Evaluation and comparison of mesh deformation techniques for industrial aerospace applications

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Aim of the work

The aim of this research is to evaluate and compare various state of the art mesh deformation methods to assess their suitability to be used in industrial aerospace optimisation.

The key features of a successful mesh deformation approach are accuracy, robustness and the quality of the resulting mesh.

Many mesh deformation approaches are used across research and industry, but their performance on industrial-representative cases has not been compared.

Comparison study

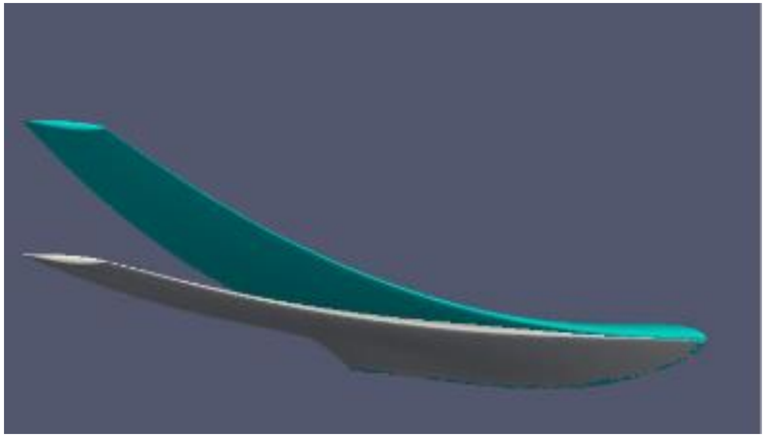
A comparison study was planned to compare the performance of various industrial and academic mesh deformation methods using a common case.

The CRM wing was selected as the common test case, with all partners testing their methods for a series of common deformations.

Comparison study

Common case CRM for study

- CRM wing
- 3M and 28M structured meshes
- Three basic deformations (upwards bending, downwards bending, twisting)
- One more complex test case to assess robustness (blended flap ±45º)



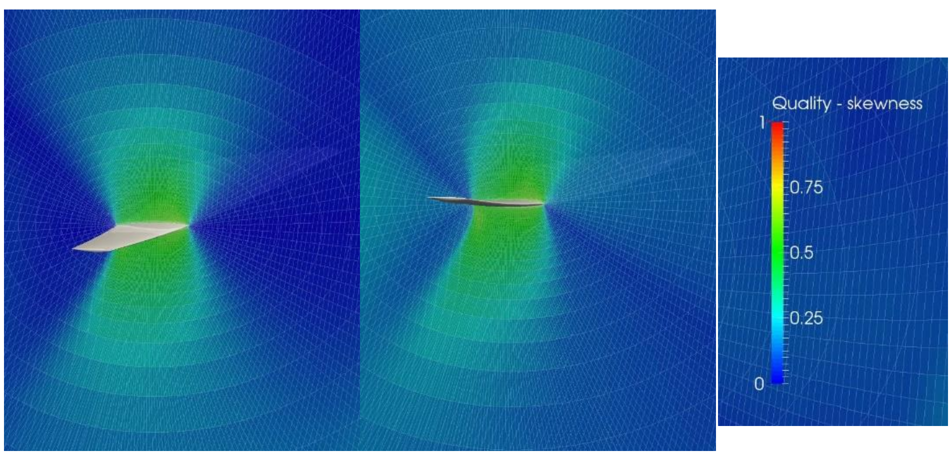
Common CRM upward bending case

Blended flap case

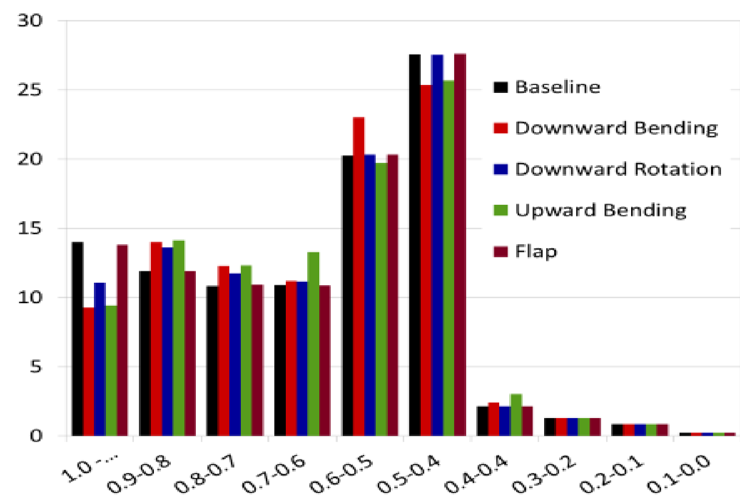
Comparison study

Mesh deformation

- Each partner is using a histogram approach to assess the mesh quality (focus on skewness) of the resulting deformations
- Attention will be paid to the computational cost of each method and the increase in cost as the mesh size is increased
- The results will be combined and the various methods compared



