

# 2025 Activity Report

RESEARCH CENTRE: Inria Saclay Centre

IN PARTNERSHIP WITH: Office national d'études et de recherches aérospatiales

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Project-Team

## GAMMAO

Adaptive Mesh Generation and Advanced Numerical  
Methods

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## **Project-Team GAMMAO**

*Creation of the Project-Team: 2023 January 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

A6.2. – Scientific computing, Numerical Analysis & Optimization

A6.2.7. – HPC for machine learning

A6.2.8. – Computational geometry and meshes

A6.5.1. – Solid mechanics

A6.5.2. – Fluid mechanics

### Other research topics and application domains

B5.2.3. – Aviation

B5.2.4. – Aerospace

B9.5.1. – Computer science

B9.5.2. – Mathematics

B9.5.3. – Physics

B9.5.5. – Mechanics

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## **1 Team members, visitors, external collaborators**

### **Research Scientists**

- Frederic Alauzet [Team leader, INRIA, Senior Researcher, HDR]
- Alain Dervieux [INRIA, Emeritus, from Apr 2025, HDR]
- Paul George [INRIA, Emeritus]
- Cosimo Tarsia Morisco [INRIA, ISFP, from Oct 2025]
- Julien Vanharen [INRIA, Senior Researcher]

### **Post-Doctoral Fellow**

- Cosimo Tarsia Morisco [INRIA, Post-Doctoral Fellow, until Sep 2025]

### **PhD Students**

- Thomas Gauchery [INRIA]
- Andrea Gobbi [INRIA]
- Valentin Golliet [ONERA]
- Eloi Guilbert [INRIA]
- Paolo Masson [INRIA, from Oct 2025]

### **Technical Staff**

- Loic Marechal [INRIA, Engineer]
- Matthieu Maunoury [INRIA, Engineer]

### **Interns and Apprentices**

- Julie Chineaud [INRIA, Intern, from Jun 2025 until Aug 2025]
- Paolo Masson [INRIA, Intern, from Feb 2025 until Jul 2025]

### **Administrative Assistant**

- Melanie Da Silva [INRIA]

### **External Collaborators**

- Francois Pechereau [ONERA, from Sep 2025]
- Francois Pechereau [ONERA, until Aug 2025]
- Christophe Peyret [ONERA]
- Guillaume Puigt [ONERA]

## 2 Overall objectives

Numerical simulation has been booming over the last thirty years, thanks to increasingly powerful numerical methods, computer-aided design (CAD) and the mesh generation for complex 3D geometries, and the coming of supercomputers (HPC). The discipline is now mature and has become an integral part of design in science and engineering applications. This new status has led scientists and engineers to consider numerical simulation of problems with ever increasing geometrical and physical complexities. A simple observation of this chart

CAD  $\rightarrow$  Mesh  $\rightarrow$  Solver  $\rightarrow$  Visualization / Analysis .

shows: **no mesh = no simulation** along with **"bad" mesh = wrong simulation**. We have concluded that the mesh is at the core of the classic computational pipeline and a key component to significant improvements. Therefore, the requirements on meshing methods are an ever increasing need, with increased difficulty, to produce high quality meshes to enable reliable solution output predictions in an automated manner. These requirements on meshing or equivalent technologies cannot be removed and all approaches face similar issues.

Gamma's research program is motivated by four grand challenges in order to achieve certification and high-fidelity in the numerical simulation pipeline. The goal is to deliver innovative and ground-breaking solutions to each step of the adaptive numerical simulation pipeline. Not surprisingly, these challenges (and the themes that result) are clearly indicated in the NASA CFD Vision 2030 Study [33] and have been mentioned recurrently during the previous evaluations of the Gamma3 team where they have been judged as very ambitious and long-term. The four grand challenges are:

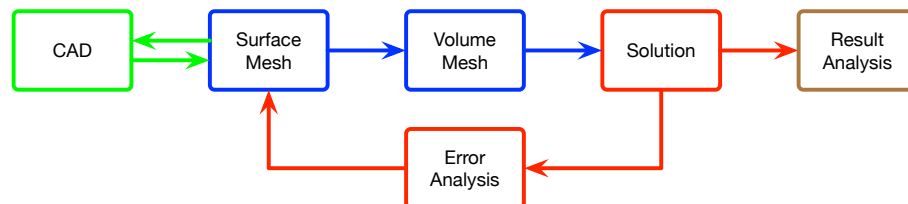
**1. Geometric modeling.** The goal is to address geometry modeling issues and their interactions with the meshing pipeline. To this end, Gamma will develop more versatile and robust geometry and modeling processes to be embedded within meshing tools.

