# Appendix M

## Finite element model reduction for spacecraft thermal analysis

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**Abstract**

The finite element method (FEM) is widely used in mechanical engineering, especially for space structure design. However, FEM is not yet often used for thermal engineering of space structures where the lumped parameter method (LPM) is still dominant.
Both methods offer advantages and disadvantages and the proposed global approach tries to combine both methods:

- The LPM conductive links are error-prone and still too often computed by hand. This is incompatible with the increasing accuracy required by the thermal control systems (TCS) and associated thermal models. Besides offering the automatic and accurate computation of the conductive links, the FEM also provides easy interaction between mechanical and thermal models, allowing better thermo-mechanical analyses.
- On another hand, due to the large number of elements composing a FE model, the computation of the radiative exchange factors (REFs) is prohibitively expensive. New methods to accelerate the REFs computation by ray-tracing are necessary. Ray-tracing enhancement methods were presented in the previous editions, providing at least a 50% reduction of the number of rays required for a given accuracy. Another way to speed up the REF computation consists in grouping the FE external facets into super-faces. Surfaces in FEM are approximated where primitives are used in the LPM. In parallel to super-faces, quadric surface fitting of selected regions in the FE mesh is therefore performed where high surface accuracy is required for the computation of the radiative links and environmental heat loads.

Last year's presentation focused solely on the first point. Developments of super-face ray-tracing with quadrics fitting will be presented. In addition to REFs, orbital heat loads computation is also implemented with significant improvement. The presentation will also address the global process involving first the detailed FE model conductive reduction, then the super-faces generation with selective quadric fitting for the computation of REFs and orbital heat loads and finally the computation of the reduced model temperatures. Detailed FE model temperature field can then be computed back from the reduced ones and the reduction matrices for potential thermo-mechanical analyses.

Université de Liège

# FINITE ELEMENT MODEL REDUCTION FOR SPACECRAFT THERMAL ANALYSIS

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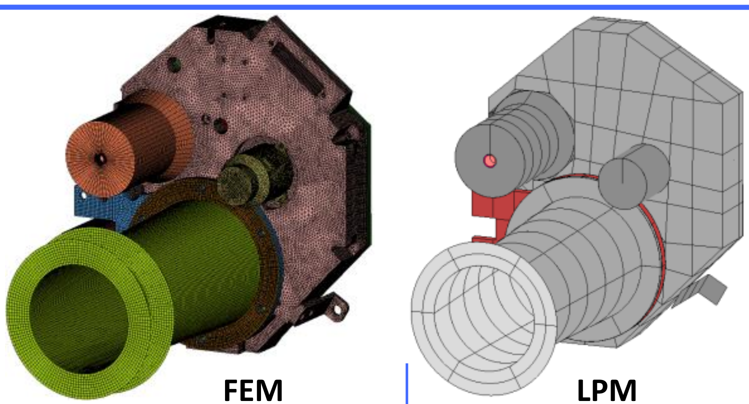
## Finite Element vs. Lumped Parameter



| | FEM | LPM |
|---|---|---|
| # nodes | $10^4$ - $10^6$ | $10^1$ - $10^3$ |
| Conductive links computation | ✓ Automatic | ✗ Manual, error-prone |
| Radiative links computation | ✗ Prohibitive | ✓ Affordable |
| Surface accuracy for ray-tracing | ✗ FE facets | ✓ Primitives |
| User-defined components | ✗ Difficult | ✓ Easy |
| Thermo-mech. analysis | ✓ Same mesh | ✗ Mesh extrapolation |

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## Reconciliation through a global approach

Radiative links computation

- Reduce # of rays: quasi-Monte Carlo method (isocell, Halton)
- Reduce # of facets: super-face concept (mesh clustering)
- Parallelization: GPUs

Surface accuracy for ray-tracing

- Quadrics fitting

Conductive links, thermo-mech. analysis and user-defined compts.

- Reduce detailed FE mesh (keep conductive info. of the detailed geometry)
- Able to recover detailed T° from reduced
- Transform reduced FE model to LP model to enable user-defined comp.