Upward bending skewness example

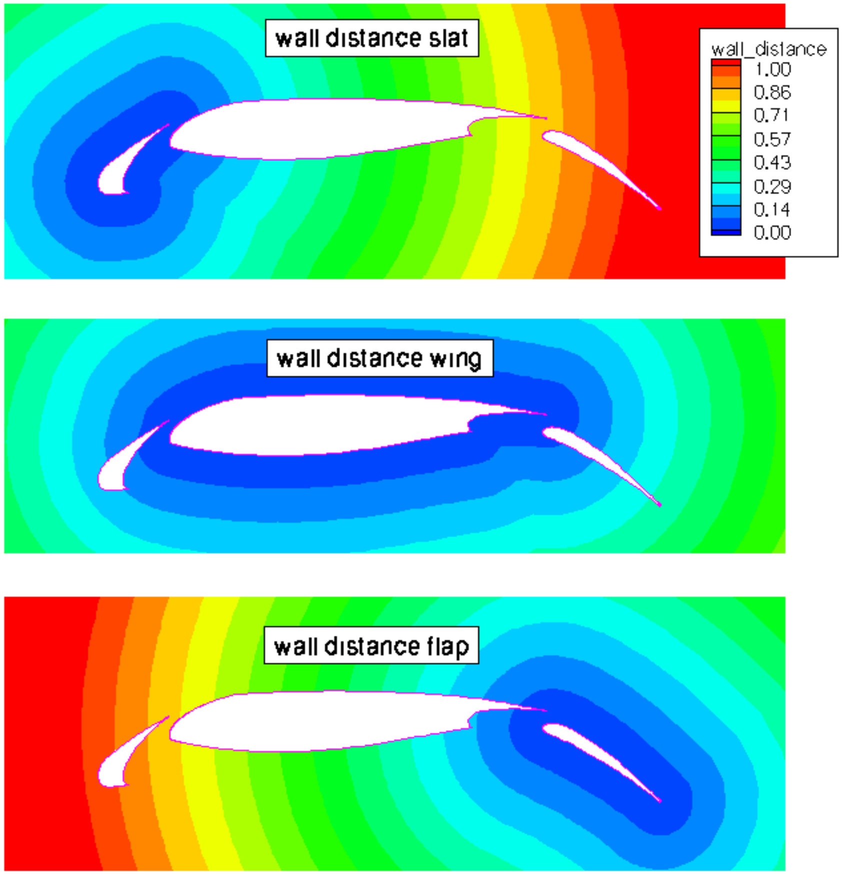


Mesh element skewness histogram example

Methods being compared

DLR – Radial Basis Functions (RBF)

- Deformation of block-structured and hybrid unstructured Meshes.
- Interpolation Functions:
  - volume-spline (used here),
  - cubic-spline,
  - thin-plate-splines.
- Blending Function based on Wall Distance:
  - Protection of Boundary Layers (no Deformation),
  - Deflections decline to zero for specified Wall Distance.
- Individual Interpolation Functions for different Aircraft Components, e.g. in High-Lift Applications.



DLR – Linear Elasticity Analogy (LEA)

- Considers the Fluid Domain as a solid Body, computes its elastic Response to prescribed deformations at the Boundary.
- Mesh is modeled as an elastic Solid with Lamé Parameters E and ν of a virtual Material.
- To protect small Cells in viscous Boundary Layer Young’s Modulus E depends on Element Volume: $E = vol(e)^{-\chi}$ with $\chi > 0$.
- Approach does not contain any explicit additional Orthogonalization of Boundary Layer, just tries to preserve Properties of undeformed Mesh.
- Implementation discretizes partial Differential Equation of linear elastic Behaviour using a linear finite-Element-Method.
- Equation System is solved in parallel using PETSc linear Algebra Routines.
- Computational Time depends on Choice of iterative Solvers and Parameter Settings.

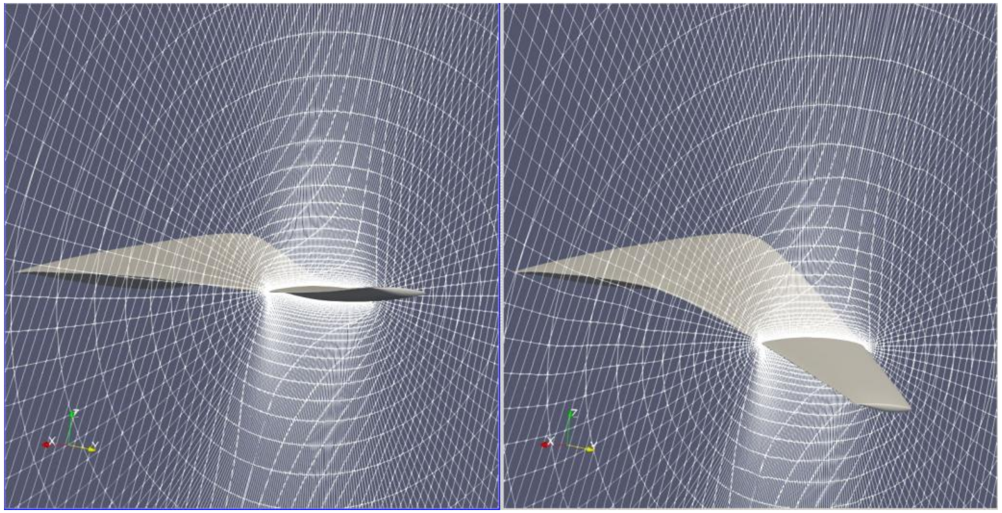
NTUA – 2 step RBF

- Predictor:
  Performs an RBF interpolation with global support using as targets a reduced set (after appropriate coarsening) of mesh nodes. The resulting linear systems, are solved with the Bi-Conjugate-Gradient-Stabilized iterative algorithm, coupled with a Sparse Approximate Inverse (SPAI) preconditioner. Once the RBF weights are known the displacement field for all mesh nodes is computed (accelerated using the Fast Multipole Method; FMM).

- Corrector:
  Aims at correcting the position of the surface nodes that do not precisely respect the a priori set displacements. In this step, all surface mesh nodes and only a few internal nodes (those located close to the surface) are used for a local RBF interpolation.

