of Wishart processes, which are of independent interest.

### *3.3.3. Optimal stopping and American options*

In joint work with A. Bouselmi, D. Lamberton studied the asymptotic behavior of the exercise boundary near maturity for American put options in exponential Lévy models. In [7], they deal with jump-diffusion models, and establish that, in some cases, the behavior differs from the classical Black and Scholes setting. D. Lamberton has also worked on the binomial approximation of the American put. The conjectured rate of convergence is $O(1/n)$ where $n$ is the number of time periods. He was able to derive a $O((\ln n)^{\alpha}/n)$ bound, where the exponent $\alpha$ is related to the asymptotic behavior of the exercise boundary near maturity.

# 4. Application Domains

## 4.1. Financial Mathematics, Insurance

The domains of application 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. Highlights of the Year

## 5.1. Highlights of the Year

The project team Mathrisk has been evaluated in March. The report was very positive.

# 6. New Software and Platforms

## 6.1. 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, Jérôme Lelong and Bernard Lapeyre
- Partners: Inria - Ecole des Ponts ParisTech - Université Paris-Est
- Contact: Agnes Sulem
- URL: http://www.premia.fr

## 6.2. Platforms

### *6.2.1. Development of the quantitative platform Premia in 2018*

Premia 20 has been delivered to the Consortium Premia on March 12th. It contains the following new algorithms :

#### *6.2.1.1. Optimal Trade Execution, Risk Management, Insurance*

- Optimal Execution Under Jump Models For Uncertain Price Impact. S.Moazeni, T.F.Coleman, Y.Li
  *The Journal of Computational Finance. Vol. 18, Issue 3, 2015.*
- Nested Monte Carlo for Risk Margin computation. L.A. Abbas-Turki, S.Crepey, B.Diallo.
- Efficient Estimation of Sensitivities for Counterparty Credit Risk with the Finite Difference Monte-Carlo Method. C. S.L. de Graaf, D.Kandhai, P.M.A.Sloot.
  *The Journal of Computational Finance, Volume 21, Issue 1, 2017.*
- Nested Simulation in Portfolio Risk Measurement. M.B.Gordy, S.Juneja
  *Management Science, Vol 56, Issue 10, 2010*
- Spectral methods for the calculation of risk measures for variable annuity guaranteed benefits. R. Feng, H.W. Volkmer
  *ASTIN Bull., 44(3), 2014*
- Fast computation of risk measures for variable annuities with additional earnings by conditional moment matching. N. Privault X.Wei
  *ASTIN Bull., 48(1):171–196, 2018.*

#### *6.2.1.2. Equity Derivatives*

- Pricing under Rough volatility. C. Bayer, P.Friz, J. Gatheral
  *Quantitative Finance, Vol. 16, No. 6, 887-904, 2016.*

- Hybrid scheme for Brownian semistationary processes. M. Bennedsen, A. Lunde, M.S.Pakkanen
  *Finance and Stochastics 21(4), 931–965, 2017.*
- Antithetic multilevel Monte Carlo estimation for multi-dimensional SDEs without Lévy area simulation. M. B. Giles and L. Szpruch
  *The Annals of Applied Probability, Vol. 24, No. 4, 2014*
- Fourier transform algorithms for pricing and hedging discretely sampled exotic variance products and volatility derivatives under additive processes. W. Zheng and Y. K. Kwok
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We benefit from the help of the engineer Pierre-Guillaume Raverdy.

# 7. New Results

## 7.1. Risk management in finance and insurance

### *7.1.1. Control of systemic risk in a dynamic framework*

Interconnected systems are subject to contagion in time of distress. Recent effort has been dedicated to understanding the relation between network topology and the scope of distress propagation. It is critical to recognize that connectivity is a result of an optimization problem of agents, who derive benefits from connections and view the associated contagion risk as a cost. In our previous works on the control of contagion in financial systems (see e.g. [80], [41], [5]), a central party, for example a regulator or government, seeks to minimize contagion. In [54], in contrast, the financial institutions themselves are the decision makers, and their decision is made before the shock, with a rational expectation on the way the cascade will evolve following the shock. We are extending these studies in a *dynamic* framework by allowing a recovery feature in the financial system during the cascade process, captured by introducing certain extent of growth of the banks' assets between each round of contagion.

