Appendix U

Finite element model reduction for the determination of accurate conductive links and application to MTG IRS BTA

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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.
The two methods offer advantages and disadvantages and the proposed global approach tries to combine both. Whereas the LPM remains very versatile and allows easy integration of user-defined components, the computation of the conductive links is 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. From this point of view, the FEM is complementary, offering the accuracy required by the always more stringent requirements of the TCS. In this framework, a FE mesh conductive reduction scheme has been developed. The detailed FE mesh is first fitted to the ESARAD geometry. The FE mesh is then partitioned, according to the ESARAD shells definition, before being reduced in an iterative procedure. The reduced conductive network, containing all the conductive information of the detailed FE mesh, and the ESARAD radiative links are then combined to form the TMM and compute the temperatures. The reduction method further allows the recovery of the detailed FE mesh temperatures back from the reduced one, therefore bridging the gap between thermal and mechanical analysis. The method has been tested and applied on the Back Telescope Assembly (BTA) on board MTG IRS.

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Finite Element Model Reduction for the Determination of Accurate Conductive Links and Application to MTG IRS BTA

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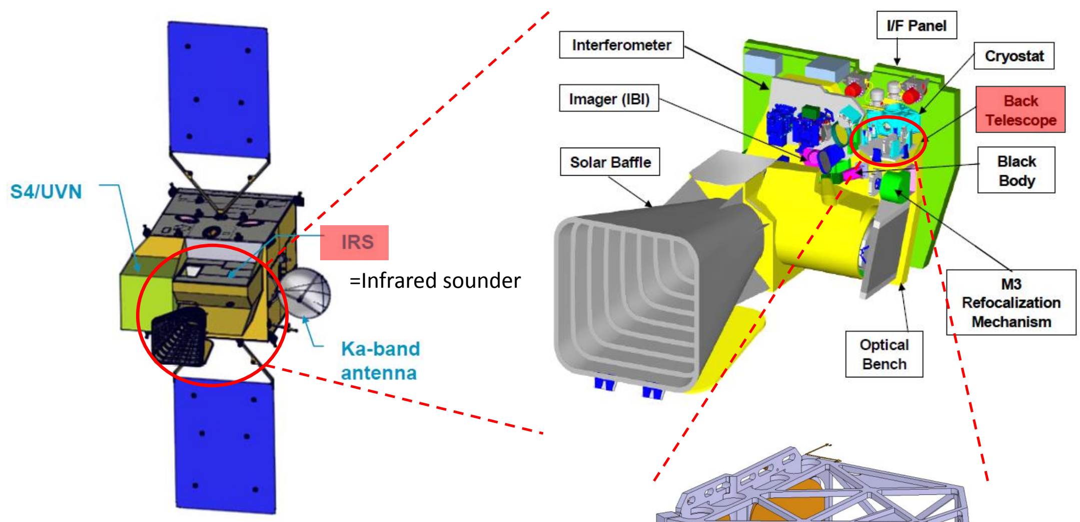
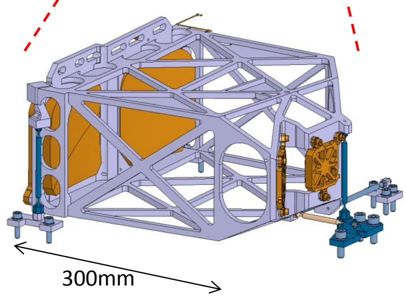
Requirements reach classical method limits



T° gradient < 1 °C

Conductive IF @ 20+/-5°C

Radiator @ [-70, -30]°C



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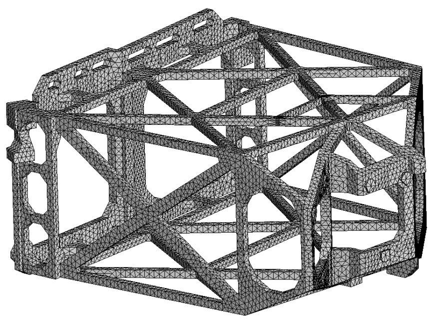
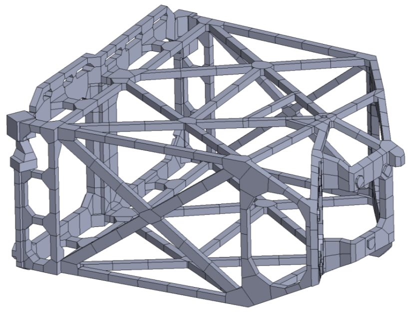
Finite Element vs. Lumped Parameter

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

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Global approach & proposed solutions