**2. Enhanced generic meshing algorithms.** Gamma will pursue its work on state-of-the-art meshing technologies which should fulfill these three requirements: adaptation, high-order and large size. Mesh adaptation and high-order meshing will be based on the well-posed metric-based mathematical framework. The generation of large size mesh will be achieved with hybrid parallelism (multi-thread and MPI).

**3. Toward certified numerical solutions to the Navier-Stokes equations.** This research axis will focus on error estimates and robust numerical schemes (flow solver). Gamma will primarily focus on the design of uncertainty aware RANS error estimates. We will pursue the work on anisotropic mesh adaptation for the turbulent Navier-Stokes equations with moving geometries. We envision to develop a new high-order mesh-adaptive solution platform which requires to design high-order error estimates and a high-order flow solver.

**4. Advanced visualization of mesh and solution.** High-order representations (both on the solver and meshing sides) use higher-degree polynomials to interpolate solution data. The challenge is to develop algorithms for pixel exact rendering of high-order meshes and solutions which will provide the potential to reveal features that otherwise might be masked by classic visualization approaches. The visualization software will be used for pre and post processing by interfacing all the Gamma's software components.

These four grand challenges cover the whole numerical simulation pipeline depicted below. The geometric modeling is represented by the green part, the enhanced generic meshing algorithms by the blue part, the certification of Navier-Stokes simulations by the red part, and the advanced mesh and solution visualization by the brown part. We can also see the clear interaction between each research axis.



Most of the proposed meshing developments and technologies are generic and can be applied to a broader field of applications in order to increase the impact of this research program. Flow solver developments and technologies focus specifically on CFD with applications to aerospace, turbomachinery, and defense.

### 3 Research program

The main axes are:

- Geometric Modeling:
  - High-fidelity discrete CAD kernel.
  - Continuous parametric CAD kernel.
- Enhanced Generic Meshing Algorithm:
  - Adaptation (extreme anisotropy, metric-aligned, metric-orthogonal).
  - High-order (tetrahedra, hexahedra, boundary layer, adapted).
  - Large meshes (tetrahedra, hexahedra, adapted).
  - Moving mesh methods for moving geometries.
- Toward Certified Solutions to the Navier-Stokes Equations:
  - Flow solver and adjoints (Finite Volumes, Finite Elements, Flux Reconstruction).
  - Error estimates and correctors.
- Advanced Mesh and Solution Visualisation:
  - Pixel exact rendering (High-Order mesh, High-Order solution).
  - Pre-processing and post-processing.

### 4 Application domains

Our research in mesh generation, mesh adaptation and certification of the Numerical Simulation Pipeline finds applications in several different domains such as aviation and aerospace but also all fields where computation and simulation are used: fluid mechanics, solid mechanics, solving wave equations (acoustic, electromagnetism, etc.), energy or biomedical.

### 5 Latest software developments, platforms, open data

#### 5.1 Latest software developments

##### 5.1.1 GHS3D

**Keywords:** Tetrahedral mesh, Delaunay, Automatic mesher

**Functional Description:** GHS3D is an automatic volume mesher

**URL:** <https://team.inria.fr/gamma/gamma-software/ghs3d/>

**Contact:** Frederic Alauzet

**Participants:** Paul Louis George, Adrien Loseille, Frederic Alauzet

### 5.1.2 HEXOTIC

**Keywords:** 3D, Mesh generation, Meshing, Unstructured meshes, Octree/Quadtree, Multi-threading, GPGPU, GPU

**Functional Description:** Input: a triangulated surface mesh and an optional size map to control the size of inner elements.

Output: a fully hexahedral mesh (no hybrid elements), valid (no negative jacobian) and conformal (no dangling nodes) whose surface matches the input geometry.

The software is a simple command line that requires no knowledge on meshing. Its arguments are an input mesh and some optional parameters to control elements sizing, curvature and subdomains as well as some features like boundary layers generation.

**URL:** <https://team.inria.fr/gamma/gamma-software/hexotic/>

**Contact:** Loic Marechal

**Participant:** Loic Marechal

**Partner:** Distene

### 5.1.3 FEFLOA-REMESH

**Keywords:** Scientific calculation, Anisotropic, Mesh adaptation

**Functional Description:** FEFLOA-REMESH is intended to generate adapted 2D, surface and volume meshes by using a unique cavity-based operator. The metric-aligned or metric-orthogonal approach is used to generate high quality surface and volume meshes independently of the anisotropy involved.

