Computer aided design of extrusion forming tools

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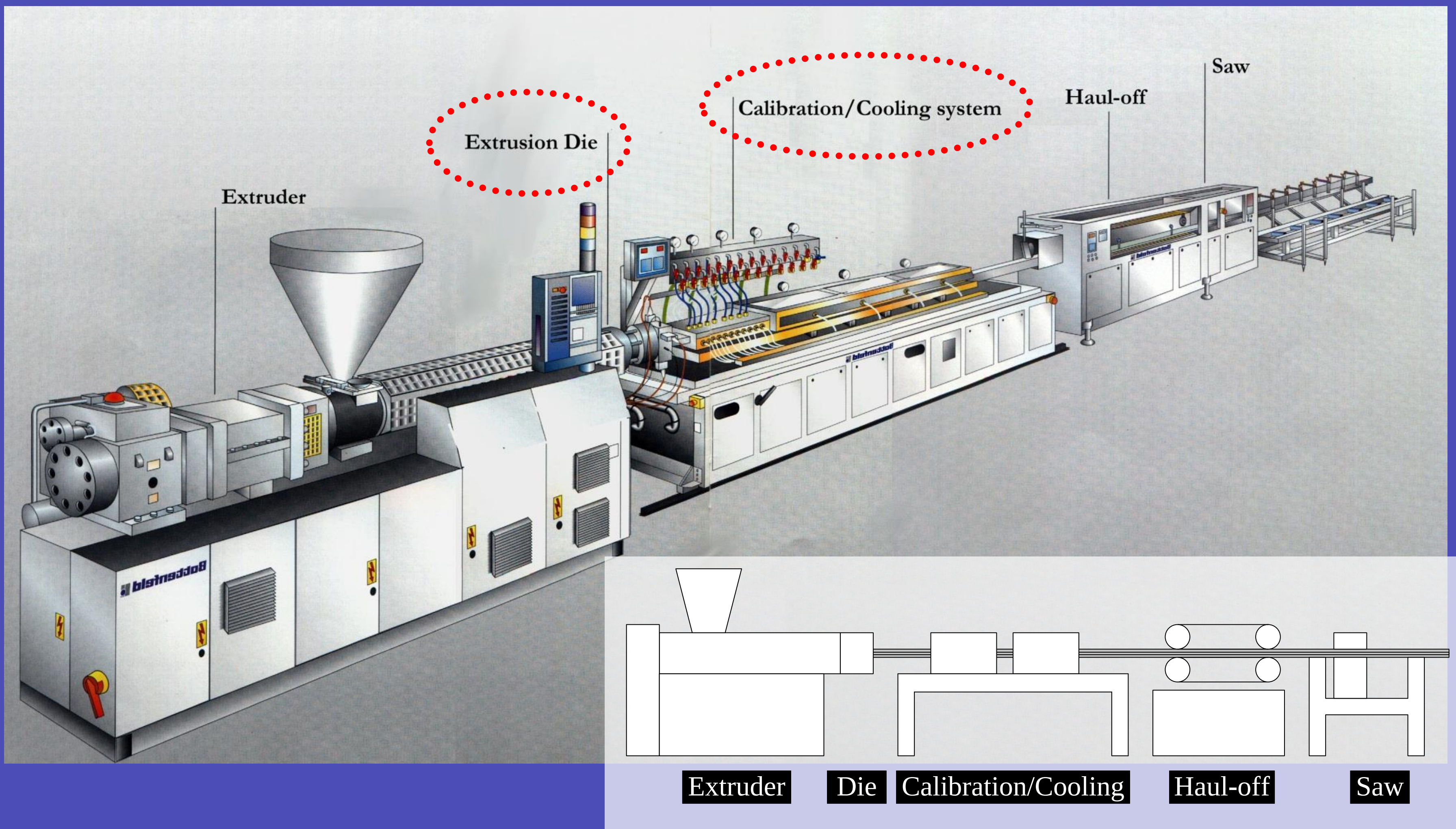
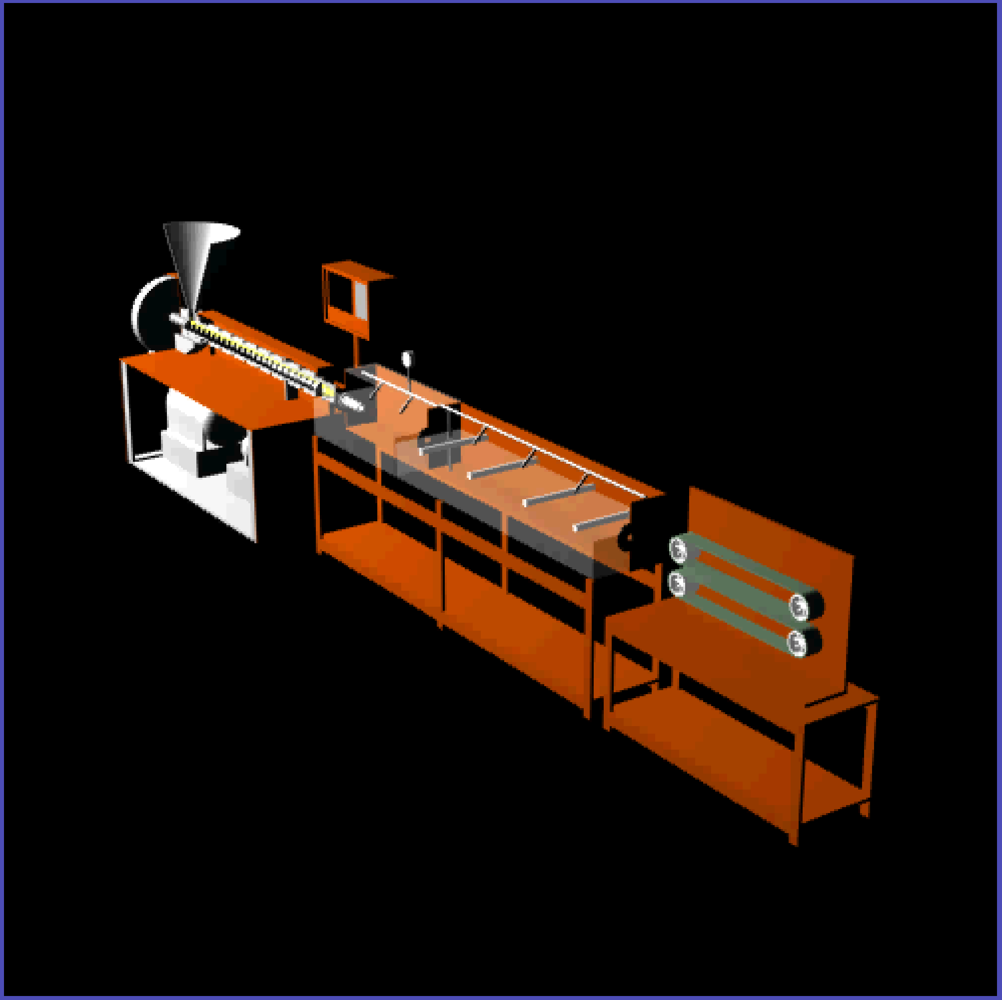
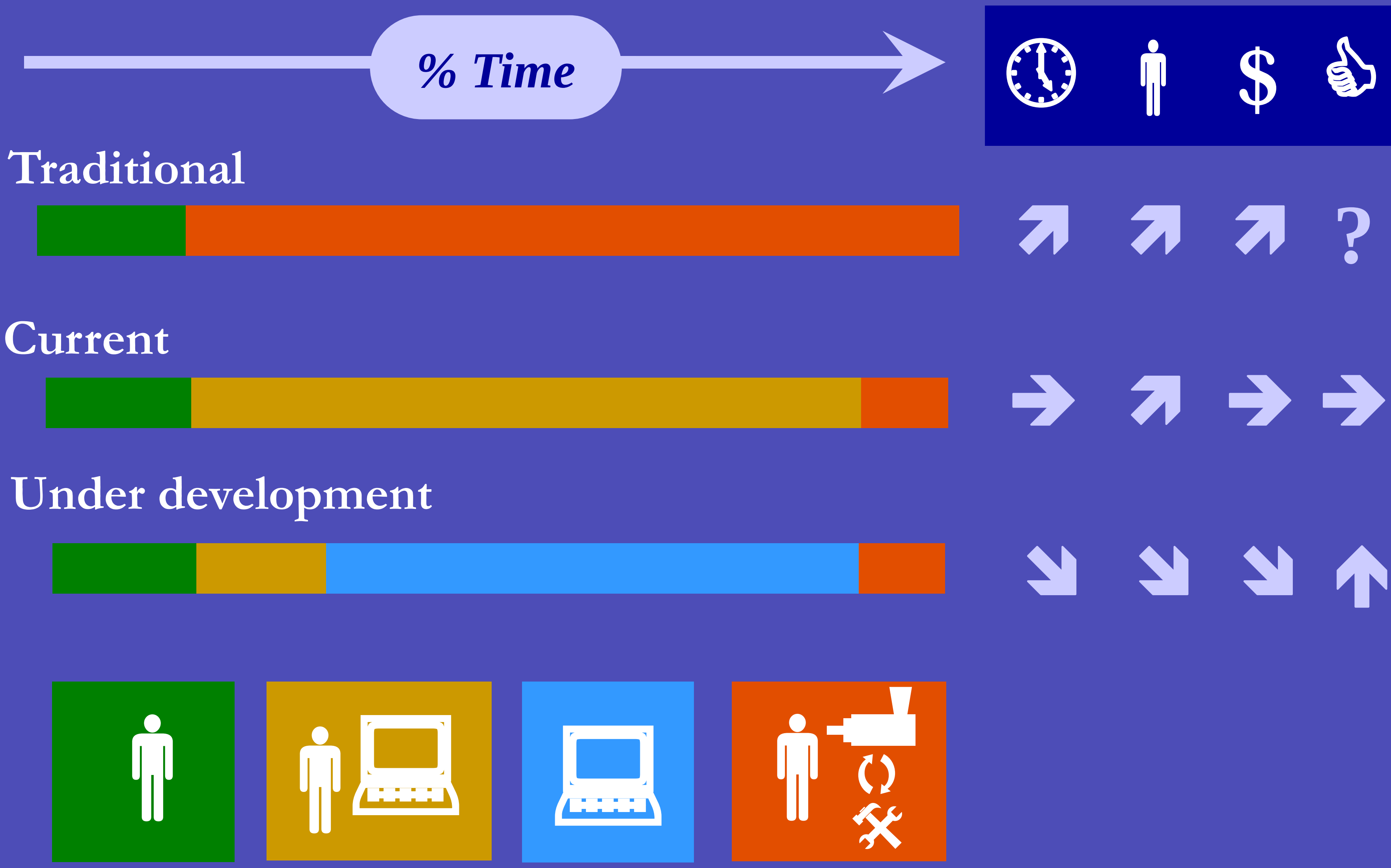
Introduction - *Profile Extrusion*



Introduction - *Profile Extrusion*



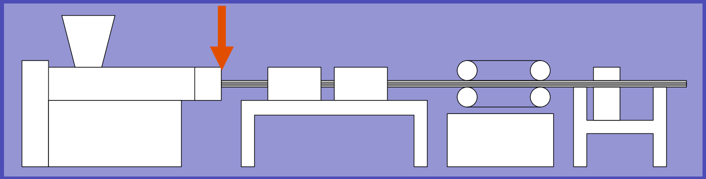
Introduction - *Design Approaches*

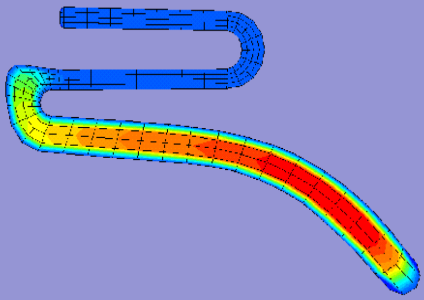
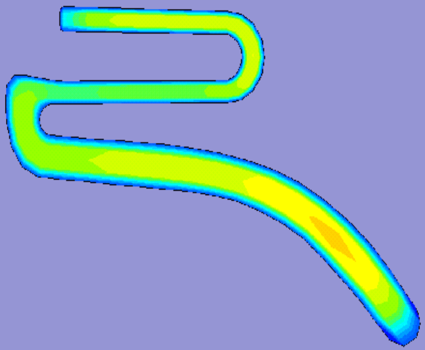


Outline

- Extrusion Dies
  - Problem Statement
  - Flow Distribution Optimisation
  - Flow Balance Strategies
  - Optimisation
  - Length vs Thickness Optimisation
  - Conclusion
- Calibrators
  - Problem Statement
  - System Behaviour
  - Optimisation Methodology
  - Case Study
  - Conclusion
- Conclusion
- Ongoing Work

Extrusion Dies – *Problem Statement*

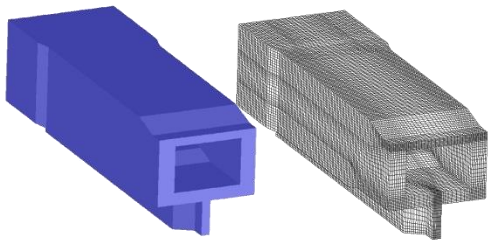


	Unbalanced	Balanced
Extrusion run		
Numerical Velocity contours		

Extrusion Dies – *Flow Distribution Optimisation*

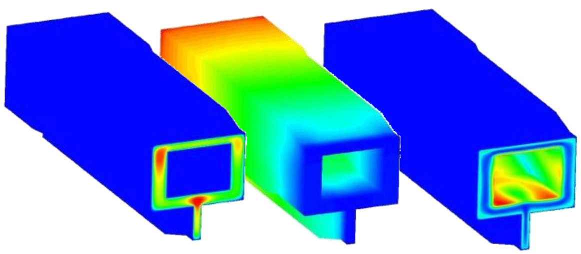
Trial Parameters

Pre-Processor



Geometry Mesh

3D non-isothermal flow field calculation (FVM)

