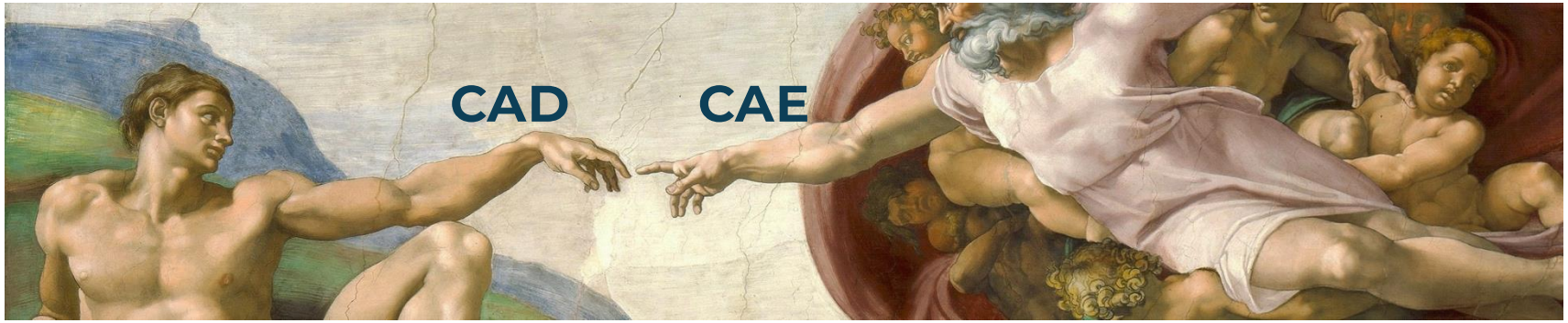


From Geometric Design to Numerical Analysis

Isogeometric CAD–CAE Integration with DTATools

SCHOOL OF MATHEMATICAL SCIENCES · DALIAN UNIVERSITY OF TECHNOLOGY

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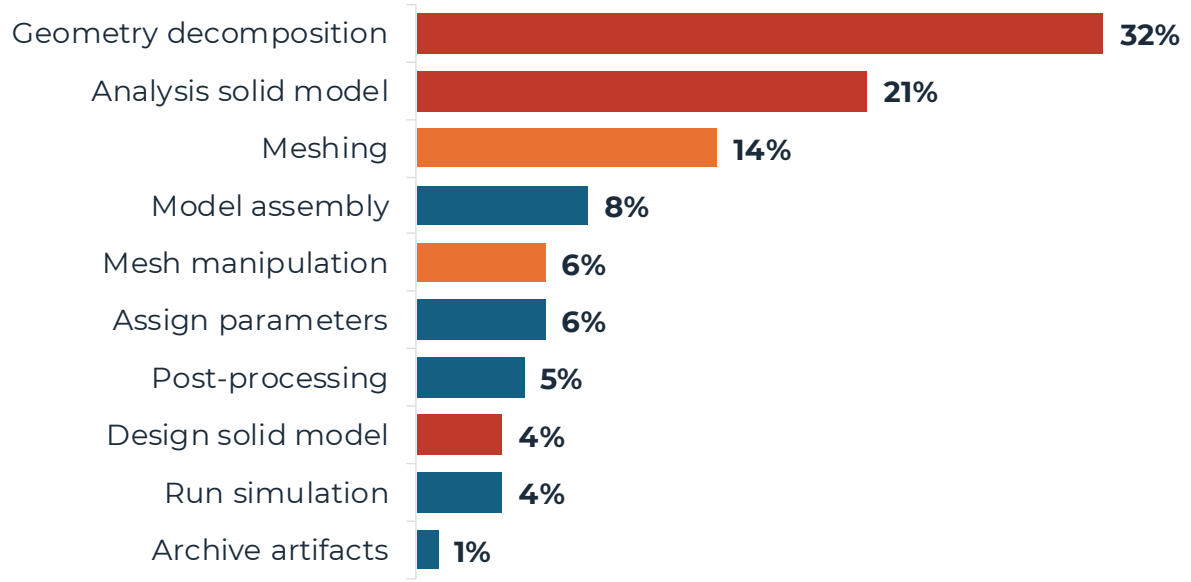
19 October 2026 · y.ji-1@tudelft.nl · jiyess.github.io



1. Introduction and motivation
2. DTATools: Design-Through-Analysis Tools
3. Analysis-suitable parameterization
4. Analysing the STEP solid directly
5. Optimization: the loop back to CAD
6. Industrial impact and open problems

Geometry preparation and meshing dominate the DTA workflow

~80% of effort spent on geometry preparation and meshing in the reported Sandia workflow



Share of time per task · red: geometry · orange: mesh · blue: analysis

57% — **Geometry preparation**
Creating analysis-suitable geometry takes the largest part

20% — **Mesh generation**
Building and modifying the mesh adds further effort

4% — **Running the simulation**
Solver execution is a small share of reported effort

- **The design-to-analysis transition is a major workflow bottleneck.**
- IGA addresses it by using the same spline representations for both geometry and solution approximation.

Source: M. Hardwick and R. Clay, Sandia National Laboratories; in Cottrell, Hughes and Bazilevs, Isogeometric Analysis (Wiley, 2009), Fig. 1.2. Shares sum to 101% due to rounding.

IGA: a shared spline basis for geometry and analysis

Isogeometric analysis

Hughes, Cottrell & Bazilevs, 2005

① **Geometry from CAD**

$$\boldsymbol{x}(\xi) = \Sigma_i N_i(\xi)\, \boldsymbol{P}_i, \quad \boldsymbol{x} : \hat{\Omega} \to \Omega$$