**URL:** <https://team.inria.fr/gamma/feflo-a/>

**Contact:** Adrien Loseille

**Participants:** Adrien Loseille, Frederic Alauzet

### 5.1.4 Ouranos

**Keywords:** Scientific computing, Unstructured meshes, HPC, MPI

**Functional Description:** Ouranos is an open-source LGPLv3 C++ library that provides a framework for handling unstructured meshes in a massively parallel environment, including mesh reading, partitioning, and migration. It offers a suite of MPI-aware services, including a testing framework, a benchmarking framework, a logging system, distributed hash tables, automatic ghost management with a user-defined number of layers, and automatic conversion between partitioned and distributed approaches.

**URL:** <https://gitlab.inria.fr/jvanhare/ouranos>

**Contact:** Julien Vanharen

### 5.1.5 ViZiR4

**Name:** ViZiR4

**Keywords:** Visualization, Pixel-exact rendering, Instant rendering, High order methods

**Functional Description:** Its main features are: - Light, simple and interactive visualization software. - Surface and volume (tetrahedra, pyramids, prisms, hexahedra) meshes. - Pixel exact rendering of high-order solutions on straight elements. - Almost pixel exact rendering on curved elements (high-order meshes). - Post-processing tools, such as picking, isolines, clipping, capping.

**URL:** <https://pyamg.saclay.inria.fr/vizir4.html>

**Publications:** [hal-01686714](#), [hal-02950321](#), [hal-03539257](#)

**Contact:** Adrien Loseille

**Participants:** Adrien Loseille, Matthieu Maunoury, Frederic Alauzet

### 5.1.6 Wolf-Metrix V3

**Keyword:** Scientific computing

**Scientific Description:** Wolf-Metrix is a software that provides by various ways metric to govern the mesh generation. Generally, these metrics are constructed from error estimates (a priori or a posteriori) applied to the numerical solution. Wolf-Metrix computes metric fields from scalar solutions by means of several error estimates: interpolation error, iso-lines error estimate, interface error estimate and goal oriented error estimate. It also contains several modules that handle meshes and metrics. For instance, it extracts the metric associated with a given mesh and it performs some metric operations such as: metric gradation, metric interpolation and metric intersection.

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**URL:** <https://pages.saclay.inria.fr/frederic.alauzet/software.html>

**Contact:** Frederic Alauzet

**Participants:** Frederic Alauzet, Cosimo Tarsia Morisco, Julien Vanharen, Matthieu Maunoury, Loic Marechal

### 5.1.7 Wolf-Nsc V3

**Keyword:** Scientific computing

**Functional Description:** Wolf-Nsc is numerical flow solver solving steady or unsteady turbulent compressible Euler and Navier-Stokes equations. The available turbulent models are the Spalart-Almaras and the Menter SST k-omega. A mixed finite volume - finite element numerical method is used for the discretization. Second order spatial accuracy is reached thanks to MUSCL type methods. Explicit or implicit time integration are available. It also resolved dual (adjoint) problem and compute error estimate for mesh adaptation.

**URL:** <https://pages.saclay.inria.fr/frederic.alauzet/software.html>

**Contact:** Frederic Alauzet

**Participants:** Frederic Alauzet, Cosimo Tarsia Morisco, Julien Vanharen, Matthieu Maunoury, Loic Marechal

### 5.1.8 Wolf-Interpol V3

**Keyword:** Scientific computing

**Functional Description:** Wolf-Interpol is a tool to transfer scalar, vector and tensor fields from one mesh to another one. Polynomial interpolation (from order 2 to 4) or conservative interpolation operators can be used. Wolf-Interpol also extract solutions along lines or surfaces.

**URL:** <https://pages.saclay.inria.fr/frederic.alauzet/software.html>

**Contact:** Frederic Alauzet

**Participants:** Frederic Alauzet, Cosimo Tarsia Morisco, Julien Vanharen, Matthieu Maunoury, Loic Marechal

## 6 New results

### 6.1 Practical Use of Metric-Based Anisotropic Mesh Adaptation for Industrial Applications

**Participants:** Cosimo Tarsia Morisco, Eloi Guilbert, Matthieu Maunoury, Frederic Alauzet (*correspondant*).

Feature-based and goal-oriented error estimates for the Reynolds-Averaged Navier-Stokes equations are presented, together with mesh adaptation algorithms for practical study where mesh convergence analysis is mandatory. Several useful results, associated with the errors estimates are demonstrated such as the equidistribution principle, handling several sensors or treating multidomain problems. Numerical results on three industrial application cases highlight the powerfulness of anisotropic mesh adaptation to achieve high-accuracy with moderate mesh size. They demonstrate that mesh-independent certified numerical solutions can be obtained thanks to anisotropic mesh adaptation and that it is possible to run high-fidelity CFD on unstructured adapted meshes composed only of tetrahedra which is fundamental to design robust meshing process for complex geometries.

