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Remapping algorithms: application to trimming operations in sheet metal forming

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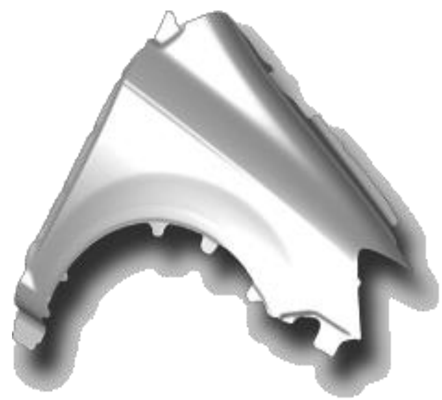
NUMISHEET 2016
The 10th International Conference and Workshop on Numerical Simulation of 3D Sheet Metal Forming Processes

4 – 9 September 2016
Marriott Bristol City Centre Hotel, Bristol, UK

Sheet metal forming processes

- Multi-step sheet metal forming process
- Commonly adopted in the production of complex automotive structural components

Forming process

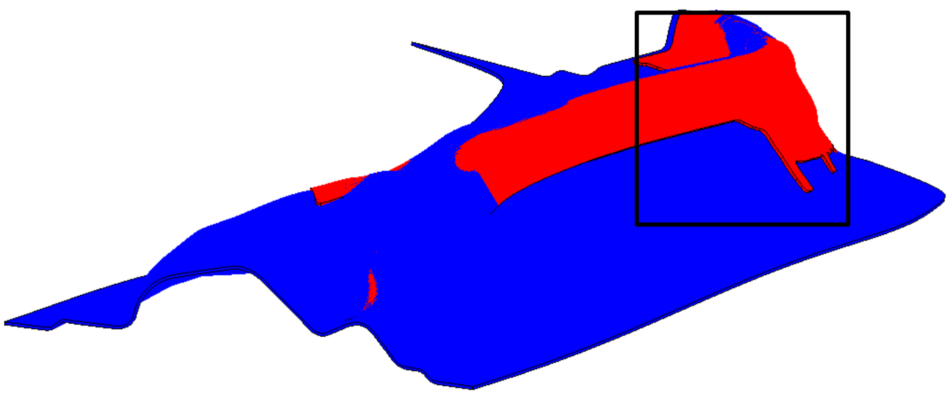


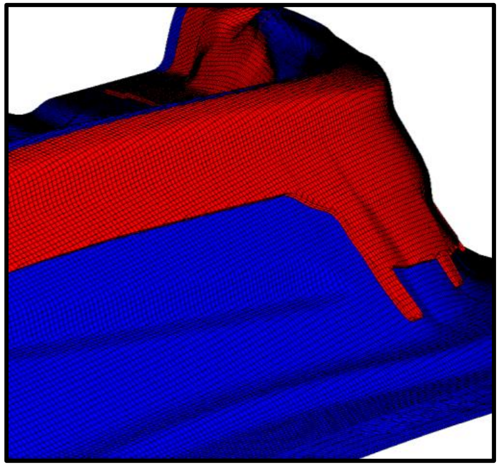
Trimming process

Front fender
(Benchmark C - Numisheet 2002)

Numerical simulation

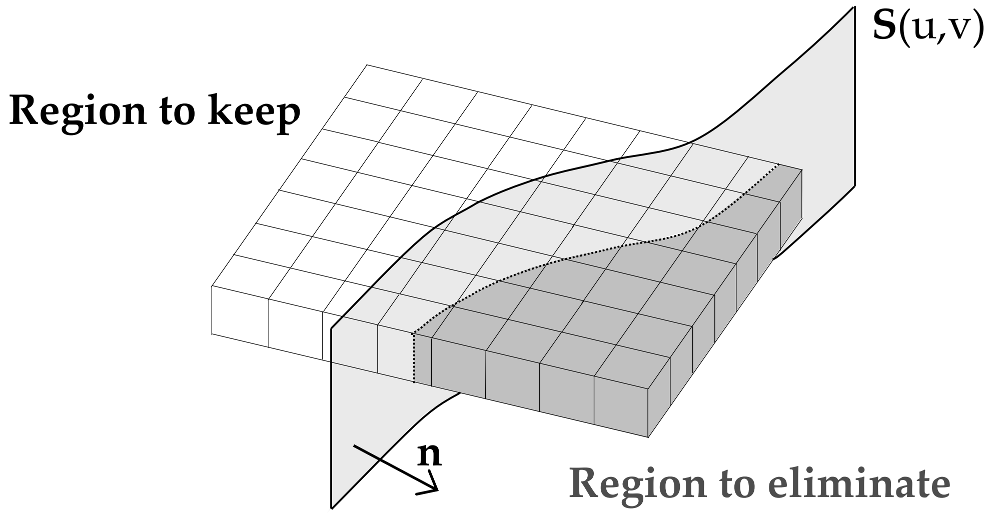
- Numerical simulation is an **indispensable tool** in the development of new automotive components manufactured by forming
- Finite element modelling of sheet metal forming processes is **very complex** due to the highly non-linear material behavior, large strains and frictional contact conditions
- Intermediate stages for trimming