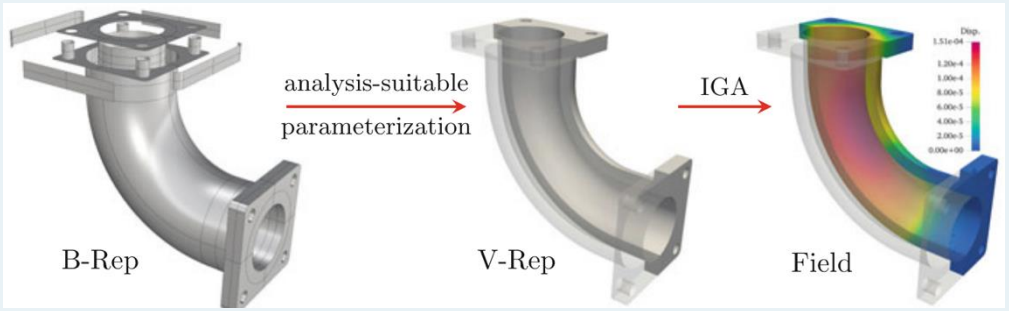
② **Solution using the mapped spline basis**

$$u_h(\boldsymbol{x}(\xi)) = \Sigma_i N_i(\xi)\, d_i$$

③ **Example: Poisson stiffness matrix**

$$A_{ij} = \int_{\hat{\Omega}} (\boldsymbol{J}^{-\mathrm{T}} \nabla_\xi N_i) \cdot (\boldsymbol{J}^{-\mathrm{T}} \nabla_\xi N_j)\, |\det J|\, \mathrm{d}\xi$$

$$J = \partial \boldsymbol{x} \,/\, \partial \xi$$



Parameterization quality matters

- **Validity:** globally bijective map, det $J > 0$
- **Accuracy:** mapping distortion affects approximation error bounds
- **Efficiency:** mapping distortion can worsen matrix conditioning

- A **shared** spline **representation** connects design and analysis;
- A **good parameterization** makes the connection **more effective**.

A shared spline basis is necessary, but not sufficient



1 Gap: No interior

A B-Rep only describes surfaces; analysis needs a bijective volumetric map.

DTATools: Spline volumes from the STEP solid (Parts 3–4)

2 Gap: Trimmed solids

Real parts are trimmed, multi-face B-Reps: no tensor-product structure.

DTATools: Immersed analysis on the exact CAD faces (Part 4)

3 Gap: Open loop

Optimizers return control points or densities, not CAD models.

DTATools: IGA shape / topology optimization → CAD (Part 5)

A shared CAD model across analysis and optimization

TYPICAL FILE-BASED WORKFLOW

CAD
B-Rep, NURBS surfaces
(.stp, .iges etc.)

→

Mesh generation
the CAD link is lost
(.msh, .node, .ele, .poly, etc.)

→

FEM
stiffness on the mesh
(.inp etc.)

→

Optimizer
densities or node positions
(.mat, .vtk etc.)

Additional reconstruction or CAD association

DTATools removes the file-conversion step

DTATOOLS · SAME WORKSPACE

Design
feature history or STEP/IGES

→

Discretization
cut cells · spline volumes · tets

→

Analysis
on the chosen discretization

→

Optimization
shape and topology

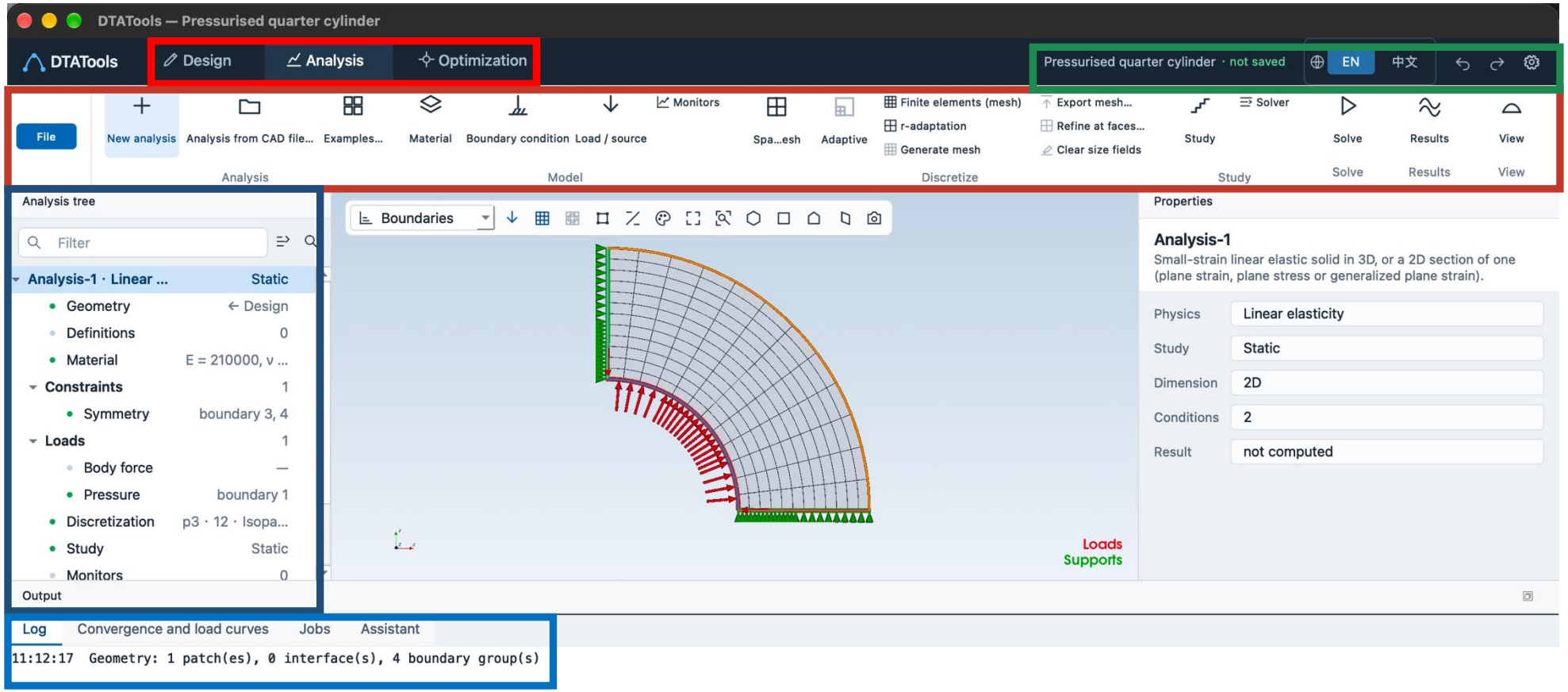
Rebuild as CAD: iso-surface → quads → motorcycle-graph patches → **watertight B-Rep**, clipped to the part

- The file-based conversion step is gone: the CAD model stays linked to the analysis.