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## Outline

Ray-tracing enhancement

FEM clustering & conductive reduction

Super-face ray-tracing

Integrating the developments

Conclusions & perspectives

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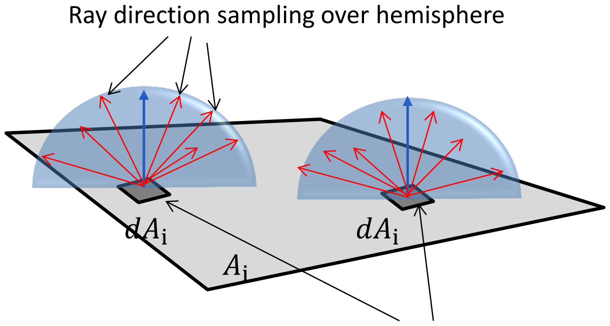
# Ray-tracing: origin + direction sampling

$$F_{ij}(B_{ij}) = \frac{\text{Number of rays emitted by facet i, directly (finally) hitting j}}{\text{total number of rays emitted by facet i}}$$




Reference solution: ESATAN-TMS

→ crude Monte Carlo: random direction & origin sampling, 1 ray / origin

$$error \propto \frac{1}{\sqrt{N_{rays}}}$$

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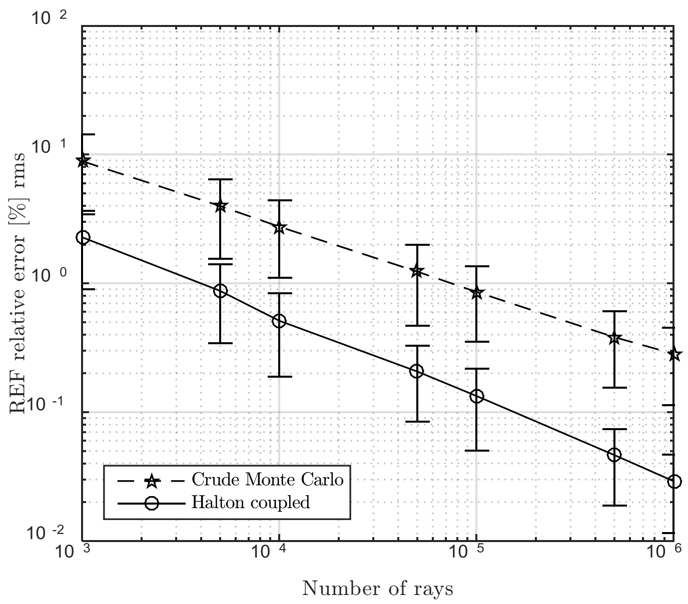
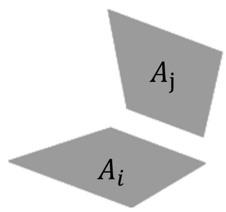
## 4-D QUASI-MC SAMPLING: 2 QUADRANGLES

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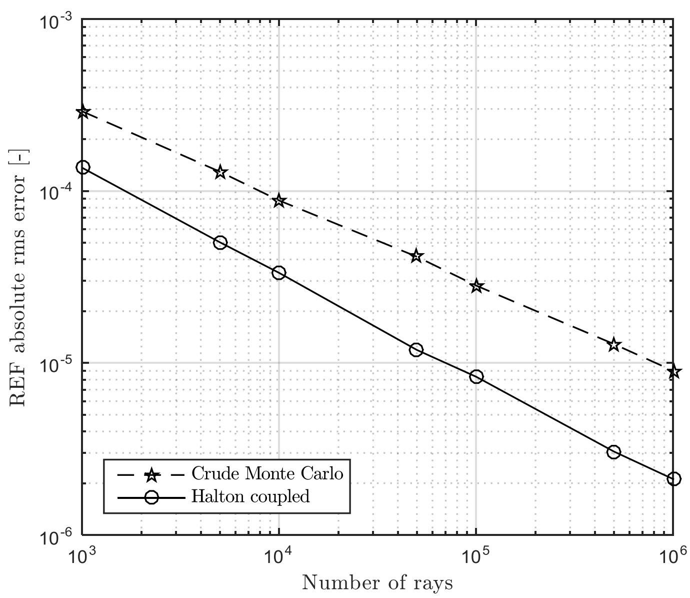
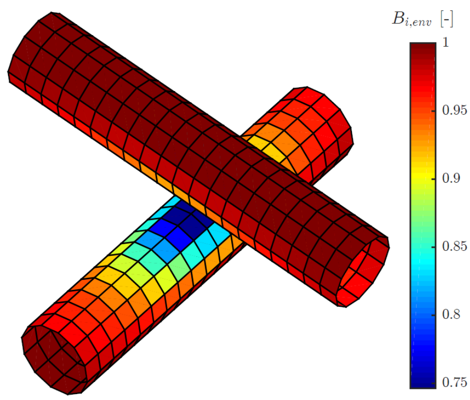
## 4-D QUASI-MC SAMPLING

