

# 2025 Activity Report

RESEARCH CENTRE: Inria Centre at Université Côte d'Azur  
IN PARTNERSHIP WITH: Université Côte d'Azur

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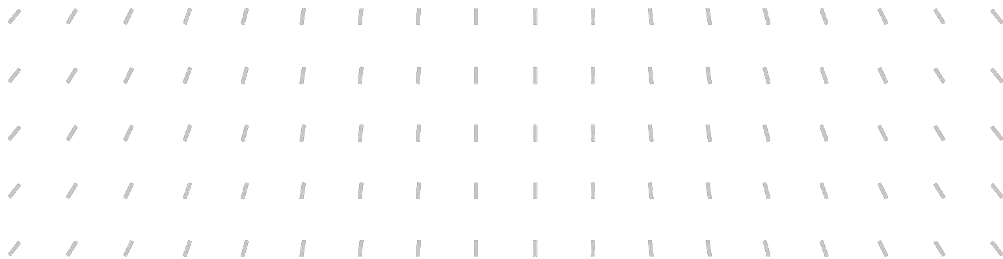
Project-Team

## ACUMES

Analysis and Control of Unsteady Models for  
Engineering Sciences

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*In collaboration with Laboratoire Jean-Alexandre Dieudonné (JAD)*



## **Project-Team ACUMES**

*Creation of the Project-Team: 2016 July 01*

Each year, Inria research teams publish an Activity Report presenting their work and results over the reporting period. These reports follow a common structure, with some optional sections depending on the specific team. They typically begin by outlining the overall objectives and research programme, including the main research themes, goals, and methodological approaches. They also describe the application domains targeted by the team, highlighting the scientific or societal contexts in which their work is situated. The reports then present the highlights of the year, covering major scientific achievements, software developments, or teaching contributions. When relevant, they include sections on software, platforms, and open data, detailing the tools developed and how they are shared. A substantial part is dedicated to new results, where scientific contributions are described in detail, often with subsections specifying participants and associated keywords. Finally, the Activity Report addresses funding, contracts, partnerships, and collaborations at various levels, from industrial agreements to international cooperations. It also covers dissemination and teaching activities, such as participation in scientific events, outreach, and supervision. The document concludes with a presentation of scientific production, including major publications and those produced during the year.

## Keywords

### Computer sciences and digital sciences

- A6.1. – Methods in mathematical modeling
  - A6.1.1. – Continuous Modeling (PDE, ODE)
  - A6.1.3. – Discrete Modeling (multi-agent, people centered)
  - A6.1.4. – Multiscale modeling
  - A6.1.5. – Multiphysics modeling
- A6.2. – Scientific computing, Numerical Analysis & Optimization
  - A6.2.1. – Numerical analysis of PDE and ODE
  - A6.2.3. – Probabilistic methods
  - A6.2.4. – Statistical methods
  - A6.2.6. – Optimization
  - A6.2.8. – Computational geometry and meshes
- A6.3. – Computation-data interaction
  - A6.3.1. – Inverse problems
  - A6.3.2. – Data assimilation
  - A6.3.4. – Model reduction
  - A6.3.5. – Uncertainty Quantification
- A6.4.1. – Deterministic control
- A6.4.4. – Stability and Stabilization
- A6.4.6. – Optimal control
- A6.5.1. – Solid mechanics
- A6.5.2. – Fluid mechanics
- A6.5.3. – Transport
- A6.5.4. – Waves
- A8.2. – Optimization
  - A8.2.6. – Numerical methods for optimization
- A8.11. – Game Theory
- A8.12. – Optimal transport
- A9.2.1. – Supervised learning
- A9.2.4. – Optimization and learning
- A9.2.5. – Bayesian methods
- A9.2.6. – Neural networks
- A9.2.7. – Kernel methods

**Other research topics and application domains**

B1.1.8. – Mathematical biology

B2.3. – Epidemiology

B4.3. – Renewable energy production

B5.2.3. – Aviation

B5.3. – Nanotechnology

B5.5. – Materials

B7.1.1. – Pedestrian traffic and crowds

B7.1.2. – Road traffic

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# 1 Team members, visitors, external collaborators

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## 2 Overall objectives

ACUMES aims at developing a rigorous framework for numerical simulations and optimal control for transportation and buildings, with focus on multi-scale, heterogeneous, unsteady phenomena subject to uncertainty. Starting from established macroscopic Partial Differential Equation (PDE) models, we pursue a set of innovative approaches to include small-scale phenomena, which impact the whole system. Targeting applications contributing to sustainability of urban environments, we couple the resulting models with robust control and optimization techniques.

Modern engineering sciences make an important use of mathematical models and numerical simulations at the conception stage. Effective models and efficient numerical tools allow for optimization before production and to avoid the construction of expensive prototypes or costly post-process adjustments. Most up-to-date modeling techniques aim at helping engineers to increase performances and safety and reduce costs and pollutant emissions of their products. For example, mathematical traffic flow models are used by civil engineers to test new management strategies in order to reduce congestion on the existing road networks and improve crowd evacuation from buildings or other confined spaces without constructing new infrastructures. Similar models are also used in mechanical engineering, in conjunction with concurrent optimization methods, to reduce energy consumption, noise and pollutant emissions of cars, or to increase thermal and structural efficiency of buildings while, in both cases, reducing ecological costs.

Nevertheless, current models and numerical methods exhibit some limitations:

- Most simulation-based design procedures used in engineering still rely on steady (time-averaged) state models. Significant improvements have already been obtained with such a modeling level, for instance by optimizing car shapes, but finer models taking into account unsteady phenomena are required in the design phase for further improvements.
- The classical purely macroscopic approach, while offering a framework with a sound analytical basis, performing numerical techniques and good modeling features to some extent, is not able to reproduce some particular phenomena related to specific interactions occurring at a lower (possibly micro) level. We refer for example to self-organizing phenomena observed in pedestrian flows, or to the dynamics of turbulent flows for which large scale / small scale vortical structures interfere. These flow characteristics need to be taken into account to obtain more precise models and improved optimal solutions.
- Uncertainty related to operational conditions (e.g. inflow velocity in aerodynamics), or models (e.g. individual behavior in crowds) is still rarely considered in engineering analysis and design, yielding solutions of poor robustness.

This project focuses on the analysis and optimal control of classical and non-classical evolutionary systems of Partial Differential Equations (PDEs) arising in the modeling and optimization of engineering problems related to safety and sustainability of urban environments, mostly involving fluid-dynamics and structural mechanics. The complexity of the involved dynamical systems is expressed by multi-scale, time-dependent phenomena, possibly subject to uncertainty, which can hardly be tackled using classical approaches, and require the development of unconventional techniques.

## 3 Research program

### 3.1 Research directions

The project develops along the following two axes:

- modeling complex systems through novel (unconventional) PDE systems, accounting for multi-scale phenomena and uncertainty;
- optimization and optimal control algorithms for systems governed by the above PDE systems.

These themes are motivated by the specific problems treated in the applications, and represent important and up-to-date issues in engineering sciences. For example, improving the design of transportation means and civil buildings, and the control of traffic flows, would result not only in better performances of the object of the optimization strategy (vehicles, buildings or road networks level of service), but also in enhanced safety and lower energy consumption, contributing to reduce costs and pollutant emissions.

### 3.2 PDE models accounting for multi-scale phenomena and uncertainties

Dynamical models consisting of evolutionary PDEs, mainly of hyperbolic type, appear classically in the applications studied by the previous Project-Team Opale (compressible flows, traffic, cell-dynamics, medicine, etc). Yet, the classical purely macroscopic approach is not able to account for some particular phenomena related to specific interactions occurring at smaller scales. These phenomena can be of greater importance when dealing with particular applications, where the "first order" approximation given by the purely macroscopic approach turns out to be inadequate. We refer for example to self-organizing phenomena observed in pedestrian flows [123], or to the dynamics of turbulent flows for which large scale / small scale vortical structures interfere [149].

Nevertheless, macroscopic models offer well known advantages, namely a sound analytical framework, fast numerical schemes, the presence of a low number of parameters to be calibrated, and efficient optimization procedures. Therefore, we are convinced of the interest of keeping this point of view as dominant, while completing the models with information on the dynamics at the small scale / microscopic level. This can be achieved through several techniques, like hybrid models, homogenization, mean field games. In this project, we will focus on the aspects detailed below.

The development of adapted and efficient numerical schemes is a mandatory completion, and sometimes ingredient, of all the approaches listed below. The numerical schemes developed by the team are based on finite volumes or finite elements techniques, and constitute an important tool in the study of the considered models, providing a necessary step towards the design and implementation of the corresponding optimization algorithms, see Section 3.3.

#### 3.2.1 Micro-macro couplings

Modeling of complex problems with a dominant macroscopic point of view often requires couplings with small scale descriptions. Accounting for systems heterogeneity or different degrees of accuracy usually leads to coupled PDE-ODE systems.

In the case of heterogeneous problems the coupling is "intrinsic", i.e. the two models evolve together and mutually affect each-other. For example, accounting for the impact of a large and slow vehicle (like a bus or a truck) on traffic flow leads to a strongly coupled system consisting of a (system of) conservation law(s) coupled with an ODE describing the bus trajectory, which acts as a moving bottleneck. The coupling is realized through a local unilateral moving constraint on the flow at the bus location, see [94] for an existence result and [80, 95] for numerical schemes.

If the coupling is intended to offer higher degree of accuracy at some locations, a macroscopic and a microscopic model are connected through an artificial boundary, and exchange information across it through suitable boundary conditions. See [86, 112] for some applications in traffic flow modeling, and [105, 109, 111] for applications to cell dynamics.

The corresponding numerical schemes are usually based on classical finite volume or finite element methods for the PDE, and Euler or Runge-Kutta schemes for the ODE, coupled in order to take into account the interaction fronts. In particular, the dynamics of the coupling boundaries require an accurate handling

capturing the possible presence of non-classical shocks and preventing diffusion, which could produce wrong solutions, see for example [80, 95].

We plan to pursue our activity in this framework, also extending the above mentioned approaches to problems in two or higher space dimensions, to cover applications to crowd dynamics or fluid-structure interaction.

### 3.2.2 Micro-macro limits

Rigorous derivation of macroscopic models from microscopic ones offers a sound basis for the proposed modeling approach, and can provide alternative numerical schemes, see for example [87, 100] for the derivation of Lighthill-Whitham-Richards [135, 148] traffic flow model from Follow-the-Leader and [106] for results on crowd motion models (see also [125]). To tackle this aspect, we will rely mainly on two (interconnected) concepts: measure-valued solutions and mean-field limits.

The notion of **measure-valued solutions** for conservation laws was first introduced by DiPerna [101], and extensively used since then to prove convergence of approximate solutions and deduce existence results, see for example [107] and references therein. Measure-valued functions have been recently advocated as the appropriate notion of solution to tackle problems for which analytical results (such as existence and uniqueness of weak solutions in distributional sense) and numerical convergence are missing [69, 108]. We refer, for example, to the notion of solution for non-hyperbolic systems [114], for which no general theoretical result is available at present, and to the convergence of finite volume schemes for systems of hyperbolic conservation laws in several space dimensions, see [108].

In this framework, we plan to investigate and make use of measure-based PDE models for vehicular and pedestrian traffic flows. Indeed, a modeling approach based on (multi-scale) time-evolving measures (expressing the agents probability distribution in space) has been recently introduced (see the monograph [91]), and proved to be successful for studying emerging self-organized flow patterns [90]. The theoretical measure framework proves to be also relevant in addressing micro-macro limiting procedures of mean field type [115], where one lets the number of agents going to infinity, while keeping the total mass constant. In this case, one must prove that the *empirical measure*, corresponding to the sum of Dirac measures concentrated at the agents positions, converges to a measure-valued solution of the corresponding macroscopic evolution equation. We recall that a key ingredient in this approach is the use of the *Wasserstein distances* [157, 156]. Indeed, as observed in [142, Section 6], the usual  $L^1$  spaces are not natural in this context, since they do not guarantee uniqueness of solutions.

This procedure can potentially be extended to more complex configurations, like for example road networks or different classes of interacting agents, or to other application domains, like cell-dynamics.

Another powerful tool we shall consider to deal with micro-macro limits is the so-called **Mean Field Games (MFG)** technique (see the seminal paper [134]). This approach has been recently applied to some of the systems studied by the team, such as traffic flow and cell dynamics. In the context of crowd dynamics, including the case of several populations with different targets, the mean field game approach has been adopted in [77, 76, 102, 133], under the assumption that the individual behavior evolves according to a stochastic process, which gives rise to parabolic equations greatly simplifying the analysis of the system. Besides, a deterministic context is studied in [144], which considers a non-local velocity field. For cell dynamics, in order to take into account the fast processes that occur in the migration-related machinery, a framework such as the one developed in [93] to handle games "where agents evolve their strategies according to the best-reply scheme on a much faster time scale than their social configuration variables" may turn out to be suitable. An alternative framework to MFG is also considered. This framework is based on the formulation of -Nash- games constrained by the **Fokker-Planck (FP, [67])** partial differential equations that govern the time evolution of the probability density functions -PDF- of stochastic systems and on objectives that may require to follow a given PDF trajectory or to minimize an expectation functional.

### 3.2.3 Non-local flows

Non-local interactions can be described through macroscopic models based on integro-differential equations. Systems of the type

$$\partial_t u + \operatorname{div}_{\mathbf{x}} F(t, \mathbf{x}, u, W) = 0, \quad t > 0, \mathbf{x} \in \mathbb{R}^d, d \geq 1, \quad (1)$$

where  $u = u(t, \mathbf{x}) \in R^N$ ,  $N \geq 1$  is the vector of conserved quantities and the variable  $W = W(t, \mathbf{x}, u)$  depends on an integral evaluation of  $u$ , arise in a variety of physical applications. Space-integral terms are considered for example in models for granular flows [64], sedimentation [71], supply chains [119], conveyor belts [117], biological applications like structured populations dynamics [141], or more general problems like gradient constrained equations [66]. Also, non-local in time terms arise in conservation laws with memory, starting from [92]. In particular, equations with non-local flux have been recently introduced in traffic flow modeling to account for the reaction of drivers or pedestrians to the surrounding density of other individuals, see [72, 79, 83, 116, 152]. While pedestrians are likely to react to the presence of people all around them, drivers will mainly adapt their velocity to the downstream traffic, assigning a greater importance to closer vehicles. In particular, and in contrast to classical (without integral terms) macroscopic equations, these models are able to display finite acceleration of vehicles through Lipschitz bounds on the mean velocity [72, 116] and lane formation in crossing pedestrian flows.