### 6.2 Assessment of Spalart-Allmaras One-equation BCM Transitional Model using anisotropic metric-based mesh adaptation

**Participants:** Cosimo Tarsia Morisco (*correspondant*), Frederic Alauzet.

The intent of this work is to investigate whether the Anisotropic Metric-Based mesh adaptation can provide mesh convergence for transitional flows. The model considered is the Spalart-Allmaras BCM Transitional Model. Three test cases of the 1st AIAA CFD Transition Modeling and Prediction Workshop are considered: two-dimensional Zero-Pressure-Gradient Flat Plate; two-dimensional subsonic flow past the NLF-0416 airfoil; three-dimensional subsonic flow past the 6:1 Prolate Spheroid. Attention is dedicated to the mesh-convergence of the transition point, which is automatically detected and meshed with low level of anisotropy. Conversely, high level of anisotropy is observed before and after transition. These requirements permit to significantly limit the number of Degrees of Freedom.

### 6.3 Applications of Implicit Edge-Based Gradients to Third-Order Edge-Based Scheme for Adaptive Tetrahedral Grids.

**Participants:** Cosimo Tarsia Morisco (*correspondant*), Hiroaki Nishikawa.

We investigated the use of the implicit edge-based gradient method to a third-order edge-based Euler solver on adaptive tetrahedral grids. The third-order edgebased method is an economical high-order discretization method, typically implemented with a quadratic least-squares gradient method, achieving third-order accuracy on arbitrary tetrahedral grids. For robustness, however, the least-squares gradient stencil often needs to be extended beyond neighbors, which not only increases the cost of gradient computations but also increases the error level. To preserve high accuracy and maintain robustness, we employ the implicit edge-based gradient method instead of a quadratic least-squares method, and investigate the performance of the resulting third-order solver with a special focus on adaptive grids.

#### 6.4 5th AIAA CFD High Lift Prediction Workshop Results Using Metric-Based Anisotropic Mesh Adaptation.

**Participants:** Frederic Alauzet (*correspondant*), Thomas Gauchery, Matthieu Maunoury, Cosimo Tarsia Morisco, Sylvain Mouton.

We performed Computational Fluid Dynamics (CFD) analyses with the Inria metric-based mesh adaptation platform for the 5th AIAA CFD High-Lift Prediction Workshop (HLPW-5) on the Common Research Model High-Lift (CRM-HL) geometry. The HLPW-5 is organized to assess the numerical prediction and physical modeling capabilities of CFD technology on a realistic aircraft shape in landing and takeoff high lift configurations. Multiple CRM-HL variants with increasing geometry complexity are the target of this investigation. This work shows the obtained results for Case 1 and all the Cases 2 geometries proposed by the workshop for RANS modeling with the baseline Spalart-Allmaras (SA) turbulence model. Validation and verification results are presented with mesh convergence study for some of the test cases and comparison with experimental data.

#### 6.5 Reviewing the Vertex-Centered V4 Scheme for More Accurate Mesh Adaptation.

**Participants:** Yoan Gorschka, Guillaume Puigt (*correspondant*), Alberto Remigi, Cedric Content, Bruno Maugars, Cosimo Tarsia Morisco.

In this study, we focus on the V4 vertex-centered finite volume scheme developed initially by A. Dervieux. This scheme has shown very high robustness on highly anisotropic meshes, with an anisotropy factor of the order of a million. This is why it is today one of the preferred schemes for anisotropic mesh adaptation. In our work, we propose two approaches for improving the vertex-centered V4 scheme for more accurate mesh adaptation. On the one hand, we tackle the problems associated with deconvolution. On the other, we look at the geometric error made when calculating convective flux. We propose a new correction based on the derivative of the numerical flux and the mesh metrics. Several deconvolution approaches are studied on stationary cases.

#### 6.6 From simplex to mixed element: extension of a vertex-centered discretization, focus on accuracy analysis and 3D RANS applications.