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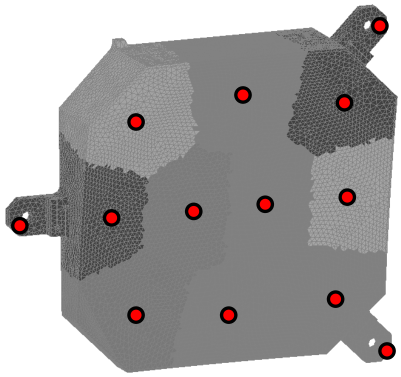
# Mesh clustering: 3 steps

K-mean clustering initialization (user input # cluster) → cluster center



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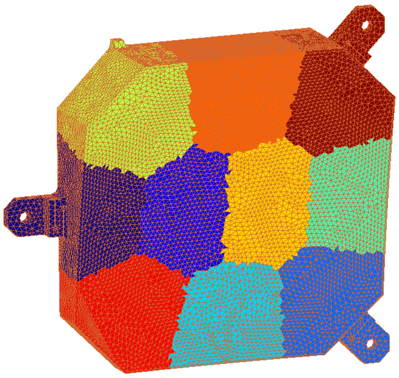
## Mesh clustering: 3 steps

K-mean clustering initialization (user input # cluster) → cluster center

Greedy region growing



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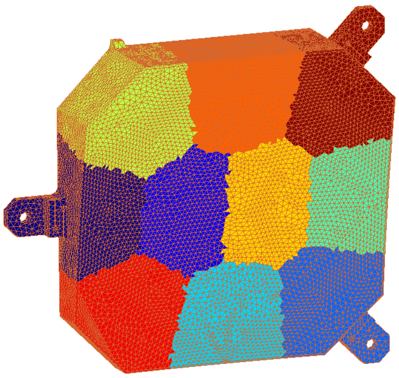
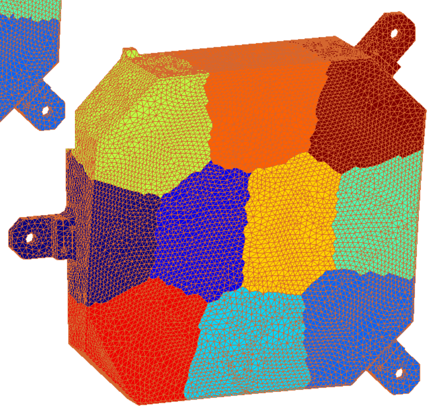
## Mesh clustering: 3 steps