General analytical results on non-local conservation laws, proving existence and possibly uniqueness of solutions of the Cauchy problem for (1), can be found in [65] for scalar equations in one space dimension ( $N = d = 1$ ), in [84] for scalar equations in several space dimensions ( $N = 1, d \geq 1$ ) and in [62], [85, 89] for multi-dimensional systems of conservation laws. Besides, specific finite volume numerical methods have been developed recently in [62, 116] and [132].

Relying on these encouraging results, we aim to push a step further the analytical and numerical study of non-local models of type (1), in particular concerning well-posedness of initial - boundary value problems, regularity of solutions and high-order numerical schemes.

### 3.2.4 Uncertainty in parameters and initial-boundary data

Different sources of uncertainty can be identified in PDE models, related to the fact that the problem of interest is not perfectly known. At first, initial and boundary condition values can be uncertain. For instance, in traffic flows, the time-dependent value of inlet and outlet fluxes, as well as the initial distribution of vehicles density, are not perfectly determined [78]. In aerodynamics, inflow conditions like velocity modulus and direction, are subject to fluctuations [121, 140]. For some engineering problems, the geometry of the boundary can also be uncertain, due to structural deformation, mechanical wear or disregard of some details [104]. Another source of uncertainty is related to the value of some parameters in the PDE models. This is typically the case of parameters in turbulence models in fluid mechanics, which have been calibrated according to some reference flows but are not universal [150, 155], or in traffic flow models, which may depend on the type of road, weather conditions, or even the country of interest (due to differences in driving rules and conductors behavior). This leads to equations with flux functions depending on random parameters [151, 154], for which the mean and the variance of the solutions can be computed using different techniques. Indeed, uncertainty quantification for systems governed by PDEs has become a very active research topic in the last years. Most approaches are embedded in a probabilistic framework and aim at quantifying statistical moments of the PDE solutions, under the assumption that the characteristics of uncertain parameters are known. Note that classical Monte-Carlo approaches exhibit low convergence rate and consequently accurate simulations require huge computational times. In this respect, some enhanced algorithms have been proposed, for example in the balance law framework [139]. Different approaches propose to modify the PDE solvers to account for this probabilistic context, for instance by defining the non-deterministic part of the solution on an orthogonal basis (Polynomial Chaos decomposition) and using a Galerkin projection [121, 131, 136, 159] or an entropy closure method [99], or by discretizing the probability space and extending the numerical schemes to the stochastic components [61]. Alternatively, some other approaches maintain a fully deterministic PDE resolution, but approximate the solution in the vicinity of the reference parameter values by Taylor series expansions based on first- or second-order sensitivities [145, 155, 158].

Our objective regarding this topic is twofold. In a pure modeling perspective, we aim at including uncertainty quantification in models calibration and validation for predictive use. In this case, the choice of the techniques will depend on the specific problem considered [70]. Besides, we plan to extend previous works on sensitivity analysis [104, 137] to more complex and more demanding problems. In particular, high-order Taylor expansions of the solution (greater than two) will be considered in the framework of the Sensitivity Equation Method [73] (SEM) for unsteady aerodynamic applications, to improve the accuracy of mean and variance estimations. A second targeted topic in this context is the study of the uncertainty related to turbulence closure parameters, in the sequel of [155]. We aim at exploring the capability of the SEM

approach to detect a change of flow topology, in case of detached flows. Our ambition is to contribute to the emergence of a new generation of simulation tools, which will provide solution densities rather than values, to tackle real-life uncertain problems. This task will also include a reflection about numerical schemes used to solve PDE systems, in the perspective of constructing a unified numerical framework able to account for exact geometries (isogeometric methods), uncertainty propagation and sensitivity analysis with respect to control parameters.

### 3.3 Optimization and control algorithms for systems governed by PDEs

The non-classical models described above are developed in the perspective of design improvement for real-life applications. Therefore, control and optimization algorithms are also developed in conjunction with these models. The focus here is on the methodological development and analysis of optimization algorithms for PDE systems in general, keeping in mind the application domains in the way the problems are mathematically formulated.

#### 3.3.1 Sensitivity vs. adjoint equation

Adjoint methods (achieved at continuous or discrete level) are now commonly used in industry for steady PDE problems. Our recent developments [147] have shown that the (discrete) adjoint method can be efficiently applied to cost gradient computations for time-evolving traffic flow on networks, thanks to the special structure of the associated linear systems and the underlying one dimensionality of the problem. However, this strategy is questionable for more complex (e.g. 2D/3D) unsteady problems, because it requires sophisticated and time-consuming check-pointing and/or re-computing strategies [68, 118] for the backward time integration of the adjoint variables. The sensitivity equation method (SEM) offers a promising alternative [103, 126], if the number of design parameters is moderate. Moreover, this approach can be employed for other goals, like fast evaluation of neighboring solutions or uncertainty propagation [104].

Regarding this topic, we intend to apply the continuous sensitivity equation method to challenging problems. In particular, in aerodynamics, multi-scale turbulence models like Large-Eddy Simulation (LES) [149], Detached-Eddy Simulation (DES) [153] or Organized-Eddy Simulation (OES) [74], are more and more employed to analyze the unsteady dynamics of the flows around bluff-bodies, because they have the ability to compute the interactions of vortices at different scales, contrary to classical Reynolds-Averaged Navier-Stokes models. However, their use in design optimization is tedious, due to the long time integration required. In collaboration with turbulence specialists (M. Braza, CNRS - IMFT), we aim at developing numerical methods for effective sensitivity analysis in this context, and apply them to realistic problems, like the optimization of active flow control devices. Note that the use of SEM allows computing cost functional gradients at any time, which permits to construct new gradient-based optimization strategies like instantaneous-feedback method [129] or multiobjective optimization algorithm (see section below).

#### 3.3.2 Integration of Computer-Aided Design and analysis for shape optimization

A major difficulty in shape optimization is related to the multiplicity of geometrical representations handled during the design process. From high-order Computer-Aided Design (CAD) objects to discrete mesh-based descriptions, several geometrical transformations have to be performed, that considerably impact the accuracy, the robustness and the complexity of the design loop. This is even more critical when multiphysics applications are targeted, including moving bodies.

To overcome this difficulty, we intend to investigate *isogeometric analysis* [127] methods, which propose to use the same CAD representations for the computational domain and the physical solutions yielding geometrically exact simulations. In particular, hyperbolic systems and compressible aerodynamics are targeted.

#### 3.3.3 Multi-objective descent algorithms for multi-disciplinary, multi-point, unsteady optimization or robust-design

In differentiable optimization, multi-disciplinary, multi-point, unsteady optimization or robust-design can all be formulated as multi-objective optimization problems. In this area, we have proposed the *Multiple-Gradient*

*Descent Algorithm (MGDA)* to handle all criteria concurrently [97] [96]. Originally, we have stated a principle according to which, given a family of local gradients, a descent direction common to all considered objective-functions simultaneously is identified, assuming the Pareto-stationarity condition is not satisfied. When the family is linearly-independent, we have access to a direct algorithm. Inversely, when the family is linearly-dependent, a quadratic-programming problem should be solved. Hence, the technical difficulty is mostly conditioned by the number  $m$  of objective functions relative to the search space dimension  $n$ . In this respect, the basic algorithm has recently been revised [98] to handle the case where  $m > n$ , and even  $m \gg n$ , and is currently being tested on a test-case of robust design subject to a periodic time-dependent Navier-Stokes flow.

The multi-point situation is very similar and, being of great importance for engineering applications, will be treated at large.

Moreover, we intend to develop and test a new methodology for robust design that will include uncertainty effects. More precisely, we propose to employ MGDA to achieve an effective improvement of all criteria simultaneously, which can be of statistical nature or discrete functional values evaluated in confidence intervals of parameters. Some recent results obtained at ONERA [143] by a stochastic variant of our methodology confirm the viability of the approach. A PhD thesis has also been launched at ONERA/DADS.

Lastly, we note that in situations where gradients are difficult to evaluate, the method can be assisted by a meta-model [161].

### 3.3.4 Bayesian Optimization algorithms for efficient computation of general equilibria

Bayesian Optimization (BO) relies on Gaussian processes, which are used as emulators (or surrogates) of the black-box model outputs based on a small set of model evaluations. Posterior distributions provided by the Gaussian process are used to design acquisition functions that guide sequential search strategies that balance between exploration and exploitation. Such approaches have been transposed to frameworks other than optimization, such as uncertainty quantification. Our aim is to investigate how the BO apparatus can be applied to the search of general game equilibria, and in particular the classical Nash equilibrium (NE). To this end, we propose two complementary acquisition functions, one based on a greedy search approach and one based on the Stepwise Uncertainty Reduction paradigm [110]. Our proposal is designed to tackle derivative-free, expensive models, hence requiring very few model evaluations to converge to the solution.

### 3.3.5 Decentralized strategies for inverse problems

Most if not all the mathematical formulations of inverse problems (a.k.a. reconstruction, identification, data recovery, non destructive engineering,...) are known to be ill posed in the Hadamard sense. Indeed, in general, inverse problems try to fulfill (minimize) two or more very antagonistic criteria. One classical example is the Tikhonov regularization, trying to find artificially smoothed solutions close to naturally non-smooth data.

We consider here the theoretical general framework of parameter identification coupled to (missing) data recovery. Our aim is to design, study and implement algorithms derived within a game theoretic framework, which are able to find, with computational efficiency, equilibria between the "identification related players" and the "data recovery players". These two parts are known to pose many challenges, from a theoretical point of view, like the identifiability issue, and from a numerical one, like convergence, stability and robustness problems. These questions are tricky [63] and still completely open for systems like coupled heat and thermoelastic joint data and material detection.

## 4 Application domains

### 4.1 Active flow control for vehicles

The reduction of CO2 emissions represents a great challenge for the automotive and aeronautic industries, which committed respectively a decrease of 20% for 2020 and 75% for 2050. This goal will not be reachable, unless a significant improvement of the aerodynamic performance of cars and aircrafts is achieved (e.g. aerodynamic resistance represents 70% of energy losses for cars above 90 km/h). Since vehicle design cannot be significantly modified, due to marketing or structural reasons, active flow control technologies are one of the most promising approaches to improve aerodynamic performance. This consists in introducing

micro-devices, like pulsating jets or vibrating membranes, that can modify vortices generated by vehicles. Thanks to flow non-linearities, a small energy expense for actuation can significantly reduce energy losses. The efficiency of this approach has been demonstrated, experimentally as well as numerically, for simple configurations [160].

However, the lack of efficient and flexible numerical tools, that allow to simulate and optimize a large number of such devices on realistic configurations, is still a bottleneck for the emergence of this technology in industry. The main issue is the necessity of using high-order schemes and complex models to simulate actuated flows, accounting for phenomena occurring at different scales. In this context, we intend to contribute to the following research axes:

- *Sensitivity analysis for actuated flows.* Adjoint-based (reverse) approaches, classically employed in design optimization procedure to compute functional gradients, are not well suited to this context. Therefore, we propose to explore the alternative (direct) formulation, which is not so much used, in the perspective of a better characterization of actuated flows and optimization of control devices.
- *Isogeometric simulation of control devices.* To simulate flows perturbed by small-scale actuators, we investigate the use of isogeometric analysis methods, which allow to account exactly for CAD-based geometries in a high-order hierarchical representation framework. In particular, we try to exploit the features of the method to simulate more accurately complex flows including moving devices and multiscale phenomena.

## 4.2 Vehicular and pedestrian traffic flows

Intelligent Transportation Systems (ITS) is nowadays a booming sector, where the contribution of mathematical modeling and optimization is widely recognized. In this perspective, traffic flow models are a commonly cited example of "complex systems", in which individual behavior and self-organization phenomena must be taken into account to obtain a realistic description of the observed macroscopic dynamics [122]. Further improvements require more advanced models, keeping into better account interactions at the microscopic scale, and adapted control techniques, see [75] and references therein.

In particular, we will focus on the following aspects:

- *Junction models.* We are interested in designing a general junction model both satisfying basic analytical properties guaranteeing well-posedness and being realistic for traffic applications. In particular, the model should be able to overcome severe drawbacks of existing models, such as restrictions on the number of involved roads and prescribed split ratios [88, 113], which limit their applicability to real world situations. Hamilton-Jacobi equations could be also an interesting direction of research, following the recent results obtained in [128].
- *Data assimilation.* In traffic flow modeling, the capability of correctly estimating and predicting the state of the system depends on the availability of rich and accurate data on the network. Up to now, the most classical sensors are fixed ones. They are composed of inductive loops (electrical wires) that are installed at different spatial positions of the network and that can measure the traffic flow, the occupancy rate (i.e. the proportion of time during which a vehicle is detected to be over the loop) and the speed (in case of a system of two distant loops). These data are useful / essential to calibrate the phenomenological relationship between flow and density which is known in the traffic literature as the Fundamental Diagram. Nowadays, thanks to the wide development of mobile internet and geolocalization techniques and its increasing adoption by the road users, smartphones have turned into perfect mobile sensors in many domains, including in traffic flow management. They can provide the research community with a large database of individual trajectory sets that are known as Floating Car Data (FCD), see [124] for a real field experiment. Classical macroscopic models, say (hyperbolic systems of) conservation laws, are not designed to take into account this new kind of microscopic data. Other formulations, like Hamilton-Jacobi partial differential equations, are most suited and have been intensively studied in the past five years (see [81, 82]), with a stress on the (fixed) Eulerian framework. Up to our knowledge, there exist a few studies in the time-Lagrangian as well as space-Lagrangian frameworks, where data coming from mobile sensors could be easily assimilated, due to the fact that the Lagrangian coordinate (say the label of a vehicle) is fixed.

- *Control of autonomous vehicles.* Traffic flow is usually controlled via traffic lights or variable speed limits, which have fixed space locations. The deployment of autonomous vehicles opens new perspectives in traffic management, as the use of a small fraction of cars to optimize the overall traffic. In this perspective, the possibility to track vehicles trajectories either by coupled micro-macro models [94, 112] or via the Hamilton-Jacobi approach [81, 82] could allow to optimize the flow by controlling some specific vehicles corresponding to internal conditions.

