Appendix G

Thermal Model Reduction using the Super-Face Concept

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Abstract

The objective of this presentation is to carry out model reduction of radiative problems in the context of the finite element method. The finite element model is decomposed into several sets of adjacent faces called super-faces. Specialized algorithms such as the METIS partitioning algorithm are used to automatically generate the super-faces. Several constraints may be imposed, e.g., the size of the super-face, its aspect ratio or its aperture angle. Once the model is decomposed, view factors between super-faces are calculated with direct numerical integration or ray-tracing methods. This method offers a very substantial reduction of the computational burden compared to the full model, which is particularly interesting for pre-design studies or specific applications such as deployable structures.

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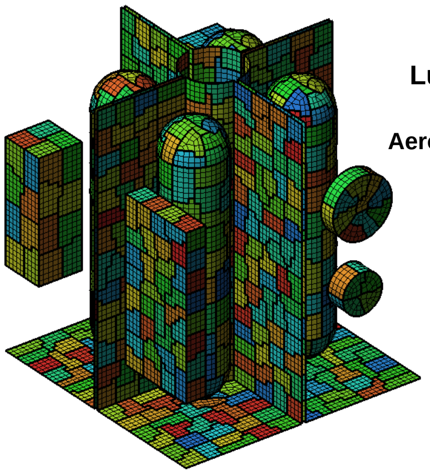
Thermal Model Reduction Using the Super-Face Concept



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Research framework

- Research project funded by the Walloon Region
- Developments of multiphysics tools
- Efficient modeling of thermal problems, especially radiative problems
- Collaboration with Simulation Software Editors
  - Samtech, **Samcef**, FE solution (www.samtech.com)
  - Open Engineering, **OOfelie**, multiphysics FE solution (http://www.open-engineering.com)

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Industrial Collaboration

Open Engineering

- Belgian company
- Member of the SAMTECH Group
- Focused on multiphysics CAE activities
  - OOFELIE::Multiphysics software
  - Engineering services

OOFELIE::Multiphysics is a CAE solution for applications in

- **Vibro Acoustics**: Piezo loudspeaker, muffler noise prediction, acoustic response
- **Electro Technics**: Joule heating, EM devices, piezo actuators
- **FSI-CFD**: Conduction, convection, cooling
- **Optics devices**: Impact of thermomechanical deformations on optical perf
- **MEMS Design**: Accelerometer, gyrometer, sensors, energy harvesting
- **Thermo Mechanics**: Package/Board Heat mgmnt, deformation, stresses

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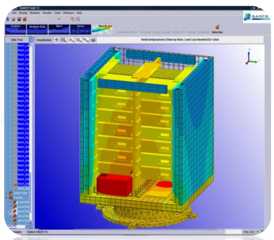
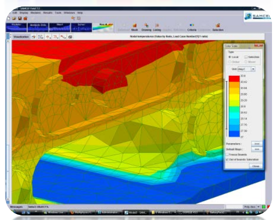
Industrial Collaboration

- COMPONENT RELIABILITY
  - Low Temperatures
- SENSITIVITY OF DETECTORS AND UNITS
  - Narrow Temperature Ranges
- POINTING OF INSTRUMENTS
  - Small Temperature Gradients
- MODELING TAKES INTO ACCOUNT
  - Magneto-Torque
  - Satellite Orbit, Satellite Rotation
  - Solar Radiation, Earth Albedo, Cooling
  - Electronic Component Dynamic Power Dissipation





Work performed under contract for LUXSPACE

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Why thermal model reduction ?

Solving radiative problems require the view factors between faces.

View factors are computed with ray-tracing methods.

Ray-tracing is easy to implement and general (diffuse, specular, transparency).

But ray-tracing requires lots of computer resources (time, memory).