USFD – Inverse Distance Weighting

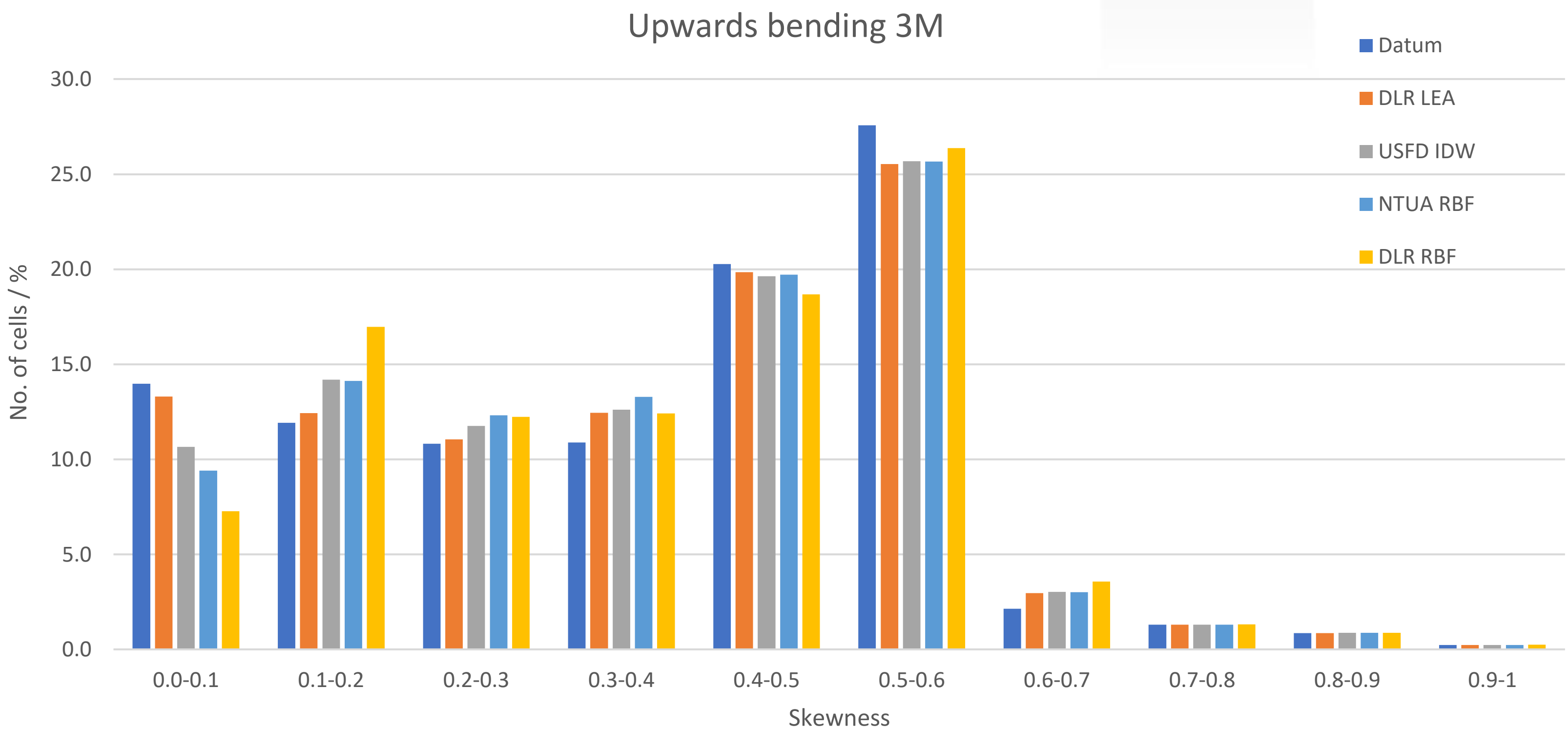
- IDW is an explicit interpolation technique, which computes the interpolation function as a weighted average of the known boundary node displacements. The weights are inversely proportional to the distances between the inner mesh nodes and the boundary nodes.