**Participants:** Cosimo Tarsia Morisco (*correspondant*), Frederic Alauzet, Guillaume Puigt.

Standard unstructured-grid CFD simulations generally rely on a cell-centered Finite Volume discretization applied to mixed-element grids. The interest in such approach is using elements that are aligned along a privileged direction in the region close to the boundary, and at the same time unstructured elements near complex geometrical details or in farfield regions. This paper proposes a novel version of the mixed Finite Element / Finite Volume approximation, which is a vertex-centered method known to produce second-order accurate solutions even on highly anisotropic adapted meshes composed of simplex elements (i.e., triangles and tetrahedra). The extension of this approach for two-dimensional mixed-element meshes involves the APproximated Finite Element -APFE- method to discretize diffusion. In this work we make the definitive step forward to handle three-dimensional mixedelement meshes: designing a second-order accurate scheme for smooth meshes involving tetrahedra, prisms and pyramids. The present work focuses on two key aspects. One concerns the 3D extension of the APFE method. A detailed error analysis of this vertex-centered approach is provided for prisms and pyramids. The second ingredient deals with an innovative algorithm to compute the truncation error for linear problems. In contrast to usual methods, the one proposed here permits to compute exactly the coefficients related to each terms of error for any mesh, and can be implemented in any solver with a low development effort.

## 6.7 Metric-based mesh adaptation for hypersonic flows

**Participants:** Guillaume Puigt (*correspondant*), Valentin Golliet, Frederic Alauzet.

Reentry is the capability of an object launched from Earth to leave Earth's atmosphere and then come again. During reentry at the hypersonic regime, the object encounters essentially two energetic phenomena: a strong bow shock and the transformation of kinetic velocity into heat in the boundary layer. The most important quantity to compute is the wall heat flux since dimensioning the object requires good confidence in its computation. Heat flux in the boundary layer varies mainly in the direction normal to the wall. So, a standard prerequisite is the definition of a mesh with mesh lines perpendicular to the wall. The technique cannot be applied successfully to complex geometry because the required human resources are larger. On the other hand, unstructured grids are generated automatically, even on complex geometry. In this work, we introduce a metric-based mesh adaptation procedure. Contrary to standard computation, the mesh adaptation procedure converges the couple mesh and solution. The automaticity of the process relies on specific ingredients: a CFD solver robust on anisotropic meshes composed of simplexes (triangles in 2D and tetrahedrons in 3D) an error estimate procedure to define the metrics for generating the new mesh a mesh generator method to build the mesh from metrics an interpolation algorithm to interpolate the previous solution on the new mesh. The full procedure is applied using a node-centered solver, and the remesher is the library `fflo.a` from Inria. The efficiency of the mesh adaptation procedure will be demonstrated on test cases of increasing complexity. Laminar hypersonic flow over a cylinder at Mach=5.73 and Re=2050. Comparison between error estimate efficiency. Edney Type IV shock/shock interaction. Effect of geometry. Holden compression ramps. 2D/3D effects BOLT and HyTRV configurations. Pure 3D configurations. The metric-based mesh adaptation is an automatic computational chain. It enables efficient capturing of wall heat flux and highlights model limits, with a limited human being influence. We are currently extending the procedure to deal with reactive flows.

## 6.8 Pixel-exact rendering for high-order meshes and solutions

**Participants:** Adrien Loseille, Matthieu Maunoury (*correspondant*).

We are developing `ViZiR 4`, a visualization software with pixel exact rendering to address the high-order visualization challenges [29, 5]. `ViZiR 4` is bundled as a light, simple and interactive high-order meshes and solutions visualization software. It is based on OpenGL 4 core graphic pipeline. The use of OpenGL Shading Language (GLSL) allows to perform pixel exact rendering of high order solutions on straight elements (without extra subdivision or ray casting) and almost pixel exact rendering on curved elements (high-order meshes). `ViZiR 4` enables the representation of high order meshes (up to degree 4) and high order solutions (up to degree 10) with pixel exact rendering. Unlike other visualization software (`ParaView` [17], `TecPlot` [18], `Medit` [6], `Vizir` (OpenGL legacy based version) [24], `Gmsh` [15]), there is no subdivision process that is expensive nor visualization error that has to be controlled. Moreover, the subdivision of the curved entities is done on the fly on GPU which leaves the RAM memory footprint at the size of the loaded mesh. Furthermore, in comparison with standard visualization techniques based on legacy OpenGL, the use of OpenGL 4 core version improves the speed of rendering, reduces the memory footprint and increases the flexibility. Many post-processing tools, such as picking, hiding surfaces, isolines, clipping, capping, are integrated to enable on the fly the analysis of the numerical results.