### 4.3 Combined hormone and brachy therapies for the treatment of prostate cancer

The latest statistics published by the International Agency for Research on Cancer show that in 2018, 18.1 million new cancer cases have been identified and 9.6 million deaths have been recorded worldwide making it the second leading cause of death globally. Prostate cancer ranks third in incidence with 1.28 million cases and represents the second most commonly diagnosed male cancer.

Prostate cells need the hormone androgen to survive and function properly. For this to happen, the androgens have to bind to a protein in the prostate cells called Androgen Receptor and activate it. Since androgens act as a growth factor for the cells, one way of treating prostate cancer is through the antihormone therapy that hinder its activity. The Androgen Deprivation Therapy (ADT) aims to either reduce androgen production or to stop the androgens from working through the use of drugs. However, over time, castration-resistant cells that are able to sustain growth in a low androgen environment emerge. The castration-resistant cells can either be androgen independent or androgen repressed meaning that they have a negative growth rate when the androgen is abundant in the prostate. In order to delay the development of castration resistance and reduce its occurrence, the Intermittent Androgen Deprivation Therapy is used.

On the other hand, brachytherapy is an effective radiation therapy used in the treatment of prostate cancer by placing a sealed radiation source inside the prostate gland. It can be delivered in high dose rates (HDR) or low dose rates (LDR) depending on the radioactive source used and the duration of treatment.

In the HDR brachytherapy, the source is placed temporarily in the prostate for a few minutes to deliver high dose radiation while for the LDR brachytherapy low radiations dose are delivered from radioactive sources permanently placed in the prostate. The radioactivity of the source decays over time, therefore its presence in the prostate does not cause any long-term concern as its radioactivity disappears eventually. In practice, brachytherapy is prescribed either as monotherapy, often for localized tumors, or combined with another therapy such as external beam radiation therapy for which the total dose prescribed is divided between internal and external radiation. Brachytherapy can also be prescribed in combination with hormone therapy.

However, in the existing literature there is currently no mathematical model that explores this combination of treatments. Our aim is to develop a computational model based on partial differential equations to assess the effectiveness of combining androgen deprivation therapy with brachytherapy in the treatment of prostate cancer. The resulting simulations can be used to explore potential unconventional therapeutic strategies.

### 4.4 Other application fields

Besides the above mentioned axes, which constitute the project's identity, the methodological tools described in Section 3 have a wider range of application. We currently carry on also the following research actions, in collaboration with external partners.

- **Game strategies for thermoelastography.** Thermoelastography is an innovative non-invasive control technology, which has numerous advantages over other techniques, notably in medical imaging [138]. Indeed, it is well known that most pathological changes are associated with changes in tissue stiffness, while remaining isoechoic, and hence difficult to detect by ultrasound techniques. Based on elastic waves and heat flux reconstruction, thermoelastography shows no destructive or aggressive medical sequel, unlike X-ray and comparables techniques, making it a potentially prominent choice for patients. Physical principles of thermoelastography originally rely on dynamical structural responses of tissues, but as a first approach, we only consider static responses of linear elastic structures. The mathematical formulation of the thermoelasticity reconstruction is based on data completion and material identification, making it a harsh ill-posed inverse problem. In previous works [120, 130], we have demonstrated that Nash game approaches are efficient to tackle ill-posedness. We intend to extend the results obtained for Laplace equations in [120], and the algorithms developed in Section 3.3.5 to

the following problems (of increasing difficulty):

- Simultaneous data and parameter recovery in linear elasticity, using the so-called Kohn and Vogelius functional (ongoing work, some promising results obtained).
- Data recovery in coupled heat-thermoelasticity systems.
- Data recovery in linear thermoelasticity under stochastic heat flux, where the imposed flux is stochastic.
- Data recovery in coupled heat-thermoelasticity systems under stochastic heat flux, formulated as an incomplete information Nash game.
- Application to robust identification of cracks.

- **Constraint elimination in Quasi-Newton methods.** In single-objective differentiable optimization, Newton's method requires the specification of both gradient and Hessian. As a result, the convergence is quadratic, and Newton's method is often considered as the target reference. However, in applications to distributed systems, the functions to be minimized are usually "functionals", which depend on the optimization variables by the solution of an often complex set of PDE's, through a chain of computational procedures. Hence, the exact calculation of the full Hessian becomes a complex and costly computational endeavor.

This has fostered the development of *quasi-Newton's methods* that mimic Newton's method but use only the gradient, the Hessian being iteratively constructed by successive approximations inside the algorithm itself. Among such methods, the Broyden-Fletcher-Goldfarb-Shanno (BFGS) algorithm is well-known and commonly employed. In this method, the Hessian is corrected at each new iteration by rank-one matrices defined from several evaluations of the gradient only. The BFGS method has "super-linear convergence".

For constrained problems, certain authors have developed so-called *Riemannian BFGS*, e.g. [146], that have the desirable convergence property in constrained problems. However, in this approach, the constraints are assumed to be known formally, by explicit expressions.

In collaboration with ONERA-Meudon, we are exploring the possibility of representing constraints, in successive iterations, through local approximations of the constraint surfaces, splitting the design space locally into tangent and normal subspaces, and eliminating the normal coordinates through a linearization, or more generally a finite expansion, and applying the BFGS method through dependencies on the coordinates in the tangent subspace only. Preliminary experiments on the difficult Rosenbrock test-case, although in low dimensions, demonstrate the feasibility of this approach. On-going research is on theorizing this method, and testing cases of higher dimensions.

- **Multi-objective optimization for nanotechnologies.** Our team takes part in a larger collaboration with CEA/LETI (Grenoble), initiated by the Inria Project-Team Nachos (now Atlantis), and related to the Maxwell equations. Our component in this activity relates to the optimization of nanophotonic devices, in particular with respect to the control of thermal loads. We have first identified a gradation of representative test-cases of increasing complexity:
  - infrared micro-source;
  - micro-photoacoustic cell;
  - nanophotonic device.

These cases involve from a few geometric parameters to be optimized to a functional minimization subject to a finite-element solution involving a large number of degrees of freedom. CEA disposes of such codes, but considering the computational cost of the objective functions in the complex cases, the first part of our study is focused on the construction and validation of meta-models, typically of RBF-type (Radial Basis Functions). Multi-objective optimization will be carried out subsequently by MGDA, and possibly Nash games.

## 5 Social and environmental responsibility

### 5.1 Impact of research results

Acumes's research activity in traffic modeling and control is intended to improve road network efficiency, thus reducing energy consumption and pollutant emission.

The research activities related to isogeometric analysis and physics-informed neural networks (PINNs) aim at facilitating the use of numerical simulations and design optimization in engineering, yielding a gain of efficiency, for instance in transportation industry (cars, aircrafts) or energy industry (air conditioning, turbines).

The research conducted in ANR NEMATIC aims at exploring the ability to control the growth of filamentous fungi, which have the potential for the production of biofuels and biosourced chemicals. Investigations started with the arrival of Nicolas Fricker in January 2023.

The research conducted with company Altair on code OpenRadioss aims at improving the resolution of multimaterial flows in presence of large density ratios, with a view to security applications such as shaped-charge detonation. It started with the arrival of Alexandre Vieira in October 2024.

With the increasing demands of modern applications such as electric and hybrid vehicles and renewable energy storage, the limitations of current commercial batteries using liquid or gel electrolytes have become critical. We initiated a research activity on solid state batteries. Their better understanding and hence optimization is expected to strikingly improve industrial properties, such as higher energy densities, longer lifespans, cost-effectiveness, low maintenance, and enhanced safety. These objectives are under investigation within the PhD thesis of M. Bouchaara (UM6P, Morocco).

## 6 Highlights of the year

Chiara Simeoni passed away on July 10th, 2025, at the age of 49.

She began her academic journey working on well-balanced schemes for conservation laws with source term, before turning her attention to applications in biology and life sciences. Throughout the years, we were inspired by her boundless energy and remarkable strength. Her sudden passing has deeply affected us all.

### 6.1 Awards

Paola Goatin: *Chevalier de l'Ordre National du Mérite*, French Republic President award (2025).

## 7 Latest software developments, platforms, open data

### 7.1 Latest software developments

#### 7.1.1 Igloo

**Name:** Iso-Geometric anaLysis using discOntinuOus galerkin methods

**Keywords:** Numerical simulations, Isogeometric analysis

**Scientific Description:** Igloo contains numerical methods to solve partial differential equations of hyperbolic type, or convection-dominant type, using an isogeometric formulation (NURBS bases) with a discontinuous Galerkin method.

**Functional Description:** Simulation software for NURBS meshes

**URL:** <https://gitlab.inria.fr/igloo/igloo/-/wikis/home>

**Contact:** Régis Duvigneau

#### 7.1.2 pinnacle

**Name:** Physics-Informed Neural Networks Computational Library and Environment

**Keywords:** Neural networks, Partial differential equation, Physical simulation, Data assimilation, Inverse problem, Multiphysics modelling

**Scientific Description:** Set of methods for rapid implementation of physics-informed neural networks to solve direct and inverse problems: space-time sampling with refinement algorithms, dense multi-layer neural networks, library of physical models (mechanics, fluid, heat transfer, electromagnetics), optimisation algorithms, import/export tools for meshes and solutions.

**Functional Description:** Software library for implementation of physics informed neural networks.

**Contact:** Régis Duvigneau

**Participant:** 4 anonymous participants

### 7.1.3 MovingBottleneck

**Keywords:** Finite volume methods, Numerical optimization

**Functional Description:** Matlab code for solving numerically a system coupling a first order traffic model and ODEs describing moving bottleneck trajectories in one space dimension, based on original ideas developed in <https://hal.inria.fr/hal-01070262> In particular, we use Godunov scheme to solve the PDE, with a specific flux correction at the moving bottleneck positions consisting in a conservative reconstruction of the jump discontinuity. The code also allows for Model Predictive Control implementation. It has been used to produce results published in <https://hal.inria.fr/hal-01644823> , <https://www.aimspress.com/article/doi/10.3934/nhm.2023040> , <https://inria.hal.science/hal-03648482> , <https://hal.science/hal-04366870>

**URL:** <https://gitlab.inria.fr/pgoatin/movingbottleneck>

**Publications:** [hal-01644823](https://hal.inria.fr/hal-01644823), [hal-03648482](https://hal.inria.fr/hal-03648482), [hal-04366870](https://hal.inria.fr/hal-04366870), [hal-01070262](https://hal.inria.fr/hal-01070262)

**Contact:** Paola Goatin

**Participant:** 4 anonymous participants

### 7.1.4 PyLate

**Name:** Python Library for Aggregate Traffic Estimation

**Keywords:** Macroscopic traffic flow models, Numerical simulations

**Scientific Description:** PyLate: Python Library for Aggregate Traffic Estimation

PyLate is a Python library designed for macroscopic traffic simulation. It enables the creation of road networks using the NetworkX library, representing the network as a directed graph object (`networkx.DiGraph`). The library implements the Godunov numerical scheme and supports multi-class traffic flows, with each class having its own fundamental diagram and routing strategy.

Currently supported fundamental diagrams: • Triangular Fundamental Diagram • Greenshields Fundamental Diagram

Each class is characterised by: • An origin node (where its demand flow is generated). • A set of parameters for the fundamental diagram. • A routing strategy.

The following routing strategies are currently available: • Fixed-ratios: At each node, flows are routed according to a fixed, predefined distribution matrix. • Follow1Path: All flows are routed along a single path connecting the origin node to a destination node. • LogitDynamic: At each node, flows are distributed across up to n paths ending at the destination node in proportions defined by a Logit distribution. • LogitPredefined: Users are distributed according to a Logit model across a predefined set of paths between their origin and destination nodes. • LogitOD: Users are distributed according to a Logit model across up to n paths connecting their origin and destination nodes (different from LogitDynamic because the set of paths is fixed between origin and destination).

The library supports extending routing strategies and fundamental diagrams by creating subclasses of the respective abstract classes, without altering the core source code.

Integration with OpenStreetMap: Thanks to the osmnx library, PyLate allows importing road network data directly from OpenStreetMap, simplifying the setup of realistic traffic networks. However, when importing networks from OpenStreetMap, the generated graph is typically a MultiDiGraph, which allows multiple edges between nodes. To use PyLate, it is necessary to convert the MultiDiGraph into a DiGraph, which simplifies the handling of the network for the macroscopic traffic simulation.

**Functional Description:** PyLate is a Python library for macroscopic traffic simulation, built on the NetworkX library. It enables the creation of road networks as directed graphs (DiGraph) and implements the Godunov numerical scheme. PyLate supports multi-class traffic flows, each with its own fundamental diagram and routing strategy.

Currently supported fundamental diagrams include Triangular and Greenshields. Routing strategies include Fixed-ratios, Follow1Path, LogitDynamic, LogitPredefined, and LogitOD, each offering different methods for flow distribution across paths.

PyLate allows extension of routing strategies and diagrams via subclassing. It integrates with OpenStreetMap using osmnx to import road network data.

**URL:** <https://gitlab.inria.fr/pgoatin/pylate>

**Publications:** [hal-04206281](#), [hal-04206328](#)

**Contact:** Paola Goatin

**Participant:** 2 anonymous participants

### 7.1.5 CELIA2D

**Keywords:** 2D, Finite volume methods, Computational Fluid Dynamics, Free surface flows

**Functional Description:** The CELIA2D implements the Finite Volume method with cut cells for hyperbolic systems of conservation laws in 2D : compressible Euler and Saint-Venant. Mobile obstacles interact with fluid: the obstacles can be deformable, crack or come into contact.

**Contact:** Laurent Monasse

### 7.1.6 Precis

**Keywords:** Finite volume methods, 3D, Computational Fluid Dynamics

**Functional Description:** The Precis code implements Finite Volumes for compressible Euler equations on cut cells in three space dimensions.

**Contact:** Laurent Monasse

### 7.1.7 ShockFitting

**Keywords:** 2D, 3D, Discontinuous Galerkin, Finite volume methods, Compressible flows

**Functional Description:** The ShockFitting code implements in Julia the simulation of discontinuity interface tracking (contact discontinuities and shocks) for compressible fluids. The methods used are space-time cut cells in dimensions 1, 2 and 3 for a space discretization of Finite Volume of Discontinuous Galerkin type.