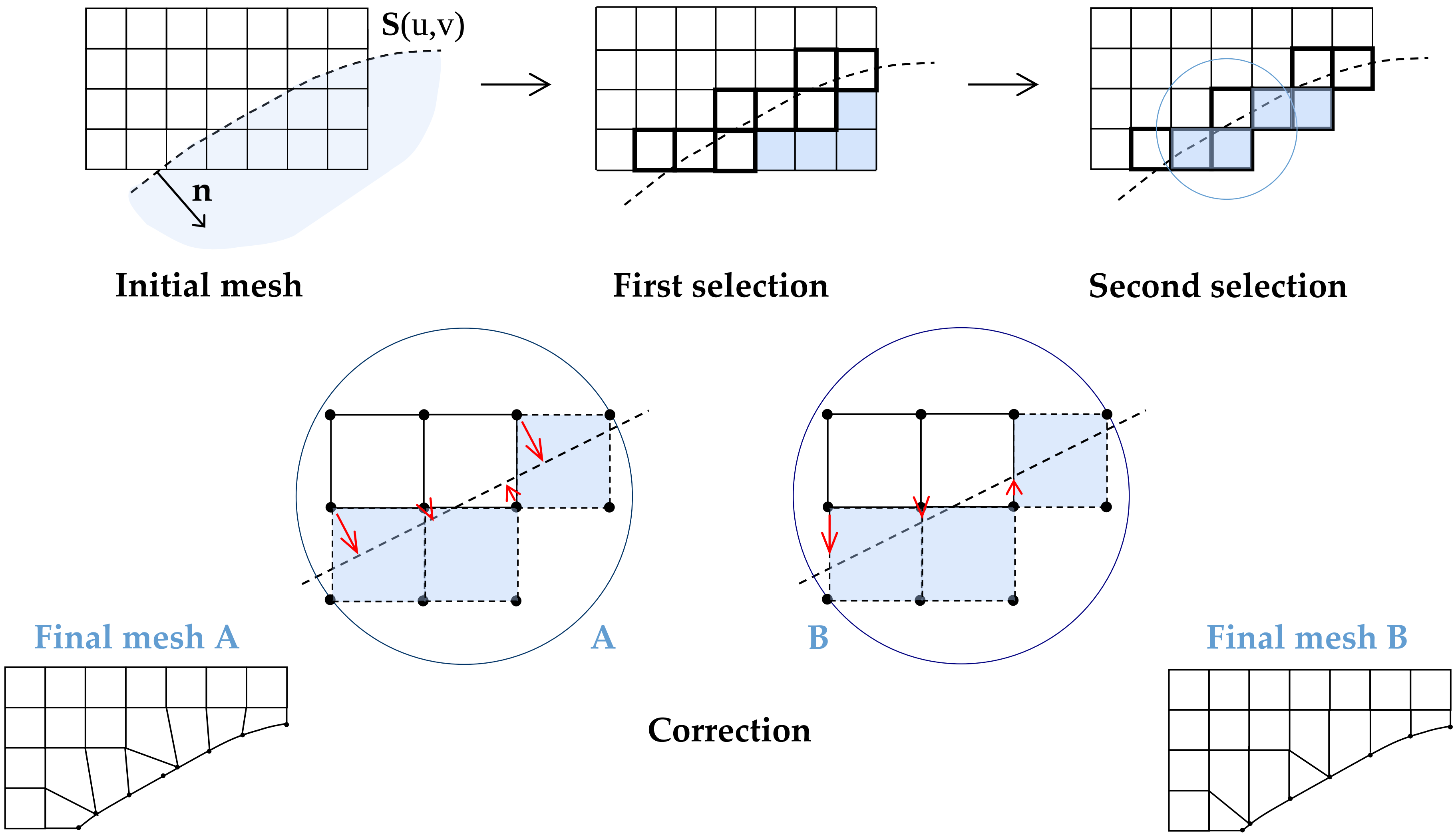


Aluminium Panel
(Benchmark 2 - Numisheet 2016)

Trimming

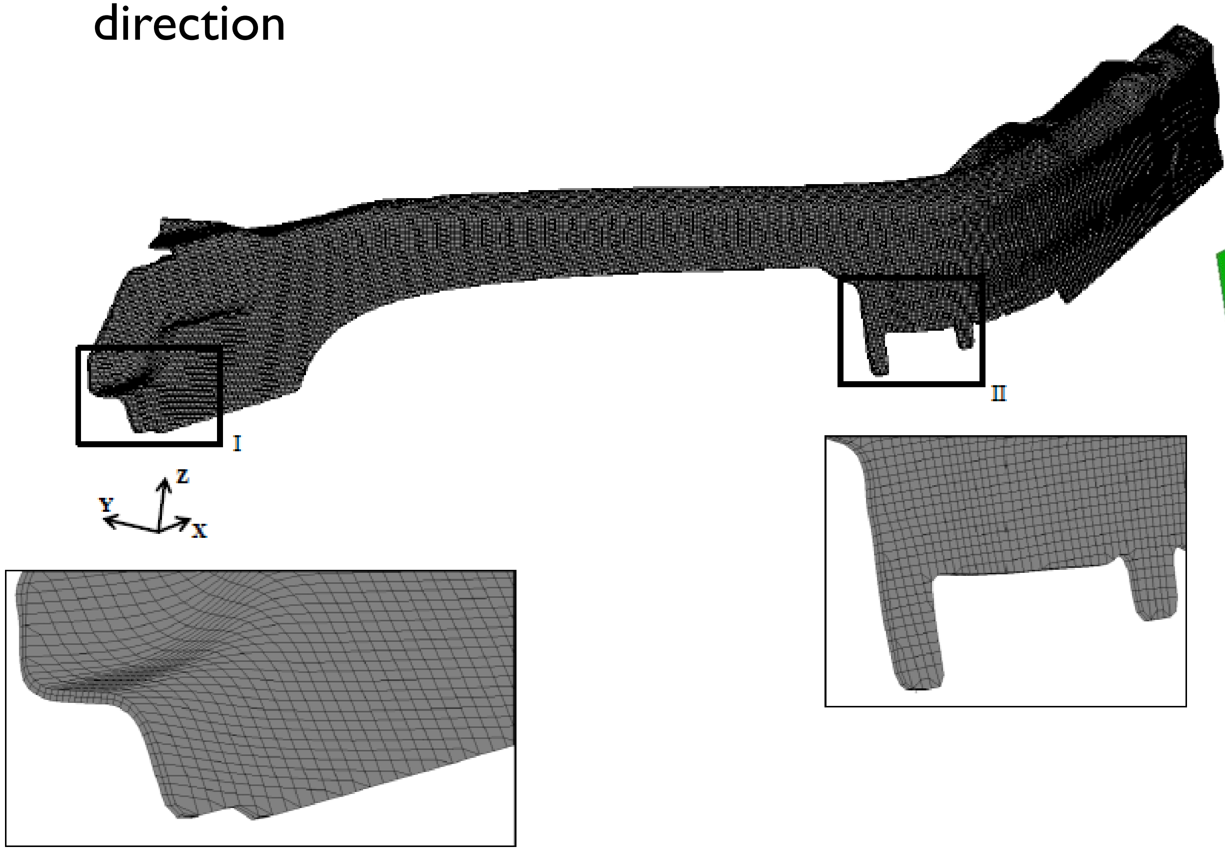


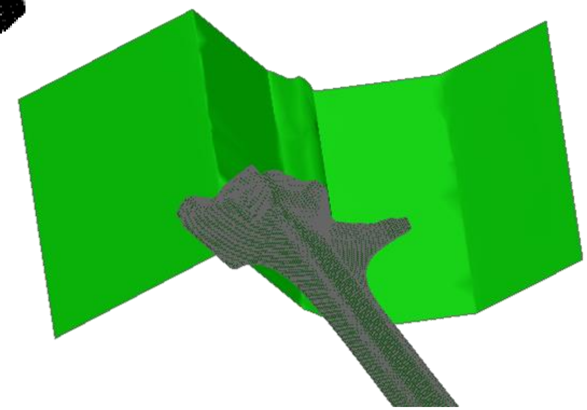
Trimming


S(u,v)
n
Initial mesh
First selection
Second selection
A
B
Final mesh A
Final mesh B
Correction

Trimming

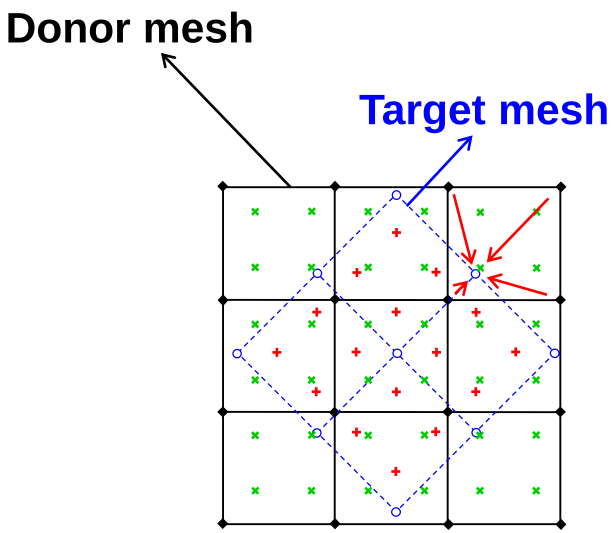
- Implies the definition of trimming surfaces properly aligned with the thickness direction



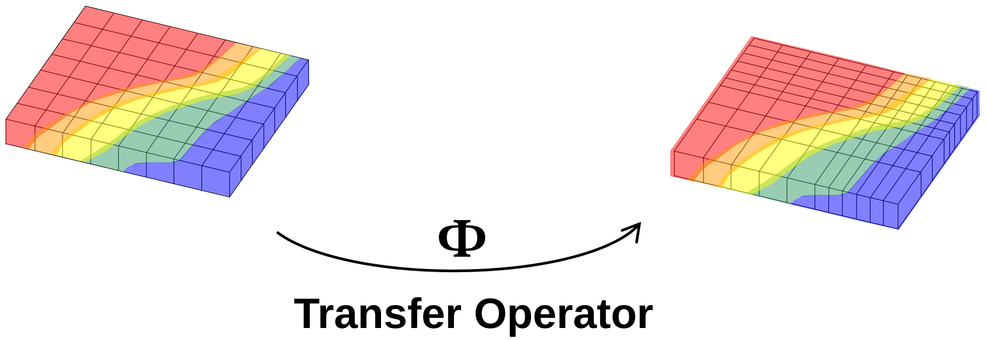


Aluminium Panel
(Benchmark 2 - Numisheet 2016)

Remapping



- **Remapping in the Nodes**
  (Nodal Variables: Force, displacement, etc.)
- **Remapping in the Gauss Points**
  (State Variables: Stress, density, etc.)