## 6.9 Easy multithreaded parallelisation of solvers dealing with unstructured and anisotropic meshes

**Participants:** Loïc Maréchal.

The previous year experimentations with colored grains partitioning have proved successful so this new concurrent computing scheme has been integrated into the production version of the *LPLib*. A new high-level API has been developed to take care of all partitioning and renumbering aspects of a single procedure call. Likewise, the whole colored-based parallelism is handled by a single procedure call that processes each color sequentially and all of the color's subdomains (grains) concurrently. Thanks to its integration in the *LPLib*, the colored-grain method now benefits from the library's dynamic scheduling capacity to avoid costly synchronizations and allows for concurrency levels that are closer to the theoretical limit. This new approach and the associated code have been validated on several examples and the results have been presented and published at the AIAA conference. Furthermore, this new high-level API was also used to renumber the meshes using the original Hilbert scheme, making the integration of the *LPLib* even more straightforward.

## 6.10 INRIA HPC developers day

**Participants:** Loïc Maréchal, Luca Cirrotola, Alexandre Bilger, Florent Pruvost, Nathalie Furmento.

In October 2025 we organized a two-day event in Bordeaux to gather many INRIA's engineers developing numerical simulation software. This event was aimed at building a closer community as all engineers are scattered between different teams and INRIA facilities across the country. Talks were given on topics covering many aspects of HPC software development like, CI/CD, portability of numerical accuracy, data structures and best practices. Round tables were organized to discuss and address common issues like mutualizing linear algebra toolkits or exchanging experiences with new programming languages.

## 6.11 Addition of Mixing Plane in Wolf

**Participants:** Frédéric Alauzet, Eloi Guilbert (*correspondant*).

The mixing plane method is used typically on turbomachinery in order to model the interaction between a rotor (rotating part) and a stator (static part). Each row (stator, rotor) has its own computation which is coupled with his surroundings rows with the mixing plane. The idea is to average quantities along the pitch direction at the outlet of a row, those averaged values are transferred to the next row. The same process is done at the inlet of a row and transferred at the previous row. Associating mesh adaptation with mixing planes requires that the position and the distribution radial discretization must be automatic and consistent with the current adapted mesh. Therefore, after each mesh adaptation, a specific radial discretization for the mixing plane is built based on the current adapted mesh size. These radial discretizations are different on either side of the mixing plane as the adapted meshes do not match on either side. It allows removing the dependency of the results on the relative position between the rotor and the stator. Thus, RANS simulation can be used, even if the problem is naturally unsteady.

## 6.12 Localized flux limiting for Mixed Element Volume scheme on anisotropic adapted meshes

**Participants:** Frédéric Alauzet, Julien Vanharen, Andrea Gobbi (*correspondant*).

We are working on decreasing the amount of numerical dissipation introduced by flux limiters in a Mixed Element Volume (MEV) scheme, that uses MUSCL extrapolations and the HLLC approximated Riemann solver to solve the convective part of the compressible Navier-Stokes equations. The computations are performed in the context of metric-based anisotropic mesh adaptation, thus it is essential to be both accurate and robust. The numerical approach consists in using the Larsson sensor in order to detect shocks

and possibly other unstable regions of the solution, and use the flux limiters locally in those regions. The strategy is being tested for different flow configurations, both transonic, where shocks are expected and need to be treated accordingly, and subsonic, where flux limiters should not be needed. A case with a contact discontinuity is also considered.

### 6.13 Comparison of several shared-memory parallel linear solvers for the Navier-Stokes primal and adjoint equations on anisotropic adapted meshes

**Participants:** Frédéric Alauzet, Loïc Maréchal, Julien Vanharen, Thomas Gauchery (*correspondant*).

We presented and studied a new methodology to improve linear solvers on parallel shared-memory architecture in the context of Reynolds-Averaged Navier-Stokes primal and adjoint equations. The computations are realized in the context of metric-based anisotropic mesh adaptation, thus efficiency and robustness of the new approach are crucial. For this purpose, a domain decomposition approach coupled with coloring algorithm for unstructured meshes is considered. It improves the convergence of the iterative solvers considered to solve the linear systems. The new strategy is validated on multiple realistic test cases to highlight the improved convergence for primal and adjoint problems. The results obtained have been presented during the AIAA SciTech 2025 conference in Orlando [8].