K-mean clustering initialization (user input # cluster) → cluster center

Greedy region growing



Boundary smoothing



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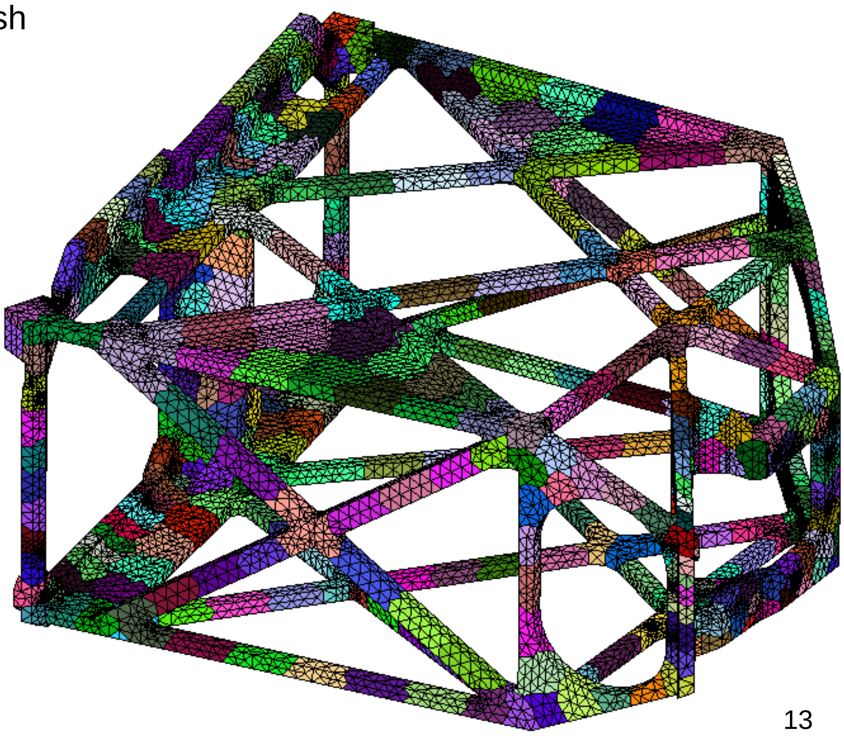
## Mesh clustering: 3 steps

Heterogeneous mesh

Material constraints



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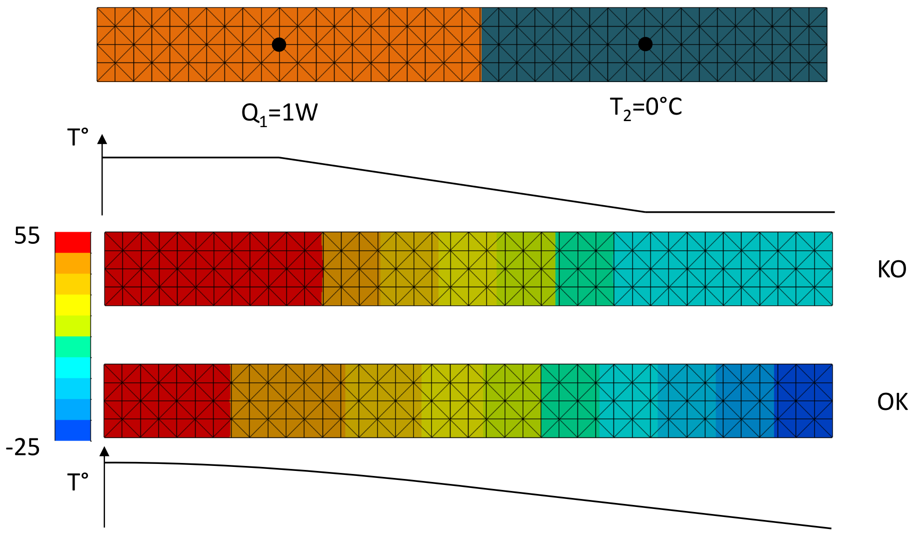
## Problem of Guyan condensation

Cannot use cluster center as retained node

No (or known) heat load on condensed nodes

Heat load on selected node ≠ heat load on cluster

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## Create new “super-nodes”