(2) Radiative links computation

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

(3) Surface accuracy for ray-tracing

- Quadrics fitting

(1,4,5) 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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Today's topic

(2) Radiative links computation

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

(3) Surface accuracy for ray-tracing

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Outline

Mesh clustering

Mathematical reduction

Step by step procedure

Benchmarking

Conclusions

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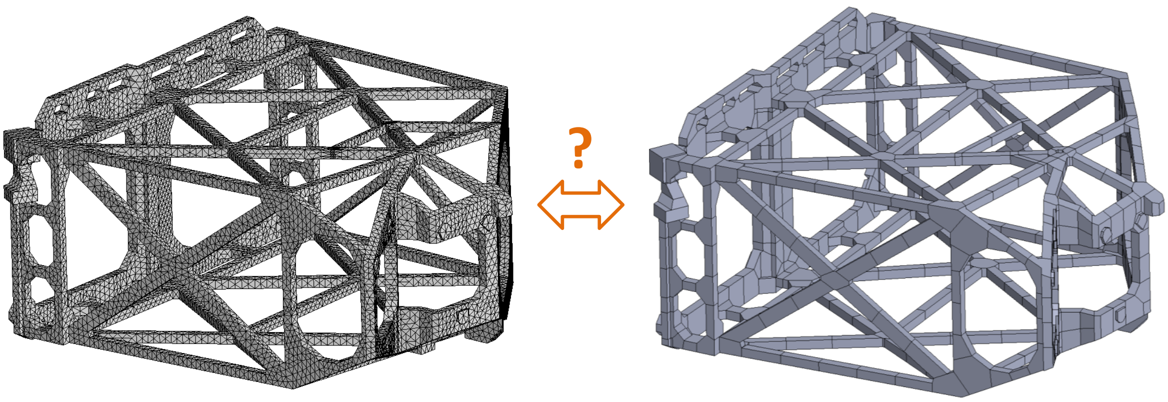
How to reduce the system accurately?



2 step process:

- FE mesh partitioning matching ESARAD mesh
- FE mesh reduction to determine the GLs

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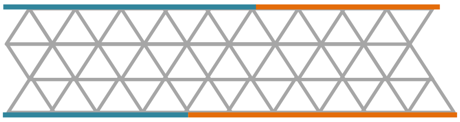
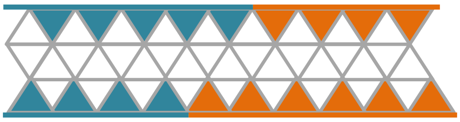
Merging meshes

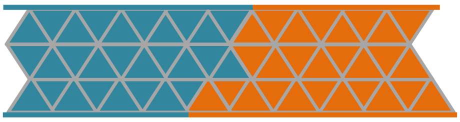
Superimpose ESARAD and FE meshes



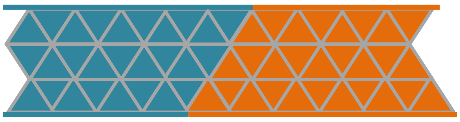
Assign skin FE to ESARAD shells



Greedy region growing



Cluster boundary smoothing



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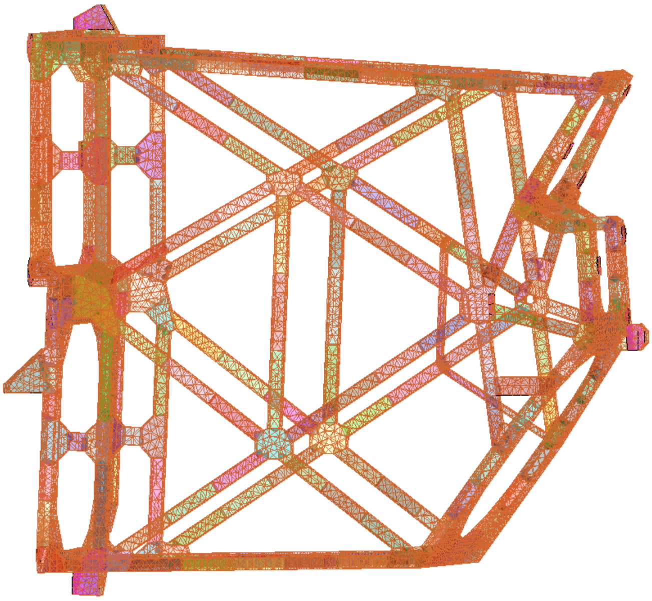
From FE clusters to GLs



$\mathbf{K_D}$ (65k × 65k) ? ⇔ $\mathbf{K_R}$ (340 × 340)