## 7 Bilateral contracts and grants with industry

### 7.1 Bilateral contracts with industry

**Participants:** Frédéric Alauzet.

#### Safran Tech

- Duration: 2017 - 2027
- Inria PI: Frédéric Alauzet
- Budget for GammaO: Salary for non-permanent staff, travels
- Objectives: Practical use of metric-based mesh adaptation for turbomachinery industrial applications

## 8 Partnerships and cooperations

### 8.1 European initiatives: NumPEX

**Participants:** Loïc Marechal, Julien Vanharen.

Since COVID crisis the air traffic is getting back to normal with a growing trend. Aeronautical engines' manufacturer did realize this as a critical time for aviation and huge effort should be made to reduce our environmental impact. For instance, The Advisory Council for Aeronautics Research in Europe aka ACARE 2050 objectives set a reduction of 75% in production of CO<sub>2</sub> and of 90% of NO<sub>x</sub>. This objective brings to the design of new and groundbreaking parts and requires more efficient and complex numerical tools. To cope with new challenges an increase in simulation complexity and representativity is needed. It leads industrials like Safran to wonder if current numerical toolchains can still address those issues or should we

optimize it. Parts, like propellers and turbines are very complex with a large number of technological effect, taking into account all physical aspect is often not possible since it leads to an exponential growth of the number of degrees of freedom with no convergence or accuracy guarantee. Thus designers simplify the geometry to use their traditional old simulation methods. For this reason, SAFRAN is pushing to develop new numerical toolchains that allows to reach better accuracy and scalability on the key design parameters. The recent studies in this sense ([3] is an example of application of remeshing technique with a turbine) highlights how the combination of an anisotropic meshing technique, a robust and accurate solver and the use of a remeshing technology would bring an improvement on physical quantities accuracy and reliability. The need of testing integrated parts, like propellers installed on wide body aircraft or multi-stage turbomachine, shows the interest for industrials of scaling the numerical toolchain to exascale machines in order to have accurate results to real world design problems.

Nowadays, industrials such as Airbus, Safran or ArianeGroup, are facing major technological challenges, which include the design of the Airbus A350 high-lift configuration, the cooling system of turbomachinery involving microperforated panels, the Ariane 6 launch vehicle or the consideration of ice accretion on aircraft wings. All of these challenges imply an intensive use of Computational Fluid Mechanics (CFD) in order to alleviate design and manufacturing costs and environmental impacts. However, three technological roadblocks need to be overwhelmed in the coming decades to treat the previous quoted industrial applications: the ability to handle **very complex geometries**, to predict unsteady turbulent flows with a **high-fidelity** and **very quickly**, which necessitates the High-Performance Computing (HPC). The application proposed in this project is out of reach with the present technology. Hence, disruptive methods need to be proposed to maximize the socio-economic impact. The first challenge requires to use the **automatic generation of tetrahedra meshes**, which is developed in our team for more than thirty years [10, 30, 16, 7, 11, 9, 12, 13, 14, 21, 20, 19, 32, 31, 22, 23]. Indeed, it is for instance impossible to generate a structured mesh around a real landing gear and even if it would be possible, it would require an enormous amount of time and resources compared with our automatic unstructured mesh generator. The last two challenges deal with the importance of having **accurate and fast numerical methods** on unstructured tetrahedra meshes to capture unsteady turbulent three-dimensional flows. Last but not least, these challenges have to be **simultaneously** addressed and impose strong constraints on the whole computational workflow. Moreover, **anisotropic mesh adaptation**, developed in our team [27, 26, 25, 28] works like a catalyst since it allows to:

1. efficiently discretize complex industrial geometries,
2. increase accuracy of numerical schemes,
3. reduce the computational time to achieve the same accuracy thanks to the generation of an optimal mesh in terms of degrees of freedom for a given configuration.

Our simulation suite is made of two main softwares: Feflo.a and Wolf. Feflo.a is our robust anisotropic local remeshing software for three-dimensional volume and parametric surface mesh generation conforming in sizes and orientations to a prescribed input metric field. It is based on a unique cavity-based operator [28, 34]. It also includes many components required to generate an initial mesh or generate highly-adapted meshes. It also handles non-manifold geometries and boundary layer mesh generation. Wolf is a mixed Finite Volume Finite Element flow solver for the compressible Euler and Navier Stokes equations with or without moving geometries. It also solves the steady and unsteady adjoint problems. It achieves second-order accuracy in space and up to fourth-order accuracy in time with explicit or implicit schemes. These suite has demonstrated its incredible potential and provided substantial breakthroughs in industrial applications [35, 34, 4].