Not picking a representative node of the cluster but creating new nodes

A super-node = weighted (area, volume) average each node cluster

$$\mathbf{T_{SN}} = \mathbf{AT}$$

$$T_{SN_i} = \sum_{j=1}^{N} A_{ij} T_j \qquad \sum_{j=1}^{N} A_{ij} = 1$$

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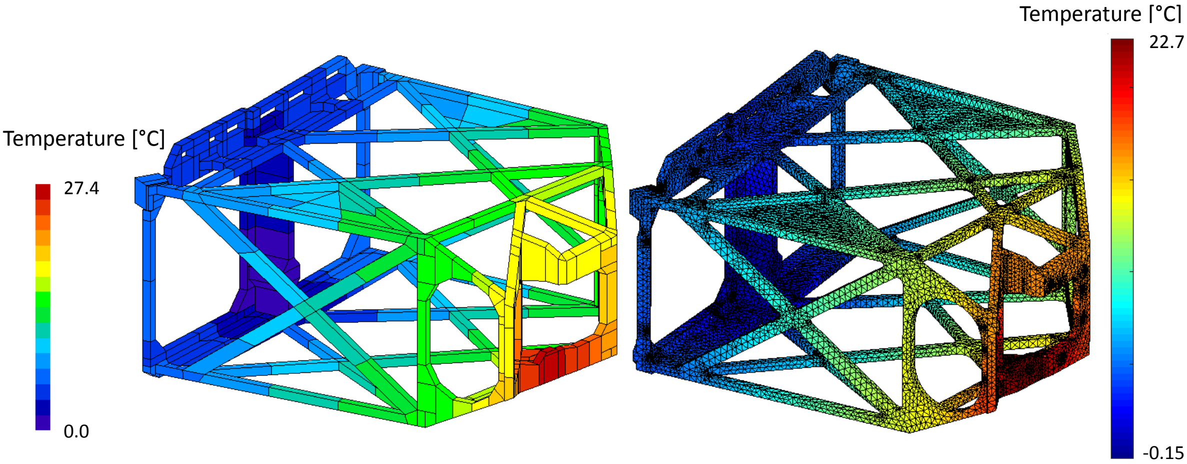
## More than 10% error

| | Detailed | ESATAN | Reduced |
|---|---|---|---|
| ΔT [K] | 22.5 | 27.4 | 22.5 |
| # nodes | 35k | 422 | 397 |
| # links | >200000 | 473 | 78600 |

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## Selective quadric fitting

Automatic quadric mesh fitting of user selected regions (e.g. optics)

$$f(\mathbf{x}) = \mathbf{C}^{\mathrm{T}}\mathbf{F} \qquad \mathbf{F}(\mathbf{x}) = [1, x, y, z, xy, xz, yz, x^2, y^2, z^2]^{\mathrm{T}}$$

$$\mathbf{C} = [c_0, \ldots, c_9]^{\mathrm{T}}$$

$$error \approx \sum_{S_i \in R} \int_{S_i} \frac{f(\mathbf{x})^2}{|\nabla f(\mathbf{x})|^2} d\sigma \approx \frac{\mathbf{C}_0^{\mathrm{T}} M \mathbf{C}_0^{\mathrm{T}}}{\mathbf{C}_0^{\mathrm{T}} N \mathbf{C}_0^{\mathrm{T}}}$$

With $\mathbf{M} = \frac{1}{n} \sum_{\substack{i=1, \\ \mathbf{x}_i \in R}}^{n} \mathbf{F}(\mathbf{x}_i)\mathbf{F}(\mathbf{x}_i)^{\mathrm{T}}$ $\qquad$ $\mathbf{N} = \frac{1}{n} \sum_{\substack{i=1, \\ \mathbf{x}_i \in R}}^{n} \nabla\mathbf{F}(\mathbf{x}_i)\nabla\mathbf{F}(\mathbf{x}_i)^{\mathrm{T}}$

$\mathbf{C}$ is the eigen vector associated with minimum eigen value of

$$\mathbf{M} - \lambda \mathbf{N}$$

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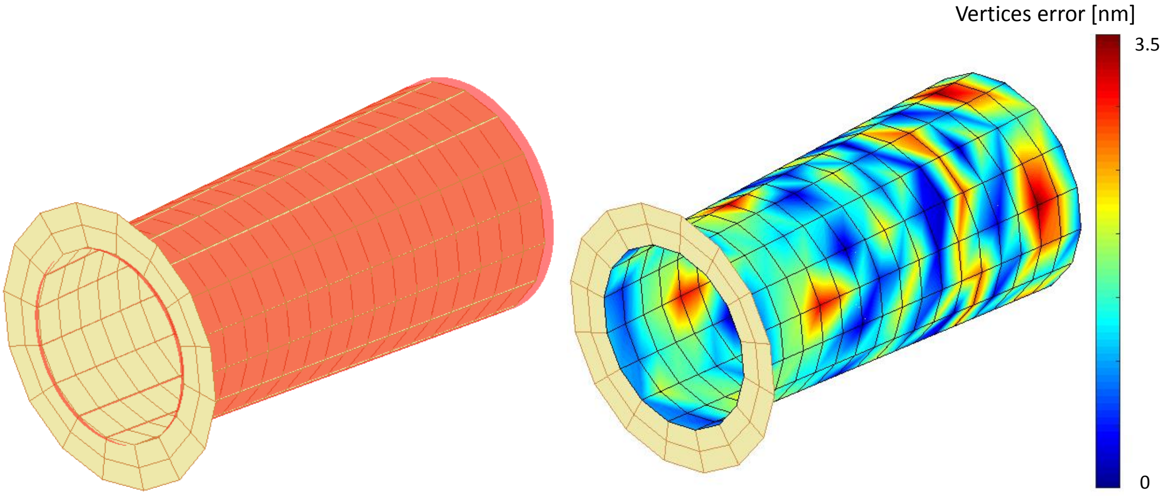
# Selective quadric fitting