Remapping

APPLICATION FIELDS

- Solid Mechanics
- Fluid Dynamics
- Combustion
- Multidisciplinary subjects

NECESSITY

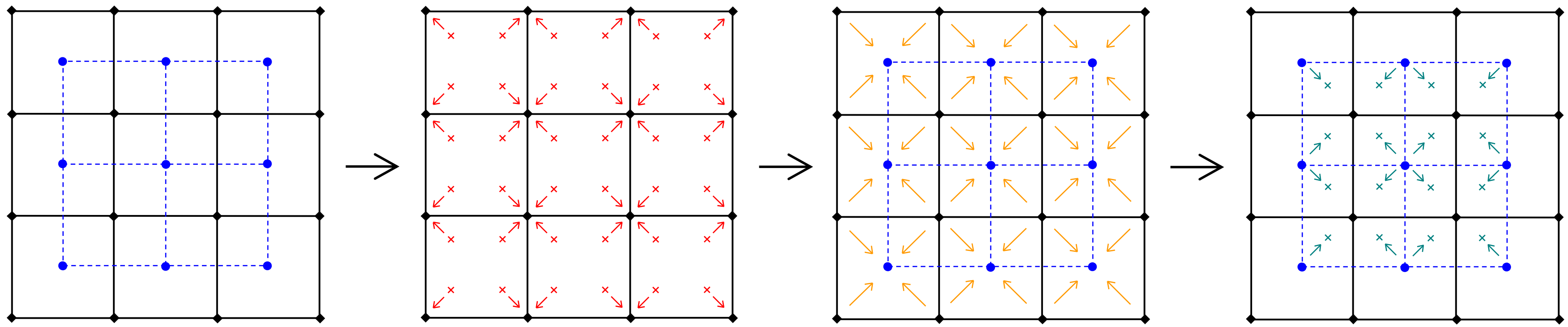
- Adaptive mesh operations
- Multigrid methods
- Texture mapping
- Trimming operations

REMAPPING

OPERATION REQUIREMENTS

- Keep the equilibrium state
- Minimize the transfer error
- Overall accuracy of the simulations

Remapping methodologies



Original meshes **Extrapolation** **Interpolation I** **Interpolation II**

$$\alpha_j = \sum_{i=1}^{n} \tilde{N}_{i\,j}(\xi,\eta,\zeta)\,\alpha_i \qquad \alpha_{ig} = \sum_{j=1}^{n} \tilde{N}_{j\,ig}(\xi,\eta,\zeta)\,\alpha_j$$

- **Finite element shape functions**

$$\alpha_i = \sum_{ig=1}^{ng} \left[\tilde{N}_{ig\,i}(\xi,\eta,\zeta) \right]^{-1} \alpha_{ig}$$

- **Minimum least square**

$$I(\mathbf{x}_i) = \sum_{ig}^{N} w(\mathbf{x}_{ig}) \left[\alpha(\mathbf{x}_i) - \alpha_{ig} \right]^2$$

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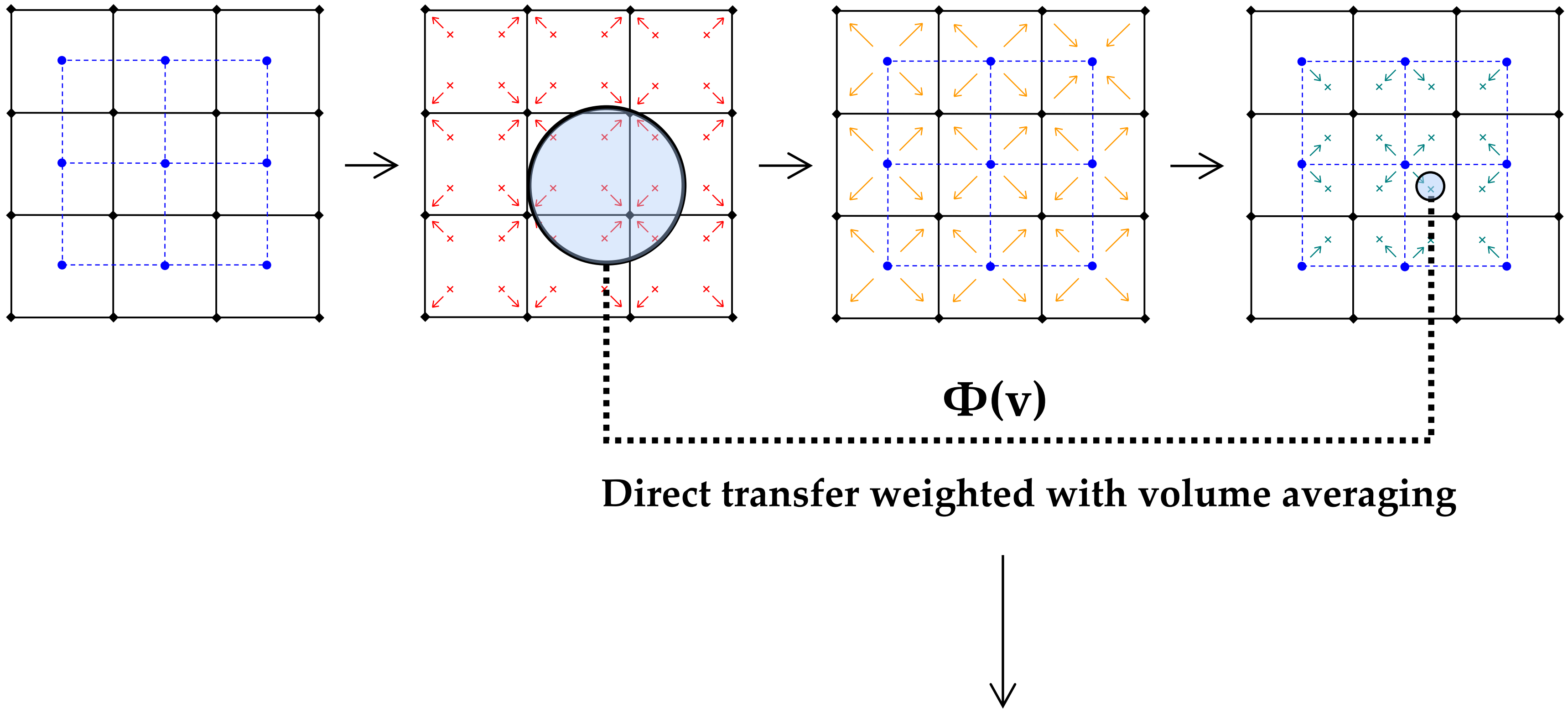
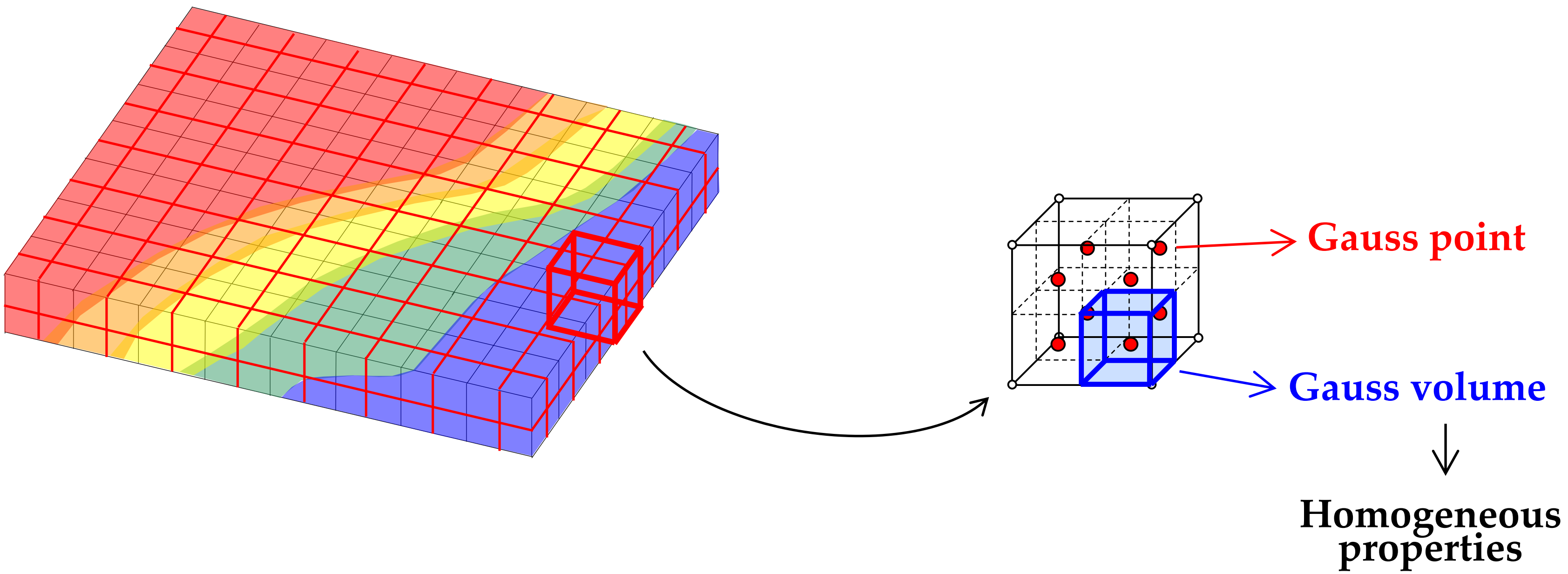
Remapping – Incremental Volumetric Remapping