Mesh quality results

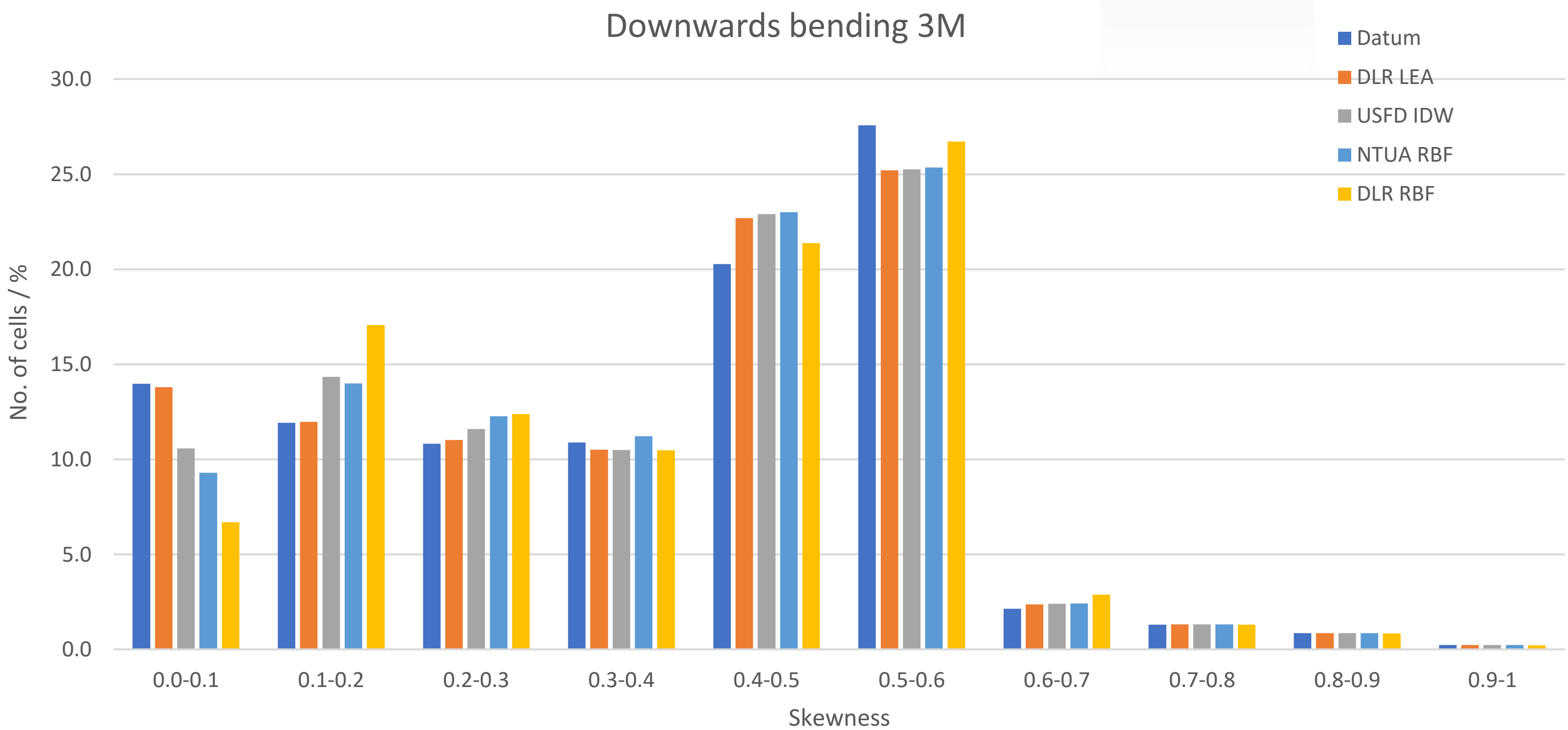
Results – upwards bending 3M

Quality 'ranking'



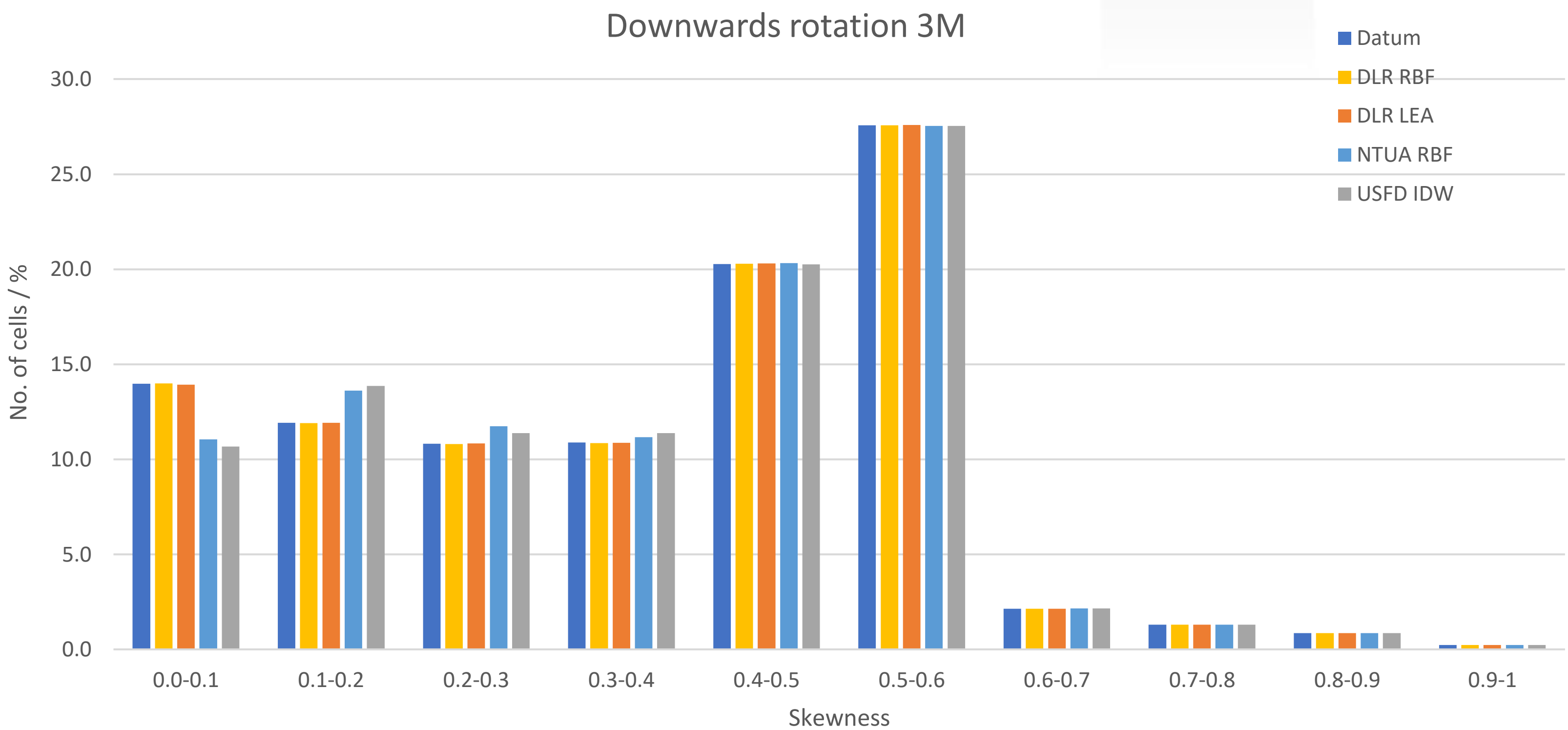
Key region to focus on is the change in the high quality cells (low skewness)