### *7.1.2. Option pricing in financial markets with imperfections and default*

A. Sulem, M.C. Quenez and R. Dumitrescu have studied robust pricing in an imperfect financial market with default. In this setting, the pricing system is expressed as a nonlinear g-expectation $\mathcal{E}^g$ induced by a nonlinear BSDE with nonlinear driver $g$ and default jump (see [24]). The case of American options in this market model is treated in [19]. The incomplete market case is under study.

### *7.1.3. American options*

With Giulia Terenzi, D. Lamberton has been been working on American options in Heston's model. They have 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). Their paper "Variational formulation of American option prices in the Heston model" [32] is now in minor revision for *SIAM Journal on Financial Mathematics*.

They also have some results on monotonicity and regularity properties of the price function.

D. Lamberton has also a paper on the binomial approximation of the American put, in which a new bound for the rate of convergence of the binomial approximation of the Black-Scholes American put price is derived [32].

Optimal stopping problems involving the maximum of a diffusion is currently under investigation. Partial results obtained by D. Lamberton and M. Zervos) enable them to treat reward functions with little regularity.

### *7.1.4. Monte-Carlo methods for the computation of the Solvency Capital Requirement (SCR) in Insurance*

A. Alfonsi has obtained a grant from AXA Foundation on a Joint Research Initiative with a team of AXA France working on the strategic asset allocation. This team has to make recommendations on the investment over some assets classes as, for example, equity, real estate or bonds. In order to do that, each side of the balance sheet (assets and liabilities) is modeled in order to take into account their own dynamics but also their interactions. Given that the insurance products are long time contracts, the projections of the company's margins have to be done considering long maturities. When doing simulations to assess investment policies, it is necessary to take into account the SCR which is the amount of cash that has to be settled to manage the portfolio. Typically, the computation of the future values of the SCR involve expectations under conditional laws, which is greedy in computation time. The goal of this project is to develop efficient Monte-Carlo methods to compute the SCR for long investment strategies. A. Cherchali has started his PhD thesis in September 2017 on this topic.

A. Alfonsi and A. Cherchali are developing a model of the ALM management of insurance companies that takes into account the regulatory constraints on life-insurance. We are testing this model. The purpose is then to use this model to develop Monte-Carlo methods to approximate the SCR (Solvency Capital Requirement).

## 7.2. Optimal transport and applications

### *7.2.1. Martingale Optimal Transport.*

B. Jourdain and W. Margheriti exhibit a new family of martingale couplings between two one-dimensional probability measures $\mu$ and $\nu$ in the convex order. This family is parametrised by two dimensional probability measures on the unit square with respective marginal densities proportional to the positive and negative parts of the difference between the quantile functions of $\mu$ and $\nu$. It contains the inverse transform martingale coupling which is explicit in terms of the cumulative distribution functions of these marginal densities. The integral of $|x-y|$ with respect to each of these couplings is smaller than twice the $W^1$ distance between $\mu$ and $\nu$. When the comonotoneous coupling between $\mu$ and $\nu$ is given by a map $T$, the elements of the family minimize $\int_{\mathbf{R}} |y-T(x)|M(dx,dy)$ among all martingale couplings $M$ between $\mu$ and $\nu$. When $\mu$ and $\nu$ are in the decreasing (resp. increasing) convex order, the construction can be generalized to exhibit super (resp. sub) martingale couplings.

A. Alfonsi and B. Jourdain show that any optimal coupling for the quadratic Wasserstein distance $W_2^2(\mu,\nu)$ between two probability measures $\mu$ and $\nu$ with finite second order moments on $\mathbf{R}^d$ is the composition of a martingale coupling with an optimal transport map $\mathcal{T}$. They check the existence of optimal couplings in which this map gives the unique optimal coupling between $\mu$ and $\mathcal{T}\#\mu$. Next, they prove that $\sigma \mapsto W_2^2(\sigma,\nu)$ is differentiable at $\mu$ in both Lions and the geometric senses iff there is a unique optimal coupling between $\mu$ and $\nu$ and this coupling is given by a map.

### *7.2.2. Numerical methods for optimal transport.*

Optimal transport problems have got a recent attention in many different fields including physics, quantum chemistry and finance, where Martingale Optimal Transport problems allow to quantify the model risk. In practice, few numerical methods exist to approximate the optimal coupling measure and/or the optimal transport. In particular, to deal with large dimensions or with the optimal transport problems with many marginal laws, a natural direction is to develop Monte-Carlo methods.

A. Alfonsi, V. Ehrlacher (CERMICS, Inria Project-team MATHERIALS), D. Lombardi (Inria Project-team Reo) and R. Coyaud (PhD student of A. Alfonsi) are working on numerical approximations of the optimal transport between two (or more) probability measures.