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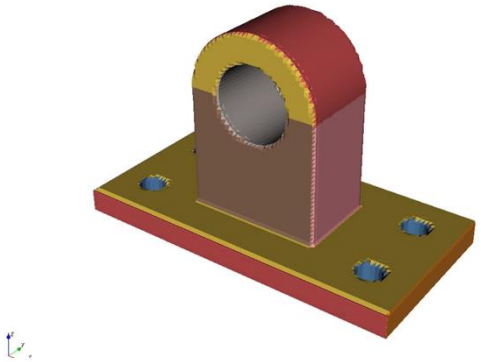
DTATools: Design-Through-Analysis Tools



- An **integrated workspace** connecting geometric design, analysis setup, and computational feedback.

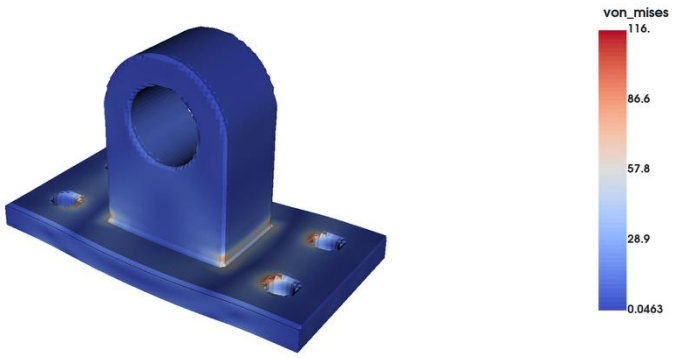
One workspace for design, analysis and optimization

Constructive Solid Geometry



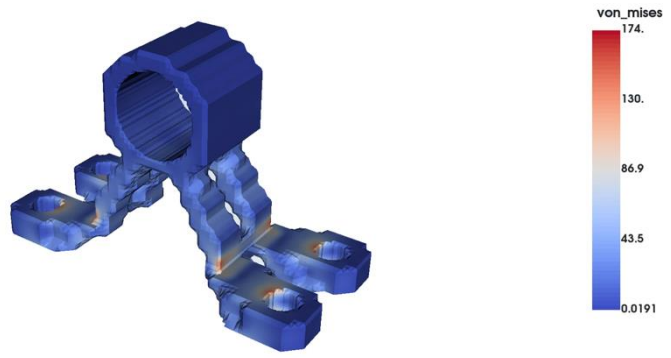
Design

- Feature history: supports various feature types
- STEP/IGES import and export
- Drag control points, Jacobian check



Analysis

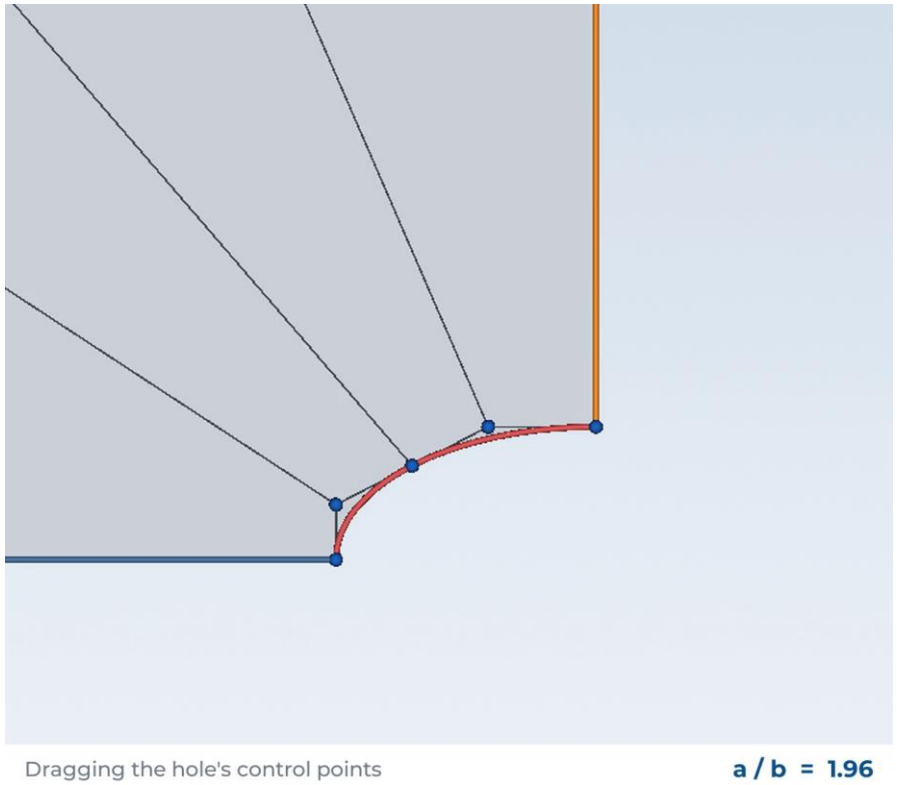
- Various analysis modules: heat, shells, solids, flow, LBM, FSI, additive manufacturing etc.
- NURBS, C^1 multi-patch, THB
- (Immersed) IGA and r-adaptive



Optimization

- Parameter, IGA shape (adjoint gradients), SIMP, level set
- MMA, OC, Nelder–Mead etc.
- Results written back to the design

Design module: spline editing with a linked analysis



The plate with a hole, in the design module: the five control points on the hole arc are dragged by hand, and the spline boundary follows them

- **Drag control points**: coincident interface points move together, the Jacobian is certified, fold-overs flagged;
- **Features**: sketch, extrude, revolve, loft, sweep, thicken, or **import STEP/IGES;**
- **Edits propagate** downstream; boundary groups follow the features;
- **An analysis references the design**: no file export between design and analysis.