Results – downwards bending 3M



Upwards and downwards bending give quite similar results

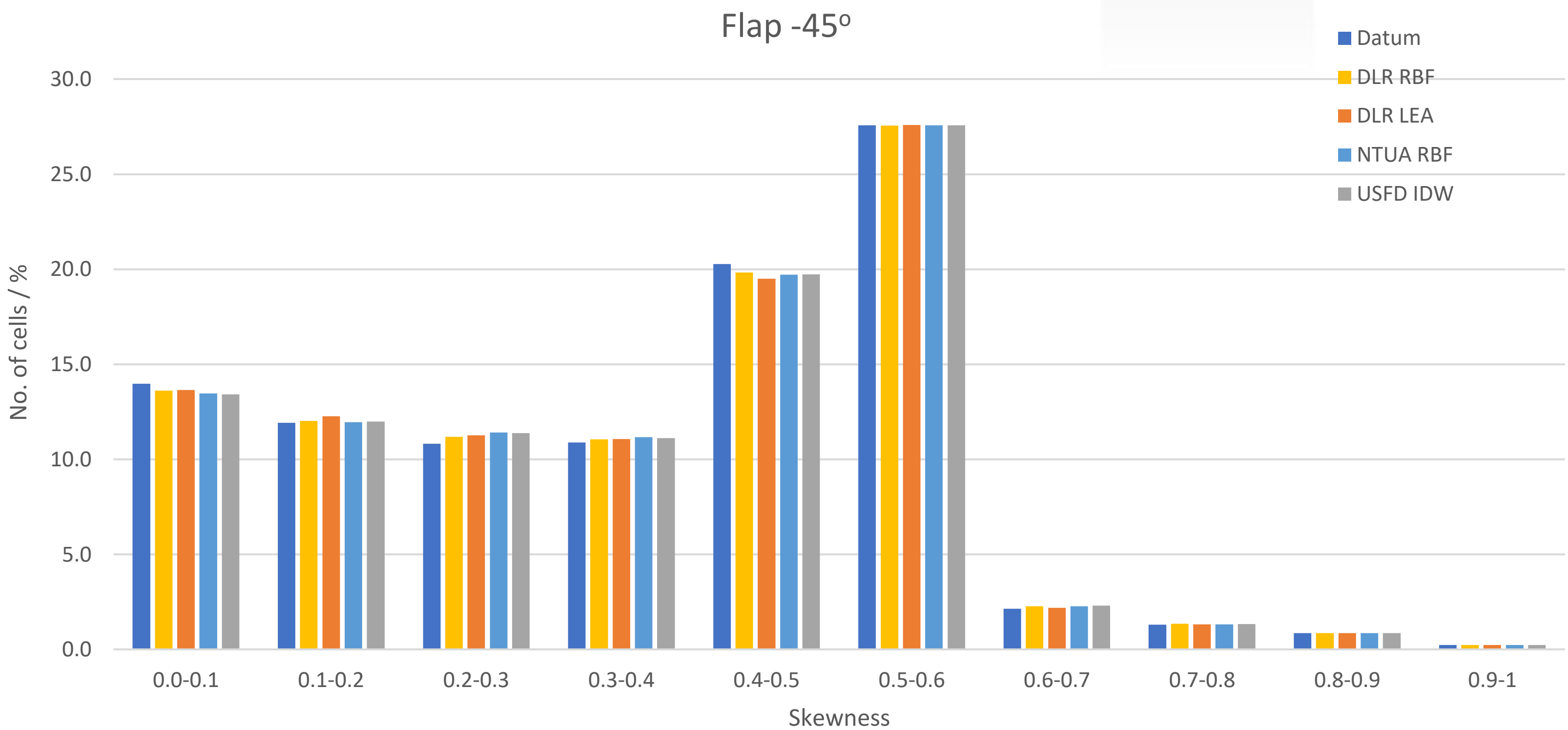
Results – upwards rotation 3M



DLR RBF and LEA cope very well with rotation, almost the same as datum

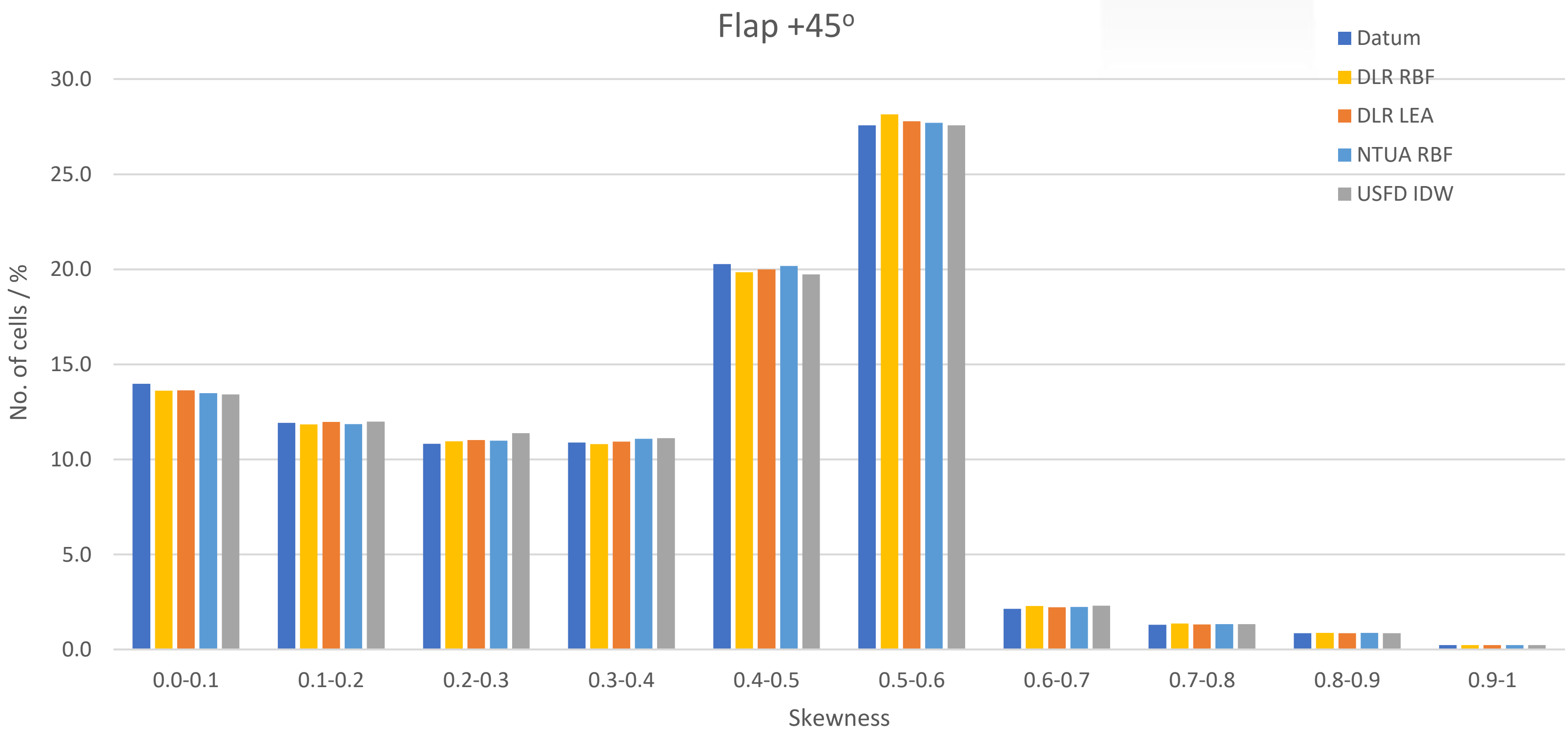
Other two are more similar to bending cases