⇨ Need for reduction techniques (approximate but fast solution)

Available solutions

Coarse finite element mesh

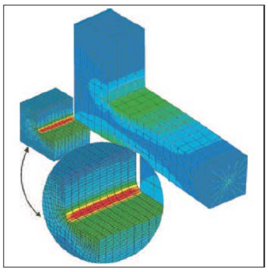
Low precision

Multi-resolution meshes (in PERMAS software)

Automatic simplification of a hi-res mesh

Local refinement (high gradient zones)

Degraded geometry



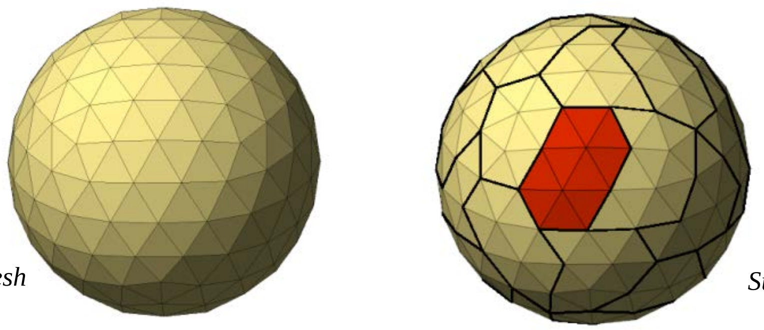
Proposed solution: decomposition in super-faces

A super-face is a group of N_s adjacent faces of the original mesh.

Decomposition in super-faces is fully automatic.

It preserves object geometry (plane/curved zones).

N faces ⇨ M super-faces



Original mesh *Super-faces*

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Step 1: decomposition according to material properties

We should avoid mixing faces corresponding to different materials, e. g. purely diffuse and purely specular faces.

The original mesh is pre-decomposed in S sub-meshes, S being the number of different materials.

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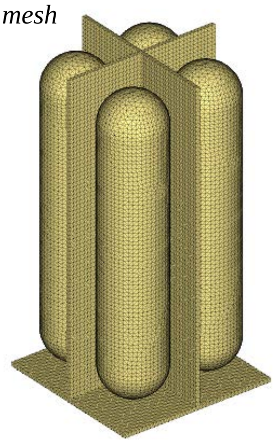
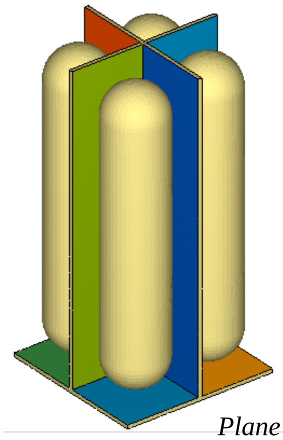
Step 2: find plane surfaces

We need to avoid mixing faces belonging to different planes and curved surfaces.

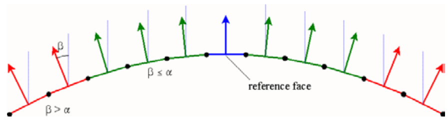
An automatic algorithm based on adjacency table and face normal vectors is used to find the plane surfaces.

Original mesh





Selection algorithm



Plane surfaces

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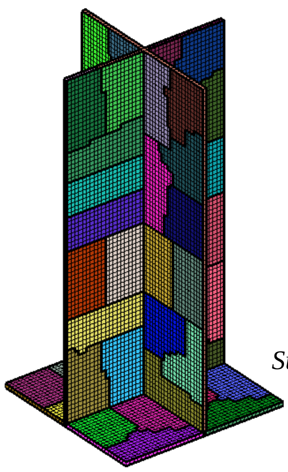
Step 3: decompose each plane surface in super-faces

Each plane surface is automatically decomposed using METIS algorithms.

We may impose constraints on the min/max number of faces for a super-face and on the super-faces aspect ratio.