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Guyan (static) condensation

Split the system

$$\mathbf{KT} = \mathbf{Q}$$

With retained and condensed nodes:

$$\begin{bmatrix} \mathbf{K}_{\mathrm{RR}} & \mathbf{K}_{\mathrm{RC}} \\ \mathbf{K}_{\mathrm{RC}}^{\mathrm{T}} & \mathbf{K}_{\mathrm{CC}} \end{bmatrix} \begin{Bmatrix} \mathbf{T}_{\mathrm{R}} \\ \mathbf{T}_{\mathrm{C}} \end{Bmatrix} = \begin{Bmatrix} \mathbf{Q}_{\mathrm{R}} \\ \mathbf{Q}_{\mathrm{C}} = 0 \end{Bmatrix}$$

Reduced system:

$$\mathbf{K}'\mathbf{T}_{\mathrm{R}} = \mathbf{Q}'$$

With

$$\mathbf{K}' = \mathbf{K}_{\mathrm{RR}} - \mathbf{K}_{\mathrm{RC}}\mathbf{K}_{\mathrm{CC}}^{-1}\mathbf{K}_{\mathrm{RC}}^{\mathrm{T}} = \mathbf{R}^{\mathrm{T}}\mathbf{KR}$$

$$\mathbf{Q}' = \mathbf{Q}_{\mathrm{R}} - \mathbf{K}_{\mathrm{RC}}\mathbf{K}_{\mathrm{CC}}^{-1}\mathbf{Q}_{\mathrm{C}} = \mathbf{R}^{\mathrm{T}}\mathbf{Q} = \mathbf{Q}_{\mathrm{R}}$$

$$\mathbf{R} = \begin{bmatrix} \mathbf{I}_{\mathrm{RR}} \\ -\mathbf{K}_{\mathrm{RC}}\mathbf{K}_{\mathrm{CC}}^{-1} \end{bmatrix}$$

Condensed temperatures can be recovered: $\mathbf{T} = \mathbf{RT}_{\mathrm{R}}$

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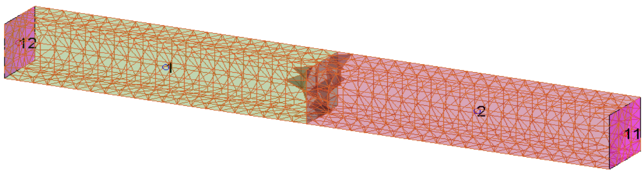
Problem of Guyan condensation

Need to select particular nodes to be retained

No (or known) heat load on condensed nodes



Heat load on selected node ≠ heat load on cluster represented by node

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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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Combining the relations

As done at element level in MSC Thermica®:

$$\begin{cases} \mathbf{KT} = \mathbf{Q} \\ \mathbf{T_{SN}} = \mathbf{AT} \end{cases} \Leftrightarrow \begin{bmatrix} \mathbf{K} & \mathbf{A^T} \\ \mathbf{A} & \mathbf{0} \end{bmatrix} \begin{Bmatrix} \mathbf{T} \\ \mathbf{0} \end{Bmatrix} = \mathbf{M} \begin{Bmatrix} \mathbf{T} \\ \mathbf{0} \end{Bmatrix} = \begin{Bmatrix} \mathbf{Q} \\ \mathbf{T_{SN}} \end{Bmatrix}$$

$$\begin{Bmatrix} \mathbf{T} \\ \mathbf{0} \end{Bmatrix} = \mathbf{M^{-1}} \begin{Bmatrix} \mathbf{Q} \\ \mathbf{T_{SN}} \end{Bmatrix} = \begin{bmatrix} \mathbf{X} & \mathbf{Y^T} \\ \mathbf{Y} & \mathbf{Z} \end{bmatrix} \begin{Bmatrix} \mathbf{Q} \\ \mathbf{T_{SN}} \end{Bmatrix}$$

$$\mathbf{YA^T} = \mathbf{I} = \mathbf{AY^T}$$

$$\mathbf{0} = \mathbf{YQ} + \mathbf{ZT_{SN}}$$

If the load is uniform over each super-node ($\mathbf{Q} = \mathbf{A^T Q_{SN}}$): $\mathbf{YQ} = \mathbf{Q_{SN}}$

$$-\mathbf{ZT_{SN}} = \mathbf{Q_{SN}}$$

$$\boxed{\mathbf{K_{SN}} = -\mathbf{Z}}$$

And the detailed T° can be recovered:

$$\mathbf{T} = \mathbf{XQ} + \mathbf{Y^T T_{SN}}$$

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You need to invert M to get $\mathbf{K_{SN}}$!

size($\mathbf{M}$) > size($\mathbf{K}$) → very expensive + $\mathbf{M}$ is not sparse!