Geometry representations and supported conversions

1 Explicit boundary

B-rep (STEP, IGES, BREP) · NURBS, B-spline, Bézier · THB · triangles (STL, OBJ)

Cut cells, or body-fitted IGA

2 Implicit

Analytic f(x) = 0 · signed distance · level sets in topology optimization

ImplicitShape: value, gradient, id

3 Constructive

CSG: primitives and booleans · feature history

Written back out as a B-Rep

4 Volumetric

Voxels (MetaImage) · octree, balanced 2:1 · tetrahedra and hexahedra · trivariate splines

Trivariate splines

5 Conversions

CSG → B-Rep · level set → triangles → quads → spline patches → watertight B-Rep

Topology optimization reconstruction

6 Currently unsupported

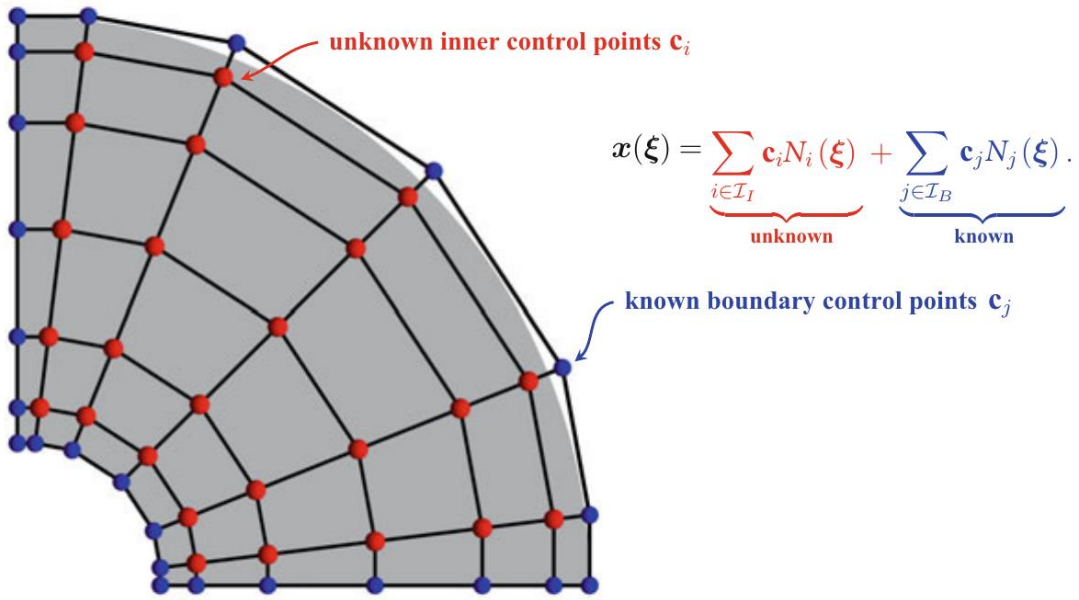
T-splines · subdivision surfaces · neural implicits · point clouds · surfels · medial axes

Point clouds: next step



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Given the boundary, find a good interior map



Blue: known boundary control points · red: unknown inner ones

Find the unknown inner control points c_i so that x is

1. **Locally regular**
   det J > 0 everywhere on Ω
2. **Low conformal distortion**
   singular values $\sigma_1 \approx \sigma_2$ of J close to each other
3. **Minimal area / volume distortion**
   uniform cells: det J ≈ vol(Ω) on $\Omega = [0,1]^d$

Quality metrics: scaled Jacobian $d_s = det\,J \,/\, \Pi_i \|x,\xi_i\| \in [-1, 1]$ · uniformity $(det\,J \,/\, area(\Omega) - 1)^2$

Methods of this part: implemented in G+Smo (github.com/gismo/gismo, examples/as_parameterization); being ported into DTATools.

Analysis-suitable parameterization techniques

Barrier function-based method Ji et al., JCAM 2021

1 Initialize · one linear solve

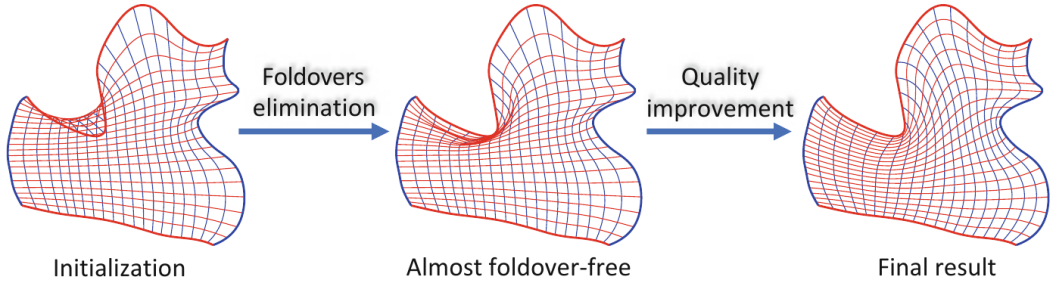
$argmin \int \|\Delta x\|^2 \, d\xi$

2 Eliminate foldovers · $\delta \downarrow$ adaptively

$argmin \int max\{0, \delta - det\, J\} \, d\xi$

3 Improve quality

$E^c = E \;\; if \; min \; det\, J > 0, \;\; else \; +\infty$



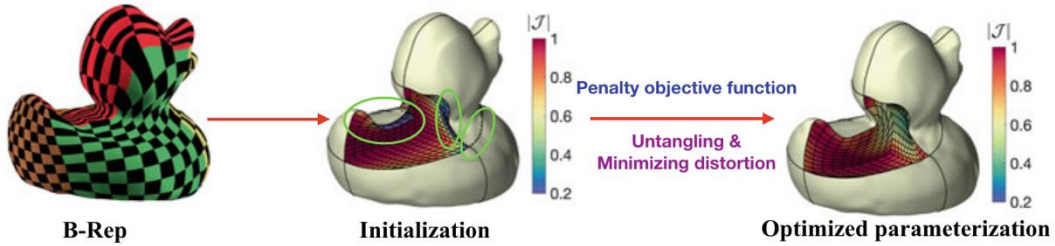
Penalty function-based method Ji et al., CAGD 2022

Regularize the Jacobian

$\chi(det\, J) = \varepsilon \cdot exp(\beta(det\, J - \varepsilon)) \;\; if \; det\, J \le \varepsilon, \;\; else \; det\, J$

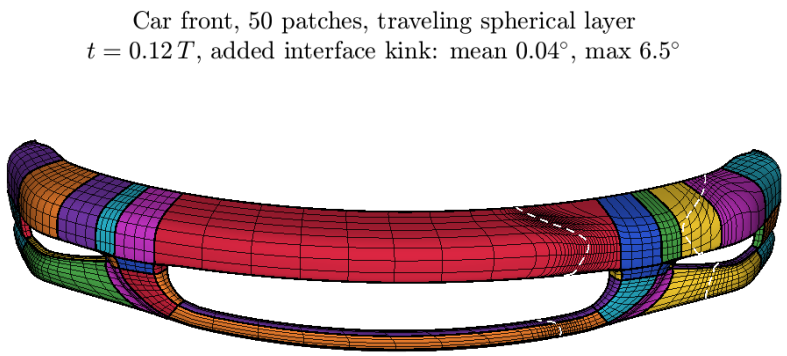
Replace det J by χ in the energy: untangling and distortion minimization **in one step**