Super-faces on planes

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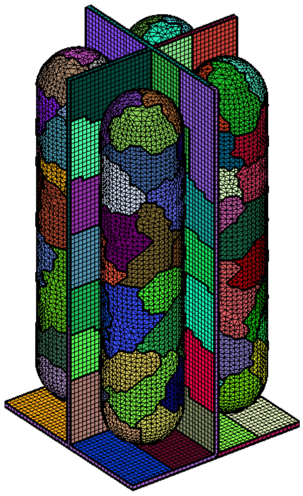
Step 4: decompose the remaining faces

The decomposition is also performed by METIS algorithms. We may add an additional constraint on super-faces aperture angle.

Super-faces on curved surfaces



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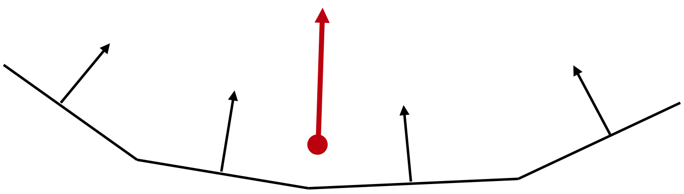
Super-face properties

- Set of N_s faces of original mesh
- Made of a single material (unique properties, emission, reflectivity …)
- Super-face center (centroid of faces)
- Super-face normal vector (mean of face normal vectors)



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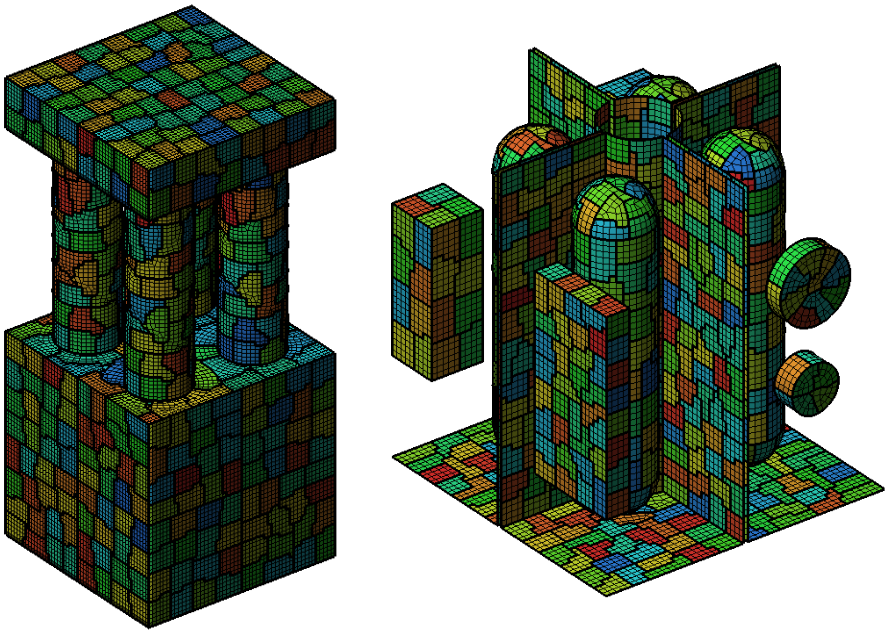
Examples



Applications of the super-face method

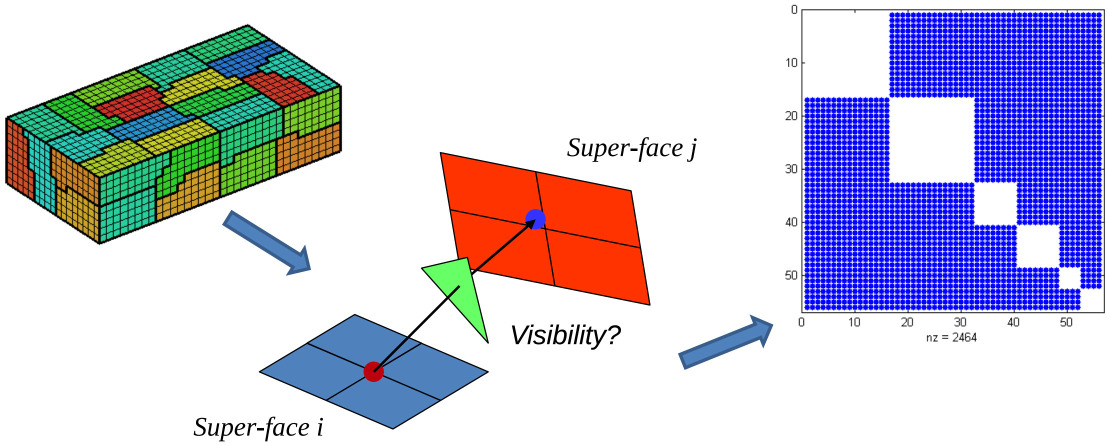
1. Estimation of the view factor matrix sparsity
2. Thermal model reduction
3. Estimation of ray number in order to reach a given accuracy