## 7.3. Optimal Control of Mean field (S)PDEs

With Rui Chen and R. Dumitrescu, A. Sulem has studied mean-field Backward SDEs driven by a Brownian motion and an independant Poisson random measure and its interpretation in terms of global risk measures. Dual representation has been provided in the convex case. Optimal stopping for these BSDEs and links with reflected mean-field BSDEs has also been investigated.

A. Sulem, R. Dumitrescu and B. Øksendal have studied optimal control for mean-field stochastic **partial** differential equations (stochastic evolution equations) driven by a Brownian motion and an independent Poisson random measure, in the case of *partial information* control [20]. One important novelty is the introduction of *general mean-field* operators, acting on both the controlled state process and the control process. A sufficient and a necessary maximum principle for this type of control is formulated. Existence and uniqueness of the solution of such general forward and backward mean-field stochastic partial differential equations are proved. These results have been applied to find the explicit optimal control for an optimal harvesting problem.

## 7.4. Analysis of probabilistic numerical methods

### *7.4.1. Particles approximation of mean-field SDEs*

O. Bencheikh and Benjamin Jourdain have proved that the weak error between a stochastic differential equation with nonlinearity in the sense of McKean given by moments and its approximation by the Euler discretization with time-step $h$ of a system of $N$ interacting particles is $\mathcal{O}(N^{-1} + h)$. Numerical experiments confirm this behaviour and show that it extends to more general mean-field interaction.

### *7.4.2. Approximation of Markov processes*

V. Bally worked on general approximation schemes in total variation distance for diffusion processes in collaboration with his former Phd student Clément Rey [52] This work includes high order schemes as Victoir-Ninomya for example. Further development in this direction is under study in collaboration with A. Alfonsi. Moreover, in collaboration with his former Phd student V. Rabiet and with D. Goreac (University Paris Est Marne la Vallée), V. Bally is studying approximations schemes for Piecewise Deterministic Markov Processes (see [17], [51]). In this framework the goal is to replace small jumps by a Brownien component - such a procedure is popular for "usual" jump equations, but the estimate of the error in the case of PDMP's is much more delicate. A significant example is the Bolzmann equation [28].

### *7.4.3. High order approximation for diffusion processes*

A. Alfonsi and V. Bally are working on a generic method to achieve any weak order of convergence for approximating SDEs.

### *7.4.4. Adaptive MCMC methods*

The Self-Healing Umbrella Sampling (SHUS) algorithm is an adaptive biasing algorithm which has been proposed in order to efficiently sample a multimodal probability measure.

In [21], G. Fort, B. Jourdain, T. Lelièvre and G. Stoltz extend previous works [68], [66], [67] and study a larger class of algorithms where the target distribution is biased using only a fraction of the free energy and which includes a discrete version of well-tempered metadynamics.

# 8. Bilateral Contracts and Grants with Industry

## 8.1. Bilateral Contracts with Industry

- Consortium PREMIA, Natixis - Inria
- Consortium PREMIA, Crédit Agricole Corporate Investment Bank (CA - CIB ) - Inria
- Chair X-ENPC-UPMC-Société Générale "Financial Risks" of the Risk fondation : A. Alfonsi, B. Jourdain, B. Lapeyre
- AXA Joint Research Initiative on Numerical methods for the ALM, from September 2017 to August 2020. PhD grant of Adel Cherchali, Supervisor: A. Alfonsi.
- CIFRE agreement Milliman company/Ecole des Ponts (http://fr.milliman.com),

  PhD thesis of Sophian Mehalla (started November 2017) on "Interest rate risk modeling for insurance companies", Supervisor: Bernard Lapeyre.
- Collaboration with IRT Systemx

  PhD grant of Adrien Touboul (started November 2017) on "Uncertainty computation in a graph of physical simulations", Supervisors: Bernard Lapeyre and Julien Reygner.