**Contact:** Laurent Monasse

## 8 New results

### 8.1 Macroscopic traffic flow models on networks

**Participants:** Eric Andoni, Paola Goatin, Rinaldo Colombo (*Univ. Brescia, Italy*), Chiara Daini (*KOPERNIC Project-Team, Inria Paris*), Maria Laura Delle Monache (*UC Berkeley, USA*), Giovanni De Nunzio (*IFPEN*), Antonella Ferrara (*Univ. Pavia, Italy*), Agatha Joumaa, Carmen Mezquita Nieto, Benedetto Piccoli (*Rutgers U, USA*), Elena Rossi (*Univ. Modena - Reggio Emilia, Italy*).

#### Traffic control by Connected and Automated Vehicles (CAVs)

We rely on a multi-scale approach to model mixed traffic composed of a small fleet of CAVs in the bulk flow. In particular, CAVs are allowed to overtake (if on distinct lanes) or queuing (if on the same lane). Controlling CAVs desired speeds allows to act on the system to minimize the selected cost function. For the proposed control strategies, we apply both global optimization and a Model Predictive Control approach. In particular, numerical tests show that few, optimally chosen CAVs are sufficient to significantly improve the selected performance indexes, even using a decentralized control policy. The studies [30] supports the attractive perspective of exploiting a very small number of vehicles as endogenous control actuators to regulate traffic flow on road networks, providing a flexible alternative to traditional control methods. Moreover, we compare the impact of the proposed control strategies (decentralized, quasi-decentralized, centralized).

In the aim of modeling the formation of stop-and-go waves (to be controlled employing CAVs), we also consider second order traffic models with relaxation, without requiring the sub-characteristic stability condition to hold. Therefore, large oscillations may arise from small perturbations of equilibria, capturing the formation of stop-and-go waves observed in reality. We then study the boundary stabilization of these  $2 \times 2$  nonlinear hyperbolic systems of balance equations with a relaxation-type source term in Lagrangian coordinates. Since the largest eigenvalue of the system is null, the boundaries are characteristic, and the available results on boundary controllability do not apply. Yet, we are able to prove that weak solutions can be steered to an equilibrium state by prescribing the corresponding equilibrium speed at the right boundary. This corresponds to controlling the speed of one vehicle to stabilize the upstream traffic flow [42].

#### Traffic flow optimization on road networks

The research focused on the development of a general multi-class macroscopic traffic model that can be applied to large-scale real-world networks.

Agatha Joumaa's PhD thesis [46] focused in particular on the design and testing of class-specific variable speed limits to mitigate the impact of traffic congestion [43]. This paper presents a novel approach to traffic management in road networks, consisting in time-varying class-specific variable speed limit (VSL) restricted to a fraction of road users. In particular, we present a macroscopic approach where traffic dynamics is described by a multi-class Lighthill-Whitham-Richards (LWR) model, with two classes of users (controlled and uncontrolled vehicles). The model can be applied to a general road network and our goal is to optimize traffic performance by minimizing both the average travel time in the network and the total time spent in virtual buffers at the network entries to prevent spill-back scenarios. The optimization is performed by acting on different ratios of controlled vehicles, and we compare the performance of the proposed control strategy with a classical inflow control at the entries of the network. The numerical tests show that class-specific speed control outperforms inflow control, and highlight the importance of tailored traffic control strategies for road networks, offering insights into optimizing mobility, safety, and traffic efficiency.

Besides, in her PhD, Carmen Mezquita Nieto applies a discrete adjoint gradient computation method to the multi-class traffic flow model on networks, where vehicle classes are characterized by their speed functions. The resulting hyperbolic system of conservation laws is discretized using a Godunov-type finite volume scheme based on demand and supply functions, which extends to coupling conditions at junctions and boundary conditions. The optimization of the different travel metrics is accomplished through the definition of a minimization problem using the adjoint gradient method. Numerical simulations are also presented to illustrate the efficiency of the method on a test network, see [54].

#### Hyperbolic-parabolic models for the management of traffic generated pollution

In [28], vehicular traffic flows through a merge regulated by traffic lights and produces pollutants that diffuse in the surrounding region. This situation motivates a general hyperbolic-parabolic system, whose well-posedness and stability are here proved in  $L^1$ . Roads are allowed to be also 2-dimensional. The effects of stop & go waves are comprised, leading to measure source terms in the parabolic equation. The traffic lights, as well as inflows and outflows, can be regulated to minimize the presence of pollutant in given regions.

## 8.2 Nonlocal flow models

**Participants:** Paola Goatin, Ilaria Ciaramaglia, Harold Deivi Contreras (*Universidad San Sebastian, Chile*), Simone Göttlich (*Univ. Mannheim, Germany*), Daniel Inzunza (*Universidad San Sebastian, Chile*), Gabriella Puppo (*Univ. Roma La Sapienza, Italy*), Elena Rossi (*Univ. Modena - Reggio Emilia, Italy*), Luis-Miguel Villada (*Universidad del Bio Bio, Chile*), Fabian Ziegler (*Univ. Mannheim, Germany*).

In the framework of Ilaria Ciaramaglia's PhD thesis, [27] provides the well-posedness of weak entropy solutions of a scalar non-local traffic flow model with time delay. Existence is obtained by convergence of finite volume approximate solutions constructed by Lax-Friedrich and Hilliges-Weidlich schemes, while the  $L^1$ -stability with respect to the initial data and the delay parameter relies on a Kruzkov-type doubling of variable technique. Numerical tests are provided to illustrate the efficiency of the proposed schemes, as well as the solution dependence on the delay and look-ahead parameters.

Besides, in [26], we present a class of systems of non-local conservation laws in one space-dimension incorporating time delay, which can be used to investigate the interaction between autonomous and human-driven vehicles, each characterized by a different reaction time and interaction range. We construct approximate solutions using a Hilliges-Weidlich scheme and we provide uniform  $L^\infty$  and BV estimates which ensure the convergence of the scheme, thus obtaining existence of entropy weak solutions of bounded variation. Uniqueness follows from an  $L^1$  stability result derived from the entropy condition. Additionally, we provide numerical simulations to illustrate applications to mixed autonomous / human-driven traffic flow modeling. In particular, we show that the presence of autonomous vehicles improves overall traffic flow and stability.

In [29], we propose and study a nonlocal system of balance laws, which models the traffic dynamics on a two-lane and two-way road where drivers have a preferred lane (the lane on their right) and the other one is used only for overtaking. In this model, the convective part is intended to describe the intralane dynamics of vehicles: the flux function includes local and nonlocal terms, namely, the velocity function in each lane depends locally on the density of the class of vehicles traveling on their preferred lane and in a nonlocal form on the density of the class of vehicles overtaking in the opposite direction. The source terms are intended to describe the coupling between the two lanes: the overtaking and return criteria depend on weighted means of the downstream traffic density of the class of vehicles traveling in their preferred lane and of the class of vehicles traveling in the opposite direction on the same lane. We construct approximate solutions using a finite volume scheme and we prove existence of weak solutions by means of compactness estimates. We also show some numerical simulations to describe the behavior of the numerical solutions in different situations and to illustrate some features of model.

In [48], we propose and analyze the well-posedness of a new class of macroscopic vehicular traffic model described by a scalar nonlocal conservation law that simultaneously incorporates both upstream and downstream effects in the flow dynamics. Unlike nonlocal models previously described in the literature, which only account for downstream density averages (look-ahead behavior), the proposed model introduces an additional term depending on an upstream average (look-behind), allowing for a more realistic representation of anticipatory driver behavior under high-density conditions. The main novelty of this work lies in establishing the existence and uniqueness theory for entropy weak solutions, together with a rigorous proof of Lipschitz continuous dependence of solutions not only on the initial data, but also on the kernel functions, under reasonable structural assumptions on the flux components. The proofs are achieved through the design of a conservative numerical scheme that preserves key structural properties of the continuous model, such as maximum principle, mass conservation, BV estimates, and  $L^1$ -stability. Finally, we present numerical

experiments that illustrate the behavior of solutions and the qualitative impact of nonlocal terms on traffic dynamics.

In [32], we consider a class of multi-population pedestrian models consisting in a system of nonlocal conservation laws coupled in the nonlocal components and describing several groups of pedestrians moving towards their respective targets while trying to avoid each other and the obstacles limiting the walking domain. Specifically, the nonlocal operators account for interactions occurring at the microscopic level as a reaction to the presence of other individuals or obstacles along the preferred path. In particular, the presence of obstacles is implemented in the nonlocal terms of the equations and not as classical boundary conditions. This allows to rewrite domain shape optimization problems as PDE-constrained problems. In this paper, we investigate the well-posedness of such optimization problems by proving the stability of solutions with respect to the positions and shapes of the obstacles. A differentiability result in the linear case is also provided. These properties are illustrated with a numerical example. See also [31].

Finally, in [53], a finite volume approximation scheme is used to solve a non-local macroscopic material flow model in two space dimensions, accounting for the presence of boundaries in the non-local terms. Based on a previous result for the scalar case, we extend the setting to a system of heterogeneous material on bounded domains. We prove the convergence of the approximate solutions constructed using the Roe scheme with dimensional splitting, where the major challenge lies in the treatment of the discontinuity occurring in the flux function. Numerical tests show a good agreement with microscopic simulations.

### 8.3 Mean Field Games

**Participants:** Abderrahmane Habbal, Amal Machtalay (*U Mohamed VI Polytech, Morocco*)(UM6P), Imad Kissami (*UM6P*), Ahmed Ratnani (*UM6P*), Meryeme Jahid (*UM6P*), Lahcen Maniar (*Univ. Cadi Ayyad, Marrakech, Morocco*), S.E. Chorfi (*Univ. Cadi Ayyad, Marrakech, Morocco*).

- **Two-class Traffic Flows:** We have explored a multi-class traffic model and examined the computational feasibility of mean-field games (MFG) in obtaining approximate Nash equilibria for traffic flow games involving a large number of players. We introduced a two-class traffic mean-field game framework, building upon classical multi-class formulations. To facilitate our analysis, we employed various numerical techniques, including high-performance computing and regularization of LGMRES solvers. By utilizing these tools, we conducted simulations at significantly larger spatial and temporal scales.

We led extensive numerical experiments considering three different scenarios involving cars and trucks, as well as three different cost functionals. Our results primarily focused on the dynamics of autonomous vehicles (AVs) in traffic, yielding results which support the effectiveness of the approach.

Moreover, we conducted original comparisons between macroscopic Nash mean-field speeds and their microscopic counterparts. These comparisons allowed us to computationally validate the  $\epsilon$ -Nash approximation, demonstrating a slightly improved convergence rate compared to theoretical expectations.

Future directions encompass second order traffic models, the multi-lane case, particularly prone to non-cooperative game considerations, and addressing some theoretical issues, see [33].

- **Degenerate mean-Field Game Systems:** We investigate inverse backward-in-time problems for a class of second-order degenerate Mean-Field Game (MFG) systems.

More precisely, given the final datum at time  $t = T$  of a solution to the one-dimensional mean-field game system with a degenerate diffusion coefficient, we aim to determine the intermediate states, at some  $t = t_0$  for any  $0 \leq t_0 < T$ , i.e., the value function and the mean distribution at intermediate times, respectively.

We prove conditional stability estimates under suitable assumptions on the diffusion coefficient and the initial state  $t = 0$ . The proofs are based on Carleman's estimates with a simple weight function. We first prove a Carleman estimate for the Hamilton-Jacobi-Bellman (HJB) equation. A second Carleman

estimate will be derived for the Fokker-Planck (FP) equation. Then, by combining the two estimates, we obtain a Carleman estimate for the mean-field game system, leading to the stability of the backward problems [25].

## 8.4 Fluid-structure interaction using isogeometric analysis

**Participants:** Régis Duvigneau.

The isogeometric analysis framework is used to develop an accurate numerical scheme for fluid-structure interaction problems, by using a mixed continuous / discontinuous Galerkin scheme [45]. The properties of NURBS basis functions are leveraged to enable an exact transfer of the structural displacement to the fluid domain, while using different discretizations and refinements on the two sides of the coupling interface [50]. The proposed approach is validated by the simulation of a compressible flow around an elastic wing membrane and the classical fluid-structure benchmark proposed by Turek & Hron, involving the flow around a cylinder equipped with a hyperelastic bar, demonstrating the interest of high-order treatment of the coupling interface.

## 8.5 Physics-informed neural networks

**Participants:** Mickaël Binois, Régis Duvigneau, Laurent Monasse, Mathilde Pascal, Nathan Ricard, Marion Vidal.

We investigate the use of the novel Physics-Informed Neural Networks (PINNs) paradigm in the context of complex PDE/ODE systems, including the following research axes:

- **Multi-objective learning for physics-informed neural networks**

It was observed that PINNs suffer from the difficulty to minimize simultaneously the loss function reflecting the physical principles (ODEs or PDEs) and the one fitting the data (boundary conditions and observations). To overcome this difficulty, we investigated the use of multi-objective strategies for PINN learning, based on game theory and multi-criteria descent algorithms [44, 59]. In particular, we aim at accounting for the conflicts in the gradient directions and amplitudes to define an efficient learning strategy. This work is achieved in the framework of N. Ricard's PhD thesis.

- **Physics-informed neural networks for shock fitting**

To overcome the limitation of PINNs in describing discontinuous solutions, we investigated a shock-fitting formulation, in which a set of neural networks are used to represent the solution fields in the continuous regions, coupled with another network that defines the discontinuity characteristics. All of them are trained using physical principles, either PDEs or Rankine-Hugoniot conditions. This approach is investigated for Burgers equation [56], revealing a real potential for the design of a parametric shock fitting method for shock waves.

- **Physics-informed neural networks for gene dynamics identification**

We also experimented the PINN formulation in a biology context. To defend themselves against biotic threats, plants rely on a complex network of signaling pathways that regulate immune responses. Understanding the dynamic modulation of these defense mechanisms is therefore crucial for advancing research in plant immunity and improving crop resilience. In this context, we employed PINNs to model gene expression dynamics in plants exposed to biotic stress, on the basis of first-order linear ordinary differential equations, whose coefficients are calibrated using experiments during the learning phase [57]. Results were encouraging and underlined the necessity to work with larger databases and account for gene interactions.

## 8.6 Including additional information in Gaussian process based surrogates

**Participants:** Mickaël Binois, Anna Flowers (*Virginia Tech, USA*), Christopher Franck (*Virginia Tech, USA*), Robert Gramacy (*Virginia Tech, USA*), Paola Goatin, Ross Hammond (*Washington University in Saint-Louis*), Chiwoo Park (*University of Washington*), Alexandra Würth (*Fraunhofer Institute, Germany*).