App. 1 - Sparsity estimation

We check the visibility between super-faces.

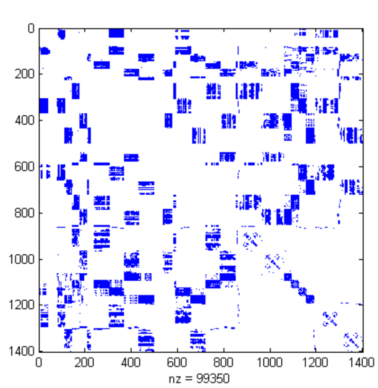
All the faces of two visible super-faces are assumed to be visible.

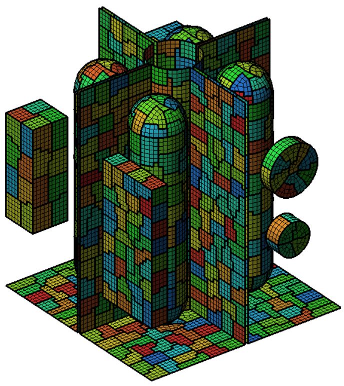
We may estimate the sparsity of the view factor matrix of the original mesh.



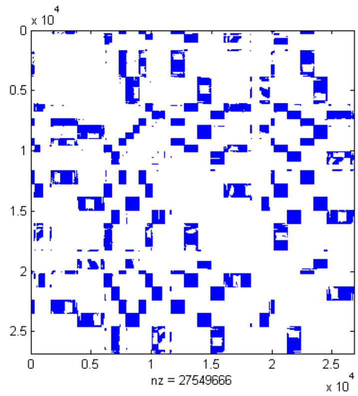
App. 1 - Sparsity estimation

1400 super-faces





26818 faces



Estimated sparsity: 4.81 %

Time: 54 sec.

Actual sparsity: 3.83 %

Time: 1900 sec.

App. 2 - Thermal model reduction

We compute the view factors between super-faces by numerical integration (purely diffuse case) or by ray-tracing (general case).

We obtain a reduced system described by a set of super-faces and radiative links between them.

The required time is the order of a minute while the required time for the original system is the order of an hour or more.

The reduced system may be solved alone (e.g. to compute the radiative heat fluxes) or linked to other thermo-mechanical systems for a coupled analysis.

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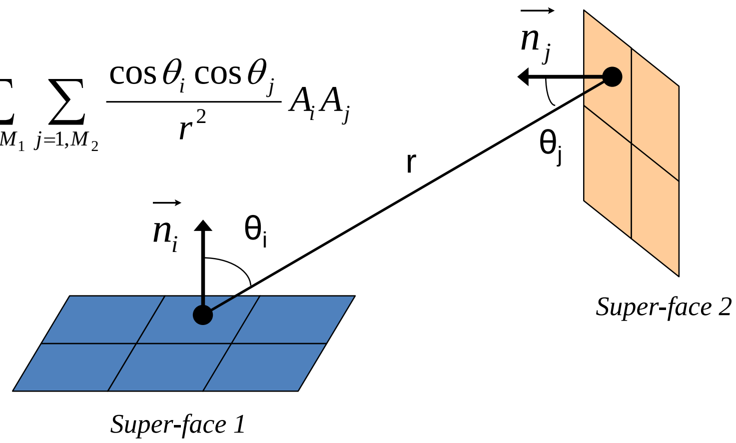
App. 2 - Numerical integration

We compute the view factors only between visible super-faces.