Starts from invalid initial guesses; works in 2D and 3D

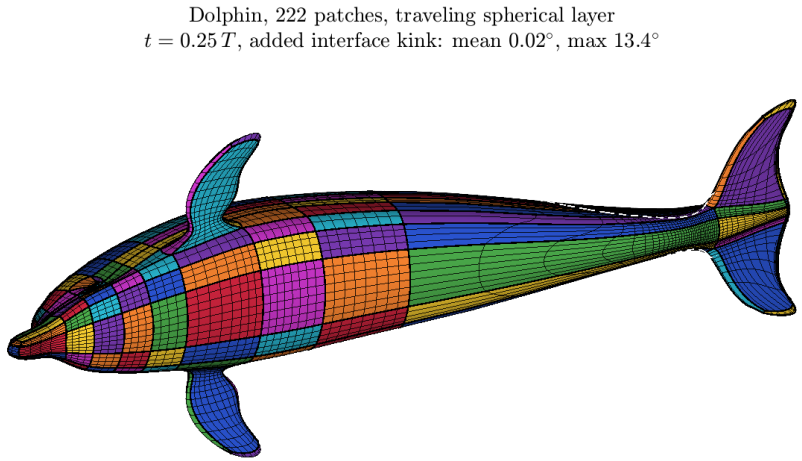


PDE-based method weighted harmonic map, accelerated by preconditioned Anderson acceleration

Multipatch CAD surface r-adaption



Car front: 50 patches · traveling layer



Dolphin: 222 patches · traveling layer

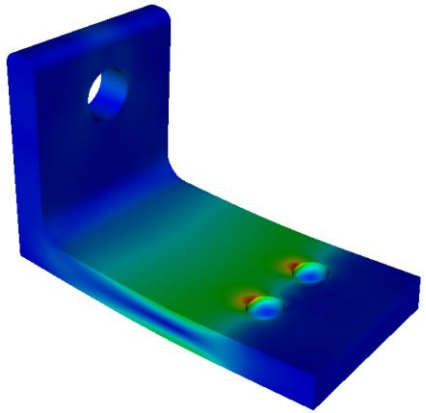
- **Winslow-type r-adaptivity** on multi-patch CAD surfaces; the map is **certified fold-free**, not just sampled;
- Low-rank Kronecker assembly makes it affordable: a low-rank weight turns the stiffness matrix into Kronecker products of banded univariate matrices — **10^2–10^5× faster than an element loop** (7–300× with the conversion to sparse), and a fast-diagonalization preconditioner replaces the direct solver: 11–110× faster.

Ongoing work: the surface reparameterizations shown here are not yet published.



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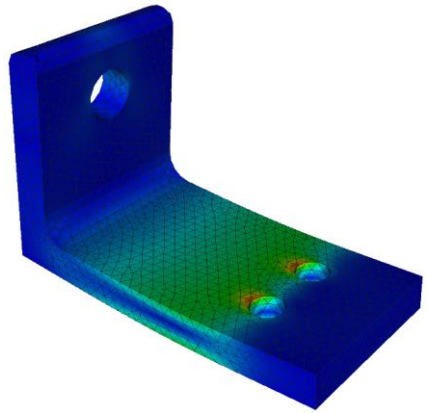
The same STEP solid, discretized four ways



Immersed cut cells

A Cartesian grid cut by the 20 CAD faces. Geometry exact; the mesh does not conform.

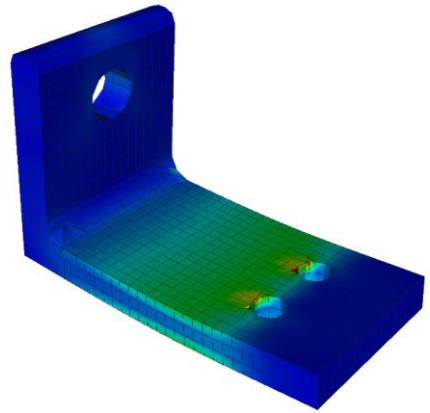
3 339 cells · 17 775 dof



Body-fitted tetrahedra

A conforming mesh; the CAD faces become flat facets.

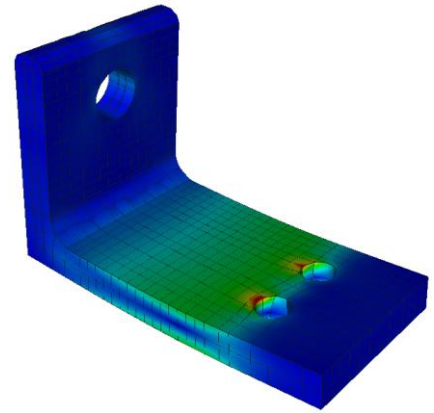
12 015 elements · 62 277 dof



Overlay hexahedra

A grid fills the interior; a fitted hex layer is snapped onto the CAD faces.

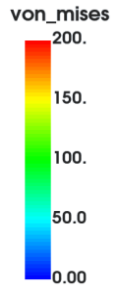
4 306 elements · 16 197 dof



Spline volumes

A polycube map turns the solid into 254 curved blocks on the exact CAD faces.