Results – flap -45^o 3M



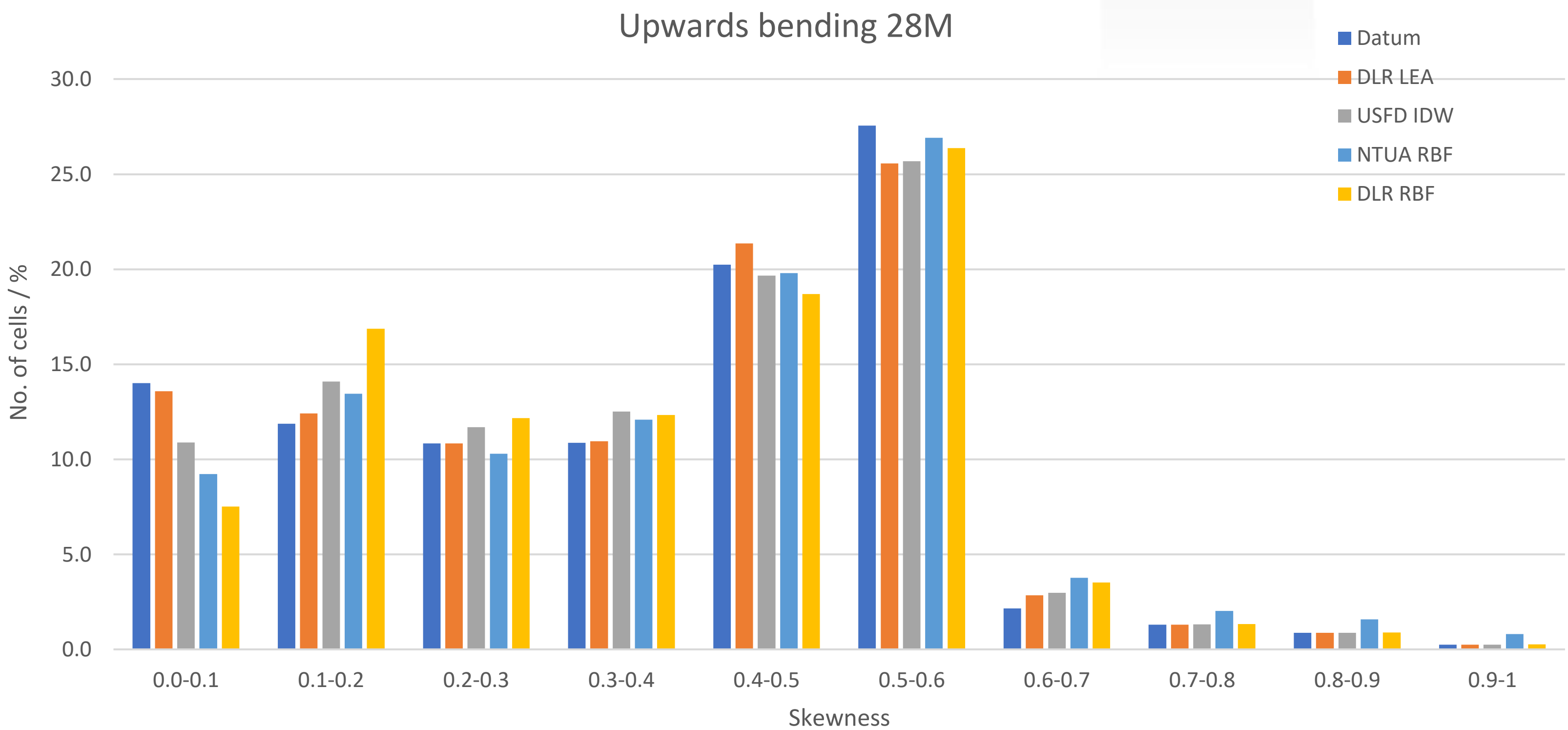
For all methods the flaps only have a very small effect because they are such a localised deflection