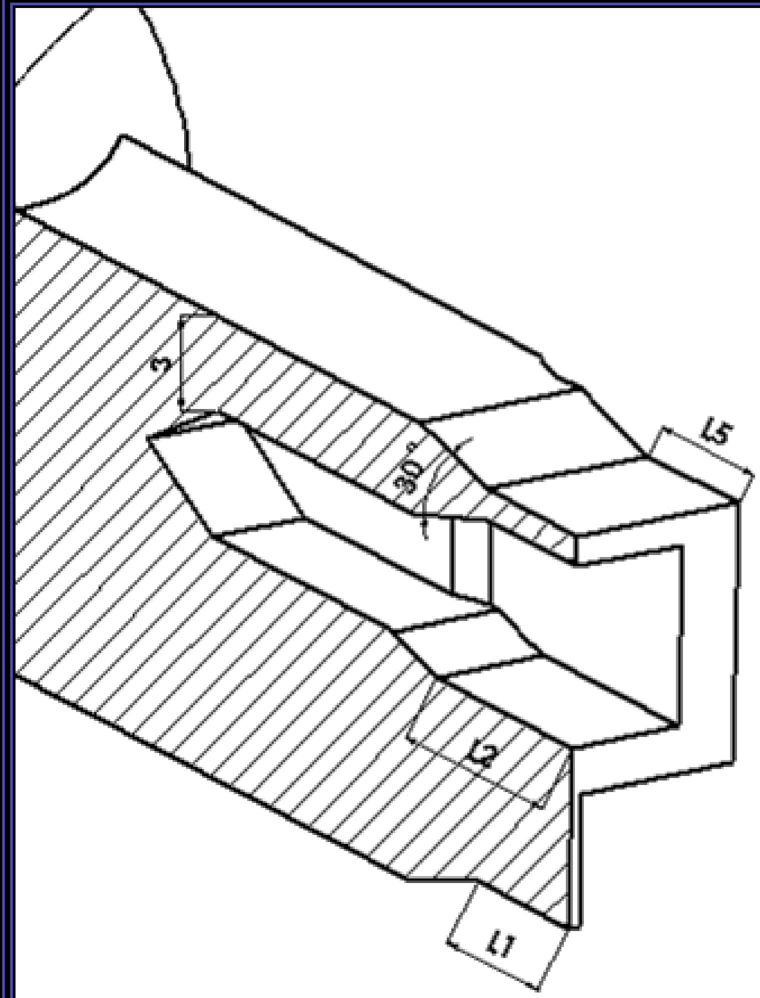


Velocity Pressure Temperature

Performance Evaluation

$$F_{obj} = \sum_{i=1}^{n} \left\{ \left[\left\{ \alpha \left(1 - \frac{V_i}{V_{obj,i}}\right)^2 + k(1-\alpha)\left[1 - \frac{(L/t)_i}{(L/t)_{\min}}\right]^2 \right\} \frac{A_i}{A} \right] \right\}$$

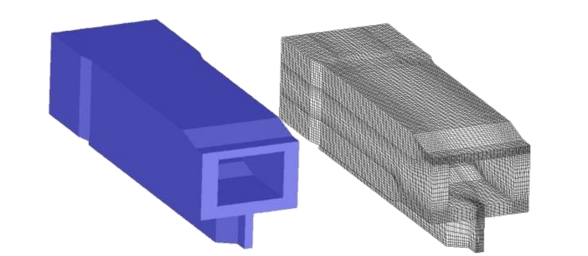
Modification of the controllable geometrical parameters until the optimum is reached



Extrusion Dies – *Flow Distribution Optimisation*

Trial Parameters

Pre-Processor



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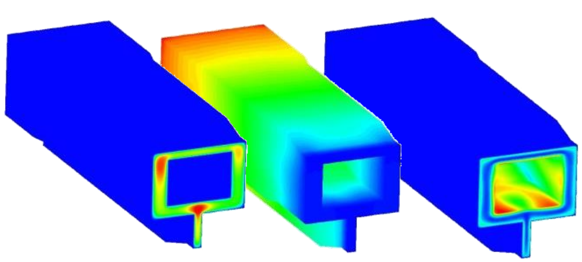

Velocity Pressure Temperature

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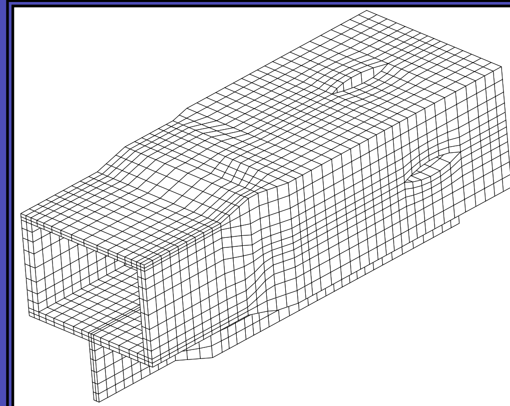
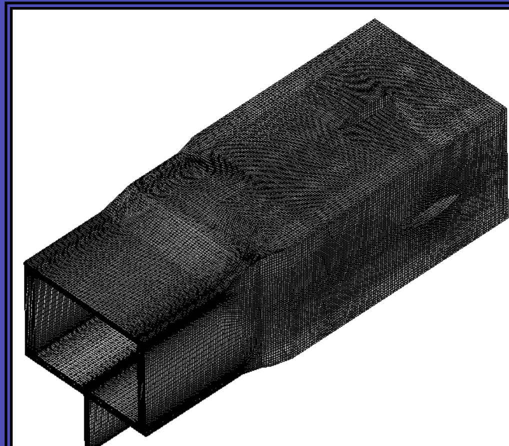
Modification of the controllable geometrical parameters until the optimum is reached

Progressive mesh refinements





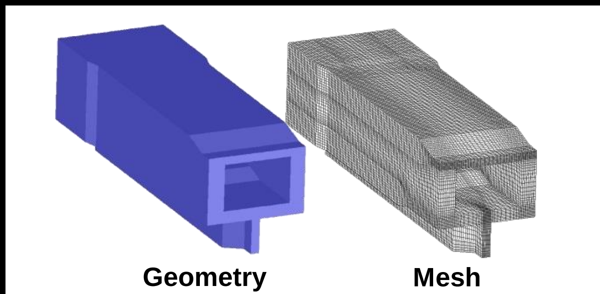
Cells along Thickness	Number of Cells	Time [h:m:s]
2	15 496	0:00:36
4	92 248	0:12:15
6	272 220	1:12:17
8	593 928	4:28:36
10	688 024	6:43:42

PIV / 2.4 GHz

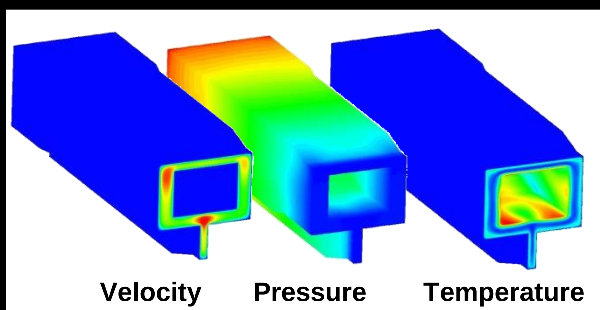
Extrusion Dies – *Flow Distribution Optimisation*

Trial Parameters

Pre-Processor



3D non-isothermal flow field calculation (FVM)



Performance Evaluation

$$F_{obj} = \sum_{i=1}^{n} \left\{ \left[\alpha \left(1 - \frac{V_i}{V_{obj,i}} \right)^2 + k(1-\alpha) \left[1 - \frac{(L/t)_i}{(L/t)_{\min}} \right]^2 \right] \frac{A_i}{A} \right\}$$

Modification of the controllable geometrical parameters until the optimum is reached

Equations to Solve

Conservation of mass:

$$\frac{\partial \rho u_j}{\partial x_j} = 0$$

Conservation of linear momentum:

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_j u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j}$$

Conservation of energy:

$$\frac{\partial \rho c T}{\partial t} + \frac{\partial \rho c u_i T}{\partial x_i} = \frac{\partial}{\partial x_i} \left(k \frac{\partial T}{\partial x_i} \right) + \tau_{ij} \frac{\partial u_i}{\partial x_j}$$

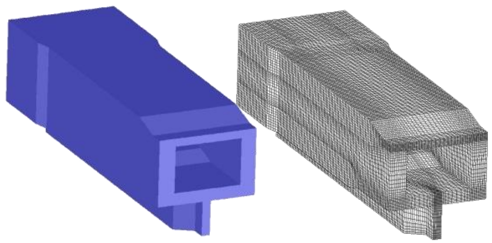
Constitutive equation (Gen. Newtonian):

$$\tau_{ij} = \eta(\dot{\gamma}) \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$$

Extrusion Dies – *Flow Distribution Optimisation*

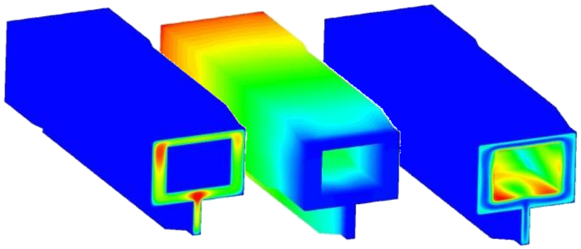
Trial Parameters

Pre-Processor



Geometry   Mesh

3D non-isothermal flow field calculation (FVM)



Velocity   Pressure   Temperature

Performance Evaluation

$$F_{obj} = \sum_{i=1}^{n} \left\{ \left[\alpha \left(1 - \frac{V_i}{V_{obj,i}} \right)^2 + k(1-\alpha) \left[1 - \frac{(L/t)_i}{(L/t)_{\min}} \right]^2 \right] \frac{A_i}{A} \right\}$$

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$$\frac{\partial \rho c T}{\partial t} + \frac{\partial \rho c u_i T}{\partial x_i} = \frac{\partial}{\partial x_i}\left(k \frac{\partial T}{\partial x_i} \right) + \tau_{ij} \frac{\partial u_i}{\partial x_j}$$

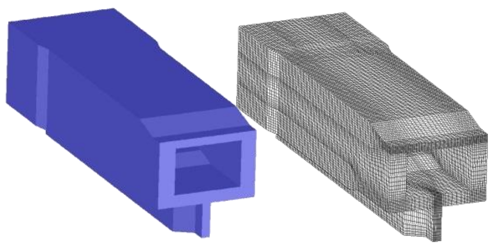
Constitutive equation (viscoelastic):

$$\tau_{ij} + \lambda \left(\frac{\partial \tau_{ij}}{\partial t} + \frac{\partial (u_k \tau_{ij})}{\partial x_k} \right) = \eta_p \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) + \lambda \left(\tau_{jk} \frac{\partial u_i}{\partial x_k} + \tau_{ik} \frac{\partial u_j}{\partial x_k} \right)$$

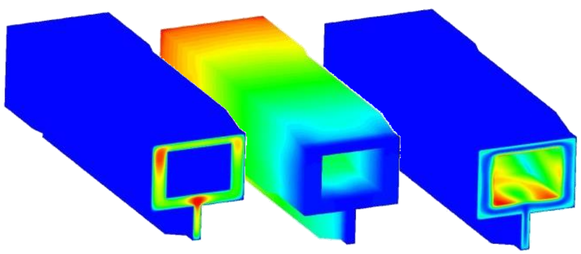
Extrusion Dies – *Flow Distribution Optimisation*

Trial Parameters

Pre-Processor



3D non-isothermal flow field calculation (FVM)



Performance Evaluation

$$F_{obj} = \sum_{i=1}^{n} \left\{ \left\{ \alpha \left(1 - \frac{V_i}{V_{obj,i}}\right)^2 + k(1-\alpha)\left[1 - \frac{(L/t)_i}{(L/t)_{\min}}\right]^2 \right\} \frac{A_i}{A} \right\}$$

Modification of the controllable geometrical parameters until the optimum is reached

Objective Function

$$F_{obj} = \sum_{i=1}^{n} \left\{ \left\{ \alpha \left(1 - \frac{V_i}{V_{obj,i}}\right)^2 + k(1-\alpha)\left[1 - \frac{(L/t)_i}{(L/t)_{\min}}\right]^2 \right\} \frac{A_i}{A} \right\}$$