It is absolutely crucial to keep in mind that the challenge to handle highly anisotropic unstructured meshes arise from the connectivity table needed to represent an unstructured mesh which induces loop indirections and load imbalances during computations and from the anisotropy which invalidates most of the standards geometric algorithms. Very simple standard algorithm such as a cut plane in an anisotropic tetrahedra mesh should be revised to efficiently run on a distributed memory architecture. Furthermore, the GPU algorithm has very little to do with the CPU one which notably increases the development cost to obtain a portable solution.

To continue and improve the capabilities of our suite, we propose a new library GMLib to specifically address the issue of handling anisotropic unstructured meshes on GPU and an industrial test case in agreement with the Safran Tech's roadmap.

## 8.2 European initiatives: Nextair

**Participants:** Frederic Alauzet, Eloi Guilbert, Cosimo Tarsia Morisco.

Radical changes in aircraft configurations and operations are required to meet the target of climate-neutral aviation. To foster this transformation, innovative digital methodologies are of utmost importance to enable the optimisation of aircraft performances. NEXTAIR will develop and demonstrate innovative design methodologies, data-fusion techniques and smart health-assessment tools enabling the digital transformation of aircraft design, manufacturing and maintenance. NEXTAIR proposes digital enablers covering the whole aircraft life-cycle devoted to ease breakthrough technology maturation, their flawless entry into service and smart health assessment. They will be demonstrated in 8 industrial test cases, representative of multi-physics industrial design, maintenance problems and environmental challenges and interest for aircraft and engines manufacturers. NEXTAIR will increase high-fidelity modelling and simulation capabilities to accelerate and derisk new disruptive configurations and breakthrough technologies design. NEXTAIR will also improve the efficiency of uncertainty quantification and robust optimisation techniques to effectively account for manufacturing uncertainty and operational variability in the industrial multi-disciplinary design of aircraft and engine components. Finally, NEXTAIR will extend the usability of machine learning-driven methodologies to contribute to aircraft and engine components' digital twinning for smart prototyping and maintenance. NEXTAIR brings together 16 partners from 6 countries specialised in various disciplines: digital tools, advanced modelling and simulation, artificial intelligence, machine learning, aerospace design, and innovative manufacturing. The consortium includes 9 research organisations, 4 leading aeronautical industries providing digital-physical scaled demonstrator aircraft and engines and 2 high-Tech SME providing expertise in industrial scientific computing and data intelligence.

## 9 Scientific production

### 9.1 Publications of the year

#### International journals

- [1] C. Tarsia Morisco and F. Alauzet. 'Assessment of Spalart-Allmaras One-Equation BCM Transitional Model Using Anisotropic Metric-Based Mesh Adaptation'. In: *AIAA Paper* (3rd Jan. 2025). DOI: [10.2514/6.2025-0146](https://doi.org/10.2514/6.2025-0146). URL: <https://hal.science/hal-05469869>.

#### Conferences without proceedings

- [2] Y. Gorschka, G. Puigt, A. Remigi, C. Content, B. Maugars and C. Tarsia Morisco. 'Reviewing the Vertex-Centered V4 Scheme for More Accurate Mesh Adaptation'. In: *AIAA SCITECH 2025 Forum*. Orlando, United States: American Institute of Aeronautics and Astronautics, 3rd Jan. 2025. DOI: [10.2514/6.2025-1108](https://doi.org/10.2514/6.2025-1108). URL: <https://hal.science/hal-05469898>.

### 9.2 Cited publications

- [3] F. Alauzet, L. Billon, E. Parente, M. Philit, A. Remigi and D. Papadogiannis. 'Evaluation of heat transfer performance of a film-cooled turbine vane using metric-based anisotropic mesh adaptation'. In: *AIAA SCITECH 2023 Forum*. National Harbor, MD, USA, 2023. DOI: [10.2514/6.2023-1399](https://doi.org/10.2514/6.2023-1399) (cit. on p. 14).
- [4] F. Alauzet, F. Clerici, A. Loseille, M. Maunoury, L. Rochery, C. Tarsia-Morisco, L.-M. Tenkes and J. Vanharen. '4<sup>th</sup> AIAA CFD High Lift Prediction Workshop results using metric-based anisotropic mesh adaptation'. In: *AIAA Fluid Dynamics Conference*. Chicago, IL, USA, June 2022 (cit. on p. 14).
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