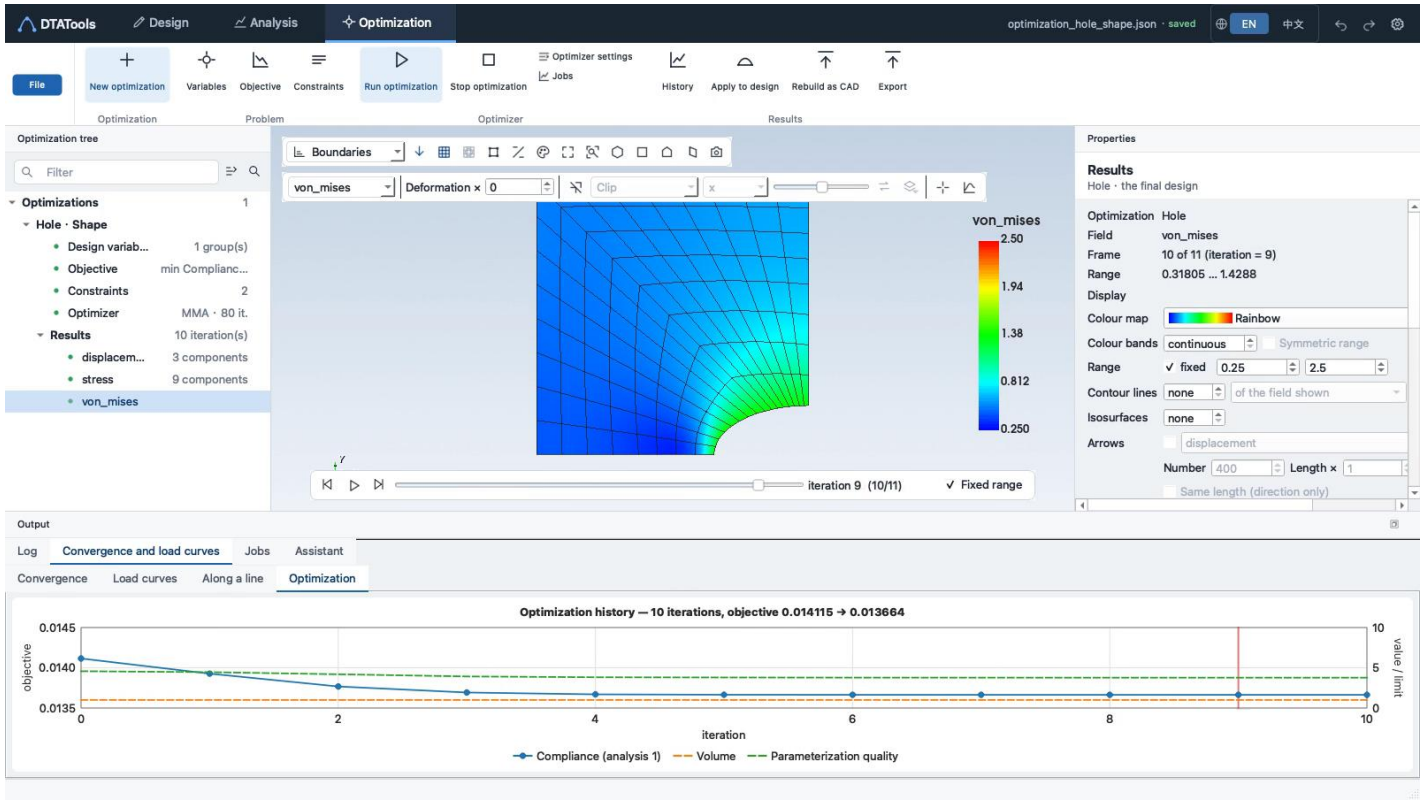
1 860 elements · 31 827 dof





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Shape optimization with spline control points



DTATools GUI: the hole reshapes iteration by iteration; peak von Mises 2.46 → 1.43 (fixed range)

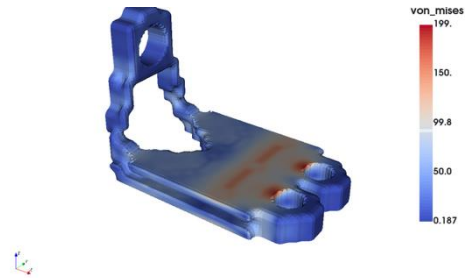
Why IGA is the natural setting

- Control points are **the design variables and define the analysis map**: the CAD geometry is kept, no remeshing;
- **Analytical discrete adjoint** shape gradients;
- A sampled lower bound on the **Jacobian** keeps the map valid while it moves;

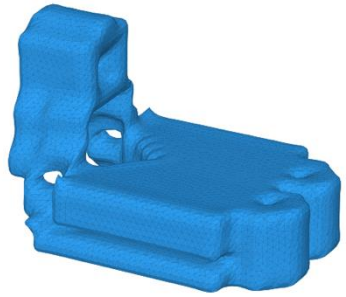
Check: optimal elliptical hole

biaxial tension $\sigma x = 2\sigma y$, area fixed: **a/b = 1.955** after 9 MMA steps (infinite plate, remote load: 2)

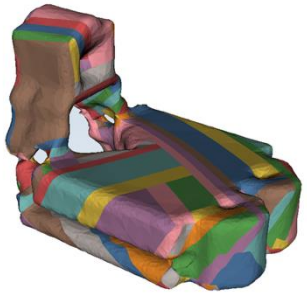
Optimized topology: CAD reconstruction and re-analysis



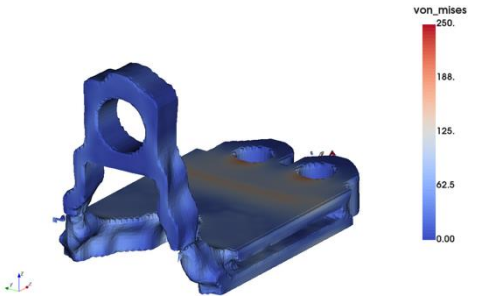
Topology optimization
cut-cell analysis · 40 % target volume



Surface extraction
iso-surface → remeshed → quad mesh



Patch reconstruction
241 B-spline patches, shared boundaries



CAD solid, re-analysed
174 faces after intersection with the part

Valid, watertight CAD solid · 0.5432 → 0.5371 mm, −1.1 % · 2 min 52 s

Retained CAD faces plus newly fitted B-spline surfaces. Re-analysed under the original loads, the lift under the pin is 0.5371 mm against 0.5432 mm for the thresholded topology; the integrated bolt reaction is 951.4 N against an applied 960 N.