Flow Balance

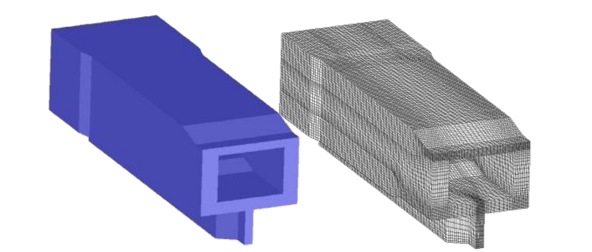
Admissible L/t value

Area Weighting

Extrusion Dies – *Flow Distribution Optimisation*

Trial Parameters

Pre-Processor



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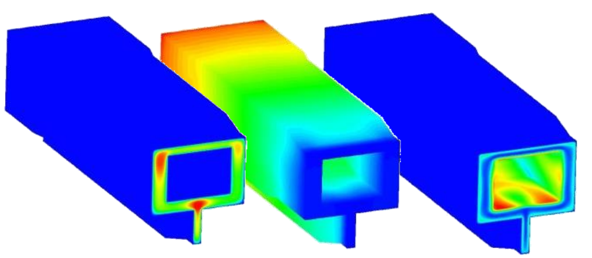


Performance Evaluation

$$F_{obj} = \sum_{i=1}^{n} \left\{ \left\{ \alpha \left(1 - \frac{V_i}{V_{obj,i}} \right)^2 + k(1-\alpha) \left[1 - \frac{(L/t)_i}{(L/t)_{\min}} \right]^2 \right\} \frac{A_i}{A} \right\}$$

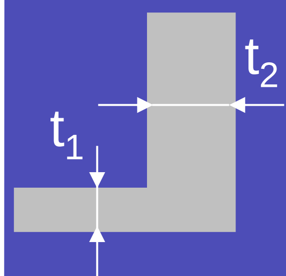
Modification of the controllable geometrical parameters until the optimum is reached

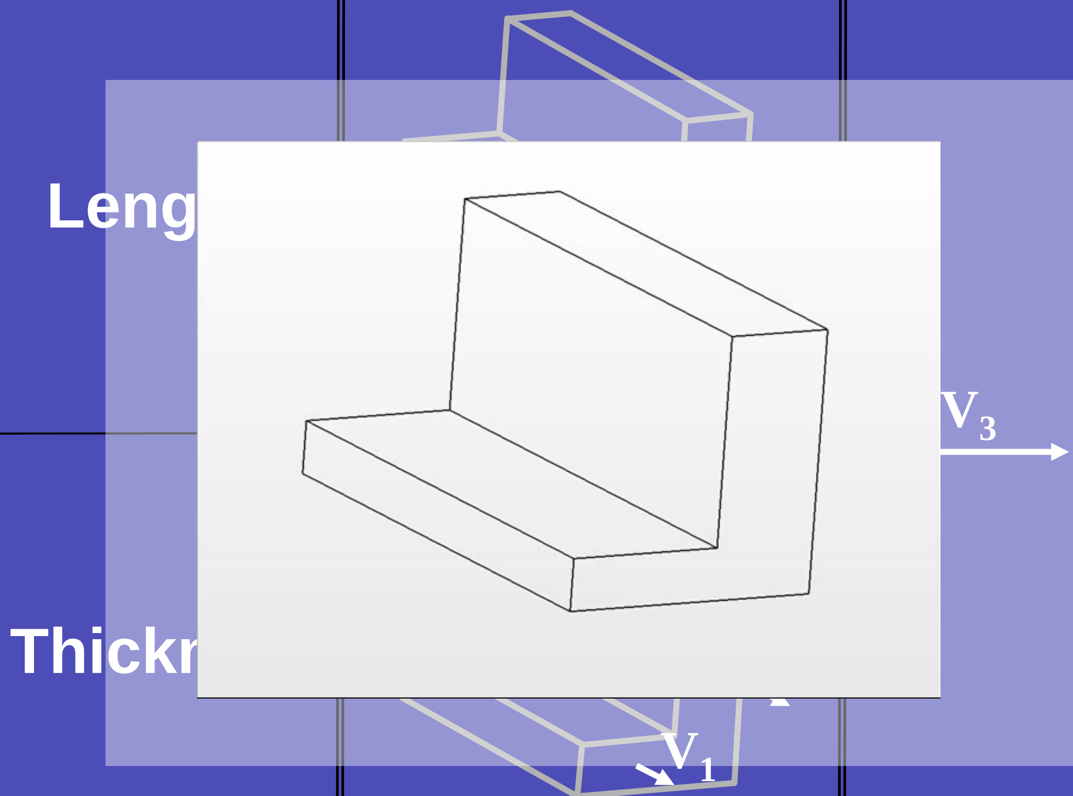
SIMPLEX Method (SM)

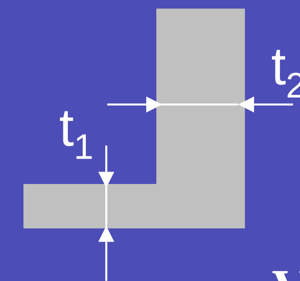
Experimental Method (EM)

Extrusion Dies – *Flow Balance Strategies*

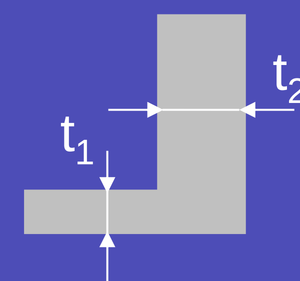
Required Profile	Optimised Variable	Die Flow Channel	Haul-off Speed	Final Profile





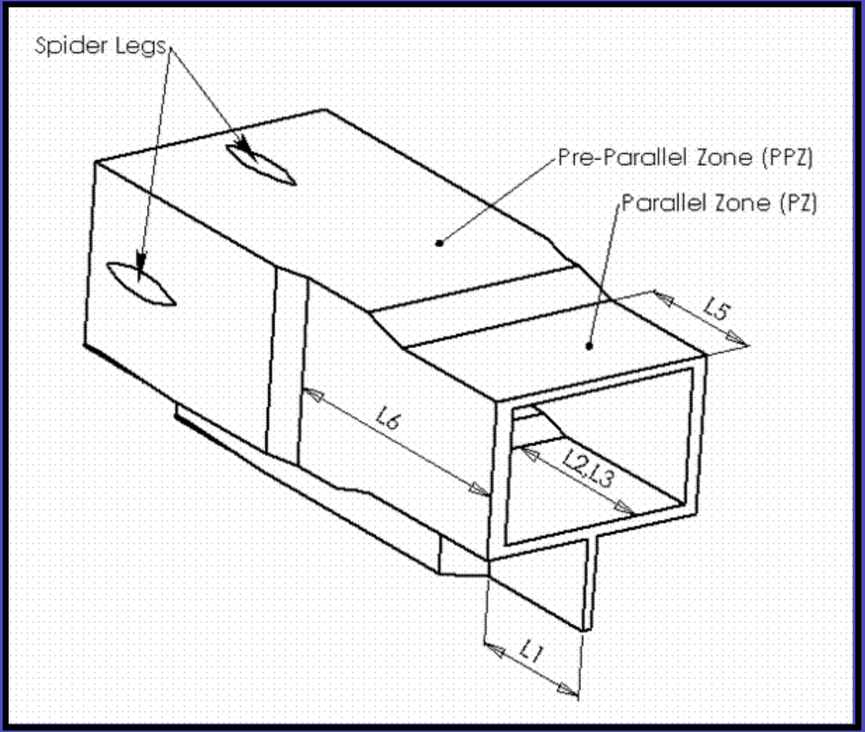


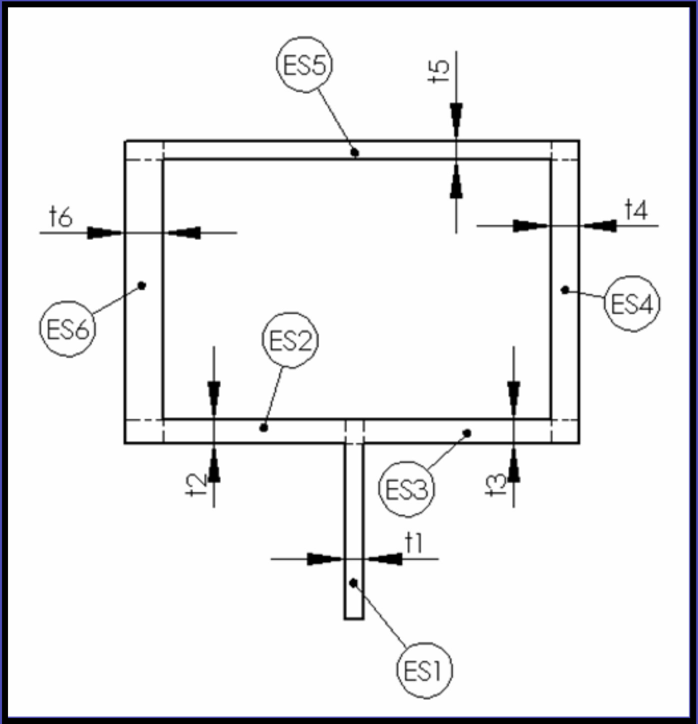
$$\frac{V_3}{V_1} = \frac{V_3}{V_2}$$



$$\frac{V_3}{V_1} \neq \frac{V_3}{V_2}$$

Extrusion Dies – *Optimisation*





Initial flow channel dimensions

ES	1	2	3	4	5	6
t_i[mm]	2.0	2.5	2.5	3.0	2.0	4.0
L_i [mm]	30.0	37.5	37.5	45.0	30.0	60.0
L_i/t_i	15.0	15.0	15.0	15.0	15.0	15.0

Extrusion Dies – *Optimisation*

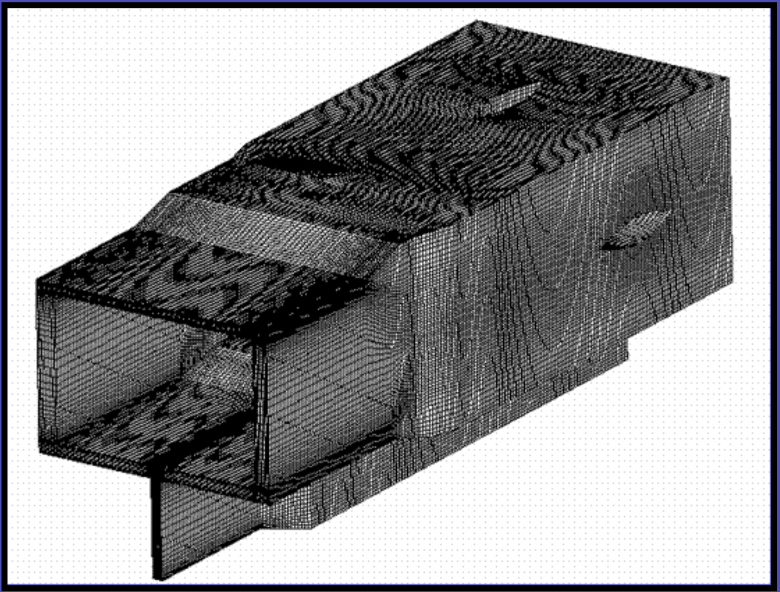
Extrusion Dies – *Optimisation*

Constitutive equation

$$\eta\left(\dot{\gamma},T\right)=F\left(\dot{\gamma}\times H\left(T\right)\right)H\left(T\right)$$

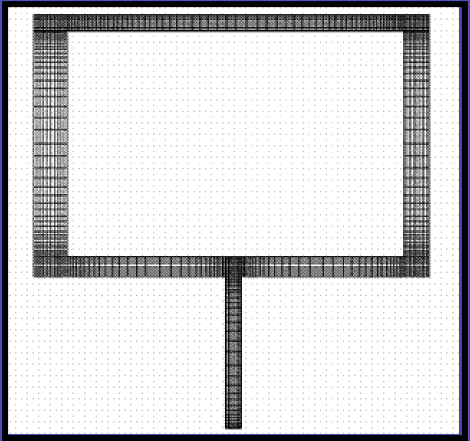
$$F\left(\dot{\gamma}\right)=\eta_\infty+\frac{\eta_0-\eta_\infty}{\left(1+\left(\lambda\dot{\gamma}\right)^2\right)^{\frac{1-n}{2}}}\qquad H\left(T\right)=\exp\left[\alpha\left(\frac{1}{T}-\frac{1}{T_\alpha}\right)\right]$$

Mesh



Operating and thermal boundary conditions

Flow rate	20 kg/h
Melt inlet temperature	230 ºC
Outer die walls temperature	230 ºC
Inner (mandrel) die walls	Adiabatic

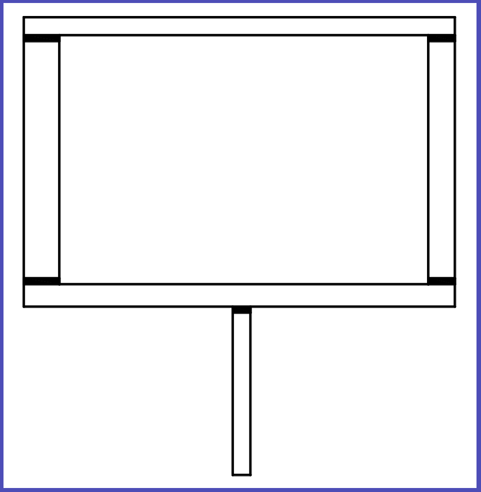


Extrusion Dies – *Optimisation*

DieINI – Initial trial

Optimizations performed

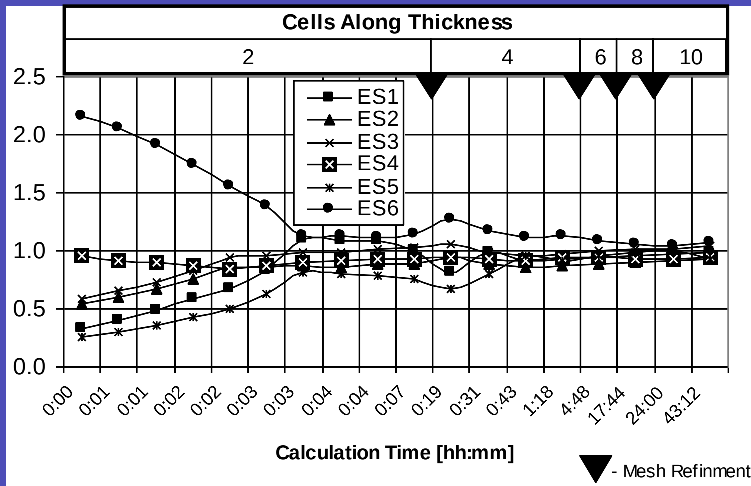
DieL – Length optimisation
DieT – Thickness optimisation
DieLS – Length optimisation + Flow separators