The computation is very fast (order of a second).

$$F'_{1\to 2} = \frac{1}{\pi A'_1} \sum_{i=1,M_1} \sum_{j=1,M_2} \frac{\cos\theta_i \cos\theta_j}{r^2} A_i A_j$$



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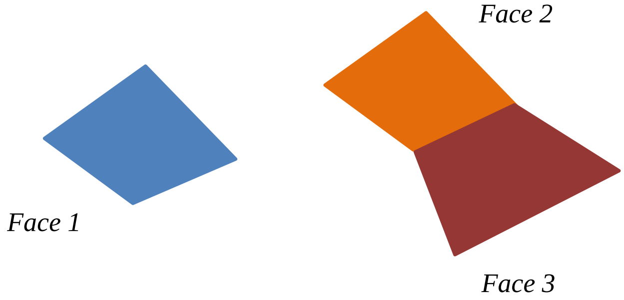
App. 2 - Check model reduction accuracy

We compute the view factors between super-faces by numerical integration.

We compute view factors between faces by ray-tracing.

We use view factor “algebra” to find back view-factors between super-faces.



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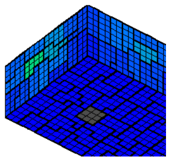
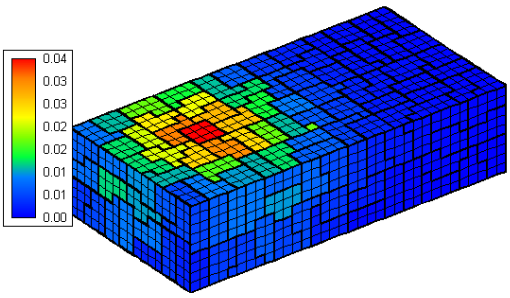
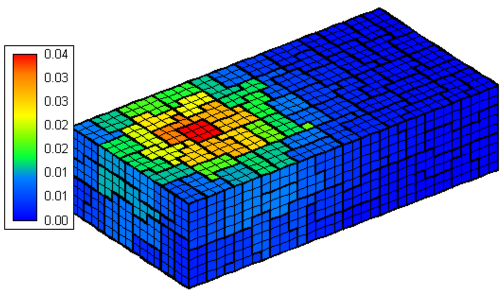
App. 2 - Check model reduction accuracy