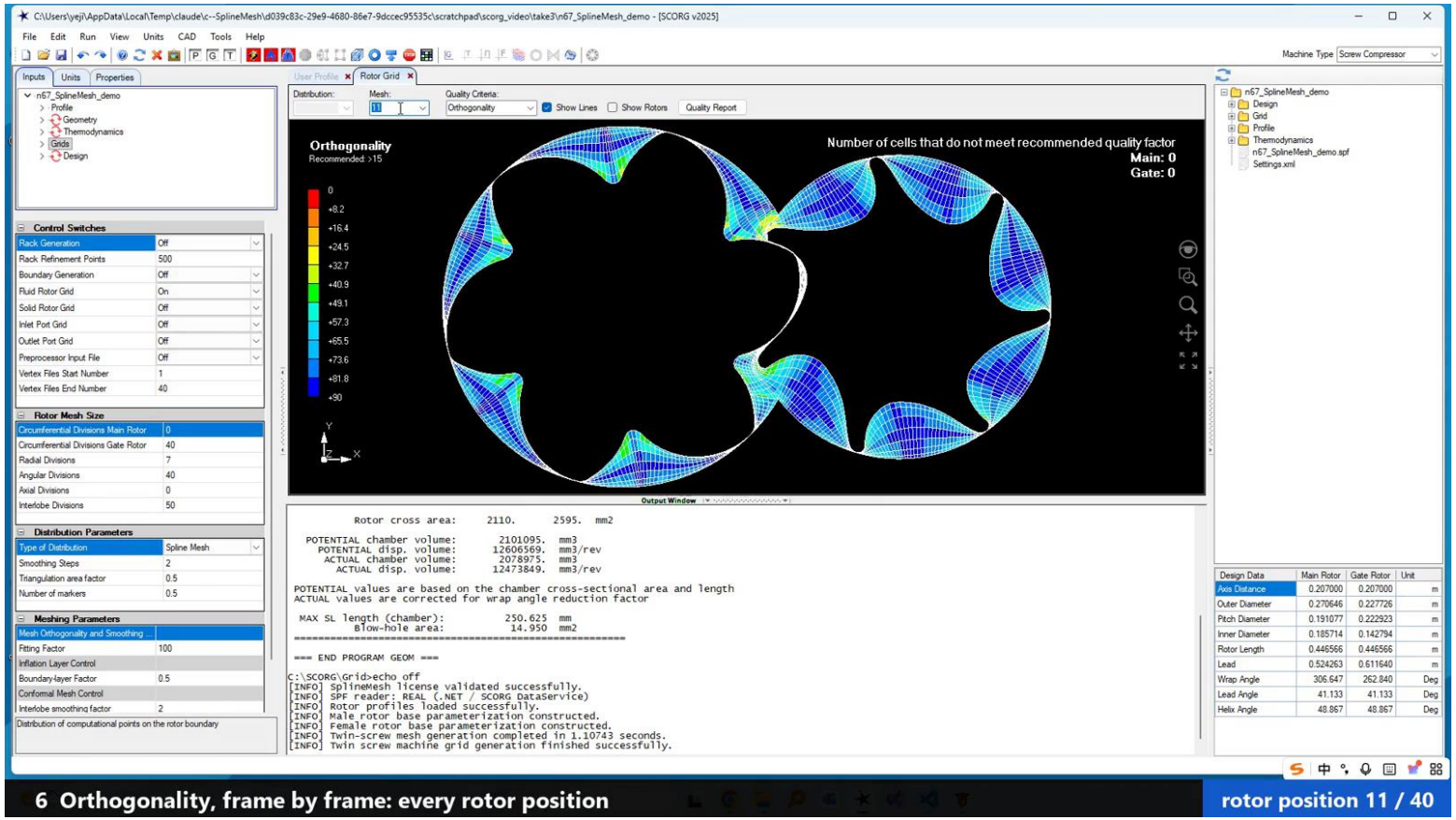
LIVE DEMO

Layout: the motorcycle graph of the quad mesh (Eppstein et al. 2008); pipeline after AMRTO (Ren et al., CMAME 435, 2025) — here every arc is fitted once, so neighbouring patches share their boundary curves exactly. Colour: von Mises stress, each plot on its own scale.



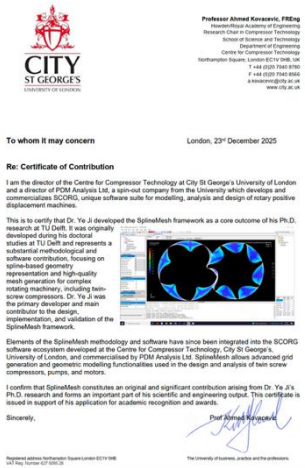
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From research code to the commercial CFD tool SCORG™



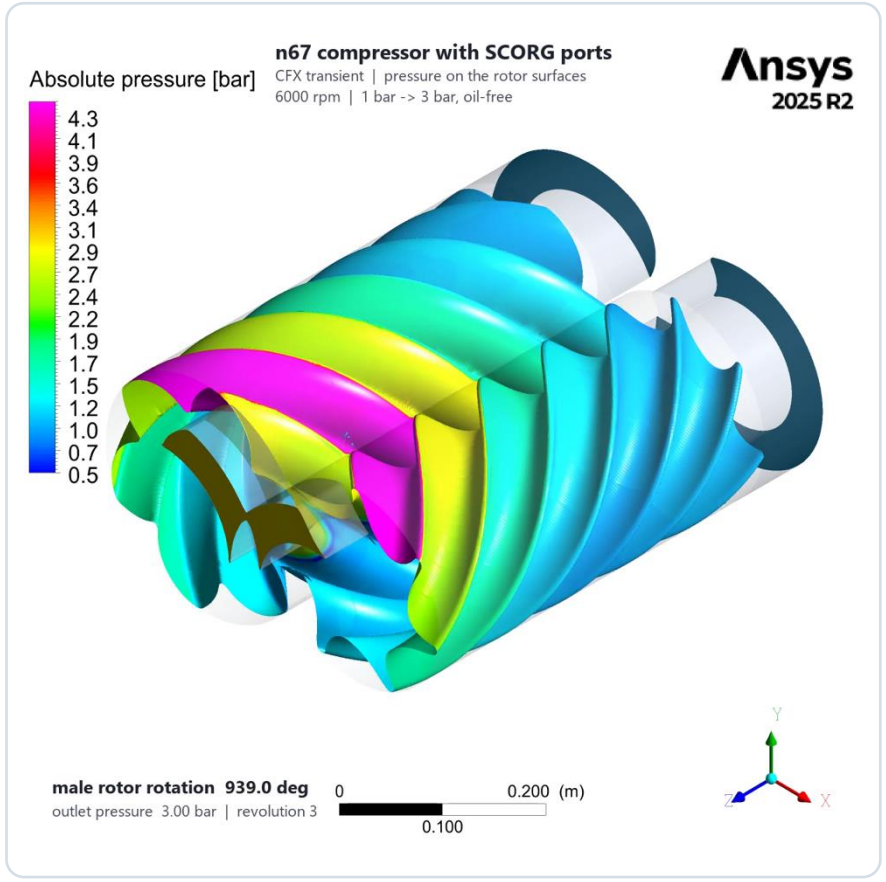
SCORG™ with SplineMesh: grid type → orthogonality per rotor position → 3D mesh