Extrusion Dies – *Optimisation*

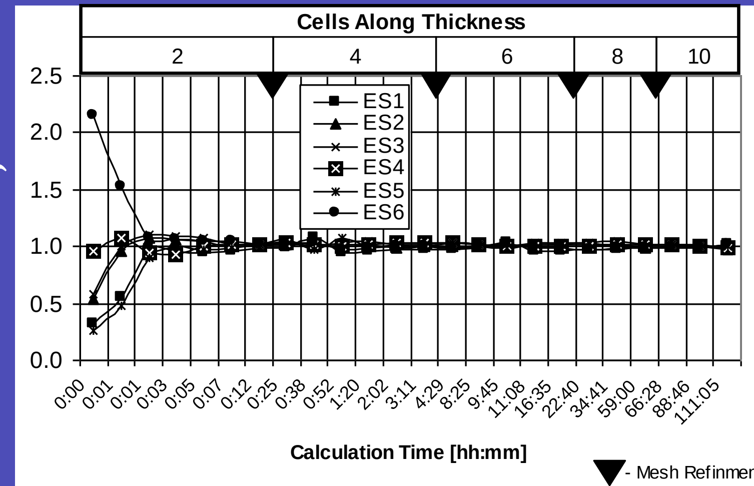
DieL

V/V_{obj}



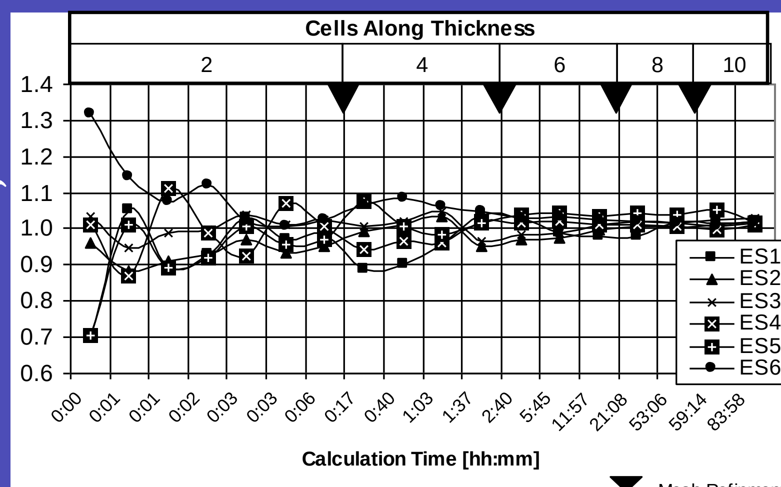
DieT

V/V_{obj}

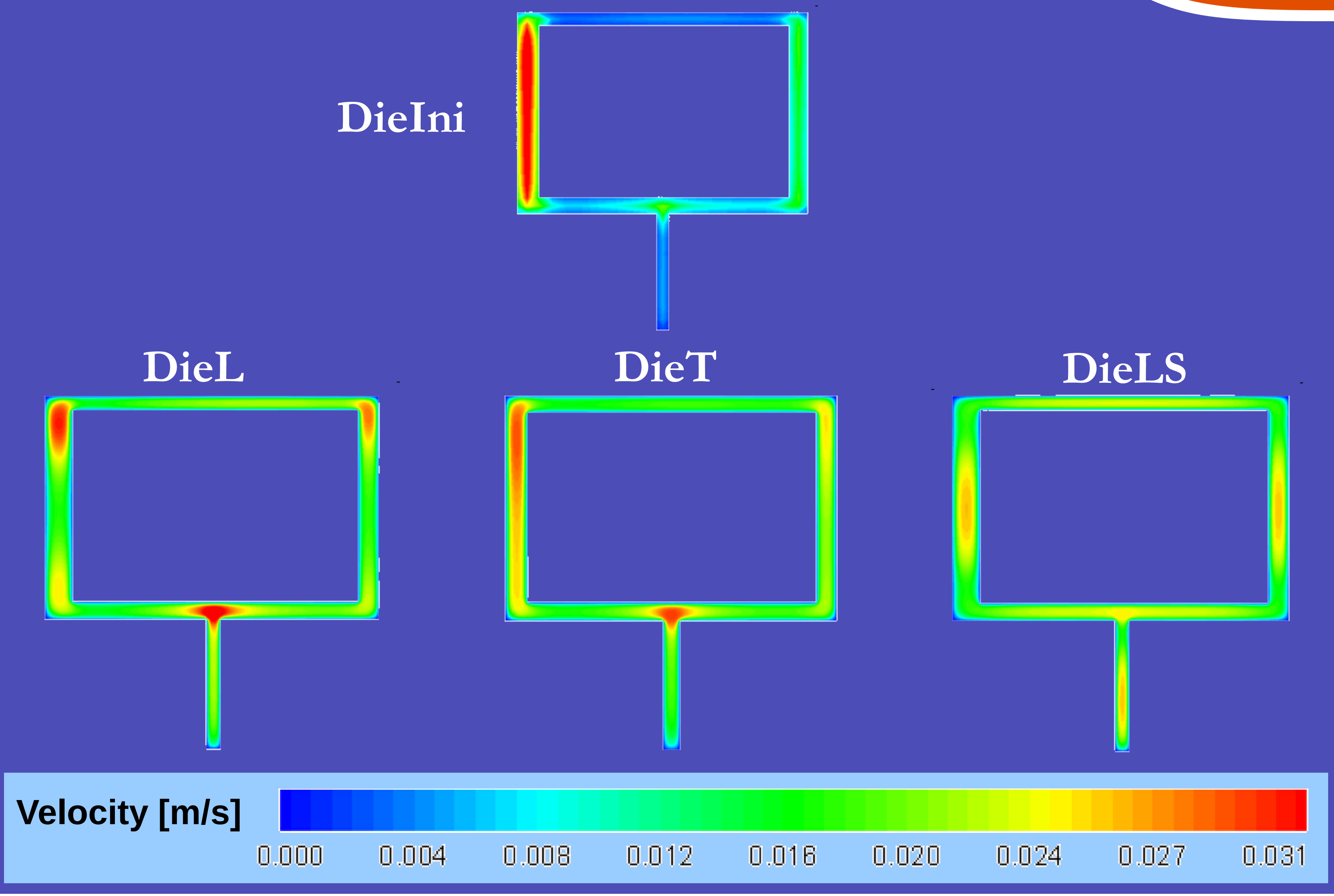


DieLS

V/V_{obj}



Extrusion Dies – *Optimisation*



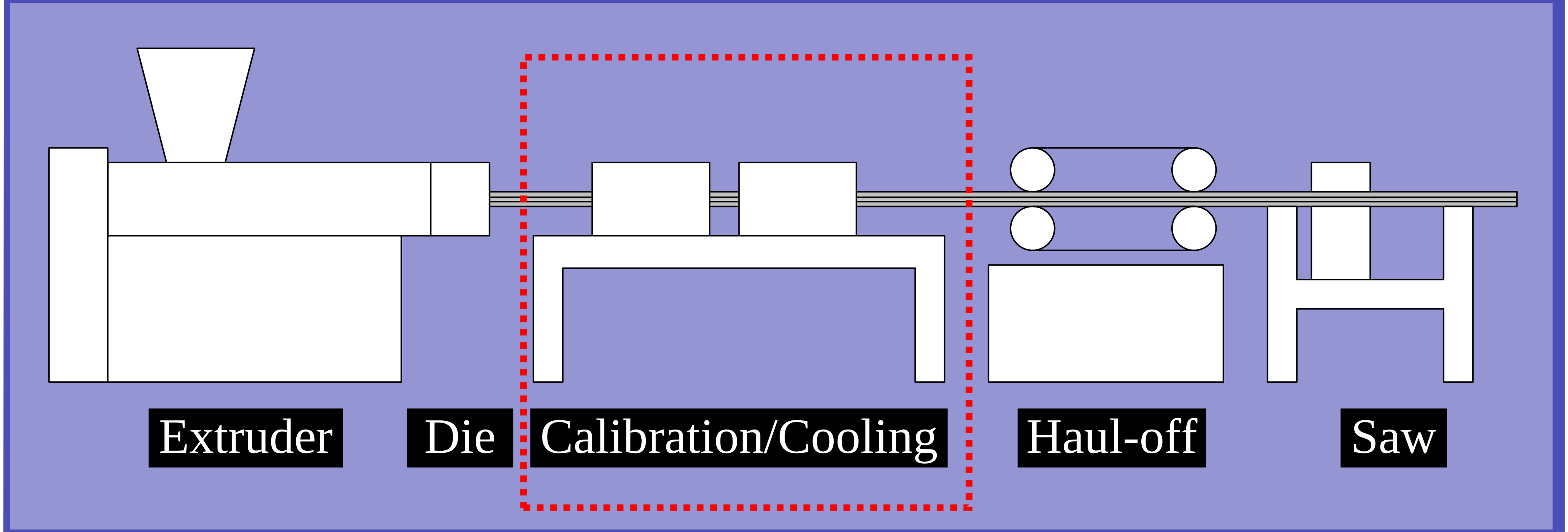
Extrusion Dies – *Optimisation*

DieIni

DieL

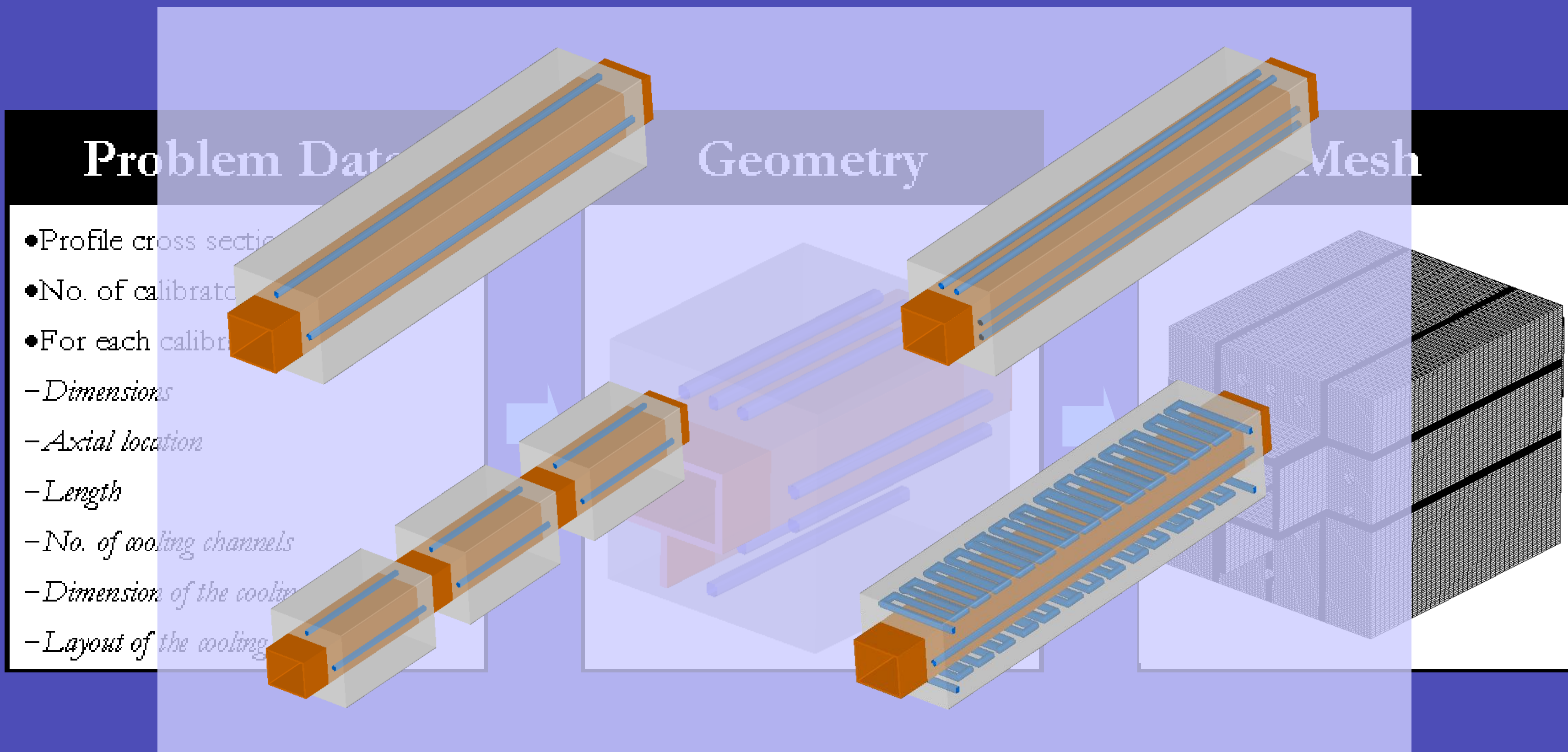
DieT

Calibrators – *Problem Statement*

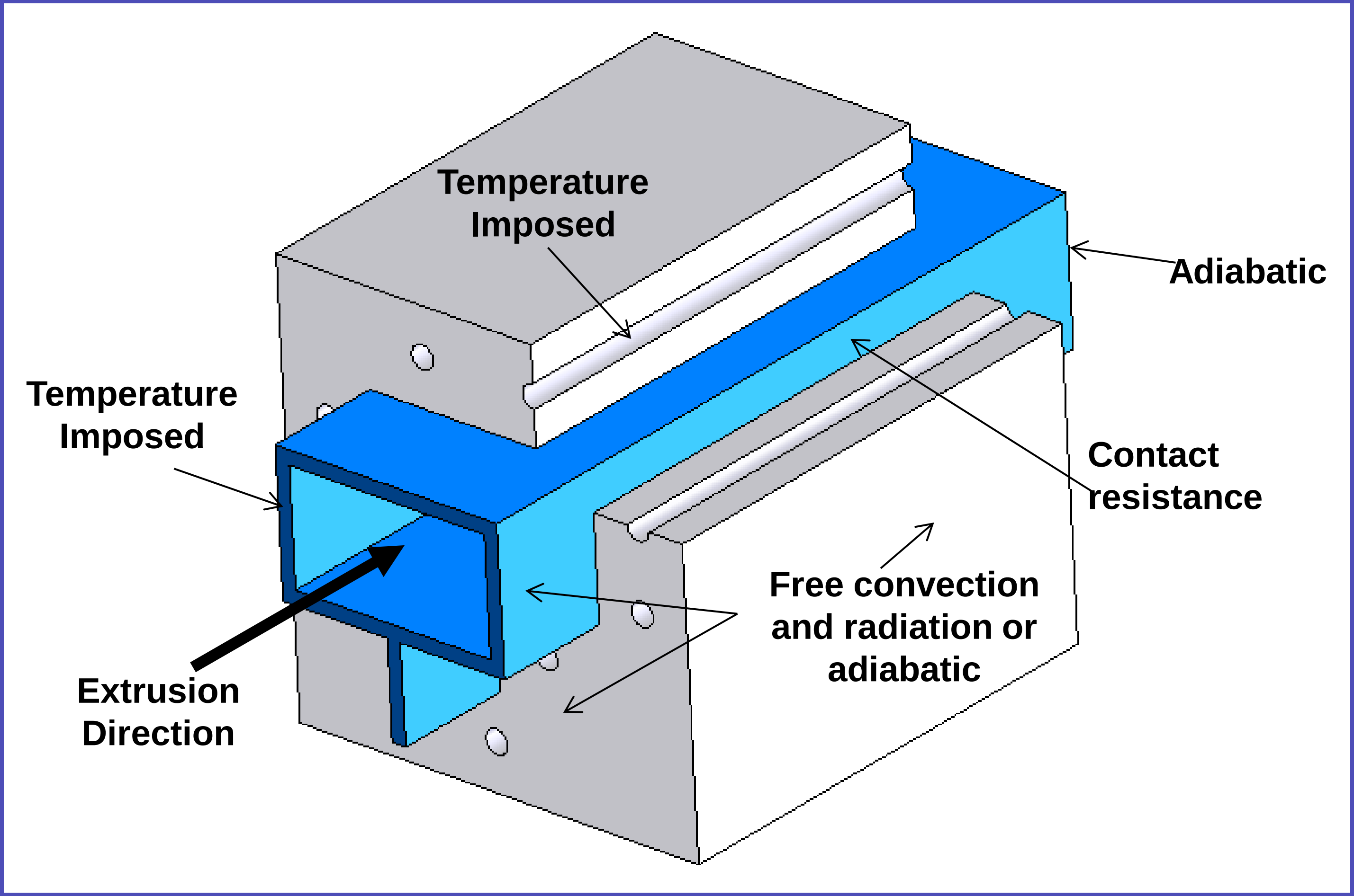


$$\bar{T} < T_s \qquad \downarrow \sigma_T$$

Calibrators - *Pre-processor*



Calibrators – *Numerical boundary conditions*



Calibrators - *Equations to solve*

Polymer

$$\frac{\partial}{\partial x}\left(k_p \frac{\partial T_p}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_p \frac{\partial T_p}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_p \frac{\partial T_p}{\partial z}\right)-\rho_p c_p \frac{\partial}{\partial z}\left(wT_p\right)=0$$

Calibrator