# 9. Partnerships and Cooperations

## 9.1. National Initiatives

- ANR Cosmos 2015-2018, Participant: B. Jourdain ; Partners : Ecole des Ponts, Telecom, Inria Rennes and IBPC
- Labex Bezout
  http://bezout.univ-paris-est.fr

### *9.1.1. Competitivity Clusters*

**Pôle Finance Innovation**

## 9.2. International Initiatives

### *9.2.1. 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).

## 9.3. International Research Visitors

### *9.3.1. Visits of International Scientists*

- Oleg Kudryavtsev, Rostov University (Russia)
- B. Stemper (Weierstrass Institute Berlin)
- A. Kohatsu Higa (Ritsumeikan University)

### *9.3.2. Internships*

Oussama Bellalah, Inria, May-August

# 10. Dissemination

## 10.1. Promoting Scientific Activities

### *10.1.1. Scientific Events Organisation*

*10.1.1.1. Member of the Organizing Committees*

- A. Alfonsi:

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

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

### *10.1.2. Journal*

*10.1.2.1. Member of the Editorial Boards*

- B. Jourdain

  Associate editor of
  - ESAIM : Proceedings and Surveys
  - Stochastic Processes and their Applications (SPA)
- D. Lamberton

  Associate editor of
  - Mathematical Finance,
  - Associate editor of ESAIM Probability & Statistics
- A. Sulem

  Associate editor of
  - Journal of Mathematical Analysis and Applications (JMAA)
  - International Journal of Stochastic Analysis (IJSA)
  - SIAM Journal on Financial Mathematics (SIFIN)

*10.1.2.2. Reviewer - Reviewing Activities*

- B. Jourdain : Reviewer for *Mathematical Reviews*
- A. Sulem: Reviewer for *Mathematical Reviews*

### *10.1.3. Invited Talks*

- A. Alfonsi
  - 15th of December 2017: "Sampling of probability measures in the convex order and approximation of Martingale Optimal Transport problems." Séminaire Bachelier, Paris.
  - 12th of June 2018: "Sampling of probability measures in the convex order and approximation of Martingale Optimal Transport problems." Conference on Stochastic modeling and financial applications, Verona.
  - 29th and 30th of August 2018: "Introduction to affine processes". Lecture given at the 11th European Summer School in Financial Mathematics, Palaiseau.
  - 29th of October 2018: "Sampling of probability measures in the convex order and approximation of Martingale Optimal Transport problems." International Conference on Control, Games and Stochastic Analysis, Hammamet.

   - 7th of December 2018: "Approximation de mesures de probabilité dans l'ordre convexe par projections pour la distance de Wasserstein." Séminaire de Mathématiques Appliquées, Collège de France.
- V. Bally
   - Conference SPA (Stochastic Processes and their Applications): "Abstract Malliavin calculus and invariance principles", 11-15 June 2018, Gothenburg, Sweden.
   - Workshop on Analytical Aspects of Stochastic Systems: "Transfer of regularity for Markov semigroups", Växjö, Sweden, June 6-8, 2018.
   - Workshop Recent Advances in Random Processes - Conference in honor of Paolo Baldi's 70th aniversary. Talk: Malliavin Calculus and Invariance Principles"
   - Workshop on Asymptotic expansions and Malliavin calculus 15-16 November 2018, Institut Henri Poincaré. Talk: Malliavin Calculus and Invariance Principles"
- B. Jourdain

  - Inria Mathrisk/LPSM university Paris Diderot seminar, 20 December 2018 : Differentiability of the squared quadratic Wasserstein distance

  - 1st Moscow-UK workshop on stochastic analysis : Wasserstein calculus and related topics, ICMS Edinburgh 19-23 November 2018 : Lifted and geometric differentiability of the squared quadratic Wasserstein distance

  - Seminar of the chair Financial Risks, IHP, 5 October 2018 : A new family of one-dimensional martingales couplings

  - Populations : Interaction and Evolution, IHP, 10-14 September 2018 : Existence of a calibrated regime-switching local volatility model

  - Journées MAS 2018, Dijon, 29-31 August : plenary talk entitled Sampling of probability measures in the convex order and approximation of martingale optimal transport problems

  - 10th world congress of the Bachelier finance society, Dublin, 16-20 July 2018 : Sampling of probability measures in the convex order and approximation of martingale optimal transport problems

  - MCQMC2018, Rennes, 2-6 July 2018 : Sampling of probability measures in the convex order and approximation of martingale optimal transport problems

  - Bachelier course : Systems of rank-based diffusions with mean-field interaction, 4 hours, 23 and 30 March 2018
- D. Lamberton

  Invited speaker: Symposium on optimal stopping, June 25-29 2018, Rice University, Houston. (USA)
- A. Sulem
   - Conference SPA (Stochastic Processes and their Applications): "Stochastic Optimal Control Under Partial Observations", 11-15 June 2018, Gothenburg, Sweden.