### Modeling output discontinuities

Gaussian processes (GPs) furnish accurate nonlinear predictions with well-calibrated uncertainty. However, the typical GP setup has a built-in stationarity assumption, making it ill-suited for modeling data from processes with sudden changes, or "jumps" in the output variable. The "jump GP" (JGP) was developed for modeling data from such processes, combining local GPs and latent "level" variables under a joint inferential framework. But joint modeling can be fraught with difficulty. In [52] we aim to simplify by suggesting a more modular setup, eschewing joint inference but retaining the main JGP themes: (a) learning optimal neighborhood sizes that locally respect manifolds of discontinuity; and (b) a new cluster-based (latent) feature to capture regions of distinct output levels on both sides of the manifold. We show that each of (a) and (b) separately leads to dramatic improvements when modeling processes with jumps. In tandem (but without requiring joint inference) that benefit is compounded, as illustrated on real and synthetic benchmark examples from the recent literature.

### Physics-informed modeling

In [38], we propose a physics informed statistical framework for traffic travel time prediction. This combined approach has the merit to address the shortcomings of the purely model-driven or data-driven approaches, while leveraging their respective advantages. Indeed, models are based on physical laws, but cannot capture all the complexity of real phenomena. Plus they are rarely used for prediction since this requires future data such as boundary conditions. On the other hand, pure statistical outputs can violate basic characteristic dynamics in their prediction and do not reconstruct traffic conditions. Here, on one side, the discrepancy of the considered mathematical model with real data is represented by a Gaussian process. On the other side, the traffic simulator is fed with boundary data predicted by a Gaussian process, forced to satisfy the mathematical equations at virtual points, resulting in a multi-objective optimization problem. We validate our approach on both synthetic and real world data, showing that it delivers more reliable results compared to other methods.

## 8.7 Advanced Bayesian optimization

**Participants:** Ayoub Bellouch (*Atlantis team*), Luca Berti (*IRMA, Institut de Recherche Mathématique Avancée*), Mickaël Binois, Nicholson Collier (*Argonne, USA*), Régis Duvinneau, Arindam Fadikar (*Argonne, USA*), Roman Garnett (*Washington University in Saint-Louis*), Laëtitia Giraldi (*Calisto team*), Ross Hammond (*Washington University in Saint-Louis*), Cliff Kerr (*Bill and Melinda Gates foundation*), Daniel Klein (*Bill and Melinda Gates foundation*), Stéphane Lanteri (*Atlantis team*), Jeffrey Larson (*Argonne, USA*), David O’Gara (*Washington University in Saint-Louis*), Jonathan Ozik (*Argonne, USA*), Lucas Palazzolo (*Calisto team*), Abby Stevens (*Argonne, USA*).

- **Handling of noisy simulators**

To reduce the number of call to epidemiology simulators, we show in [35] that heteroscedastic Gaussian process modeling can greatly help. It shows a significant reduction of the number of simulations required to calibrate the parameters of a Covid-19 simulator. A Python version of the corresponding Gaussian process regression code is provided with `hetGPy` [34].

Bayesian optimization (BO) is a powerful framework for estimating parameters of computationally expensive simulation models, particularly in settings where the likelihood is intractable and evaluations are costly. In stochastic models every simulation is run with a specific parameter set and an implicit or explicit random seed, where each parameter set and random seed combination generates an individual realization, or trajectory, sampled from an underlying random process. Existing BO approaches typically rely on summary statistics over the realizations, such as means, medians, or quantiles, potentially limiting their effectiveness when trajectory-level information is desired. In [51] we propose a trajectory-oriented Bayesian optimization method that incorporates a Gaussian process (GP) surrogate using both input parameters and random seeds as inputs, enabling direct inference at the trajectory level. Using a common random number (CRN) approach, we define a surrogate-based likelihood over trajectories and introduce an adaptive Thompson Sampling algorithm that refines a fixed-size input grid through likelihood-based filtering and Metropolis-Hastings-based densification. This approach concentrates computation on statistically promising regions of the input space while balancing exploration and exploitation. We apply the method to stochastic epidemic models, a simple compartmental and a more computationally demanding agent-based model, demonstrating improved sampling efficiency and faster identification of data-consistent trajectories relative to parameter-only inference.

Concerning optimization, in [47] we develop and analyze a method for stochastic simulation optimization relying on Gaussian process models within a trust-region framework. We are interested in the case when the variance of the objective function is large. We propose to rely on replication and local modeling to cope with this high-throughput regime, where the number of evaluations may become large to get accurate results while still keeping good performance. We propose several schemes to encourage replication, from the choice of the acquisition function to setup evaluation costs. Compared with existing methods, our results indicate good scaling, in terms of both accuracy (several orders of magnitude better than existing methods) and speed (taking into account evaluation costs).

- **Bayesian optimization of micro-swimmers**

In [37], we are interested in understanding and optimizing the design of helical micro-swimmers. This is crucial for advancing their application in various fields. This study presents an innovative approach combining Free-Form Deformation with Bayesian Optimization to enhance the shape of these swimmers. Our method facilitates the computation of generic swimmer shapes that achieve optimal average speed and efficiency. Applied to both monoflagellated and biflagellated swimmers, our optimization framework has led to the identification of new optimal shapes. These shapes are compared with biological counterparts, highlighting a diverse range of swimmers, including both pushers and pullers.

Then in [55] we consider optimizing controls for such micro-swimmers. Unlike macroscopic swimmers, microswimmers operate in a low-Reynolds-number regime dominated by viscous forces. This paper investigates the controllability of a magnetic microswimmer composed of a spherical magnetic head and an elastic, non-magnetic flagellum. The swimmer evolves in a Stokes flow and is modeled using the resistive force theory. We prove that, under planar motion, the system is not small-time locally controllable and numerically identify regions that remain inaccessible. Nevertheless, simulations show that trajectory tracking can still be achieved via Bayesian optimization, though it requires large-amplitude transverse deformations. This work was also presented during the SAMO conference (International Conference on Sensitivity Analysis of Model Output) [58].

- **Massively parallel Bayesian optimization**

Motivated by a large scale multi-objective optimization problem for which thousands of evaluations can be conducted in parallel, we develop an efficient approach to tackle this issue in [24].

One way to reduce the time of conducting optimization studies is to evaluate designs in parallel rather than just one-at-a-time. For expensive-to-evaluate black-boxes, batch versions of Bayesian optimization have been proposed. They work by building a surrogate model of the black-box that can be used to select the designs to evaluate efficiently via an infill criterion. Still, with higher levels of parallelization becoming available, the strategies that work for a few tens of parallel evaluations become limiting, in particular due to the complexity of selecting more evaluations. It is even more

crucial when the black-box is noisy, necessitating more evaluations as well as repeating experiments. Here we propose a scalable strategy that can keep up with massive batching natively, focused on the exploration/exploitation trade-off and a portfolio allocation. We compare the approach with related methods on deterministic and noisy functions, for mono- and multi-objective optimization tasks. These experiments show similar or better performance than existing methods, while being orders of magnitude faster.

- **Multi-fidelity modeling and optimization**

To reduce the computational cost related to the use of high-fidelity simulations when evaluating the cost function, we investigate the construction of multi-fidelity Gaussian Process models, that can rely on different physical models (e.g. inviscid or viscous flows) or numerical accuracy (e.g. coarse or fine meshes). The objective is to construct a model that is accurate regarding the high-fidelity evaluations, but mostly based on low-fidelity simulations. In the context of design optimization, we especially investigate the use of a multi-task entropy search approach, with applications to aerodynamics and nano-photonics (in collaboration with the Atlantis team). Results have been presented in [40].

- **Multi-objective Bayesian optimization with decoupled objectives**

In [41] we look at the experimental design for multi-objective problems, where the objectives can be evaluated independently (decoupled) and thus it may make sense to evaluate different solutions for each objective if the objectives have different evaluation costs and/or different landscape characteristics. We propose to iteratively add design points in a way that minimizes the total integrated mean squared prediction error assuming a Gaussian process response surface model, and show that allowing decoupled evaluations can lead to significantly better Pareto front estimations than a coupled design of experiments if the evaluation costs of the objectives are different. We also find that our approach of minimizing mean squared prediction error yields significantly better results than standard Latin Hypercube designs even if the evaluation costs and landscape characteristics of the objectives are the same.

## 8.8 Pareto optimality and Nash games

**Participants:** Jean-Antoine Désidéri, Mickaël Binois, Nathalie Bartoli (*ONERA/DTIS, Université de Toulouse*), Christophe David (*ONERA/DTIS, Université de Toulouse*), Sébastien Defoort (*ONERA/DTIS, Université de Toulouse*), Julien Wintz (*SED, Inria Sophia Antipolis*).

In the multi-objective optimization of a complex system, establishing the Pareto front associated with the whole set of cost functions is usually a computationally demanding task, whose results are not always easy to analyze, while the final decision still remains to be made among Pareto-optimal solutions. These observations led us to propose a prioritized approach in which the Pareto front is calculated only for a subset of primary cost functions, those of preponderant importance, followed by an economical and decisive step in which a continuum of Nash equilibria accounting for secondary functions is calculated [8].

The method has been applied to the multi-objective optimization of the flight performance of an Airbus-A320-type aircraft in terms of take-off fuel mass and operational empty weight (primary cost functions) concurrently with ascent-to-cruise altitude duration (secondary) [12]. These results have been presented at a Conference on “New Greener and Digital Modern Transport” (JyU., Finland, May 2023), and recently completed by Bayesian optimization in [13] and are currently in press for proceedings.

That work reflects our cooperation with the Information Processing and Systems Department (DTIS) of Onera Toulouse. It will be continued to account for additional criteria related to environmental impact and operational performance.

In the present prioritized approach for multiobjective optimization, after a first phase of optimization has produced a Primary Pareto Front relative to the sole primary cost functions (under functional constraints), considered to be preponderant, a second phase of optimization is initiated to yield a continuum of Nash equilibria of quasi-Pareto-optimal solutions with respect to the whole set of objective functions (primary and secondary). This second phase relies on an orthogonal decomposition of the working space, a subset of  $\mathbf{R}^N$ , referred to as “territory splitting”.

We have generalized the original method [8] by relaxing the convergence condition on the construction of the territory splitting to isolate the affine subspace locally tangent to the constraints, proposed several alternatives, and tested their efficacy on a testcase of optimal sizing of an aluminum sandwich panel [49].

A publication agreement has been established between the Society for Industrial and Applied Mathematics (SIAM) and Jean-Antoine Désidéri for a book entitled "Multiobjective of Smooth Functionals - Application to Aeronautics" (Series: Advances in Design and Control).

## 8.9 Inverse Problems solved as Nash games

**Participants:** Abderrahmane Habbal, Marwa Ouni (*U. Tunis al Manar, Tunisia*).

- **Nash games for shape and boundary identification of nonlinear PDEs.** We investigate nonlinear Cauchy-type problems arising in quasi-Newtonian Stokes flows, where the viscosity exhibits a nonlinear dependence on the deformation tensor, modeled by the Carreau law. To tackle the inherent ill-posedness of the Cauchy-Stokes problem, we propose three iterative methods, each reformulating the original problem into a sequence of well-posed mixed boundary value problems (BVPs). A classical control framework is employed to construct a control-type algorithm for the nonlinear inverse problem. Then, we introduce two novel algorithms based on a Nash game formulation; the second algorithm enables each player to linearize the adverse state equations, enhancing computational efficiency and convergence. We further extend this linearized Nash approach to simultaneously recover missing boundary data and identify the location and shape of unknown inclusions. Finite element simulations validate the robustness and effectiveness of the proposed methods [36].

## 8.10 Optimal transport and isogeometric analysis

**Participants:** Abderrahmane Habbal, Mustapha Bahari (*U Mohamed VI Polytech, Morocco, UM6P*), Ahmed Ratnani (*UM6P*), Eric Sonnendrücker (*Max Planck Institute*).

Optimal Transport for adaptive isogeometric analysis. Optimal transport offers a powerful mathematical framework for redistributing geometric or computational resources in adaptive isogeometric analysis (IGA). By treating mesh refinement as a mass-transport problem, optimal transport maps allow to smoothly reposition control points or redistribute quadrature/parameterization density according to error indicators. This leads to adaptive refinements that preserve geometric fidelity, avoid mesh distortion, and maintain the smoothness inherent to IGA bases. As a result, optimal-transport-driven adaptivity provides a principled, variational way to enhance accuracy while controlling computational cost.

- **Image Registration and Segmentation Using IGA with Optimal Transport.** We have developed a novel fast and high order method for the problem of Image Registration, using Optimal Transport and the Isogeometric Analysis paradigm. Our method is based on the resolution of the Monge-Ampère equation and ensures the one-to-one property. In addition, the use of B-Splines allows to create a map that can be evaluated everywhere, and reduces the number of degrees of freedom needed to store the constructed (gradient) map, by using e.g. high order B-Splines functions [39].

## 8.11 Shock fitting with cut cell methods

**Participants:** Laurent Monasse, Alexandre Vieira, Régis Duvigneau, Mirco Ciallolla (*Université Paris Cité*).

Compressible fluids develop shocks in finite time and transport initial material discontinuities. Accurately tracking these discontinuities in the fluid state is numerically challenging and can lead to numerical smearing

of discontinuities and loss of accuracy. This is especially difficult for discontinuities in material density and behavior laws. Instead of discontinuity capturing methods, we have proposed to use discontinuity tracking methods by following material discontinuities in a Lagrangian way. In order to enable wave interaction and topology changes, we combine discontinuity tracking with cut cell methods. We have extended the classical Finite Volume framework to Discontinuous Galerkin methods with ADER time-integration in space-time.

## 8.12 Fungal growth modeling and simulation

**Participants:** Laurent Monasse, Yves D’Angelo (*Université Côte d’Azur*), Rémi Catellier (*Université Côte d’Azur*), Claire Guerrier (*Université Côte d’Azur*), Nicolas Fricker (*Université Côte d’Azur*).

Fungi develop growing networks in the form of mycelium which explore space by branching at the tips (apex branching) and on the existing network (lateral branching). We have studied fungal growth at two scales: a large scale (of the order of the Petri dish) where the behavior of the fungus is homogenized, and a small scale (of the order of the fungus cell) in order to understand the underlying biochemical phenomena at hand in growth and branching. On the large scale, we have proposed a new partial differential equation (PDE) model for the dynamics of growth. We have computed front propagation velocities and proposed numerical schemes to approximate the solution in space and time of the PDE. The work is in its final process to submission. On the other hand, on the small scale, we have proposed a biologically informed model of filament growth. We have developed a fast and accurate numerical scheme accounting for the absorption of nutrients, their conversion to vesicles and the transport of vesicles in the cell, inducing the growth of the filament. The model is in the process of fitting unknown parameters to experimental biological data.