Results – flap +45^o 3M



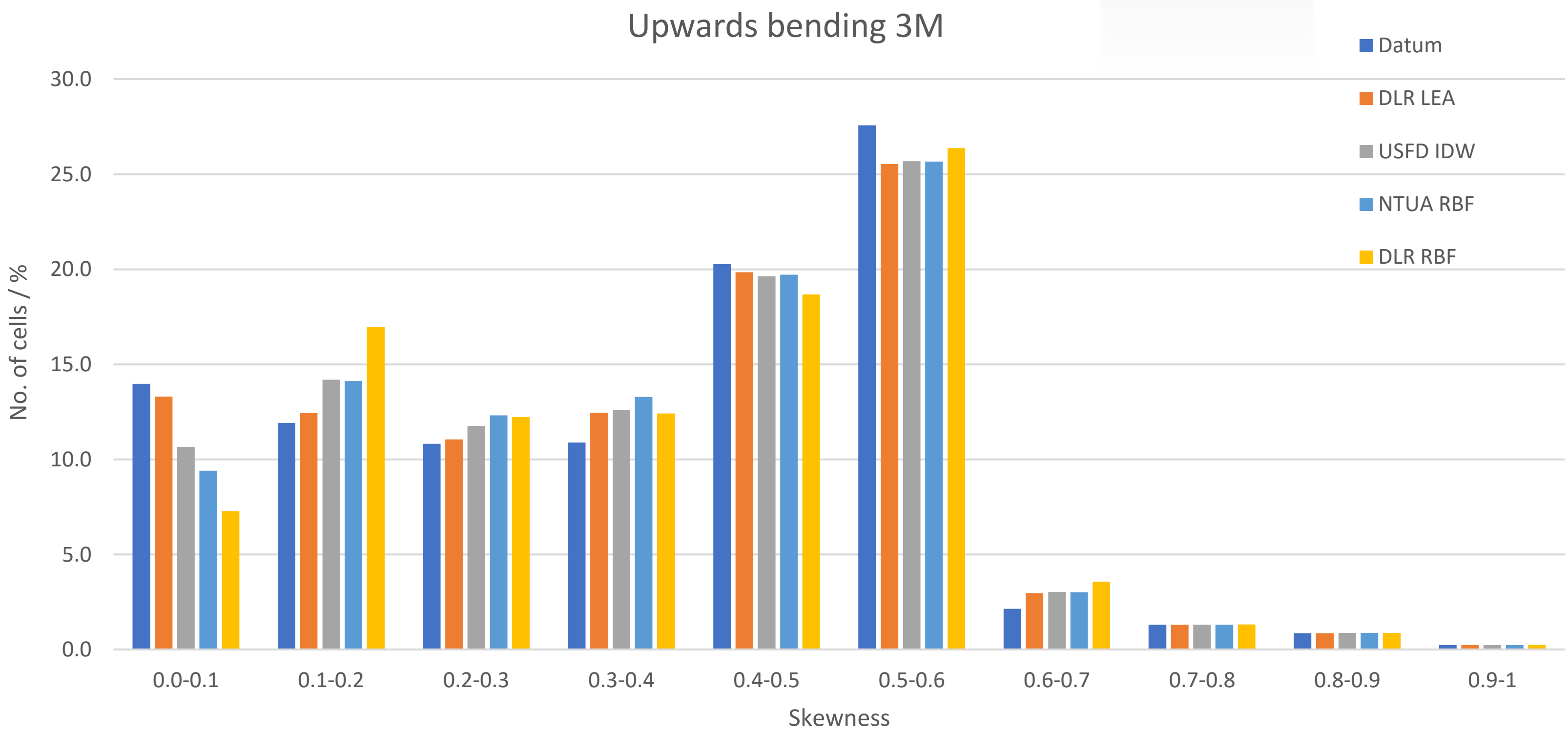
For all methods the flaps only have a very small effect because they are such a localised deflection

Results – upwards bending 28M



28M follows similar pattern to 3M for all cases, not showing all

Results – upwards bending 3M



28M follows similar pattern to 3M for all cases, not showing all

Mesh quality conclusions

- Quality of deformed Grids remains close to Baseline for all cases
- DLR LEA maintains the best quality, DLR RBF is the worst for bending cases
- DLR RBF and LEA cope very well with rotation, IDW and NTUA RBF have worse quality for rotation
- For all methods the flaps only have a very small effect because they are such a localised deflection
- 28M follows similar pattern to 3M for all cases
- More complex Configuration, including Pylons, Fairings, ..., needed to reveal Differences between Methods?

Results – robustness

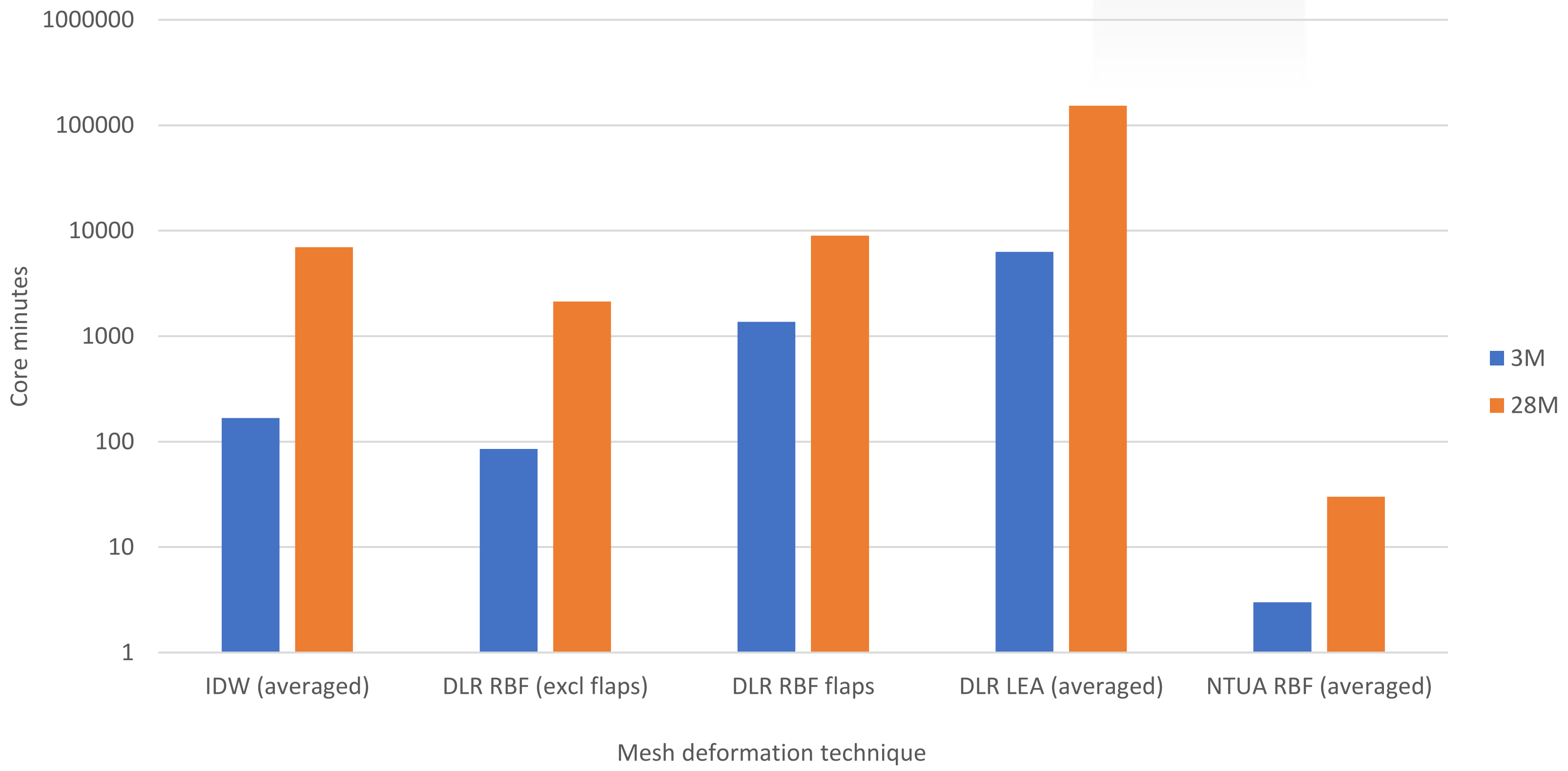
- DLR and NTUA reported no problems
- USFD IDW coped but with some adjustments