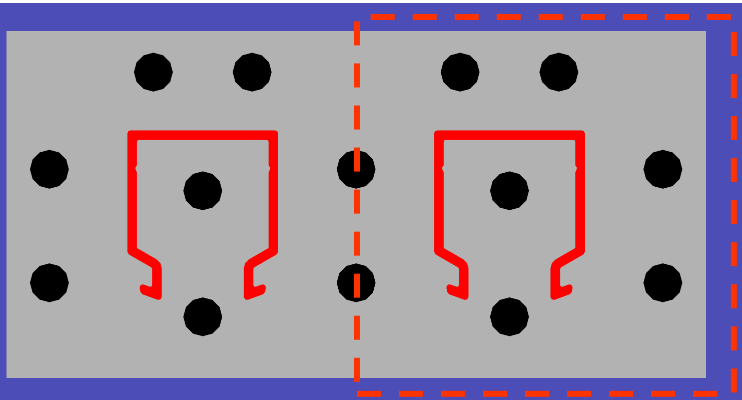
$$\frac{\partial}{\partial x}\left(k_c \frac{\partial Tc}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_c \frac{\partial T_c}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_c \frac{\partial Tc}{\partial z}\right)=0$$

Polymer-calibrator interface

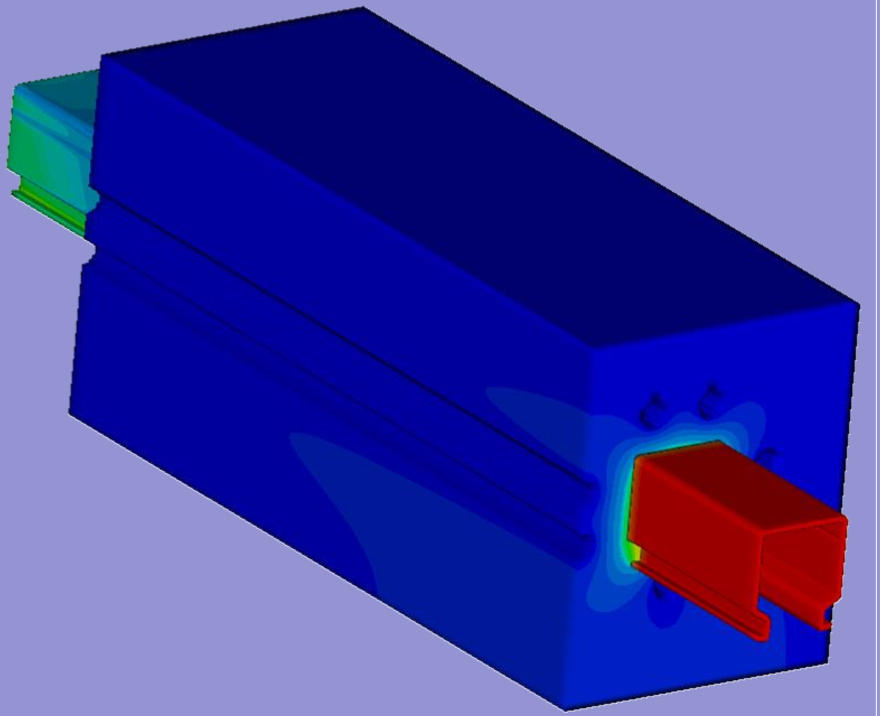
Contact Resistance

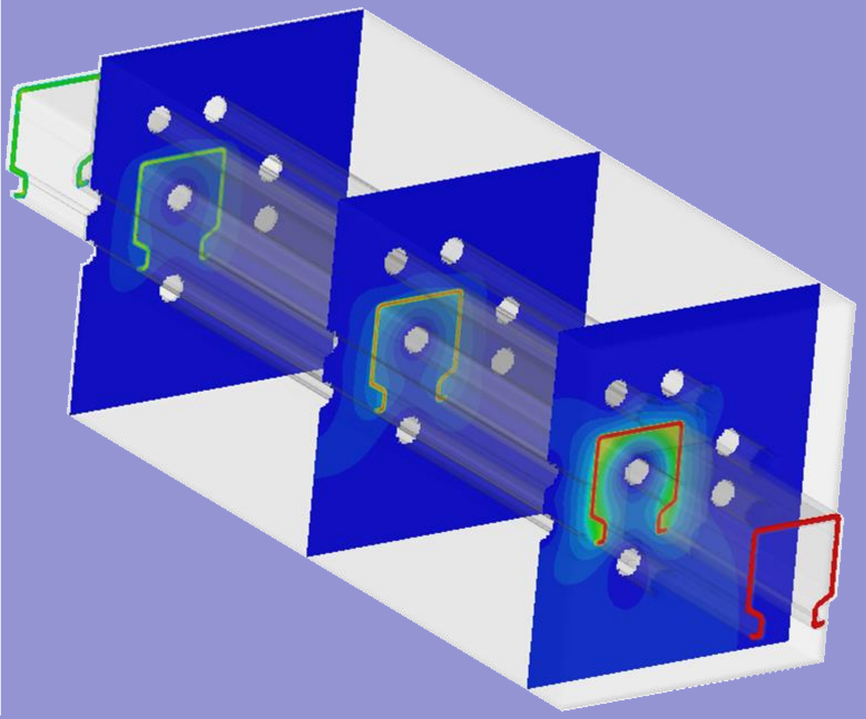
$$k_c\left(\frac{\partial T_c}{\partial n}\right)_{\text{interface}}=-k_p\left(\frac{\partial T_p}{\partial n}\right)_{\text{interface}}=h_i\left(T_p-T_c\right)_{\text{interface}}$$

Calibrators - *Typical result*



3D Temperature field calculation (FVM)





Calibrators - *System Behaviour*

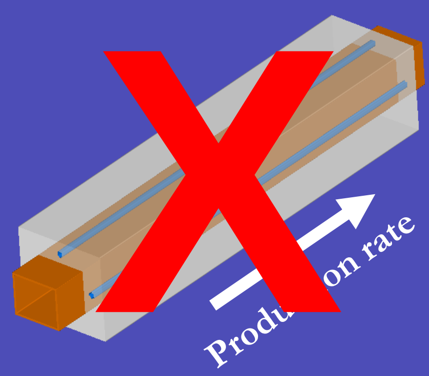
Influence of boundary conditions, process and geometrical parameters on the system performance (in terms of average temperature and temperature uniformity)

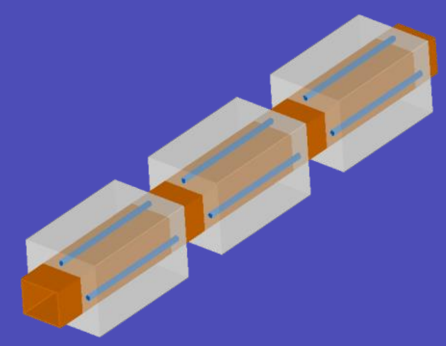
Conclusion:

In general

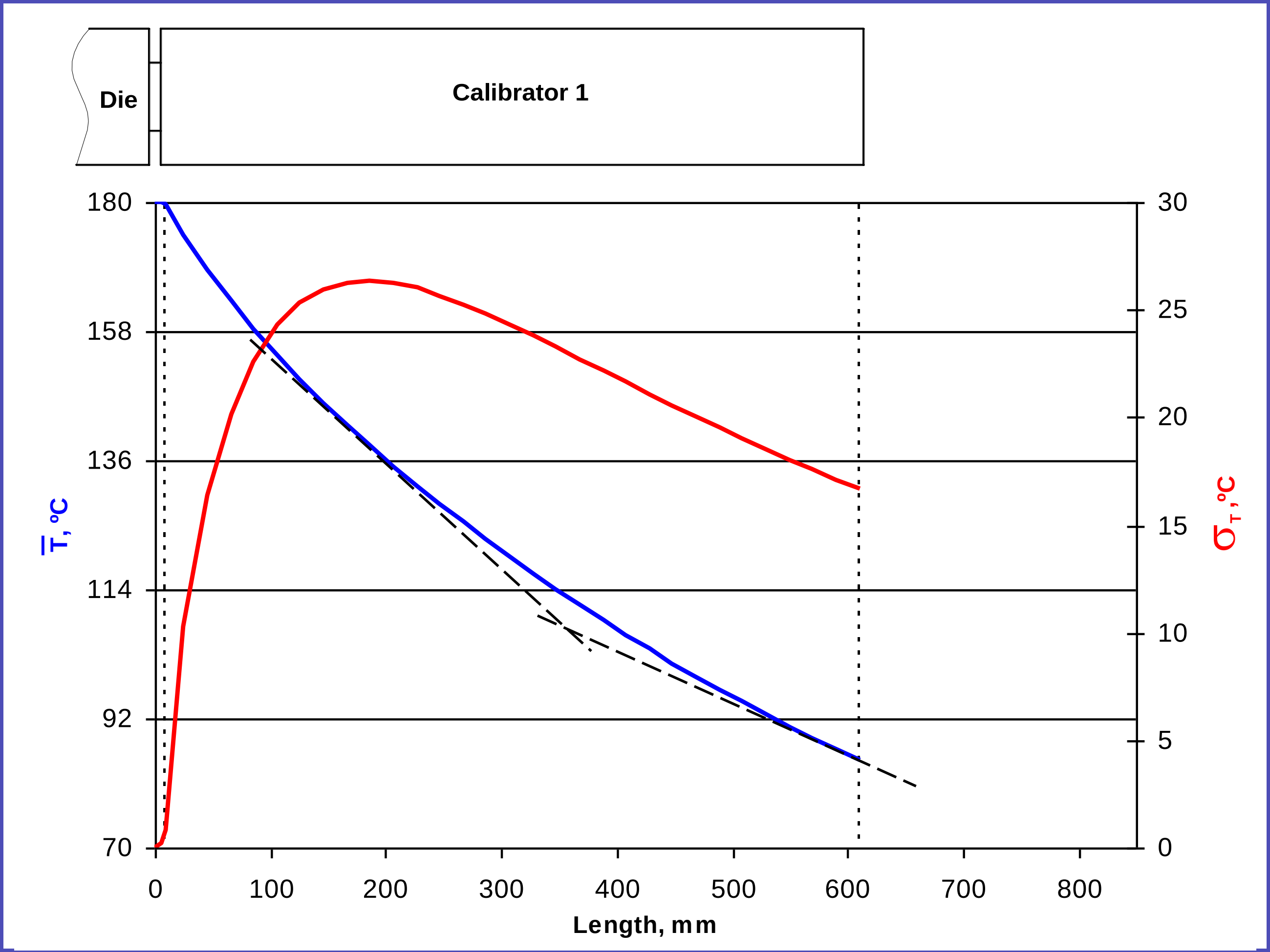
$$\downarrow \bar{T} \Rightarrow \uparrow \sigma_T$$

Exceptions





Calibrators - *System Behaviour*



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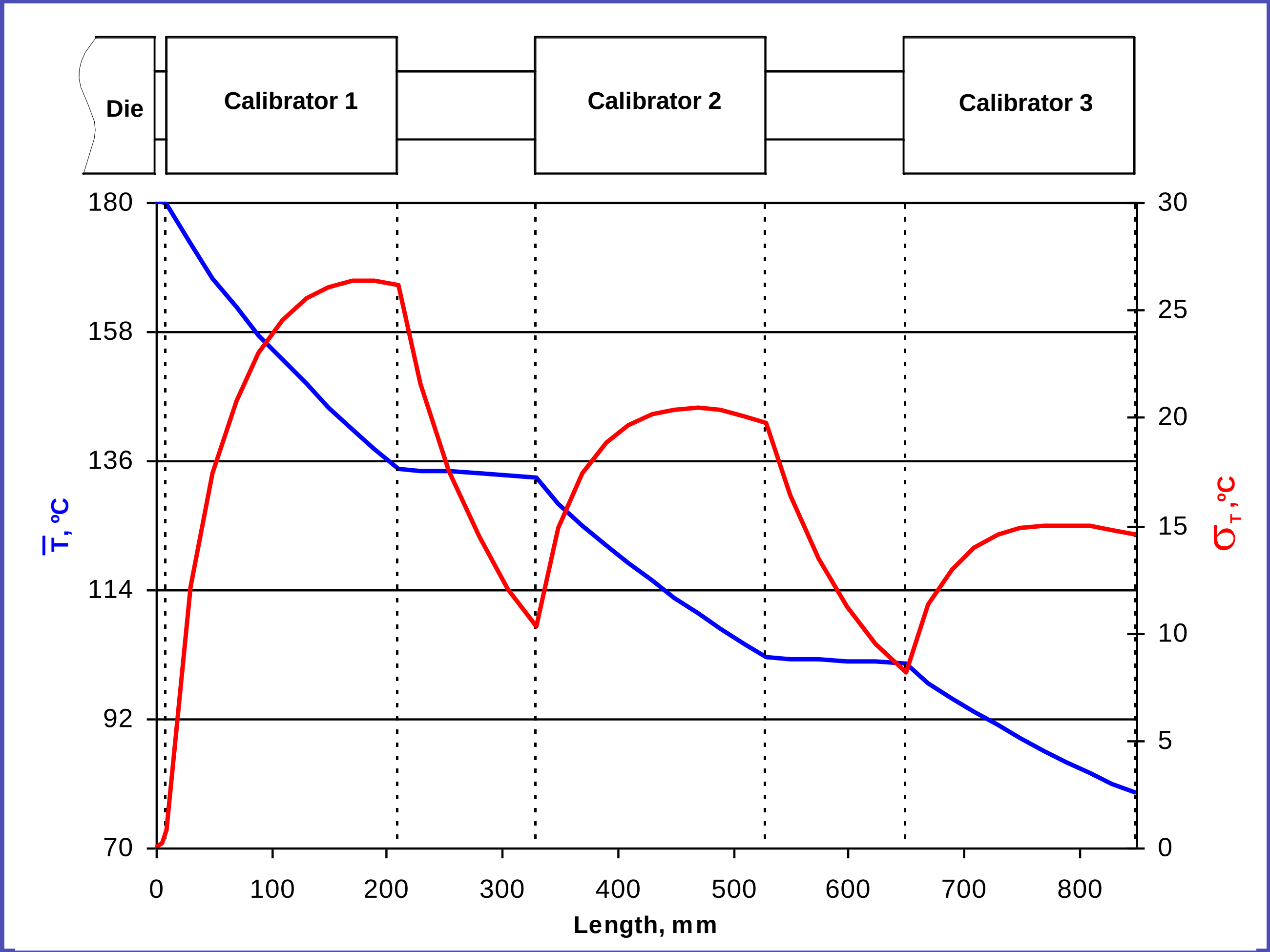
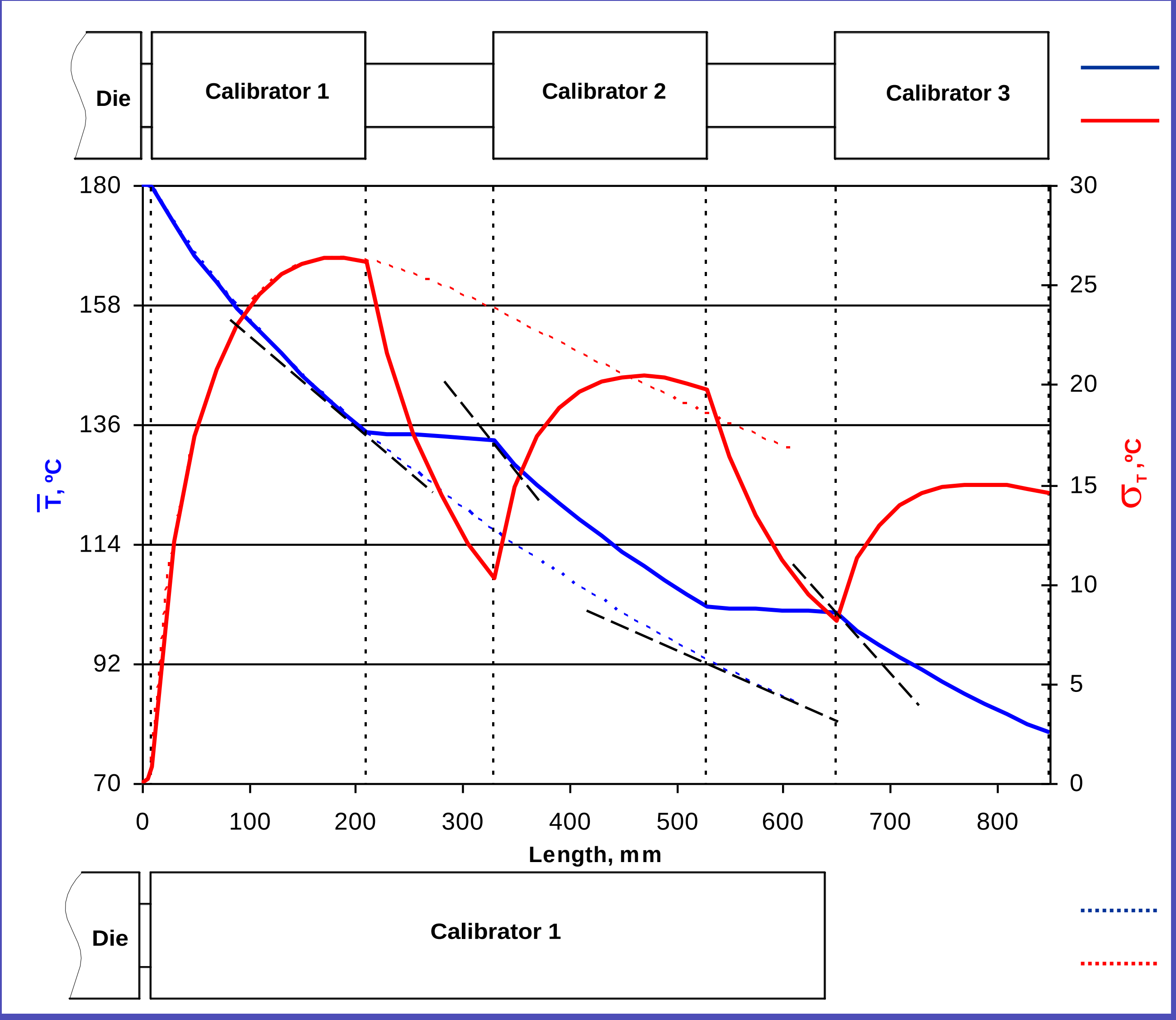


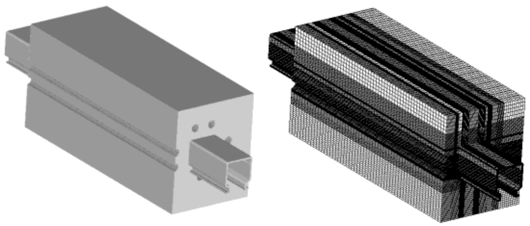
Calibrators - *System Behaviour*



Calibrators - *Optimisation Methodology*

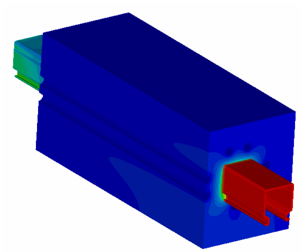
Input Data

Pre- Processor



Geometry | Mesh

3D Temperature field calculation (FVM)



Temperature

Performance Evaluation

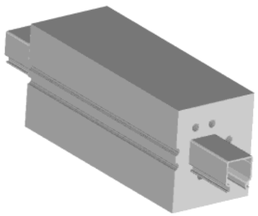
$$F_{obj} = \sum_{i=1}^{n} \alpha_i F_i$$

Optimisation: automatic generation of solutions (modification of the controllable geometrical parameters) until the optimum is reached

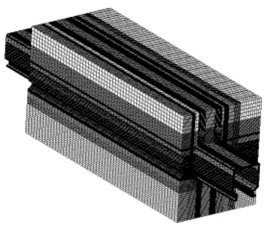
Calibrators - *Optimisation Methodology*

Input Data

Pre- Processor

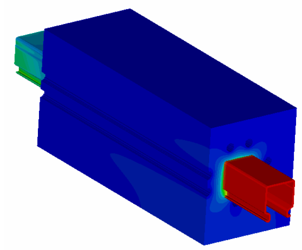


Geometry



Mesh

3D Temperature field calculation (FVM)



Temperature

Performance Evaluation

$$F_{obj} = \sum_{i=1}^{n} \alpha_i F_i$$

Optimisation: automatic generation of solutions (modification of the controllable geometrical parameters) until the optimum is reached

Temperature uniformity

$$\sigma_T = \sqrt{\frac{\sum_{i=1}^{n_f} \left(T_i - \bar{T}\right)^2 A_i}{A_T}}$$

Cooling efficiency

$$\bar{T} = \frac{\sum_{i=1}^{n_f} T_i A_i}{A_T}$$

$$F_{obj} = K\left|\bar{T} - T_S\right| + \sigma_T$$

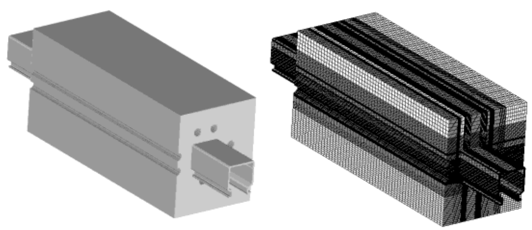
where:

$$\begin{cases} \bar{T} \le T_S \Rightarrow K = 0 \\ \bar{T} > T_S \Rightarrow K = 1000 \end{cases}$$

Calibrators - *Optimisation Methodology*

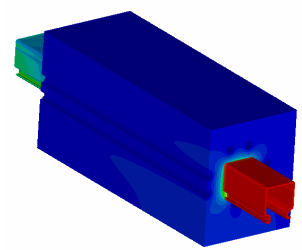
Input Data

Pre- Processor



Geometry Mesh

3D Temperature field calculation (FVM)