Entrance baffle of EUI instrument onboard Solar Orbiter

Cone recognition

Shape error ~1nm

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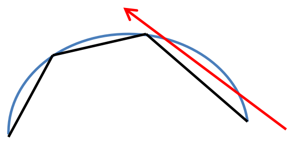
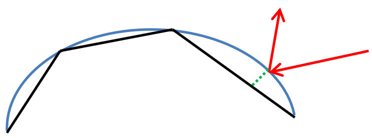
# Ray-tracing with quadrics

Use directly the quadric for the intersection computation

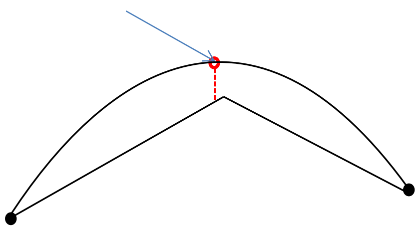
→ avoid lost grazing rays

→ better shadow





Project normally to the quadric to determine which super-face



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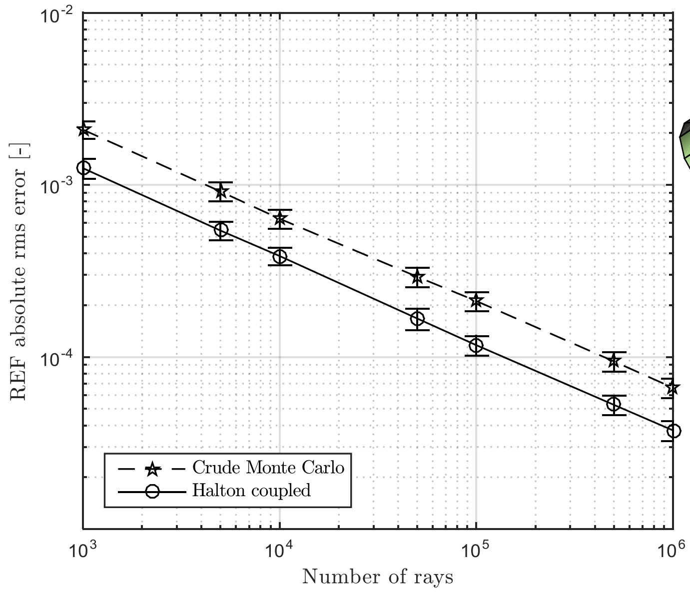
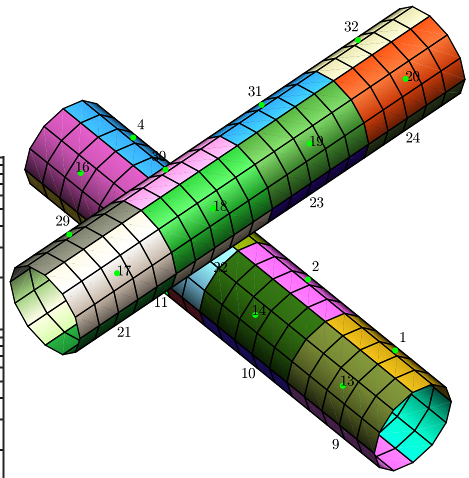
# Fitted cylinder vs. ESARAD cylinder