## 9 Bilateral contracts and grants with industry

### 9.1 Bilateral contracts with industry

- Consortium CIROQUO - Consortium Industrie Recherche pour l’Optimisation et la QUantification d’incertitude pour les données Onéreuses - gathers academical and technological partners to work on problems related to the exploitation of numerical simulators. This Consortium, created in January 2021, is the continuation of the projects DICE, ReDICE and OQUAIDO which respectively covered the periods 2006-2009, 2011-2015 and 2015-2020. CIROQUO continued from 2025 as CIROQUO 2 with new industrial partners such as EDF or Michelin [ciroquo.ec-lyon.fr](http://ciroquo.ec-lyon.fr).

**Participants:** Mickaël Binois, Régis Duvigneau.

- **IFPEN** (2022-2025): this research contract financed the PhD thesis of Agatha Joumaa on “A multi-mode macroscopic traffic model for the improvement of mobility and air quality in our cities via optimal modal share and routing”.

**Participants:** Paola Goatin, Agatha Joumaa.

- **Altair** (2024-2026): these research contracts involving AMIES and PUI Med’Innov finance the post-doctoral contract of Alexandre Vieira. The goal is to develop compressible multimaterial flow simulation using cut-cell methods in the open-source code **OpenRadioss**, in two and three space dimensions, first with Lagrangian interface tracking, then with a level-set description.

**Participants:** Laurent Monasse, Alexandre Vieira.

## 10 Partnerships and cooperations

### 10.1 International research visitors

#### 10.1.1 Visits of international scientists

##### Angelika Hirrle

**Status** researcher

**Institution of origin:** Dresden University of Technology

**Country:** Germany

**Dates:** 01/03/25-31/05/25

**Context of the visit:** research visit for collaboration on macroscopic traffic flow modeling

**Mobility program/type of mobility:** research stay

##### Anna Macaluso

**Status** PhD student

**Institution of origin:** University of Parma

**Country:** Italy

**Dates:** 06/10/25-19/12/25

**Context of the visit:** collaboration on multi-class kinetic traffic models

**Mobility program/type of mobility:** research stay

##### Stefan Moreti

**Status** PhD student

**Institution of origin:** University of Trento

**Country:** Italy

**Dates:** 02/03/2025-30/06/2025

**Context of the visit:** collaboration on conservation laws with hysteresis

**Mobility program/type of mobility:** research stay

##### Faezeh Yazdi

**Status** Post-Doc

**Institution of origin:** Simon Fraser University

**Country:** Canada

**Dates:** 01/09/25-31/10/25

**Context of the visit:** **High-Level Scientific Fellowship** project entitled “Active Learning using Deep Gaussian Processes for High Dimensional Computer Experiments”

**Mobility program/type of mobility:** research stay

## 10.2 European initiatives

### 10.2.1 Horizon Europe

**DATAHYKING** [DATAHYKING project on cordis.europa.eu](https://cordis.europa.eu/project/309204441)

**Title:** Data-driven simulation, uncertainty quantification and optimization for hyperbolic and kinetic models

**Duration:** From March 1, 2023 to September 30, 2027

**Partners:**

- TRANSPORT & MOBILITY LEUVEN (TML), Belgium
- INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET AUTOMATIQUE (INRIA), France
- ASML NETHERLANDS B.V., Netherlands
- UNIVERSITE COTE D'AZUR, France
- RHEINISCH-WESTFAELISCHE TECHNISCHE HOCHSCHULE AACHEN (RWTH AACHEN), Germany
- KEYSIGHT TECHNOLOGIES FRANCE S.A.S. (KEYSIGHT TECHNOLOGIES FRANCE), France
- Cassa di Compensazione e Garanzia s.p.a. (CC&G), Italy
- STUDIECENTRUM VOOR KERNENERGIE / CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE (SCK CEN), Belgium
- NEOVYA Mobility by Technology (NEOVYA Mobility by Technology), France
- INCICO (INICIO SPA), Italy
- SIEMENS INDUSTRY SOFTWARE NETHERLANDS BV (Siemens Industry Software Netherlands B.V.), Netherlands
- RHEINLAND-PFALZISCHE TECHNISCHE UNIVERSITAT, Germany
- CENTRE DE RECHERCHE EN AERONAUTIQUE ASBL - CENAERO (CENAERO), Belgium
- UNIVERSITE DE LILLE (UNIVERSITE DE LILLE), France
- ZENSOR (ZENSOR), Belgium
- KATHOLIEKE UNIVERSITEIT LEUVEN (KU Leuven), Belgium
- GFM GmbH (GFM GmbH), Austria
- UNIVERSITA DEGLI STUDI DI ROMA LA SAPIENZA (UNIROMA1), Italy
- UNIVERSITA DEGLI STUDI DI FERRARA (Unife), Italy

**Inria contact:** Paola Goatin

**Coordinator:** Giovanni Samaey (KU Leuven)

**Summary:** Europe faces major challenges in science, society and industry, induced by the complexity of our dynamically evolving world. To tackle these challenges, mathematical models and computer simulations are indispensable, for instance to design and optimize systems using virtual prototypes. Moreover, while the big data revolution provides additional possibilities, it is currently unclear how to optimally combine simulation results with observation data into a digital. Many systems of interest consist of large numbers of particles with highly non-trivial interaction (e.g., fine dust in pollution, vehicles in mobility).

However, to date, computer simulation of such systems is usually done with highly approximate (macroscopic) models to reduce computational complexity. Facing these challenges without sacrificing the complexity of the underlying particle interactions requires a fundamentally new type of scientist that uses an interdisciplinary approach and a solid mathematical underpinning. Hence, we aim at

training a new generation of modeling and simulation experts to develop virtual experimentation tools and workflows that can reliably and efficiently exploit the potential of mathematical modeling and simulation of interacting particle systems.

To this end, we create a data-driven simulation framework for kinetic models of interacting particle systems, and define a common methodology for these future modeling and simulation experts. The network focuses on (i) reliable and efficient simulation; (ii) robust consensus-based optimization, also for machine learning; (iii) multifidelity methods for uncertainty quantification and Bayesian inference; and (iv) applications in fluid flow, traffic flow, and finance, also in collaboration with industry. Moreover, the proposed EJD program will create a closely connected new generation of highly demanded European scientists, and initiate long-term partnerships to exploit synergy between academic and industrial partners.

## 10.3 National initiatives

### 10.3.1 ANR

- **COSS - Control on Stratified Structures** (ANR-22-CE40-0010, PI Nicolas Forcadel, INSA Rouen): The central theme of this project lies in the area of control theory and partial differential equations (in particular Hamilton-Jacobi equations), posed on stratified structures and networks. These equations appear very naturally in several applications. Indeed, many practical optimal control problems, such as traffic flow modeling or energy management in smart-grids networks or sea-land trajectories with different dynamics, involve a state space in a stratified form (a collection of manifolds with different dimensions and associated to different dynamics). These control problems can be studied within the framework of Hamilton Jacobi equations theory; in particular, they involve admissible trajectories that have to stay in the stratified domain.

**Participants:** Paola Goatin.

- **NEMATIC - Analysis Modelling Simulation Multiscale** (ANR-21-CE45-0010, PI Eric Herbert, LIED, Université de Paris): The objective of the project is to experimentally characterize, analyze, model and simulate the multiscale dynamics of complex and growing branching random networks. Both analytical and numerical means as well as experimental realizations are used and developed. In a biological context, the growth of the filamentous fungus *Podospora anserina* will be used as a model, by systematically comparing modeling and experiments. The project brings together biologists, who are specialists in this field, as well as physicists and mathematicians in charge of acquiring and analyzing experimental data and designing the models as well as simulations. On the one hand, we plan to develop the numerical reconstruction of the network, by transforming the raw experimental data into a spatio-temporal graph, the dynamics of which will be included in an efficient labelling of the temporal evolution of the nodes, capable of interpreting anastomosis and branching, and thus of following through time and space a node of the network. By varying the type of constraints applied during model validation, we expect a fine-grained understanding of emergent processes (such as branching) and resilience. NEMATIC aims to provide the scientific community with the experimental, theoretical and numerical data and tools necessary for such analyses.

**Participants:** Laurent Monasse, Nicolas Fricker.

- **NEMO - ControlliNg a magnEtic Micro-swimmer in a cOnfined area** (ANR-21-CE45-0013, PI Laetitia Giraldi, EPI CALISTO, Inria): NEMO aims to develop numerical methods to control a micro-robot swimmer in the arteries of the human body. These robots could deliver drugs specifically to cancer cells before they form new tumors, thus avoiding metastasis and the traditional chemotherapy side effects. NEMO will focus on micro-robots, called MagnetoZoons, composed of a magnetic head

and an elastic tail immersed into a laminar fluid possibly non-Newtonian. These robots imitate the propulsion of spermatozoa by propagating a wave along their tail. Their movement is controlled by an external magnetic field that produces a torque on the head of the robot, producing a deformation of the tail. The tail then pushes the surrounding fluid and the robot moves forward. The advantage of such a deformable swimmer is its aptness to carry out a large set of swimming strategies, which could be selected according to the geometry or the rheology of the biological media where the swimmer evolves (blood, eye retina, or other body tissues). Although the control of a such micro-robots has mostly focused on simple unconfined environment, the main challenge is today to design external magnetic fields that allow them to navigate efficiently in complex realistic environments. NEMO aims to elaborate efficient controls, which will be designed by tuning the external magnetic field, through a combination of Bayesian optimization and accurate simulations of the swimmer's dynamics with Newtonian or non-Newtonian fluids. Then, the resulting magnetic fields will be validated experimentally in a range of confined environments. In such an intricate situation, where the surrounding fluids is bounded laminar and possibly non-Newtonian, optimization of a strongly nonlinear, and possibly chaotic, high-dimensional dynamical system will lead to new paradigms. The results of NEMO will be the subject of several publications in mathematical modeling, numerical analysis, optimization, control, physics and multidisciplinary journals. The numerical developments will be provided as open-source softwares. The experiments will contribute as a proof of concept validating the NEMO control approach.

**Participants:** Mickaël Binois, Laurent Monasse.

- **FREEFORM - Refinable Freeform Splines with Theoretical Guarantees for their Approximation Power via Polynomial Reproduction** (ANR-24-CE91-0001, PI Angelos Mantzaflaris, EPI AROMATH, Inria). This project started in 2024 and aims at the development of a novel framework for high-order discretization of partial differential equations on general domains. The latter pose challenges related to their topology and in particular at the vicinity of, so called, extraordinary vertices where smoothness requirements and superior approximation power are paramount for efficient simulations. We propose a framework of geometrically continuous splines called RFF-Splines (Refinable FreeForm Splines) that shall enable numerical schemes for topologically unrestricted design and analysis.

**Participants:** Régis Duvigneau.

## 11 Dissemination

### 11.1 Promoting scientific activities

#### 11.1.1 Scientific events: organization

##### General chair, scientific chair

- **MT-ITS 2025** “9th International Conference on Models and Technologies for Intelligent Transportation Systems”, Luxembourg, September 2025 (Paola Goatin member of the scientific committee).

##### Member of the organizing committees

- Workshop “*Round Meanfield IV: N-body sul Canal Grande*”, Venice (Italy), September 2025 (Paola Goatin member of the organizing committee).
- **POPULATE - Thematic Semester on “Population Dynamics”**, Nice (France), 2025 (Paola Goatin and Abderrahmane Habbal members of the organizing committee)

### 11.1.2 Scientific events: selection

#### Reviewer

- Mickael Binois reviewed for the following international conferences: AISTATS 2026, ICML 2025, NeurIPS 2025, ICLR 2026, and GECCO 2025.

### 11.1.3 Journal

#### Member of the editorial boards

- Mickael Binois is Associate Editor of [ACM Transactions on Evolutionary Learning and Optimization](#).
- Paola Goatin is Associate Editor of [Mathematical Modelling and Numerical Analysis - ESAIM: M2AN](#) (since 2022) and Associate Editor of [SIAM Journal on Applied Mathematics](#) (since 2020).

#### Reviewer - reviewing activities

- Mickael Binois is reviewer for the following journals: ACM Trans. Evol. Learn., Comput. Optim. Appl., European J. Oper. Res, Inform. J. Comput., J. Mater. Sci, Knowl.-Based Syst., Oper. Res., Optim. Eng., Technometrics, Sci. Rep., Transact Mach Learn Res.
- Régis Duvigneau is reviewer for the following journals: J. of Computational Physics, Computers & Fluids.
- Paola Goatin reviewed for the following journals: Communications in Mathematical Sciences; ESAIM: Control, Optimisation and Calculus of Variations; Journal of Mathematical Analysis and Applications; Mathematics and Computational Sciences.
- Abderrahmane Habbal reviewed for the following journals: Boletín de la Sociedad Matemática Mexicana, Journal of Optimization Theory and Applications, ARIMA.
- Laurent Monasse reviewed for the following journals: Journal of Scientific Computing, ESAIM: Mathematical Modelling and Numerical Analysis.

### 11.1.4 Invited talks

- Mickael Binois: Dagstuhl seminar on Bayesian optimization, Dagstuhl, Germany (November 2025).  
Talk: Possible snags in benchmarking noisy or high-dimensional BO.
- Régis Duvigneau : CEA-DAM, Bruyère-Le-Chatel, February 2025 France.  
Talk: Simulation of compressible flows using NURBS meshes.
- Paola Goatin: Workshop: “HyPNuT: Hyperbolic Problems - Numerics and Theory”, Amiens (France).  
Invited talk: *Nonlocal macroscopic models of multi-population pedestrian flows for walking facilities optimization*.
- Paola Goatin: ECC 2025 - European Control Conference, Thessaloniki (Greece), June 2025  
Invited session: “Novel Methods for Modeling and Control of Mobility and Traffic Systems”.  
Talk: *Traffic Flow Stabilization Using a Single Controlled Vehicle*.
- Paola Goatin: Workshop : “Hydrodynamic limits of interacting agent systems”, Venice (Italy), June 2025.  
Invited talk: *Nonlocal macroscopic models of multi-population pedestrian flows for walking facilities optimization*.
- Paola Goatin: Hyperbolic PDEs: Theorems and Applications - A Conference in honour of R.M. Colombo’s 60th birthday, Varese (Italy), May 2025.  
Invited talk: *Models and controls for mixed autonomy traffic*.