INCREMENTAL VOLUMETRIC REMAPPING – IVR

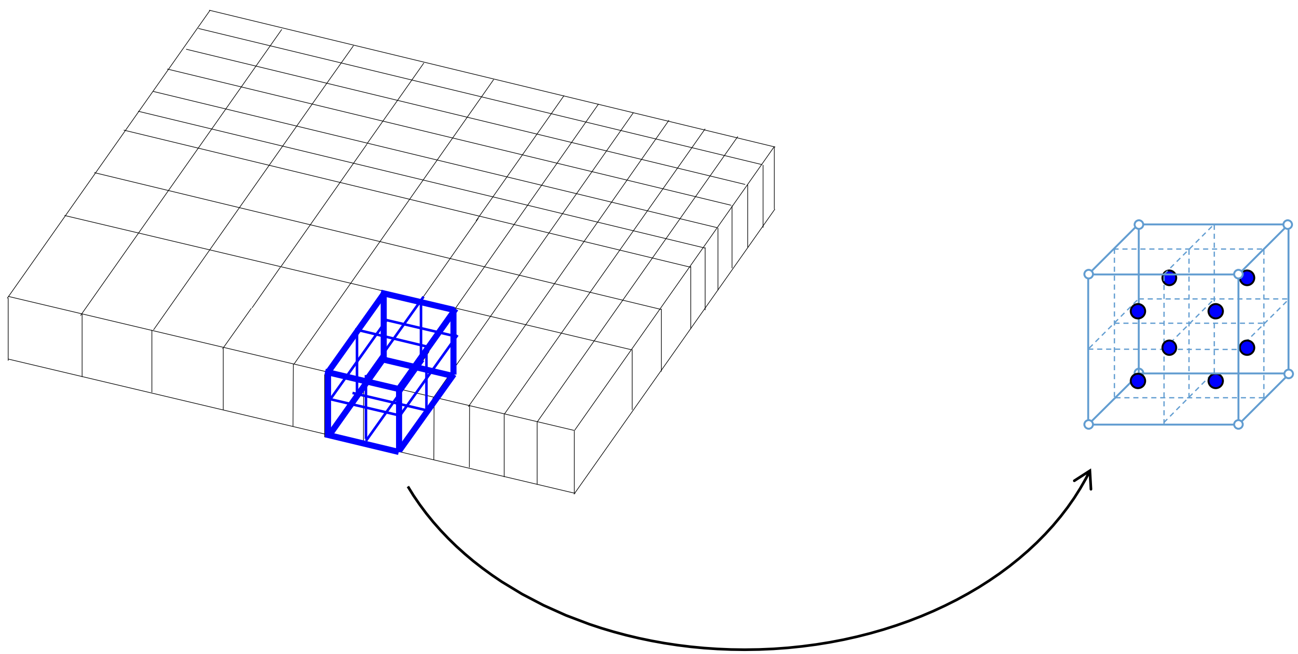
Remapping – Incremental Volumetric Remapping

i) Step 1 – Divide all donor elements in Gauss Volumes



Remapping – Incremental Volumetric Remapping

ii) Step 2 – Divide all target elements in Gauss Volumes



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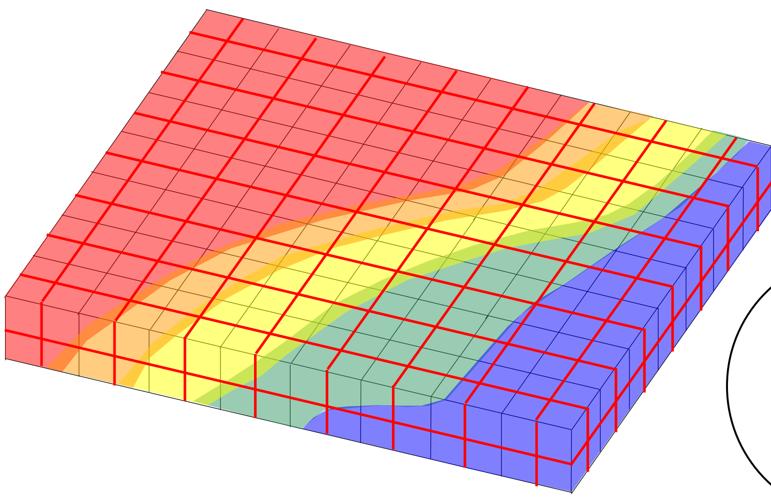
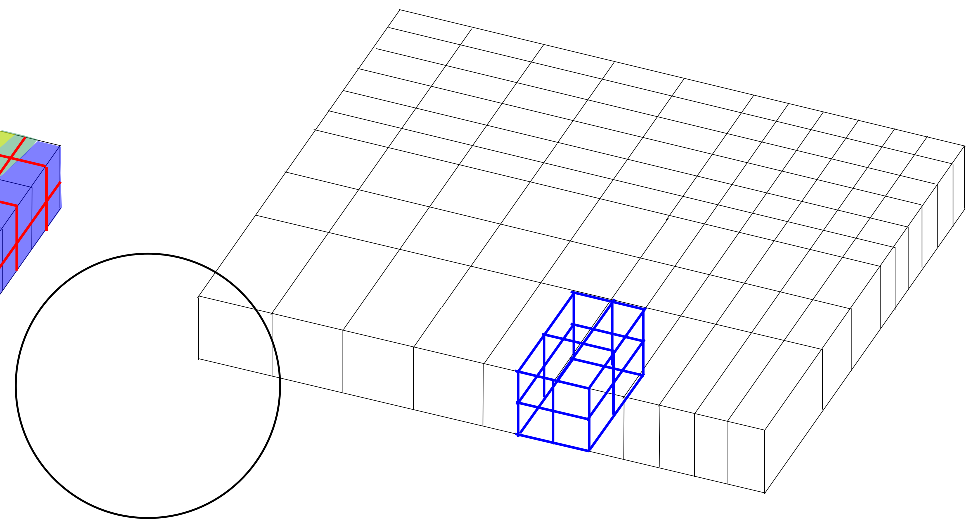
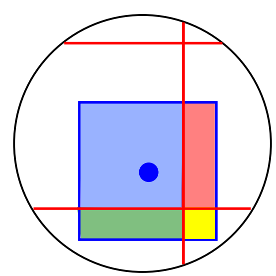
Remapping – Incremental Volumetric Remapping