Temperature

Performance Evaluation

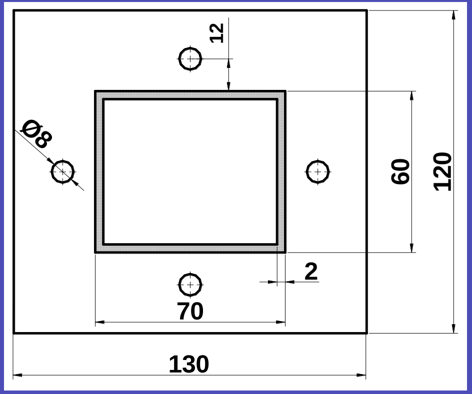
$$F_{obj} = \sum_{i=1}^{n} \alpha_i F_i$$

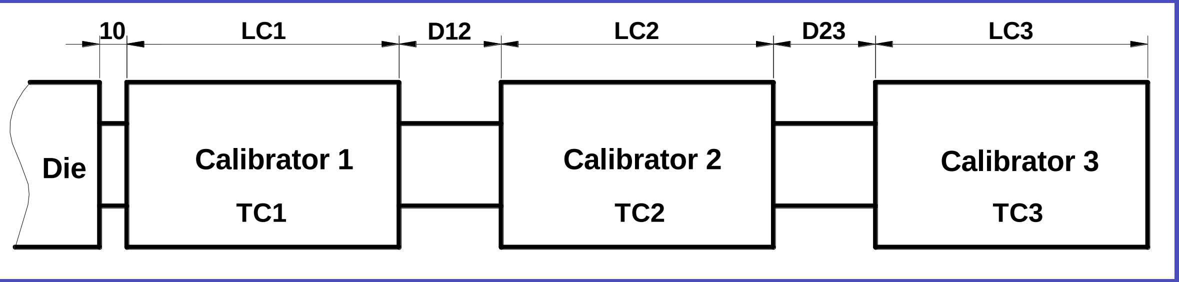
Optimisation: automatic generation of solutions (modification of the controllable geometrical parameters) until the optimum is reached

Optimisation algorithm

Non-linear SIMPLEX method

Calibrators - *Case Study*





Restrictions:

- Number of calibration/cooling units <= 3
- Total calibration length (ΣLCi) <= 600 mm
- Total system length (ΣLCi + Σ Dij + 10) <= 850 mm
- Cooling Fluid Temperature TCi $\in$ [10ºC,26ºC]

General conditions for the simulations

Processing conditions

v_p = 2 m/min

T_m = 180 ºC

T_f = 18 ºC

T_s= 80 ºC

Materials Properties

K_p = 0.18 W/mK

K_c = 14 W/mK

ρ_p = 1400 kg/m^3

c_p = 1000 J/kgK

Boundary conditions

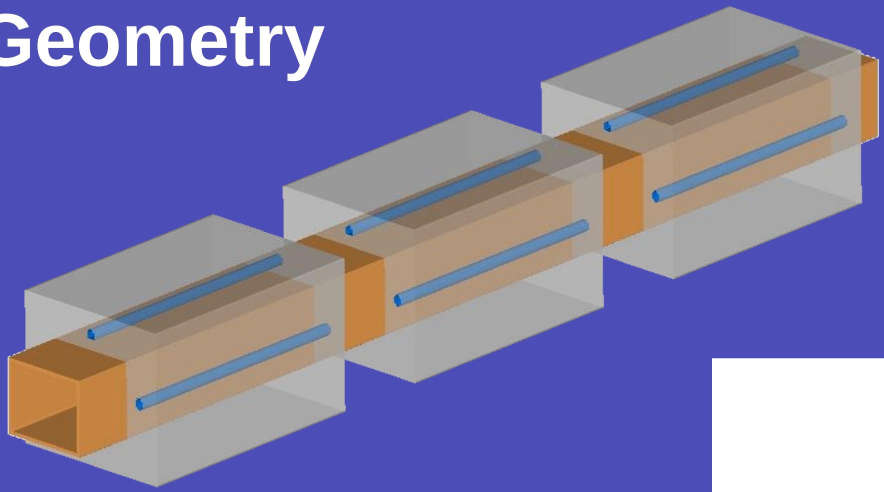
Annealing zones: free convection and radiation

Polymer-calibrator interface: contact resistance

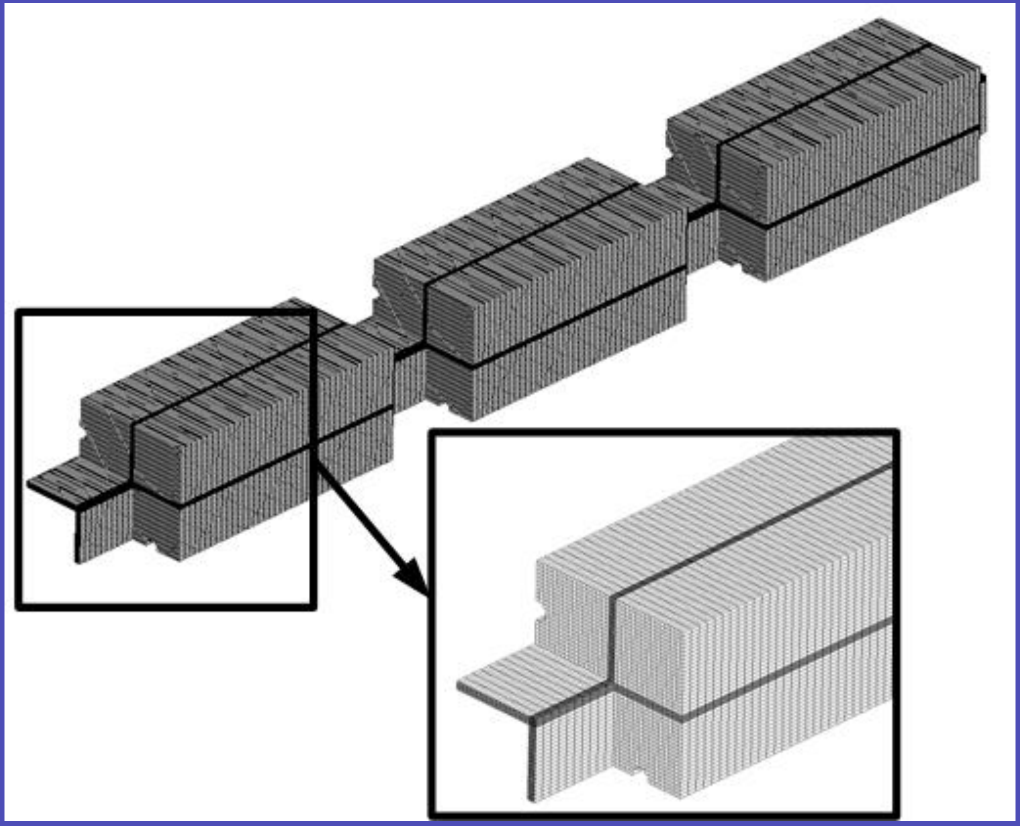
(h_i = 425 W/m^{2}K)