### *10.1.4. Research Administration*

- A. Alfonsi

  - Deputy director of CERMICS laboratory

  - 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 scientific positions (Commission des emplois scientifiques), Inria Paris

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

  - Member of the Committee for Inria international Chairs

## 10.2. Teaching - Supervision - Juries

### 10.2.1. Teaching

Licence :

- A. Alfonsi: 'Probabilités", first year course at Ecole des Ponts.

- V. Bally : "Analyse Hilbertienne", Course L3, UPEMLV

Master :

- A. Alfonsi:
  - "Données Haute Fréquence en finance",Master lectures at UPEMLV.
  - 'Traitement des données de marché : aspects statistiques et calibration", Master lectures at UPEMLV.
  - "Mesures de risque", Master course of UPEMLV and Paris VI.
  - Professeur chargé de cours at Ecole Polytechnique.

- V. Bally
  - Course on "Taux d'Intêret", M2 Finance, UPEMLV
  - Course on "Calcul de Malliavin et applications en finance", M2 Finance, UPEMLV
  - Course on "Analyse du risque", M2 Actuariat, UPEMLV
  - Course on "Processus Stochastiques", M2 Recherche, UPEMLV

- B. Jourdain
  - Course on "Mont-Carlo Markov chain methods and particle algorithms", Research Master Probabilités et Modèles Aléatoires, Sorbonne Université
  - B. Jourdain: course "Mathematical finance", M1, ENPC

- 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".

### *10.2.2. Supervision*

PhD Alexandre Zhou, "Theoretical and numerical study of problems nonlinear in the sense of McKean in finance", Ecole des Ponts, defended on October 17th 2018, supervised by B.Jourdain.

PhD Giulia Terenzi, "American options in complex financial models", université Marne la Vallée, defended on December 17th 2018, supervised by D. Lamberton and Lucia Caramellino, University Tor Vergata, Rome.

PhD Marouan Iben Taarit , “ On CVA and XVA computations ”, "Valorisation des ajustements Xva : de l’exposition espérée aux risques adverses de corrélation", CIFRE Natixis/ENPC, defended on January 8th, ENPC, Supervisor: Bernard Lapeyre.

PhD in progress :

- Anas Bentaleb (started February 2018) : Mathematical techniques for expected exposure evaluation, Supervisor: B. Lapeyre.

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

- Rafaël Coyaud, “Deterministic ans 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.

- Sophian Mehalla (started November 2017), CIFRE agreement Milliman company/Ecole des Ponts (http://fr.milliman.com, Supervisor: B. Lapeyre

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

- Ezechiel Kahn (started September 2018) "Functional inequalities for random matrices models", supervised by B. Jourdain and D. Chafai

- William Margheriti (started January 2018) "Numerical methods for martingale optimal transport problems", supervised by J.-F. Delmas and B. Jourdain

### *10.2.3. Juries*

B. Jourdain :

Jury and report on

- PhD of Hadrien De March, defended on June 29, university Paris Saclay
- PhD of David Krief, defended on September 27, University Paris Diderot

A. Sulem

- PhD of David Krief, defended on September 27, University Paris Diderot (Chair of the Committee)
- PhD of Xiao Wei, November 27, University Paris Diderot
- PhD Hadjer Moussaoui, December 14, Université de Toulon
- HdR of Thomas Lim, ENSIIE, December 4, Université Evry Val d’Essonne
- PEDR CNRS September 2018
- PRIX Inria : Grand Prix Inria - Académie des Sciences; - Prix Jeune Chercheur - Académie des Sciences ; Prix Innovation - Dassault Système (Spring 2018)

# 11. Bibliography

## Major publications by the team in recent years

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## Publications of the year

### Doctoral Dissertations and Habilitation Theses

[11] M. IBEN TAARIT. *Pricing of XVA adjustments : from expected exposures to wrong-way risks*, Université Paris-Est, January 2018, https://pastel.archives-ouvertes.fr/tel-01939269

[12] G. TERENZI. *Option prices in stochastic volatility models*, Université Paris Est - Marne-la-Vallée ; Università di Roma Tor Vergata, December 2018, https://hal.archives-ouvertes.fr/tel-01961071

[13] A. ZHOU. *Theoretical and numerical study of problems nonlinear in the sense of McKean in finance*, Université Paris Est, École des Ponts Paris Tech, 6-8 avenue Blaise Pascal, 77455 Marne La Vallée, October 2018, https://hal.inria.fr/tel-01957638

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