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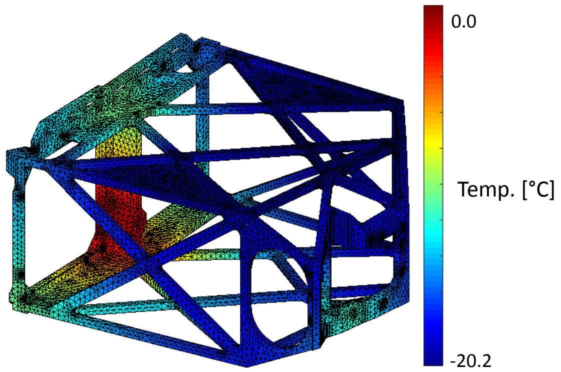
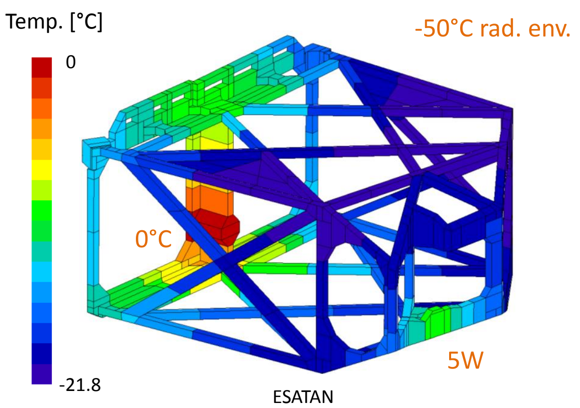
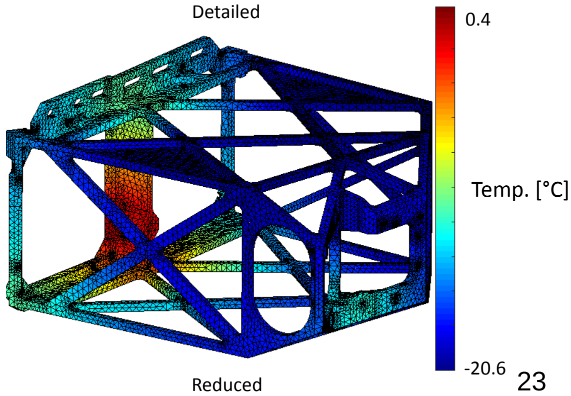
## CONDUCTION + RADIATION

| | Detailed | ESATAN | Reduced |
|---|---|---|---|
| $T_{IF}$ [°C] | -11.9 | -10.8 | -12.4 |
| $T_{min}$ [°C] | -20.2 | -21.8 | -20.6 |
| # nodes | 35k | 422 | 397 |
| # cond. links | >200k | 473 | 78.6k |
| # rad. links | 1500k | 41k | 55k |

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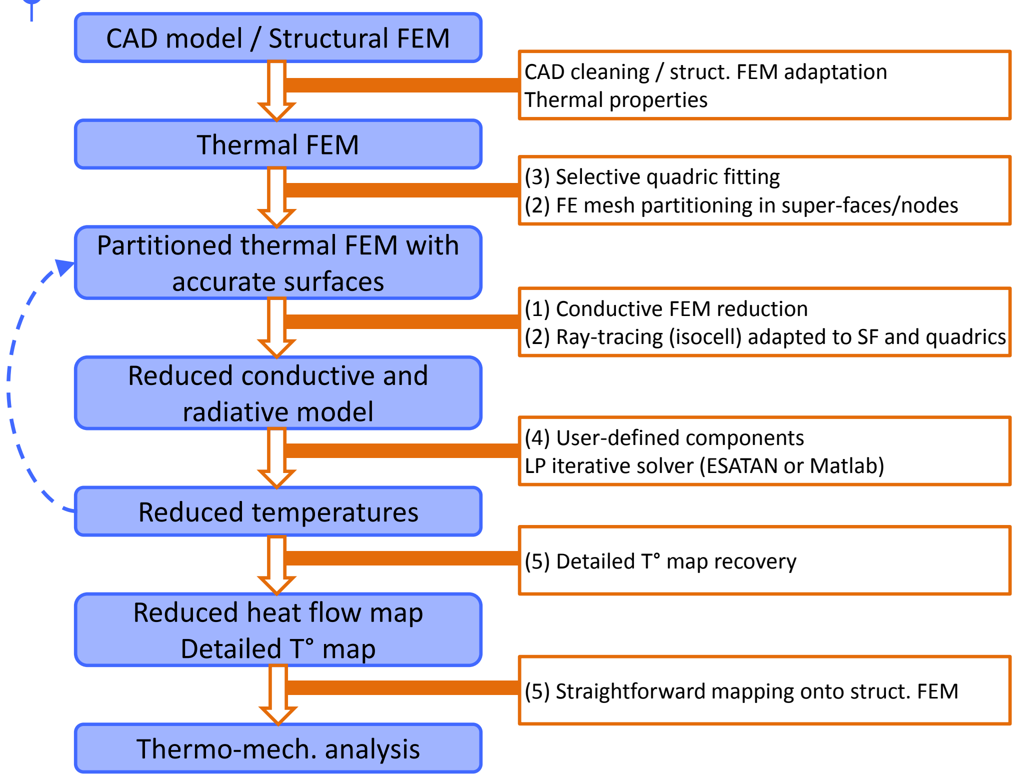
## Putting the building blocks together