iii) Step 3 – Intersect each target Gauss volume with the donor Gauss volumes







Intersection Gauss volumes

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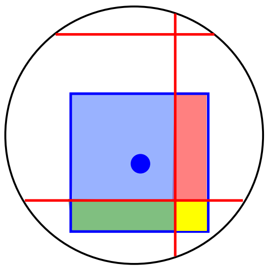
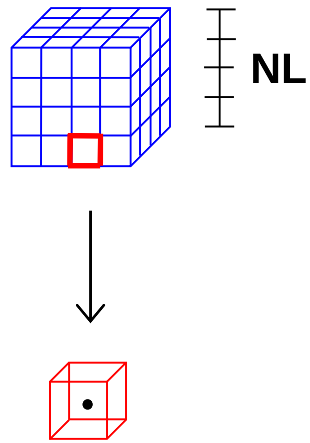
Remapping – Incremental Volumetric Remapping

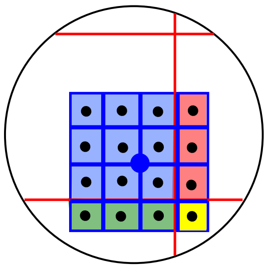
iv) Step 4 – Volume division of each target Gauss volume

v) Step 5 – Find the donor Gauss volume that encloses each target Gauss volume part centroid





Gauss volume part



Weighted volume average

$$\alpha = \sum_{i=1}^{NG} \frac{\sum_{j=1}^{NL^3} {}^{i}V_j}{{}^{i}V_{tot}} \alpha_i$$

$\Phi(\mathbf{v})$

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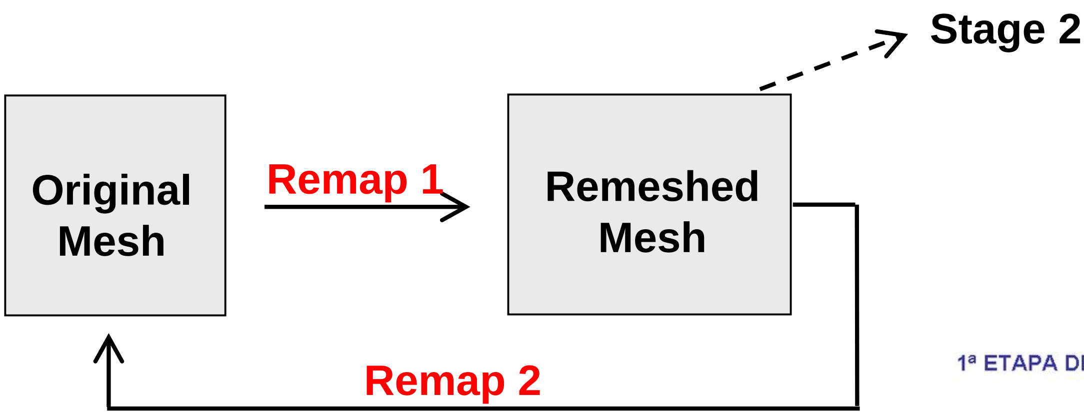
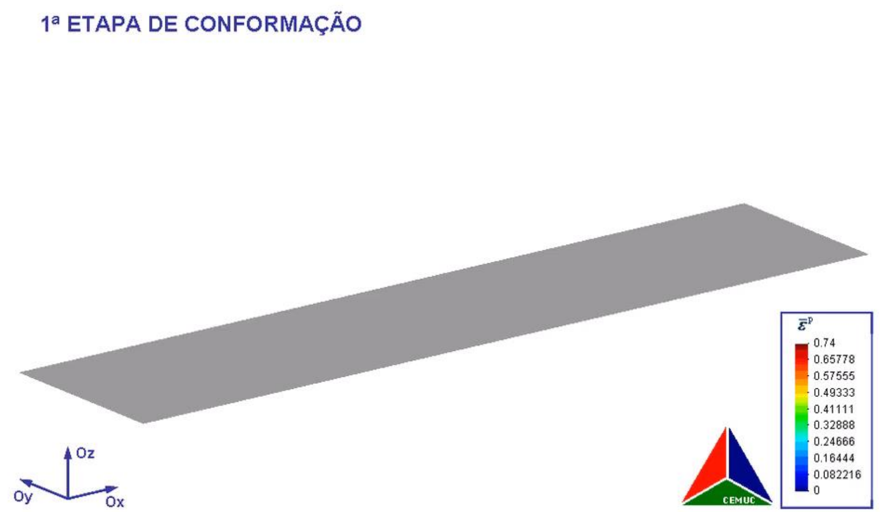
Remapping operation: Comparison of methods