Calibrators - *Case Study*

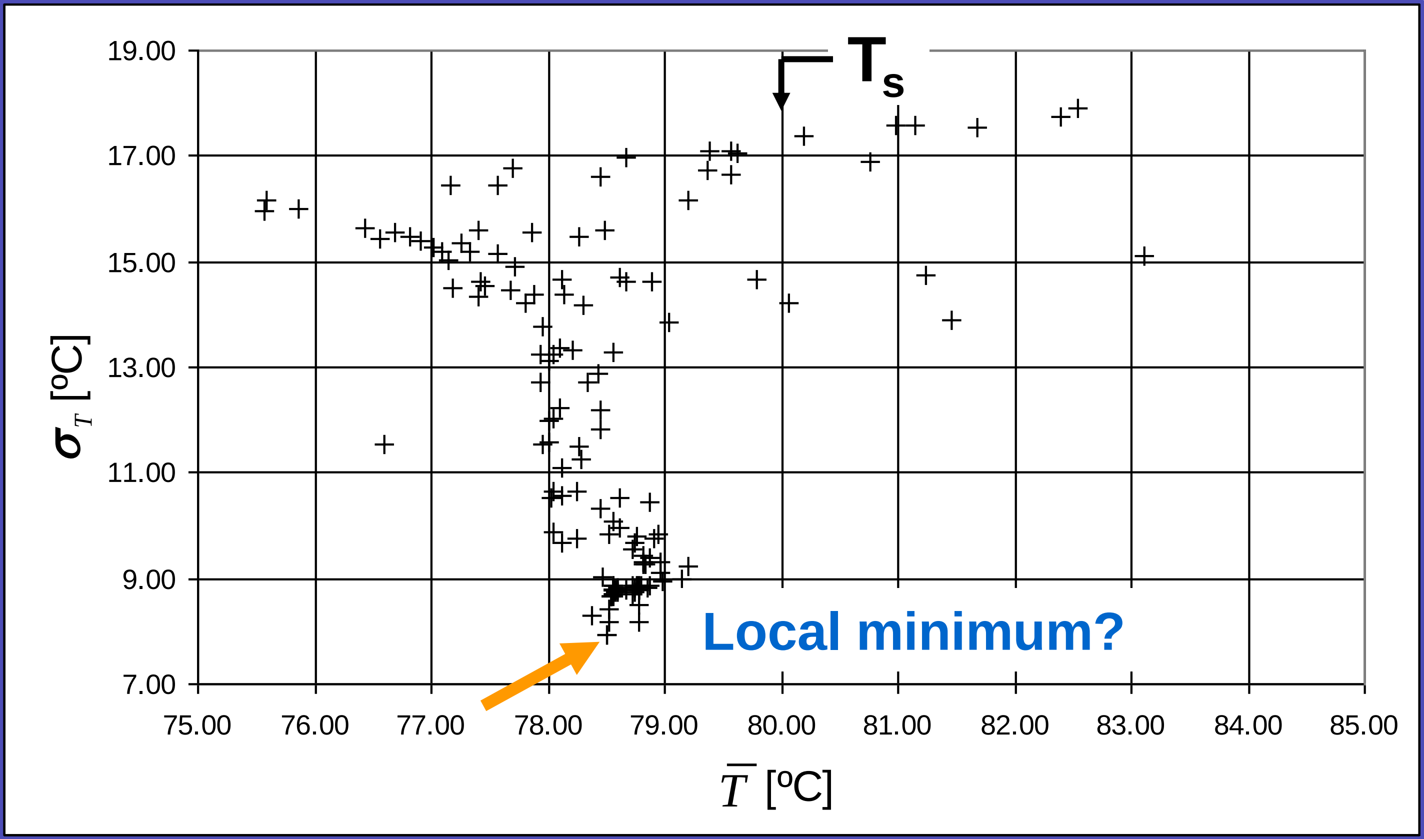
Geometry



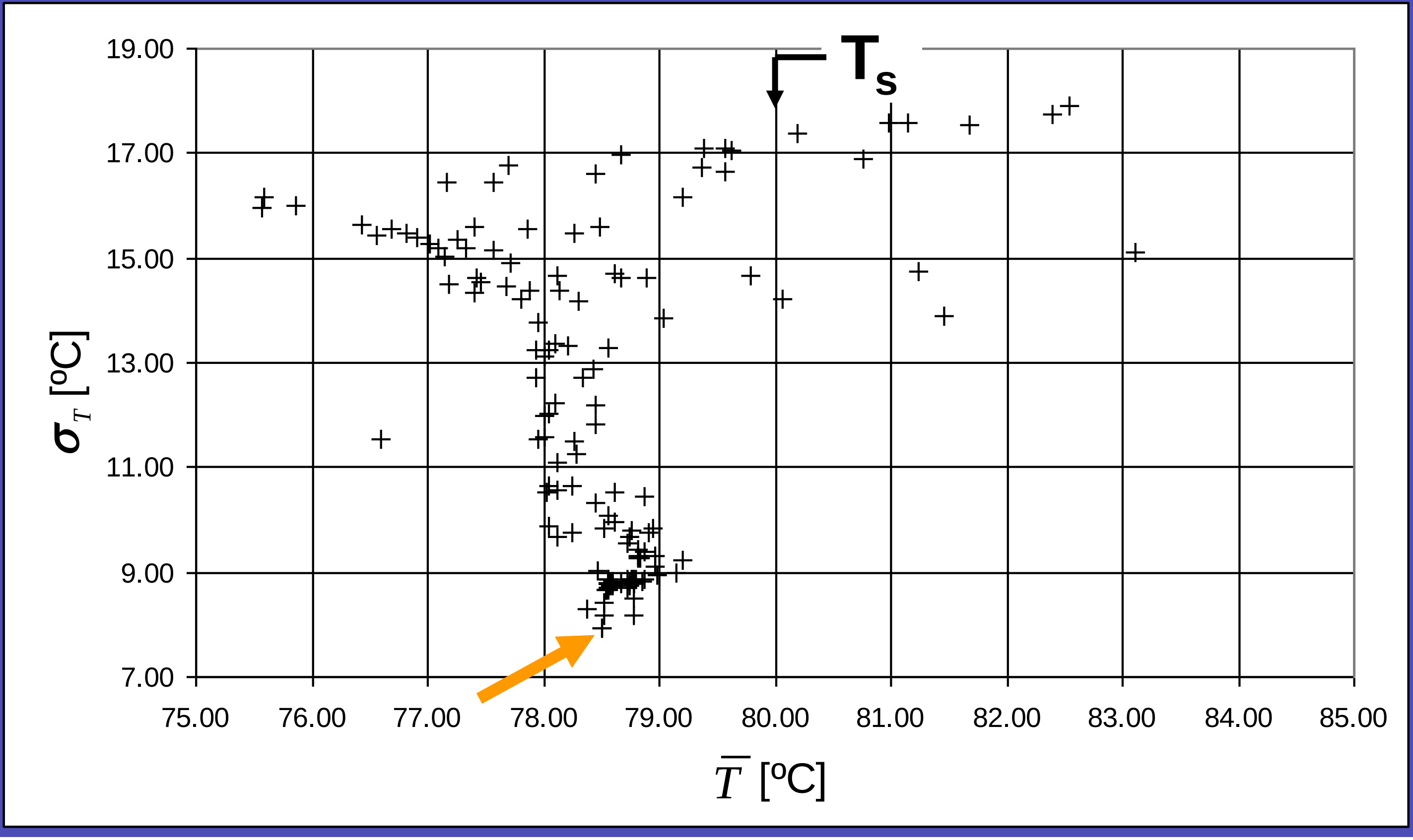
Mesh

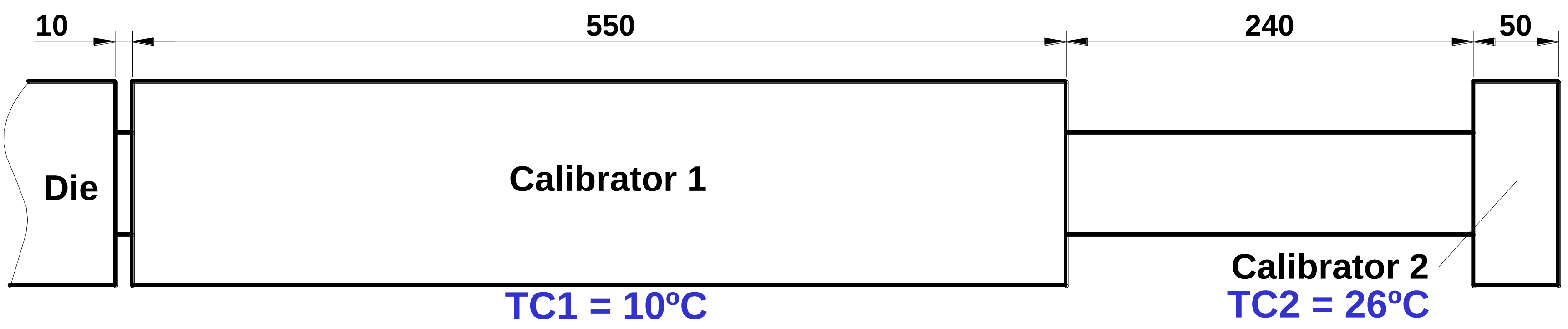


Calibrators - *Case Study*

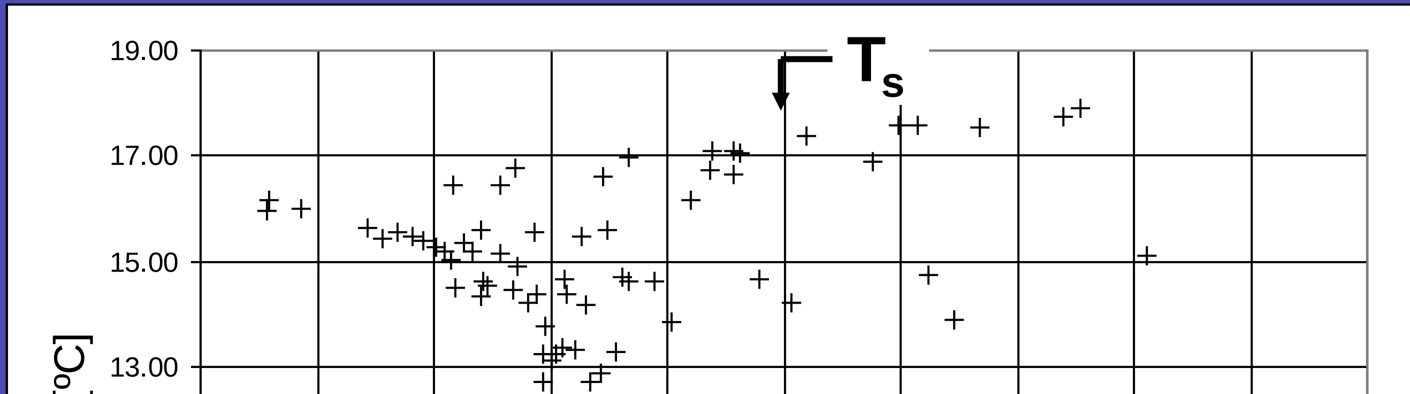


Calibrators - *Case Study*



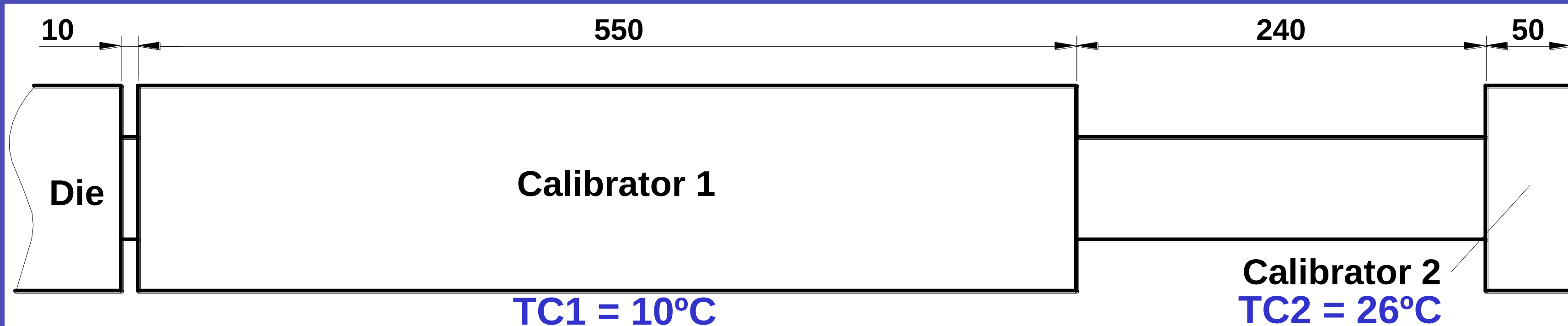


Calibrators - *Case Study*



Geometry	$\bar{T}$ [ºC]	σ_T [ºC]
One Calibrator (TC=18ºC)	84.9	16.6
Optimum Solution	78.5	7.9

- 52.4%



Recent / Ongoing work

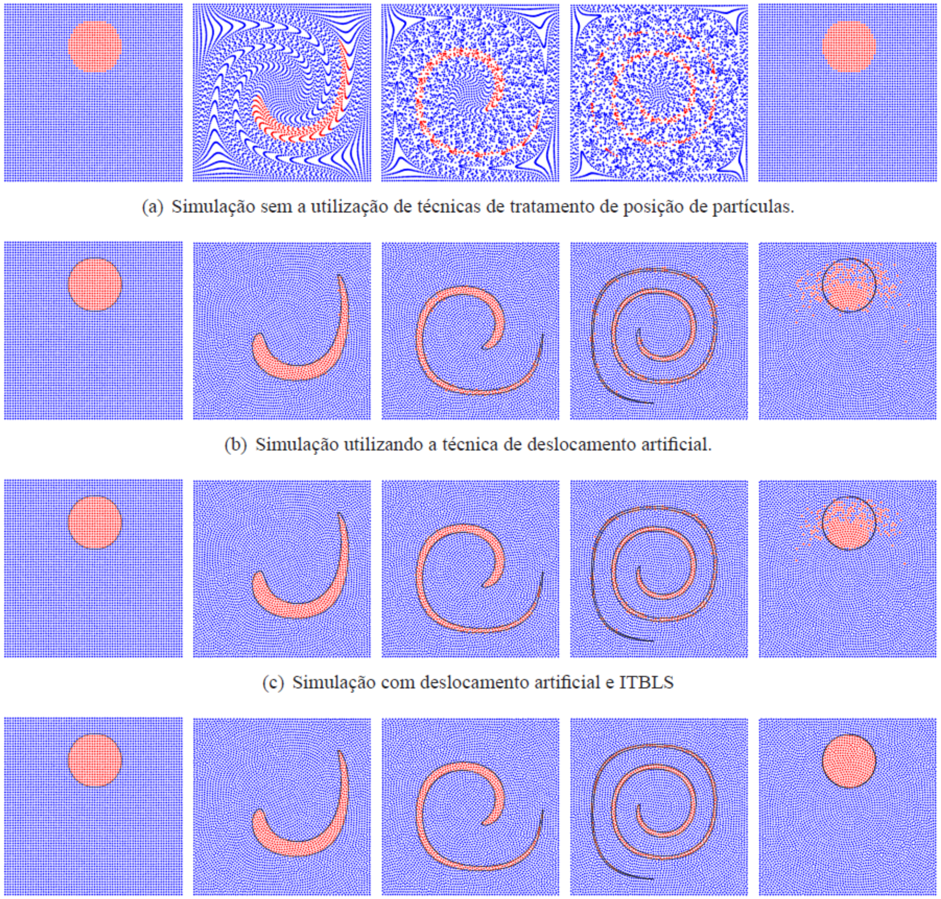
- **Implementation of the wall Slip and free-surface boundary conditions** (L.L. Ferrás, Post-doctoral project);
- **Development of unstructured numerical modelling code** (N.D. Gonçalves, PhD project);
- **Implementation of viscoelastic constitutive equations in an unstructured modelling code** (S. Reddy, MSc Eurheo project);
- **Prediction of thermal induced stresses in calibration in OpenFOAM** (S. Reddy, Research Project);
- **Development of high order interpolation schemes** (R. Costa, FCT Research Project, DMAT);
- **Portability and Performance in Heterogeneous Many-core Systems** (R. Ribeiro, PhD Project, DI) - **OpenFOAM**;

Recent / Ongoing work

- **Development of multiscale modelling approaches** (S.T. Mould, PhD Project);
- **Development of ISPH numerical modelling code (**D.F. Cordeiro, PhD/Cooperation Project, USP);
- **Development of FSI methodologies for the design of extrusion dies in OpenFOAM** (M.R. Moosavi, Post-doctoral grant);
- **Modelling the cooling stage in profile extrusion using OpenFOAM** (R. Ananth, PhD project, MIT+Soprefa);
- **Design of a new generation of car washing machines** (M. Sabet, PhD project, MIT+Petrotec);
- **Characterisation of the heat transfer coefficient at the polymer-metal interface in profile cooling** (F. Araújo, FCT Research Project);

Recent / Ongoing work

- Development of ISPH numerical modeling code (D.F. Cordeiro, PhD/Cooperation Project, USP);



(a) Simulação sem a utilização de técnicas de tratamento de posição de partículas.

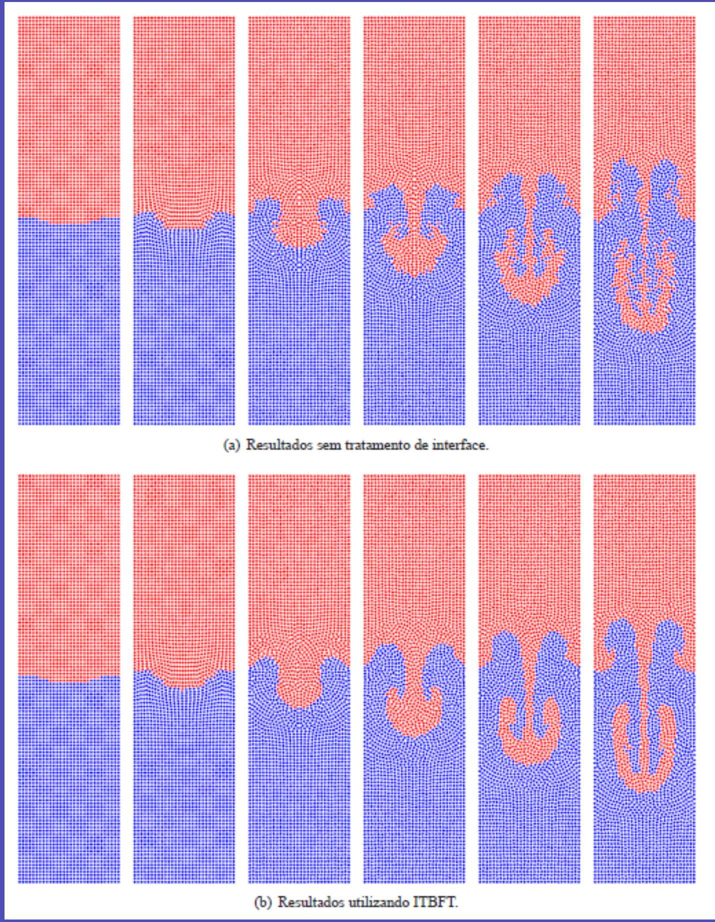
(b) Simulação utilizando a técnica de deslocamento artificial.

(c) Simulação com deslocamento artificial e ITBLS

(d) Simulação com deslocamento artificial e ITBFT.

Recent / Ongoing work

- Development of ISPH numerical modelling code (D.F. Cordeiro, PhD/Cooperation Project USP);


(a) Resultados sem tratamento de interface.

(b) Resultados utilizando ITBFT.

Recent / Ongoing work

- Development of ISPH numerical modeling code (D.F. Cordeiro, PhD/Cooperation Project, USP);