Detailed T° not needed:

- LDL decomposition of $\mathbf{M}$ → selective inversion of sparse matrix and only $\mathbf{K_{SN}}$ is computed.

Detailed T° needed: $\mathbf{X}$ and $\mathbf{Y}$ are required (size($\mathbf{X}$)=size($\mathbf{K}$), not sparse)

- Local inversion of M for each super-node
- Global inversion for small problems.

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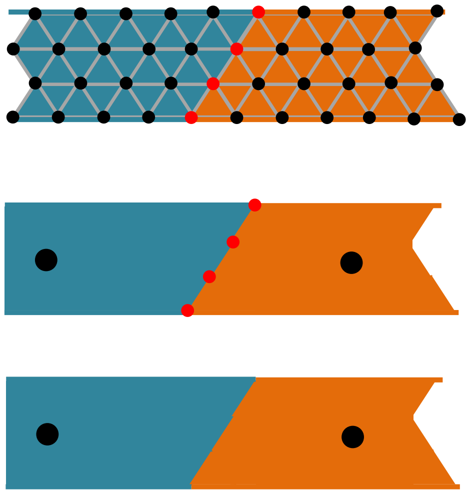
Local inversion of $\mathbf{M}$

Local inversion of M:

super-node + keep all detailed IF nodes

Guyan condensation to eliminate the

detailed IF nodes



Detailed T° recovery by inverse procedure:

no need to store the full $\mathbf{X}$ and $\mathbf{Y}$

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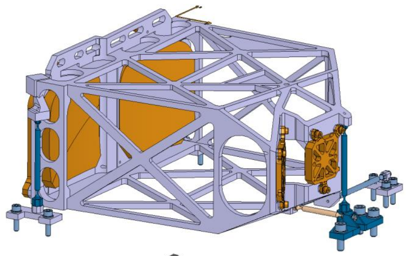
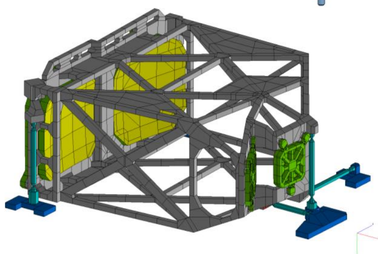
Overall procedure

- CAD cleaning + ESARAD shells drawing
- Import .step to ESARAD
- LPM nodes numbering in ESARAD
- FE meshing cleaned CAD
- Superimposition of FE & ESARAD meshes
- FE mesh partitioning
- FE assembly and detailed $\mathbf{K}$ matrix computation
- Reduction of $\mathbf{K}$ to $\mathbf{K}_{SN}$
- Export $\mathbf{K}_{SN}$ and super-nodal capacitances to ESATAN
- Compute the radiative links (with ESARAD or other)
- Combine radiative + conductive links and others → solve for $\mathbf{T}_{SN}$





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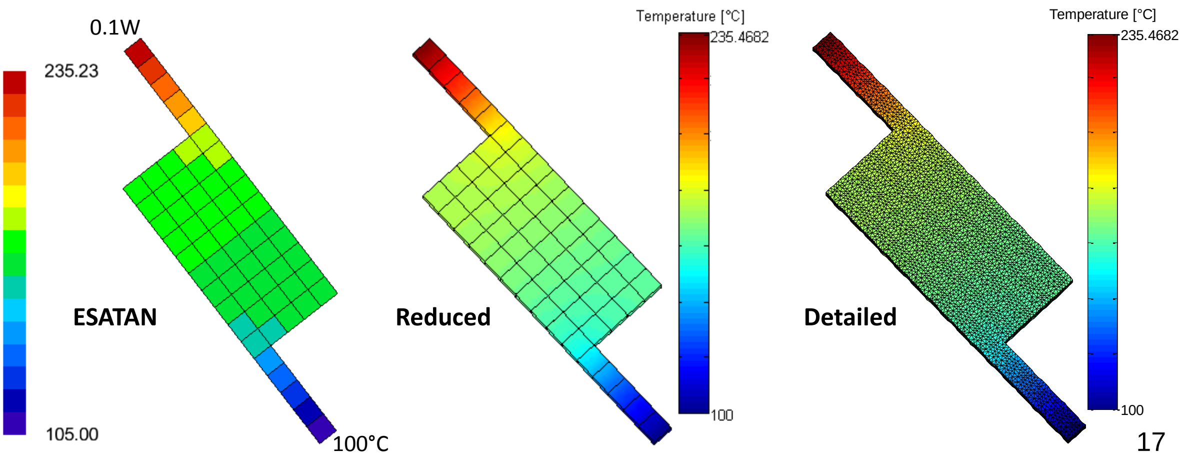
Benchmarking