Computational time results

Results – computational time

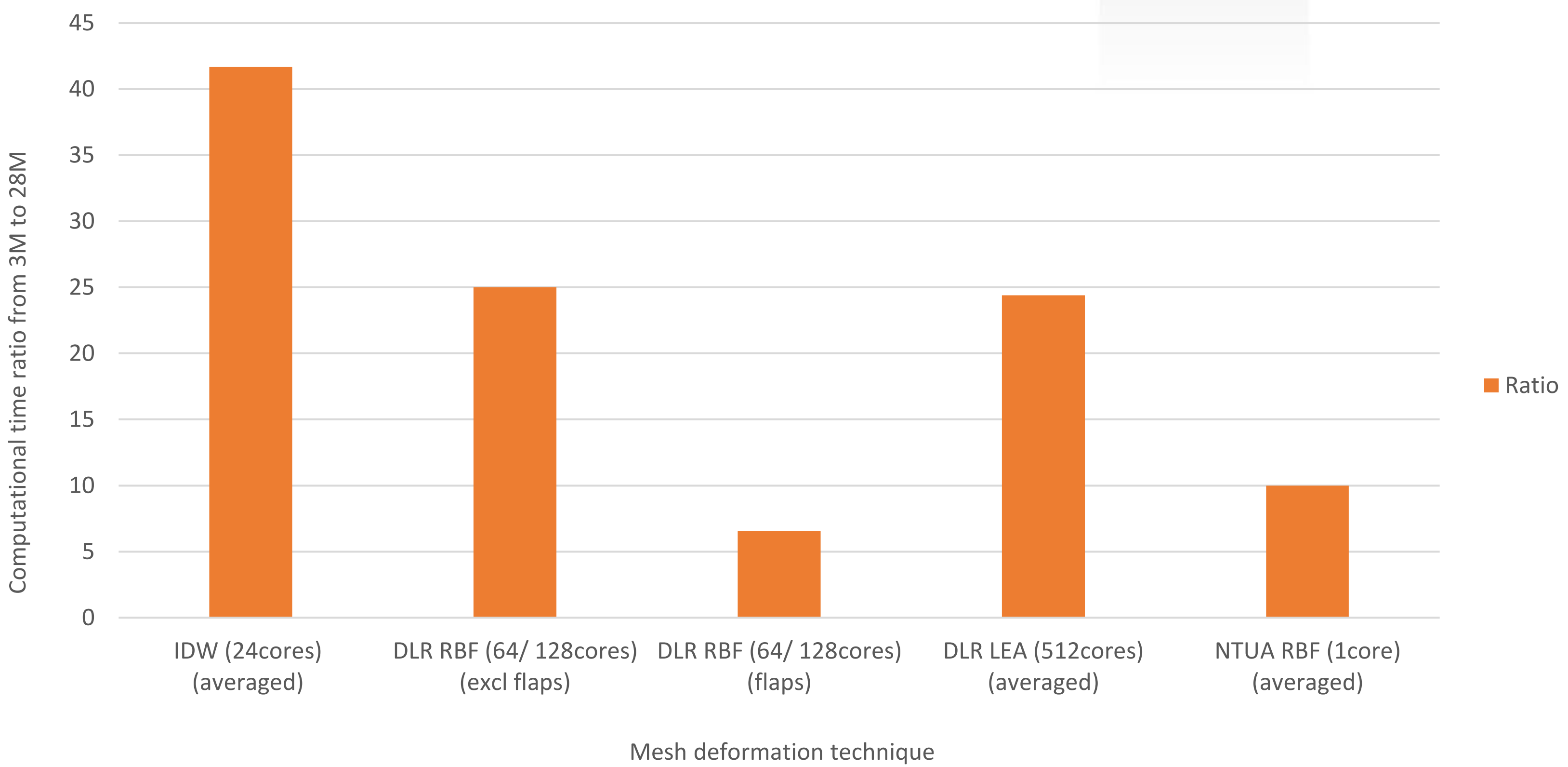
- Mostly plotted using the average time of all deflection types (upwards, downwards etc) for each method
- But DLR RBF saw a large increase in cost for the flap cases, so this is separate
- Ignoring differences between type of CPU used

Results – average computational time / core minutes



NTUA RBF clearly the most efficient by core minutes, LEA least

Results – average ratio between 3M and 28M



IDW least efficient with increasing grid size

Conclusions

- DLR LEA is the most expensive by at least an order of magnitude, but algorithms used in DLR LEA not yet optimized for Run Time
- DLR RBF took longer for Flap Deflection Cases (more Control Points needed => larger Interpolation Matrix)
- DLR RBF was sub-sampling surface points, whereas other techniques were using every surface point so comparison is hard
- NTUA two-step RBF seems very efficient when judging by core minutes (presumably this could be run in parallel too?)
- In terms of cost increase with mesh size, NTUA RBF was linear (10x mesh increase, 10x cost)
- IDW was the worst (10x mesh size, 40x cost)

Overall conclusions

- All methods demonstrated fairly robust behaviour and maintained mesh quality, and are ready to be used in adjoint optimisations
- DLR LEA gave the best quality but was the most expensive
- NTUA RBF was by far the least expensive and had good increase in cost with mesh size

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