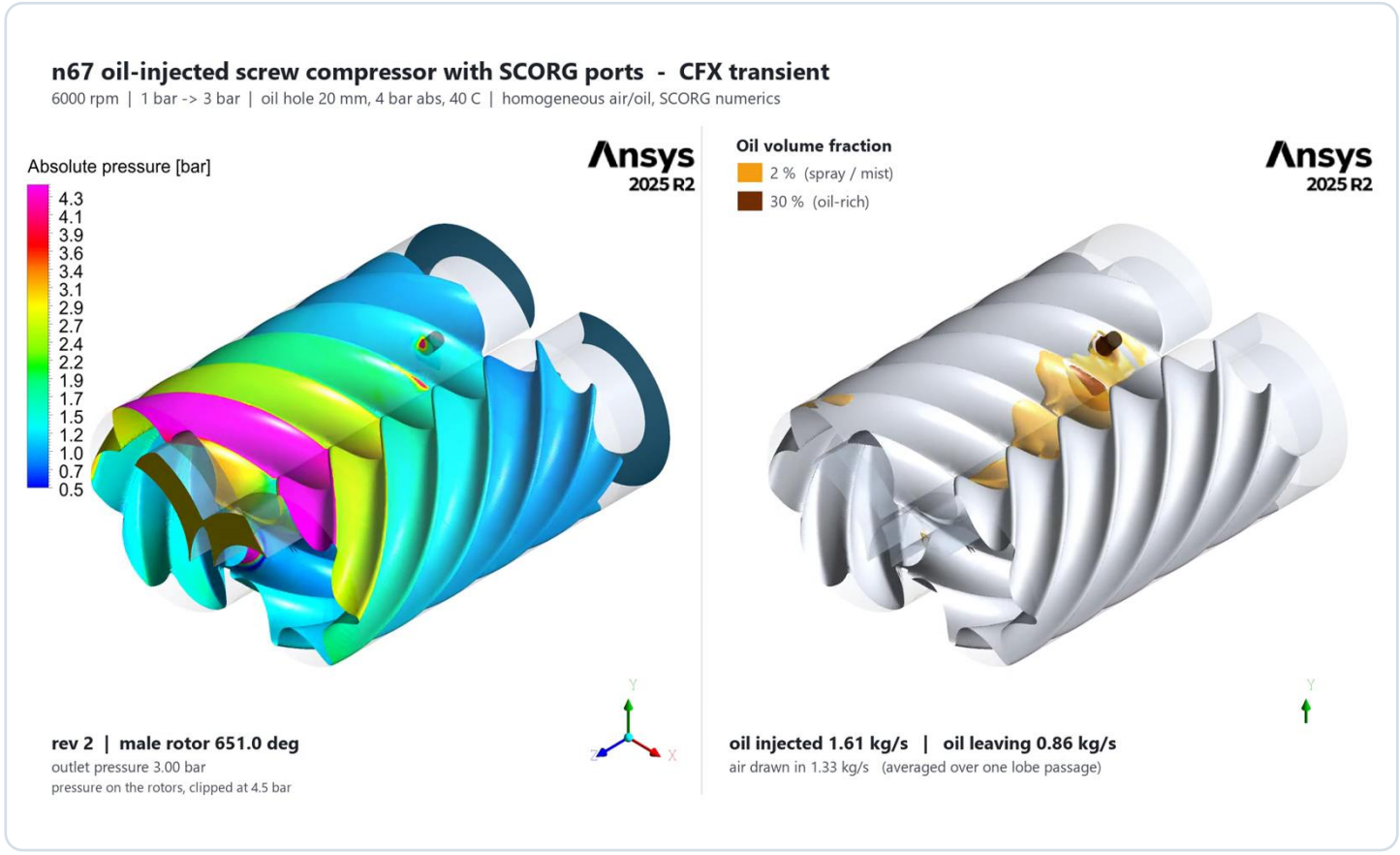
- **SplineMesh**, from my PhD work, is **integrated into SCORG™** for screw compressors, expanders and vacuum pumps;
- **Best Paper Award**, ICSM 2024 (Dortmund);
- **Short course & talk**, ICCS London 2025.



Contribution letter from the SCORG™ developer

...driving industrial CFD: screw compressors in ANSYS CFX





Dry: pressure on the rotors, 6000 rpm, 1 → 3 bar

Oil-injected: pressure and oil volume fraction

Transient CFX runs on SplineMesh grids generated in SCORG™; N67 compressor with ports.

Open mathematical questions in CAD–CAE integration

1 Certified injectivity

Today Sufficient conditions on the spline coefficients certify $\det J > 0$ patch by patch — conservative, and local.

Open Certificates for the whole multipatch map, and for trimmed volumes.

2 Analysis-aware optimality

Today Parameterizations are chosen for low geometric distortion.

Open Which map minimizes the discretization error, or the condition number, for a given PDE?

3 Moving domains

Today r-adaptation moves the mesh at fixed topology, fold-free at every step reported here.

Open Time-continuous, validity-preserving maps for FSI and rotating machines, with a bound that holds along the path.

4 Topology & 3D harmonic maps

Today Radó–Kneser–Choquet theorem gives injectivity in 2D for convex targets.

Open A 3D counterpart, and robust and efficient patch layouts chosen automatically.

On the software side Last week, NVIDIA has just opened the **SMLib NURBS kernel** as **USD BRep** (Apache 2.0, with MIT Python bindings) — a permissively licensed B-Rep kernel we could move to in place of OpenCASCADE.

A connected workflow for CAD, analysis and optimization

Where the three gaps now stand

- **Gap 1, no interior**: body-fitted analysis-suitable parameterization can be used; immersed method can be an alternative or complementary;
- **Gap 2, trimmed solids**: analysed on their own CAD faces, with one file carrying four discretizations;
- **Gap 3, open loop**: in the examples shown the optimized topology returns as a watertight CAD solid, re-analysed in the same session.

With many thanks to Prof. Chun-Gang Zhu for the invitation, and to Prof. Matthias Möller and all collaborators.

Many thanks for your kind attention!

If you are interested in my research, please feel free to contact me! ;-)

Email: y.ji-1@tudelft.nl Homepage: https://jiyess.github.io/

TU Delft Delft University of Technology

With many thanks to Prof. Chun-Gang Zhu for the invitation, and to Prof. Matthias Möller and all collaborators.

Many thanks for your kind attention!

Q&A

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- **Homepage:** https://jiyess.github.io/