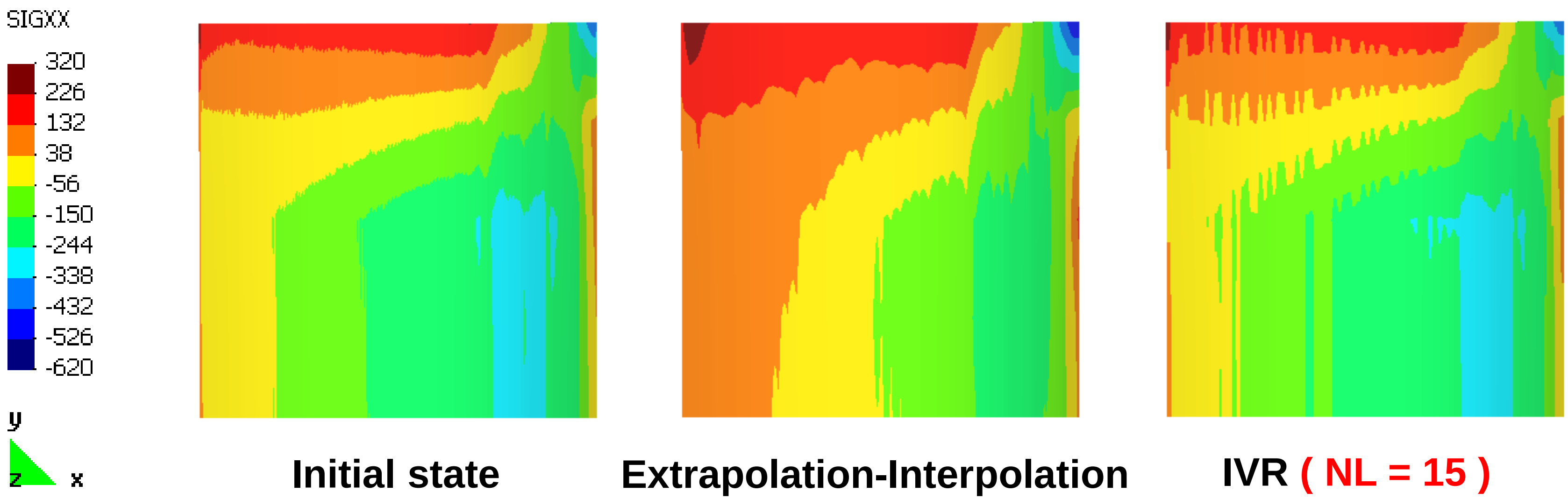
Test methodology



- **Standard extrapolation-interpolation**
- **Incremental Volumetric Remapping**
- **State variable analysed: σ_{xx} stress**

Channel draw/Cylindrical Cup 2-stage test
(Benchmark 3 - Numisheet 2005)

Remapping operation



Remapping – Dual Kriging

- For the target Gauss point (GP), $\mathbf{x}_{\mathrm{t}} = [x \quad y \quad z]^{\mathrm{T}}$, the interpolation function can be decomposed in two terms

$$\alpha(\mathbf{x}_{\mathrm{t}}) = d(\mathbf{x}_{\mathrm{t}}) + f(\mathbf{x}_{\mathrm{t}})$$

Drift

$$d(\mathbf{x}_{\mathrm{t}}) = \mathbf{d}^{\mathrm{T}} \cdot [1 \quad \mathbf{x}_{\mathrm{t}}^{\mathrm{T}}] = d_1 + d_2 x + d_3 y + d_4 z$$

Fluctuation

$$f(\mathbf{x}_{\mathrm{t}}) = \sum_{i=1}^{n} \lambda_i K(h_{\mathrm{t}i}) = \sum_{i=1}^{n} \lambda_i K(|\mathbf{x}_{\mathrm{t}} - \mathbf{x}_i|)$$

- To obtain the value of this function, it is necessary to solve a system of linear equations:

$$\begin{bmatrix} \mathbf{K}_{11} & \mathbf{K}_{12} \\ \mathbf{K}_{21} & \mathbf{K}_{22} \end{bmatrix} \times \mathbf{u} = \mathbf{f} \Leftrightarrow \left[\begin{array}{ccc|ccc} & & & 1 & & \mathbf{x}_1^{\mathrm{T}} \\ & K\left(\left|\mathbf{x}_i - \mathbf{x}_j\right|\right) & & \vdots & & \vdots \\ & & & 1 & & \mathbf{x}_n^{\mathrm{T}} \\ \hline & & & 0 & \cdots & 0 \\ 1 & \cdots & 1 & \vdots & \ddots & \vdots \\ \mathbf{x}_1 & \cdots & \mathbf{x}_n & 0 & \cdots & 0 \end{array}\right] \times \begin{bmatrix} \lambda_1 \\ \vdots \\ \lambda_n \\ \hline d_1 \\ \vdots \\ d_s \end{bmatrix} = \begin{bmatrix} \mathrm{f}_1 \\ \vdots \\ \mathrm{f}_n \\ \hline 0 \\ \vdots \\ 0 \end{bmatrix}$$

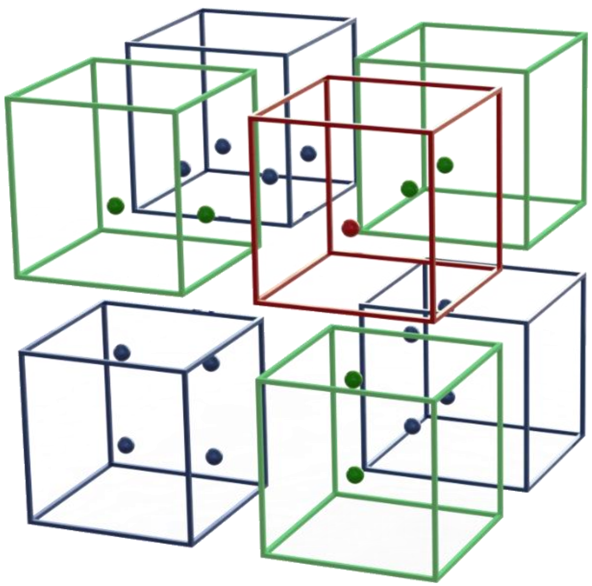
Remapping – Dual Kriging

- For each target GP:
  - Select a set of neighbour donor GPs;
  - Evaluate the kriging coefficients and weighting factors;
  - Evaluate the state variable value in the target GP.
- Several selection algorithms for choosing the set of donor GPs were tested., based on the definition:

Name	Definition
Master Node	Closest node from the donor mesh to the target GP
Master Element	Donor mesh's element partially defined by the Master Node, containing the target GP
Master GPs	Donor mesh's GPs belonging to the Master Element
Slave Elements	Donor mesh's elements that share the Master Node, but do not contain the target GP
Slave GPs	Donor mesh's GPs that belong to any Slave Element, which will be considered in the Dual Kriging process.

Remapping – Dual Kriging

Master-Slave method



Set of donor GPs (n=27):

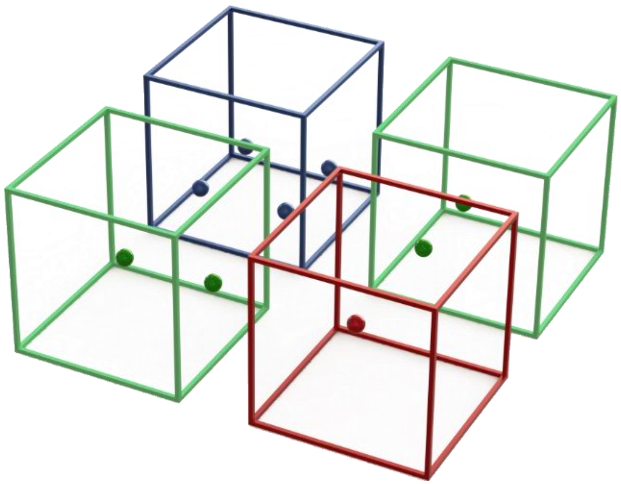
(i) 8 of the omitted Master Element;

(ii) 4 of each Slave Element with only one shared face (in blue);

(iii) 2 of each Slave Element with only one shared edge (in green);

(iv) 1 of each Slave Element with only one shared vertex (in red).

Planar selection



Set of donor GPs (n=9):

(i) 4 of the Master Element located in the same reference face (in blue);

(ii) 2 of each Element with one shared edge with Slave the reference face (in green);

(iii) 1 of each Slave Element with one shared vertex with the reference face (in red).