Super-face 30

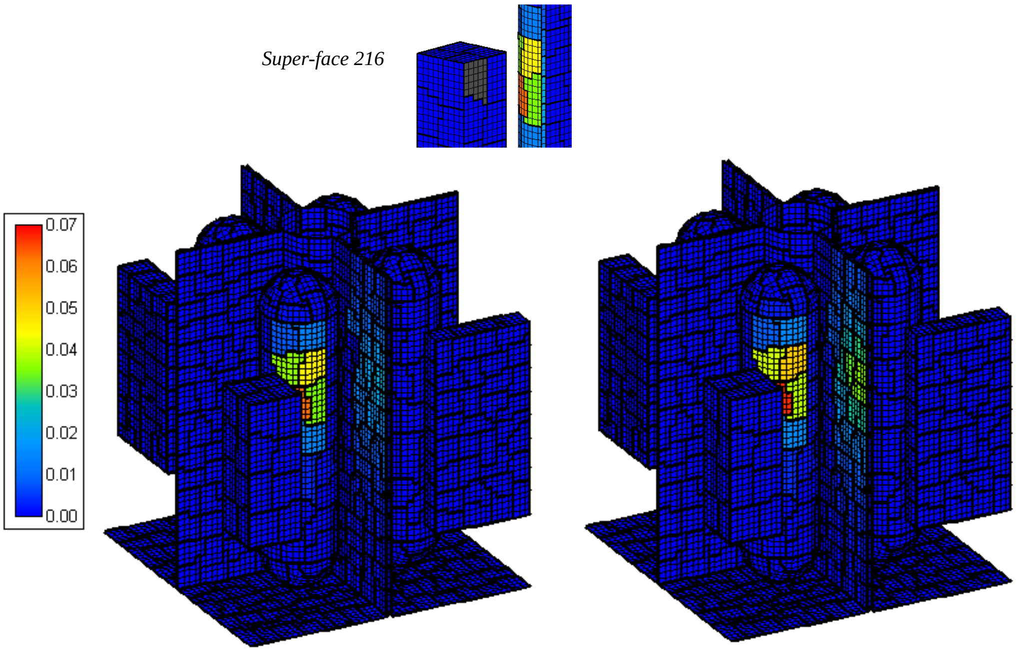


View factors between super-face 30 and super-faces (numerical integration)



View factors between super-face 30 and super-faces (ray-tracing + view factor algebra)

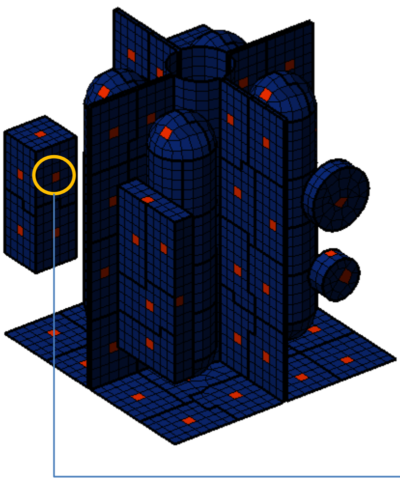
App. 2 - Check model reduction accuracy



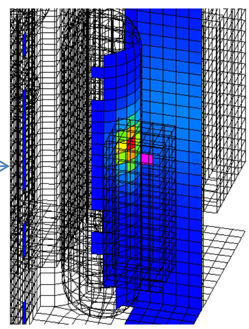
View factors (numerical integration)

View factors (ray tracing)

App. 3 - Estimation of the number of rays



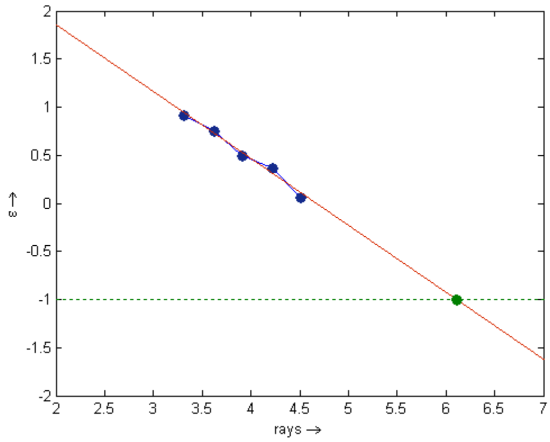
- Central face of each super-face (in red)
- Shoot 1000, 2000, 4000, … from the central faces
- Take the x greatest view factors per face
- Compute the view factor relative error ε



(%)

App. 3 - Estimation of the number of rays

- Plot mean value of ε against number of rays
- Linear fitting of the obtained points (log-log axes)
- Ray number estimation for a given precision



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Conclusions

Advantages:

- Easily customized (number of super-faces, aspect ratio, aperture angles …)
- Geometry preserved

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Conclusions

Applications:

- Sparsity estimator
- Estimation of the number of rays
- Thermal model reduction
  - Pre-design
  - Adaptative simulations
  - Objects in various configurations (deployable antenna, solar panels …)
  - Large deformations (need to update view factors several times)
  - Study of mechanism (robots, complex machines …)

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Perspectives

Further works:

- Implement local refinement (adapt the super-faces size locally)
- Implement ray-tracing method for super-faces
- Test on real spacecraft problems
- Perform coupled thermal analyses within a FE code framework

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