- Paola Goatin: MLPDES25 - Workshop on Machine Learning and PDEs , Erlangen (Germany), April 2025. Invited talk: *Modern calibration strategies for macroscopic traffic flow models*.
- Abderrahmane Habbal : Workshop Round Meanfield IV: N-body sul Canal Grande, Venice (Italy), September 2025.  
Invited talk: *A game theoretic viewpoint on boundary data recovery coupled to shape identification problems*
- Abderrahmane Habbal : Numerical Analysis and Applications to Data Science - N2ADS 2025 April 7-8 2025 N.K.U. Athens, Greece.  
Invited talk: *Boundary data recovery and shape identification for Stokes problems, a coupled inverse problem solved as a PDE-constrained game*
- Laurent Monasse : Seminar of the LMA lab, Marseille, France, Feb. 4, 2025.  
Talk: *Cut-cell methods for discontinuity fitting*.

### 11.1.5 Scientific expertise

- Régis Duvigneau was member of the expert panel for the HCERES evaluation of DTIS department at Onera.
- Paola Goatin was external reviewer for an ERC grant.

### 11.1.6 Research administration

- Paola Goatin is member of the organizing committee of Colloquium Jacques Morgenstern , Inria Centre at Université Côte d'Azur (2023-present).
- Paola Goatin is member of the board of the Doctoral School of Fundamental and Applied Sciences (ED SFA) of Université Côte D'Azur (2018-present).
- Paola Goatin was president of the local selection committee for Inria Nancy Grand Est competitive selection of young graduate scientists (CRCN-ISFP).
- Laurent Monasse is head of the Committee of Technology Development (CDT) for Inria Centre at Université Côte d'Azur.
- Régis Duvigneau is head of the Scientific Committee of Platforms for Inria Centre at Université Côte d'Azur.
- Régis Duvigneau is member of the Scientific Committee of OPAL computing Platform at Université Côte d'Azur
- Régis Duvigneau is member of the Steering Committee of "Maison de la Simulation et Interactions" at Université Côte d'Azur.

## 11.2 Teaching - Supervision - Juries - Educational and pedagogical outreach

### 11.2.1 Teaching

- Mickael Binois:
  - Master1 Labs for the optimization lecture (24 hrs), at Université Côte d'Azur.
  - Master2 lecture on "Advanced Optimization" (9h), at Université Côte d'Azur.
  - XIX GRETSI Summer School on signal and image processing, Peyresq, France (2025). Course: "Gaussian process regression" and "Sequential learning: Bayesian optimization and related approaches".
- Régis Duvigneau:

- Master2 lecture on "Advanced Optimization" (21h), at Université Côte d'Azur.
- Abderrahmane Habbal:
  - Master1&2 introductory lecture and labs on optimization and stochastic approximation (20h, 2023-2025), Université Mohammed VI Polytechnique, Ben Guérir, Maroc.
  - Master Optimization, 18 hrs, M1, Polytech Nice Sophia - Univ. Côte d'Azur.
  - Master Numerical methods for PDEs, 18 hrs, M1, Polytech Nice Sophia - Université Côte d'Azur.
  - Master Optimization, 15 hrs, Mohammed VI Polytechnic Univ. Morocco.
  - Licence Semester Project on PSO, 48 hrs, Polytech Nice Sophia - Univ. Côte d'Azur.
  - Licence Semester Project on Mathematical model of addiction, 48 hrs, Polytech Nice Sophia - Univ. Côte d'Azur.
  - Master Stochastic Processes, 24 hrs, M1, Polytech Nice Sophia - Univ. Côte d'Azur.
- Laurent Monasse:
  - Master1 Numerical methods for PDEs, 10 hrs, Polytech Nice Sophia - Université Côte d'Azur.
  - Licence Mathematics for Engineers 2, 36 hrs, Polytech Nice Sophia - Université Côte d'Azur.

### 11.2.2 Supervision

- PhD defense: Agatha Joumaa, *Optimization of the environmental performance of urban mobility via macroscopic and multimodal modeling approaches*, Univ. Côte d'Azur/IPPEN, November 2025 [46]. Supervisors: Paola Goatin, Giovanni De Nunzio.
- PhD in progress: Nathan Ricard, *Physics informed neural networks for multidisciplinary design*, Université Côte d'Azur. Supervisors: Régis Duvigneau, Mickael Binois.
- PhD in progress: Lucas Palazzolo (Calisto), *Numerical methods for optimising the locomotion of flagellate microswimmers*, Université Côte d'Azur. Supervisors: Laetitia Giraldi (Calisto), Mickael Binois, Christophe Prudhomme (Université de Strasbourg).
- PhD in progress: Ugo Labbé (Michelin), *Modèles hybrides pour la simulation des procédés industriels*, École polytechnique. Supervisors: Josselin Garnier (Polytechnique), Mickael Binois, Amina Chorfi (Michelin), Mayra Hernandez (Michelin).
- PhD in progress: Ilaria Ciaramaglia, *Interactions between microscopic and macroscopic models for autonomous vehicles in human-driven environments*, Univ. Côte d'Azur and Univerità di Roma La Sapienza. Supervisors: Paola Goatin, Gabriella Puppo.
- PhD in progress: Carmen Mezquita Nieto, *Modeling and optimization of multi-modal transportation networks based on kinetic and hyperbolic equations*, Univ. Côte d'Azur and RPTU Kaiserslautern. Supervisors: Paola Goatin, Axel Klar.
- PhD in progress: Martin Fleurial, *Microscopic and macroscopic models for multilane and multispecies traffic flow*, Univ. Côte d'Azur and Univerità di Roma La Sapienza. Supervisors: Paola Goatin, Gabriella Puppo.
- PhD in progress: Eric Andoni, *Bayesian model calibration with uncertainty for traffic flow models*, Univ. Côte d'Azur and KU Leuven. Supervisors: Paola Goatin, Giovanni Samaey.
- PhD in progress: Amal Machtalay, *From mean-field games to agent based models (and back) through markov chain agregation*, Université Côte d'Azur and UM6P, Morocco. Supervisors : Abderrahmane Habbal, A. Ratnani (UM6P)
- PhD in progress: Nicolas Fricker, *Multi-scale modeling of voltage and ionic propagation in neurons: finding the rules of experience-driven neuronal encoding*, Université Côte d'Azur. Supervisors: Laurent Monasse, Claire Guerrier.

### 11.2.3 Juries

- Mickael Binois was member of the committee of David O’Gara’s PhD thesis: “*Faster, Higher, Stronger: Modern Methodologies for the Calibration, Exploration, and Utilization of Agent-Based Models*”, Washington University in Saint-Louis, USA, 13/08/25.
- Régis Duvigneau was reviewer of the PhD thesis of Kevin Ancourt entitled “*Analyse et mise en oeuvre d’une méthode de raffinement de maillage ciblé pour les écoulements fluides compressibles*”, defended in November 2025.
- Régis Duvigneau was reviewer of the PhD thesis of Mouad Elaarabi entitled “*Real time system identification and hybrid monitoring in thermo-stamping process using physics informed set neural networks*”, defended in December 2025.
- Paola Goatin was referee of A. Bouharguane’s Habilitation thesis “*Numerical analysis and simulation for some problems in fluid mechanics and biology*”, Université de Bordeaux, November 17th, 2025.
- Paola Goatin was member of the committee of N. Bedjaoui’s Habilitation thesis “*Etude de perturbations diffusives-dispersives de lois de conservation hyperboliques*”, Université de Picardie Jules Verne, December 8th, 2025.
- Laurent Monasse was reviewer of the PhD thesis of Killian Vuillemot “*Méthodes Éléments Finis non-conformes adaptées à la conception en temps réel de jumeaux numériques d’organes*”, Université de Montpellier, December 18th, 2025.

## 11.3 Popularization

### 11.3.1 Specific official responsibilities in science outreach structures

- Régis Duvigneau is member of the editorial committee of **Interstices**, online journal for popularization of computer science and mathematics
- Laurent Monasse is local correspondant of **Fondation Blaise Pascal** at Université Côte d’Azur.
- Régis Duvigneau : article "Quand le vent nous fait vibrer", Interstices, June 2025 [60].

### 11.3.2 Others science outreach relevant activities

Paola Goatin gave the talk “*Le trafic routier en équations*” at “Maths Club”, student seminar at Université Paris Cité, February 17th, 2025.

## 12 Scientific production

### 12.1 Major publications

- [1] A. Aggarwal, R. M. Colombo and P. Goatin. ‘Nonlocal systems of conservation laws in several space dimensions’. In: *SIAM Journal on Numerical Analysis* 52.2 (2015), pp. 963–983. URL: <https://hal.inria.fr/hal-01016784>.
- [2] B. Andreianov, P. Goatin and N. Seguin. ‘Finite volume schemes for locally constrained conservation laws’. In: *Numer. Math.* 115.4 (2010). With supplementary material available online, pp. 609–645.
- [3] S. Blandin and P. Goatin. ‘Well-posedness of a conservation law with non-local flux arising in traffic flow modeling’. In: *Numerische Mathematik* (2015). DOI: [10.1007/s00211-015-0717-6](https://doi.org/10.1007/s00211-015-0717-6). URL: <https://hal.inria.fr/hal-00954527>.
- [4] R. M. Colombo and P. Goatin. ‘A well posed conservation law with a variable unilateral constraint’. In: *J. Differential Equations* 234.2 (2007), pp. 654–675.
- [5] M. L. Delle Monache and P. Goatin. ‘Scalar conservation laws with moving constraints arising in traffic flow modeling: an existence result’. In: *J. Differential Equations* 257.11 (2014), pp. 4015–4029.

- [6] M. L. Delle Monache, J. Reilly, S. Samaranyake, W. Krichene, P. Goatin and A. Bayen. ‘A PDE-ODE model for a junction with ramp buffer’. In: *SIAM J. Appl. Math.* 74.1 (2014), pp. 22–39.
- [7] J.-A. Desideri and R. Duvigneau. ‘Parametric optimization of pulsating jets in unsteady flow by Multiple-Gradient Descent Algorithm (MGDA)’. In: *Numerical Methods for Differential Equations, Optimization, and Technological Problems, Modeling, Simulation and Optimization for Science and Technology*. 1st Jan. 2017. URL: <https://hal.inria.fr/hal-01414741>.
- [8] J.-A. Désidéri. ‘Adaptation by Nash games in gradient-based multi-objective/multi-disciplinary optimization’. In: JANO13 - Mathematical Control and Numerical Applications. Vol. 372. Springer Proceedings in Mathematics & Statistics Series. Khouribga, Morocco, 22nd Feb. 2021. URL: <https://hal.inria.fr/hal-03430972> (cit. on pp. 25, 26).
- [9] J.-A. Désidéri. ‘COOPERATION AND COMPETITION IN MULTIDISCIPLINARY OPTIMIZATION Application to the aero-structural aircraft wing shape optimization’. In: *Computational Optimization and Applications* 52.1 (2012), pp. 29–68. DOI: [10.1007/s10589-011-9395-1](https://doi.org/10.1007/s10589-011-9395-1). URL: <https://hal.inria.fr/hal-00645787>.
- [10] J.-A. Désidéri. ‘Multiple-gradient descent algorithm (MGDA) for multiobjective optimization / Algorithme de descente à gradients multiples pour l’optimisation multiobjectif’. In: *Comptes Rendus. Mathématique* Tome 350.Fascicule 5-6 (20th Mar. 2012), pp. 313–318. DOI: [10.1016/j.crma.2012.03.014](https://doi.org/10.1016/j.crma.2012.03.014). URL: <https://hal.inria.fr/hal-00768935>.
- [11] J.-A. Désidéri and R. Duvigneau. ‘Prioritized optimization by Nash games : towards an adaptive multi-objective strategy’. In: *ESAIM: Proceedings and Surveys* 71 (Aug. 2021), pp. 54–63. DOI: [10.1051/proc/202171106](https://doi.org/10.1051/proc/202171106). URL: <https://hal.inria.fr/hal-03430912>.
- [12] J.-A. Désidéri, J. Wintz, N. Bartoli, C. David and S. Defoort. *Combining Pareto Optimality with Nash Games in Multi-Objective Prioritized Optimization of an Aircraft Flight Performance*. RR-9490. Inria - Sophia Antipolis; Acumes, 17th Oct. 2022, p. 29. URL: <https://inria.hal.science/hal-03817789> (cit. on p. 25).
- [13] J.-A. Désidéri, J. Wintz, M. Binois, N. Bartoli, C. David and S. Defoort. ‘Prioritized multi-objective optimization of an aircraft flight performance based on Nash games from preponderant Pareto-optimal points’. In: CM3 Transport 2023 Conference. Jyväskylä, Finland, 2023. URL: <https://inria.hal.science/hal-04826712> (cit. on p. 25).
- [14] R. Duvigneau and P. Chandrashekar. ‘Kriging-based optimization applied to flow control’. In: *Int. J. for Numerical Methods in Fluids* 69.11 (2012), pp. 1701–1714.
- [15] A. Habbal and M. Kallel. ‘Neumann-Dirichlet Nash strategies for the solution of elliptic Cauchy problems’. In: *SIAM J. Control Optim.* 51.5 (2013), pp. 4066–4083.
- [16] M. Kallel, R. Aboulaich, A. Habbal and M. Moakher. ‘A Nash-game approach to joint image restoration and segmentation’. In: *Appl. Math. Model.* 38.11-12 (2014), pp. 3038–3053. DOI: [10.1016/j.apm.2013.11.034](https://doi.org/10.1016/j.apm.2013.11.034). URL: <http://dx.doi.org/10.1016/j.apm.2013.11.034>.
- [17] M. Martinelli and R. Duvigneau. ‘On the use of second-order derivative and metamodel-based Monte-Carlo for uncertainty estimation in aerodynamics’. In: *Computers and Fluids* 37.6 (2010).
- [18] Q. Mercier, F. Poirion and J.-A. Desideri. ‘A stochastic multiple gradient descent algorithm’. In: *European Journal of Operational Research* (31st May 2018), p. 10. DOI: [10.1016/j.ejor.2018.05.064](https://doi.org/10.1016/j.ejor.2018.05.064). URL: <https://hal.archives-ouvertes.fr/hal-01833165>.
- [19] S. Roy, A. Borzì and A. Habbal. ‘Pedestrian motion modelled by Fokker–Planck Nash games’. In: *Royal Society open science* 4.9 (2017), p. 170648.
- [20] G. Todarello, F. Vonck, S. Bourasseau, J. Peter and J.-A. Desideri. ‘Finite-volume goal-oriented mesh adaptation for aerodynamics using functional derivative with respect to nodal coordinates’. In: *Journal of Computational Physics* 313 (15th May 2016), p. 21. DOI: [10.1016/j.jcp.2016.02.063](https://doi.org/10.1016/j.jcp.2016.02.063). URL: <https://hal.inria.fr/hal-01410153>.
- [21] M. Twarogowska, P. Goatin and R. Duvigneau. ‘Macroscopic modeling and simulations of room evacuation’. In: *Appl. Math. Model.* 38.24 (2014), pp. 5781–5795.