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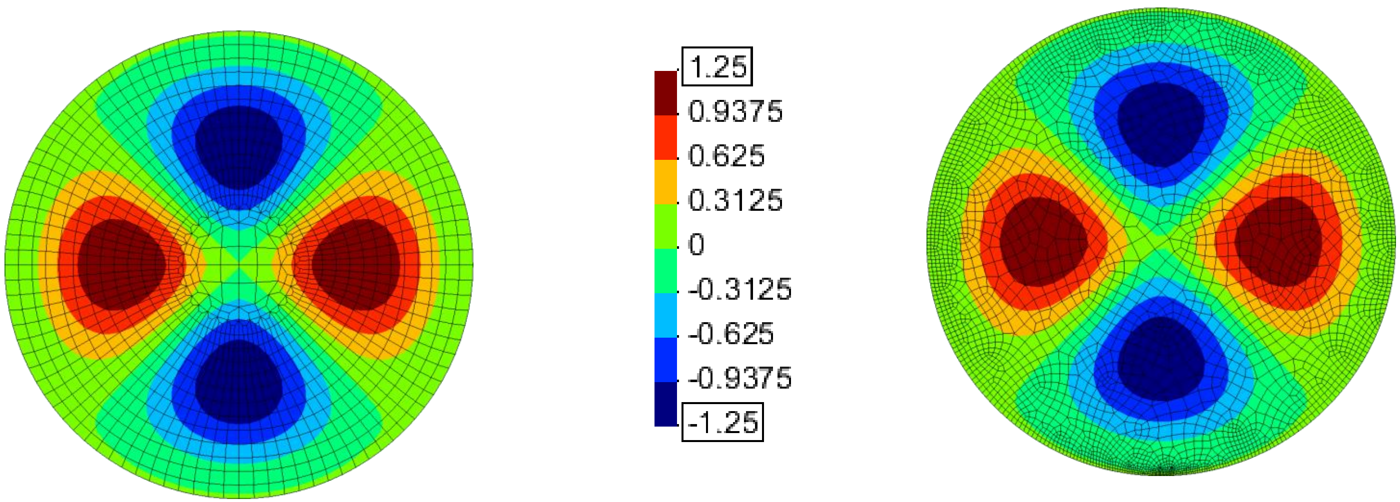
Remapping – Dual Kriging accuracy

- The remapping is carried out in two stages, first, from the structured to the unstructured mesh (called *stage 1*) and afterwards, back to the structured mesh (called *stage* 2).
- Analytical function: $T(r,\theta) = 20r^2(r-1)^2\cos(2\theta),\ r = \sqrt{\dfrac{x^2+y^2}{a^2}}$

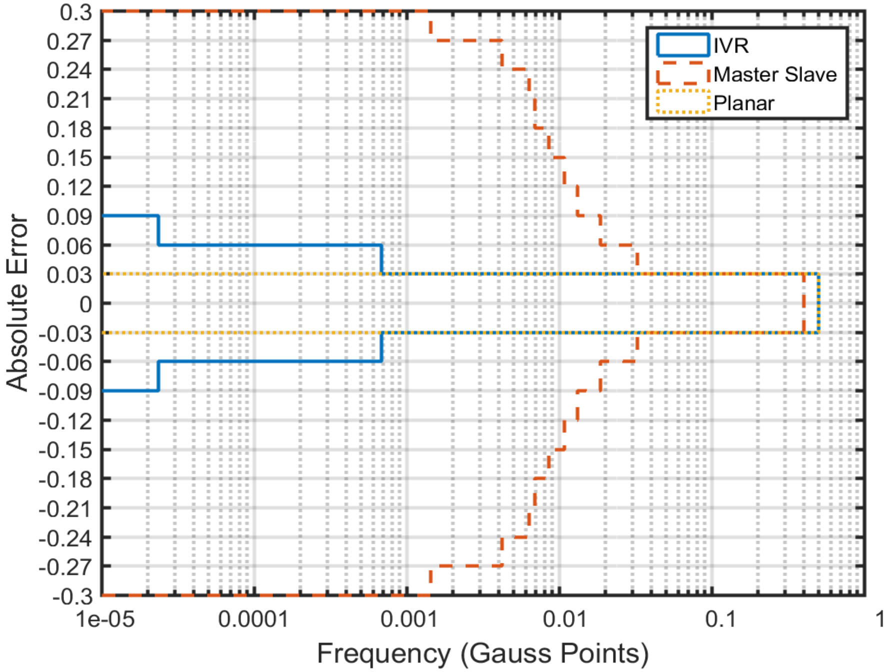


- Two FE layers through-thickness, from the top to the bottom layer, equal to: T, 0.1 T, -0.1 T, and - T.

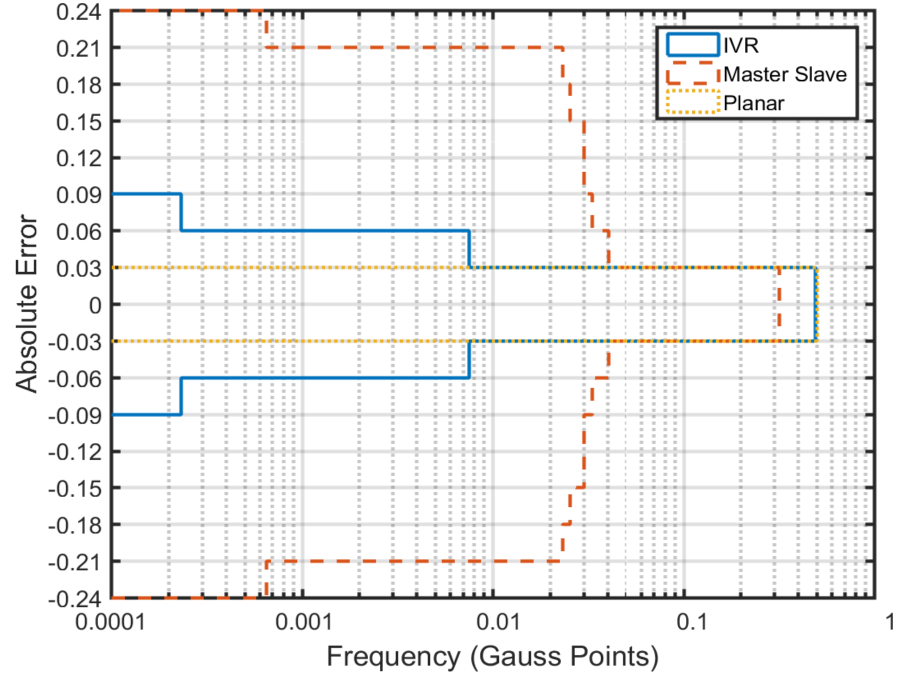
Remapping – Dual Kriging accuracy

- Absolute error associated with the remapping method: $E(r,\theta)=T(r,\theta)-\alpha(\mathbf{x}_{\mathrm{t}})$

Stage 1

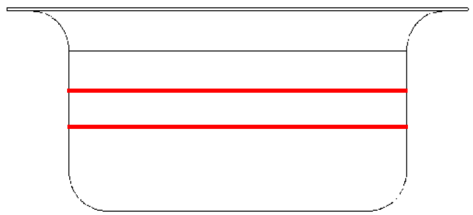


Stage 2

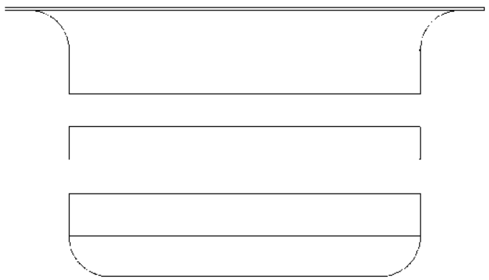


- The distribution obtained with the Master-Slave method has the highest spread and error value, particularly for *Stage 2*.