	Detailed	ESATAN	Reduced
ΔT	235.47K	240.23 K	235.47 K
# nodes	11897	62	62
# GLs	71033	97	1891



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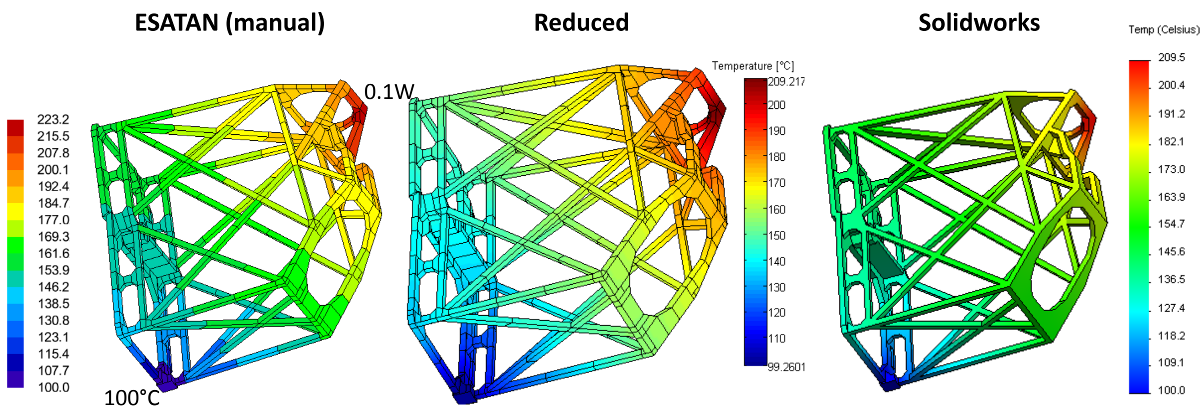
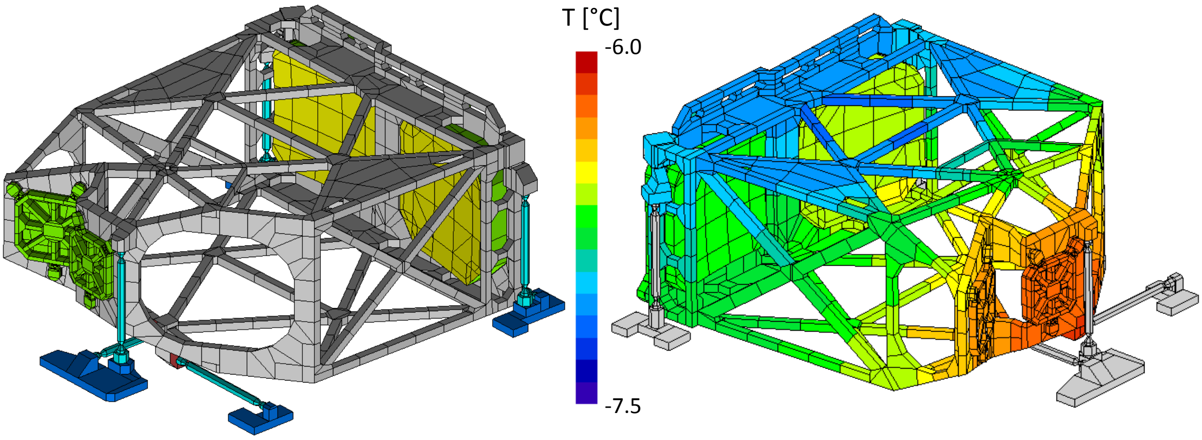
Manual GLs lead to 10% error

	Detailed (Solidworks)	ESATAN (manual)	Reduced
ΔT	107.4	123.2	107.7
# nodes	46405	280	280
# GLs	253004	402	39060



Integration of all components & run



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CONCLUSIONS

Conductive reduction method offers:

- better accuracy
- automatic GLs computation in complex 3D nodes
- detailed T° map recovery for thermo-mech. analyses

FEM vs. LPM: *Unity makes strength (Belgian motto)*

2nd step to bridge the gap between structural and thermal analysis

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Thank you for your attention…

Any question?

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REFERENCES

[1] T.D. Panczak, The failure of finite element codes for spacecraft thermal analysis, Proceedings of the International Conference on Environmental Systems, Monterey, USA, 1996.

[2] MSC THERMICA User Manual, Version 4.5.1, 2012, ASTRI.UM.757138.ASTR

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