- [22] G. Xu, B. Mourrain, A. Galligo and R. Duval. ‘Constructing analysis-suitable parameterization of computational domain from CAD boundary by variational harmonic method’. In: *J. Comput. Physics* 252 (Nov. 2013).
- [23] B. Yahyaoui, M. Ayadi and A. Habbal. ‘Fisher-KPP with time dependent diffusion is able to model cell-sheet activated and inhibited wound closure’. In: *Mathematical biosciences* 292 (2017), pp. 36–45.

## 12.2 Publications of the year

### International journals

- [24] M. Binois, N. Collier and J. Ozik. ‘A portfolio approach to massively parallel Bayesian optimization’. In: *Journal of Artificial Intelligence Research* 82 (14th Jan. 2025), pp. 137–167. DOI: [10.1613/jair.1.16868](https://doi.org/10.1613/jair.1.16868). URL: <https://inria.hal.science/hal-03383097> (cit. on p. 24).
- [25] S. Chorfi, A. Habbal, M. Jahid, L. Maniar and A. Ratnani. ‘Stability of backward inverse problems for degenerate mean-field game systems’. In: *Evolution Equations and Control Theory* 14.6 (2025), pp. 1257–1280. DOI: [10.3934/eect.2025033](https://doi.org/10.3934/eect.2025033). URL: <https://inria.hal.science/hal-04892449> (cit. on p. 22).
- [26] I. Ciaramaglia, P. Goatin and G. Puppo. ‘A multi-class non-local macroscopic model with time delay for mixed autonomous / human-driven traffic’. In: *Communications in Mathematical Sciences* 24.1 (2026), pp. 209–242. DOI: [10.4310/CMS.260103000144](https://doi.org/10.4310/CMS.260103000144). URL: <https://hal.science/hal-04880080> (cit. on p. 20).
- [27] I. Ciaramaglia, P. Goatin and G. Puppo. ‘Non-local traffic flow models with time delay: well-posedness and numerical approximation’. In: *Discrete and Continuous Dynamical Systems - Series B* 30.3 (2025), pp. 874–907. DOI: [10.3934/dcdsb.2024113](https://doi.org/10.3934/dcdsb.2024113). URL: <https://hal.science/hal-04547467> (cit. on p. 20).
- [28] R. Colombo, P. Goatin and E. Rossi. ‘A Hyperbolic -Parabolic Framework to Manage Traffic Generated Pollution’. In: *Nonlinear Analysis: Real World Applications* 85 (2025), p. 104361. DOI: [10.1016/j.nonrwa.2025.104361](https://doi.org/10.1016/j.nonrwa.2025.104361). URL: <https://hal.science/hal-04504572> (cit. on p. 20).
- [29] H. D. Contreras, P. Goatin and L.-M. Villada. ‘A two-lane bidirectional nonlocal traffic model’. In: *Journal of Mathematical Analysis and Applications* 543.2 (Mar. 2025), p. 129027. DOI: [10.1016/j.jmaa.2024.129027](https://doi.org/10.1016/j.jmaa.2024.129027). URL: <https://hal.science/hal-04528991> (cit. on p. 20).
- [30] C. Daini, M. Laura Delle Monache, P. Goatin and A. Ferrara. ‘Traffic Control via Fleets of Connected and Automated Vehicles’. In: *IEEE Transactions on Intelligent Transportation Systems* 26.2 (2025), p. 1. DOI: [10.1109/TITS.2024.3506703](https://doi.org/10.1109/TITS.2024.3506703). URL: <https://hal.science/hal-04366870> (cit. on p. 19).
- [31] P. Goatin, D. Inzunza and L. M. Villada. ‘Nonlocal macroscopic models of multi-population pedestrian flows for walking facilities optimization’. In: *Applied Mathematical Modelling* (2025), p. 115927. DOI: [10.1016/j.apm.2025.115927](https://doi.org/10.1016/j.apm.2025.115927). URL: <https://hal.science/hal-04191630> (cit. on p. 21).
- [32] P. Goatin and E. Rossi. ‘Well-posedness of nonlocal macroscopic models of multi-population pedestrian flows for domain shape optimization’. In: *Journal of Hyperbolic Differential Equations* (2025). URL: <https://hal.science/hal-04719383>. In press (cit. on p. 21).
- [33] A. Machtalay, A. Habbal, A. Ratnani and I. Kissami. ‘Computational investigations of a multi-class traffic flow model: Mean-field and microscopic dynamics’. In: *Transportation Research Part B: Methodological* 195 (Mar. 2025), p. 103196. DOI: [10.1016/j.trb.2025.103196](https://doi.org/10.1016/j.trb.2025.103196). URL: <https://inria.hal.science/hal-03495749> (cit. on p. 21).
- [34] D. O’gara, M. Binois, R. Garnett and R. Hammond. ‘hetGPpy: Heteroskedastic Gaussian Process Modeling in Python’. In: *Journal of Open Source Software* 10.106 (5th Feb. 2025), p. 7518. DOI: [10.21105/joss.07518](https://doi.org/10.21105/joss.07518). URL: <https://hal.science/hal-05372470> (cit. on p. 23).

- [35] D. O'gara, C. Kerr, D. Klein, M. Binois, R. Garnett and R. Hammond. 'Improving Policy-Oriented Agent-Based Modeling with History Matching: A Case Study'. In: *Epidemics* 52 (Sept. 2025), p. 100845. DOI: [10.1016/j.epidem.2025.100845](https://doi.org/10.1016/j.epidem.2025.100845). URL: <https://hal.science/hal-04868131> (cit. on p. 23).
- [36] M. Ouni and A. Habbal. 'Coupled data recovery and shape identification : Nash games for the nonlinear Cauchy-Stokes case'. In: *Communications in Nonlinear Science and Numerical Simulation* (2026). URL: <https://inria.hal.science/hal-03495686>. In press (cit. on p. 26).
- [37] L. Palazzolo, M. Binois, L. Berti and L. Giraldi. 'Parametric Shape Optimization of Flagellated Micro-Swimmers Using Bayesian Techniques'. In: *Physical Review Fluids* (14th Apr. 2025). DOI: [10.1103/PhysRevFluids.10.034101](https://doi.org/10.1103/PhysRevFluids.10.034101). URL: <https://hal.science/hal-04699705> (cit. on p. 24).
- [38] A. Würth, M. Binois and P. Goatin. 'Traffic prediction by combining macroscopic models and Gaussian processes'. In: *Applied Mathematical Modelling* 150 (Feb. 2026), p. 116397. DOI: [10.1016/j.apm.2025.116397](https://doi.org/10.1016/j.apm.2025.116397). URL: <https://hal.science/hal-04345140> (cit. on p. 23).

### International peer-reviewed conferences

- [39] M. Bahari, A. Habbal and A. Ratnani. 'Isogeometric Analysis For Image Registration and Segmentation Using Optimal Transport Problem'. In: *M3A 2024 - Mathematical Modeling with Modern Applications*. Vol. 497. Springer Proceedings in Mathematics & Statistics. Istanbul, Turkey: Springer Nature Switzerland, 10th July 2025, pp. 131–150. DOI: [10.1007/978-3-031-89041-3\\_7](https://doi.org/10.1007/978-3-031-89041-3_7). URL: <https://inria.hal.science/hal-05399303> (cit. on p. 26).
- [40] A. Bellouch, M. Elsayy, G. Leroy, M. Binois, R. Duvigneau and S. Lanteri. 'Multi-Fidelity Bayesian Optimization of Metasurface Designs'. In: *Technical Programme International Symposium on Electromagnetic Theory URSI EMTS 2025 / IEEE Xplore*. EMTS 2025 - 25th URSI International Symposium on Electromagnetic Theory. Bologna, Italy, 23rd June 2025. URL: <https://inria.hal.science/hal-05288409> (cit. on p. 25).
- [41] M. Binois, J. Branke, J. Fieldsend and R. Purshouse. 'Decoupled Design of Experiments for Expensive Multi-objective Problems'. In: *Lecture Notes in Computer Science*. LION 2024 - Learning and Intelligent Optimization Conference. Vol. LNCS-14990. Learning and Intelligent Optimization : 18th International Conference, LION 18, Ischia Island, Italy, June 9–13, 2024, Revised Selected Papers. Ischia, Italy: Springer Nature Switzerland, 3rd Jan. 2025, pp. 37–50. DOI: [10.1007/978-3-031-75623-8\\_4](https://doi.org/10.1007/978-3-031-75623-8_4). URL: <https://hal.science/hal-04959599> (cit. on p. 25).
- [42] P. Goatin. 'Traffic Flow Stabilization Using a Single Controlled Vehicle: Numerical Validation of a Macroscopic Approach'. In: *2025 European Control Conference (ECC)*. Thessaloniki, Greece, 24th June 2025. URL: <https://inria.hal.science/hal-05028716> (cit. on p. 19).
- [43] A. Joumaa, P. Goatin and G. D. Nunzio. 'Class-Specific Variable Speed Limit for Traffic Flow Optimization on Road Networks'. In: *MT-ITS 2025 - 9th IEEE Conference on Models and Technologies for Intelligent Transportation Systems*. 9th IEEE Conference on Models and Technologies for Intelligent Transportation Systems. Luxembourg, Luxembourg, 8th Sept. 2025. URL: <https://hal.science/hal-05244472> (cit. on p. 19).
- [44] N. Ricard, M. Binois and R. Duvigneau. 'Training of physics-informed neural networks: a multi-criterion viewpoint'. In: *DTE - AICOMAS 2025 - 3rd IACM Digital Twins in Engineering Conference (DTE 2025) & 1st ECCOMAS Artificial Intelligence and Computational Methods in Applied Science*. Paris, France, 17th Feb. 2025. URL: <https://inria.hal.science/hal-05306445> (cit. on p. 22).

### Conferences without proceedings

- [45] R. Duvigneau. 'NURBS grids for DG methods: a synthesis'. In: *SHARK-FV 2025 - Sharing Higher-order Advanced Research Known-how on Finite Volume*. Minho, Portugal, 2nd June 2025. URL: <https://inria.hal.science/hal-05306399> (cit. on p. 22).

### Doctoral dissertations and habilitation theses

- [46] A. Joumaa. ‘Optimization of the environmental performance of urban mobility via macroscopic and multimodal modeling approaches’. Université Côte d’Azur, 13th Nov. 2025. URL: <https://theses.hal.science/tel-05461388> (cit. on pp. 19, 34).

### Reports & preprints

- [47] M. Binois and J. Larson. *Adaptive Replication Strategies in Trust-Region-Based Bayesian Optimization of Stochastic Functions*. 28th Apr. 2025. URL: <https://hal.science/hal-05049210> (cit. on p. 24).
- [48] H. D. Contreras, P. Goatin and L. M. Villada. *Well-posedness of a nonlocal upstream-downstream traffic model*. 2025. URL: <https://hal.science/hal-05302417> (cit. on p. 20).
- [49] J.-A. Désidéri. *Territory splitting revisited in prioritized multiobjective optimization*. RR-9568. Inria & Université Côte d’Azur, CNRS, I3S, Sophia Antipolis, France, 8th Jan. 2025, p. 25. URL: <https://inria.hal.science/hal-04876427> (cit. on p. 26).
- [50] R. Duvigneau. *Isogeometric fluid-structure interaction using a mixed continuous/discontinuous Galerkin scheme*. Nov. 2025. URL: <https://inria.hal.science/hal-05366084> (cit. on p. 22).
- [51] A. Fadikar, A. Stevens, M. Binois, N. Collier and J. Ozik. *Adaptive Grid-Based Thompson Sampling for Efficient Trajectory Discovery*. 2025. URL: <https://hal.science/hal-05348371> (cit. on p. 24).
- [52] A. Flowers, C. Franck, M. Binois, C. Park and R. Gramacy. *Modular Jump Gaussian Processes*. 2025. DOI: [10.48550/arXiv.2505.15557](https://arxiv.org/abs/10.48550/arXiv.2505.15557). URL: <https://hal.science/hal-05176011> (cit. on p. 23).
- [53] P. Goatin, S. Göttlich and F. Ziegler. *A non-local model for heterogeneous material flow on conveyor belts*. 7th Oct. 2025. URL: <https://hal.science/hal-05301909> (cit. on p. 21).
- [54] P. Goatin, A. Klar and C. Mezquita-Nieto. *Discrete adjoint gradient computation for multiclass traffic flow models on road networks*. 27th May 2025. DOI: [10.22541/au.174469728.89614329/v1](https://arxiv.org/abs/10.22541/au.174469728.89614329/v1). URL: <https://hal.science/hal-05089123> (cit. on p. 19).
- [55] L. Palazzolo, M. Binois and L. Giraldi. *Non-Locally Controllable but Trackable Magnetic Head Flagellated Swimmer*. 2025. DOI: [10.48550/arXiv.2511.02535](https://arxiv.org/abs/10.48550/arXiv.2511.02535). URL: <https://inria.hal.science/hal-05348147> (cit. on p. 24).
- [56] M. Pascal, R. Duvigneau and L. Monasse. *Simulating Shock Solutions for Hyperbolic Conservation Laws with Physics-Informed Neural Networks*. RR-9605. Inria & Université Cote d’Azur, Sophia Antipolis, France, Dec. 2025. URL: <https://inria.hal.science/hal-05405130> (cit. on p. 22).
- [57] M. Vidal, R. Duvigneau and S. Bottini. *Modeling gene expression dynamics of plants during biotic attack by physics-informed artificial intelligence*. RR-9595. Inria & Université Cote d’Azur, Sophia Antipolis, France, 13th Aug. 2025. URL: <https://inria.hal.science/hal-05210203> (cit. on p. 22).

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