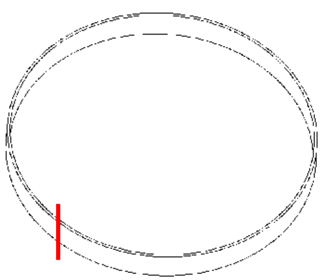
Springback – DEMERI TEST



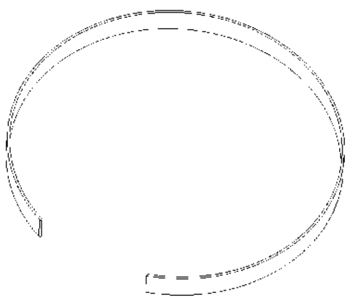
Stage I – Forming of the cup



Stage II – Cut the ring



Stage III – Split the ring



Stage IV – Open the ring

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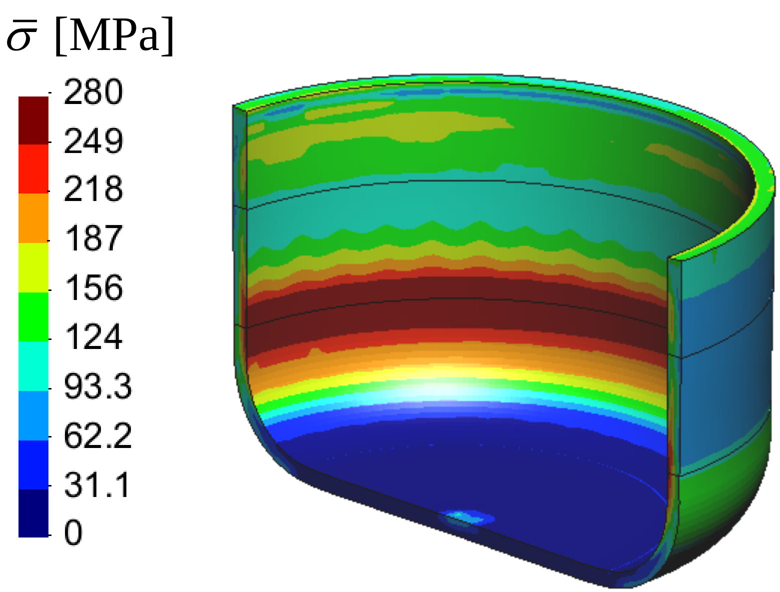
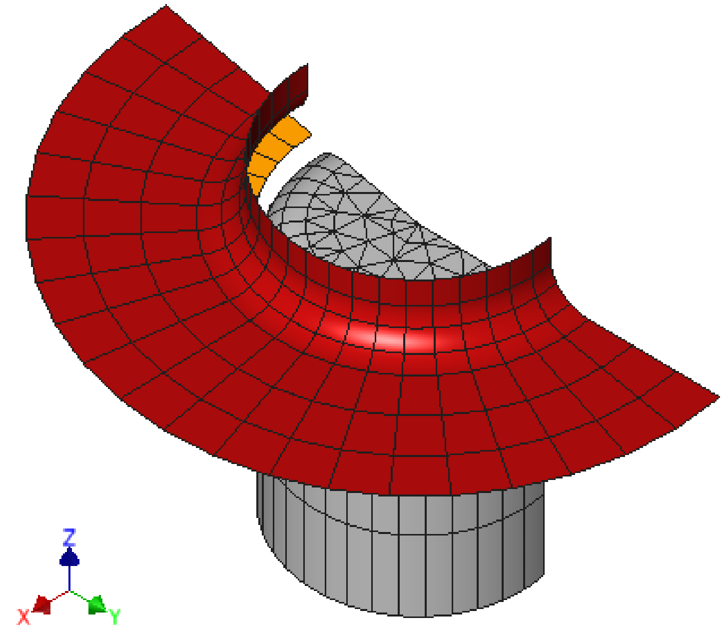
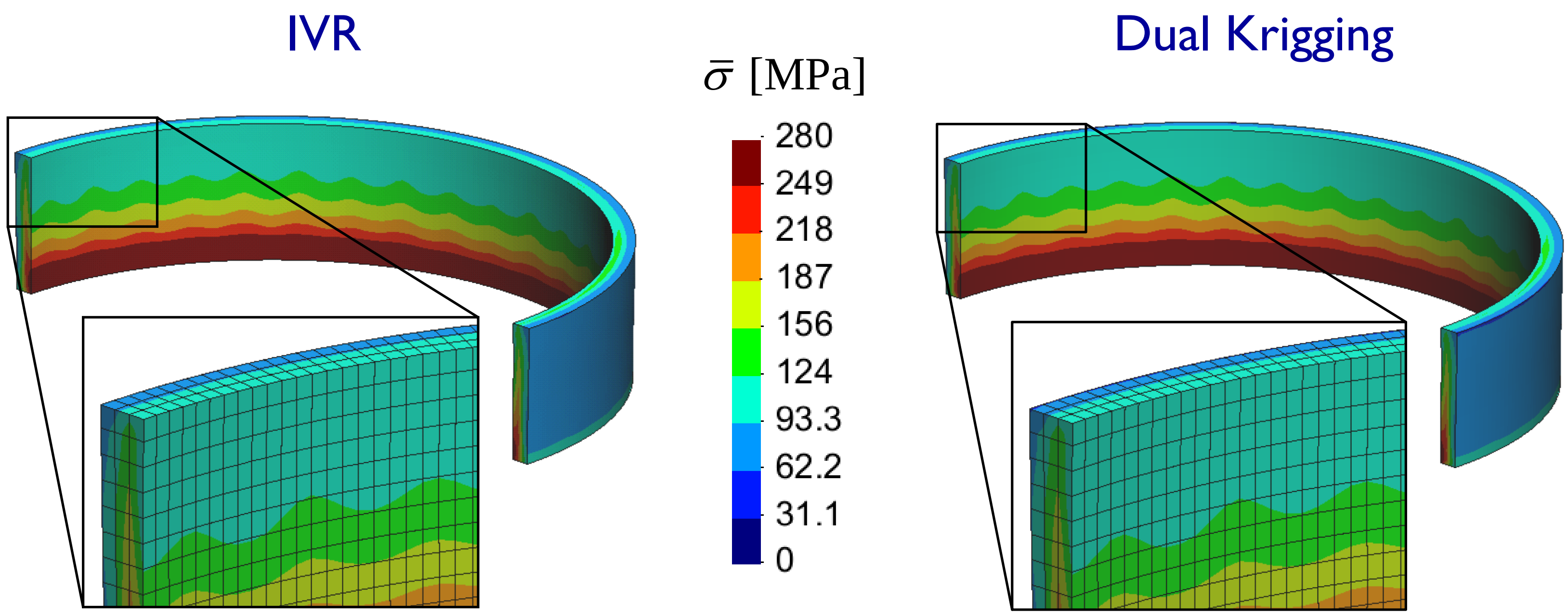
Springback – DEMERI TEST

- AA5754-O aluminum alloy
- Blank with Ø60 mm and 1 mm thickness
- 1/2 of the model (symmetry conditions)
- Isotropic work hardening (voce law) and isotropic yield criterion (von Mises)





Springback – DEMERI TEST



Ring opening	
4.3 mm	4.3 mm

Computational cost for the remapping [sec.]	
300	<2

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Conclusions

- This work presents the application of the Dual Kriging interpolation method as remapping scheme for FEM state variables between different finite element meshes.
- When considering a state variable distribution with gradient in all directions, combined with a small thickness dimension, a decrease of accuracy is observed for the Master-Slave method, due to an overweighting of the through-thickness component, while the Planar method kept its level of accuracy.
- The computational cost incurred for the Dual Kriging significantly lower than the IVR method.
- All remapping methods can provide results with a good level of accuracy.

Acknowledgements

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Thank you for your attention!