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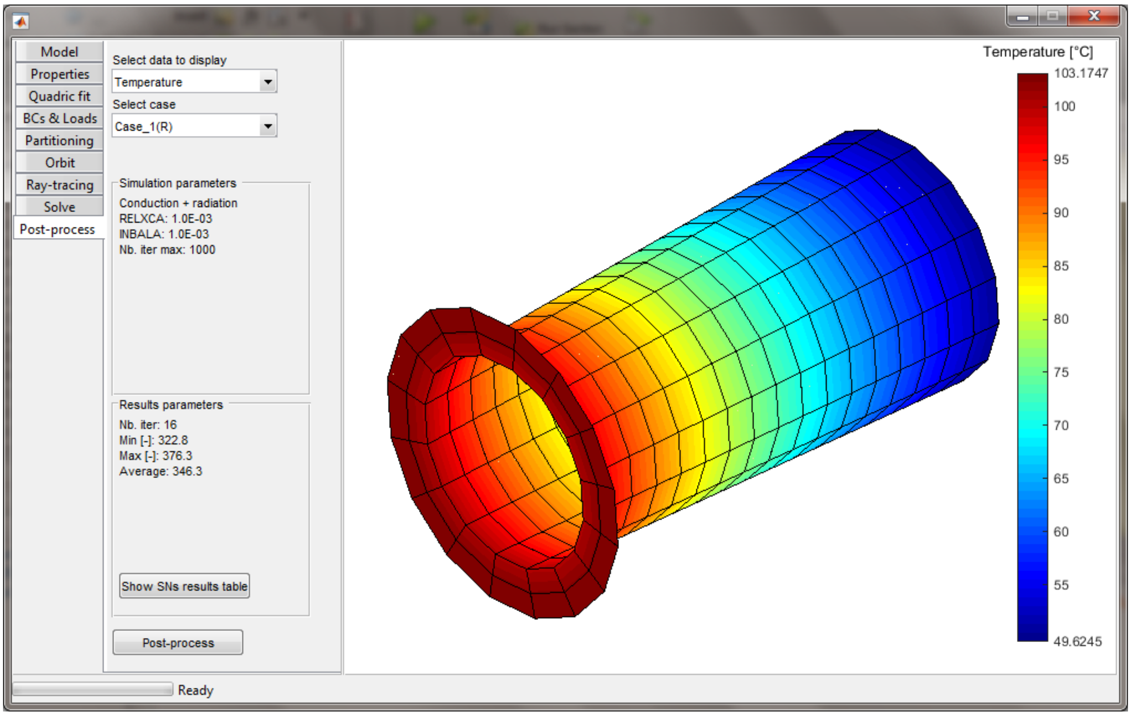
# Global tool development

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# Conclusions & perspectives

Global approach for conduction and radiation

Takes advantages of both lumped parameter and finite element methods:

- More accurate conductive links
- Accurate shape recognition used for ray-tracing
- Reduce the gap between thermal and structural analyses

Perspectives:

- Iterative process with automatic refinement in high $\Delta T$ regions
- GPUs with Matlab parallel computing toolbox® and CUDA®
- Quadric fitting → opto-thermo-structural analyses

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**Thank you for your attention…**

**Any question?**

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