Computer aided design of thermoplastic profile forming tools

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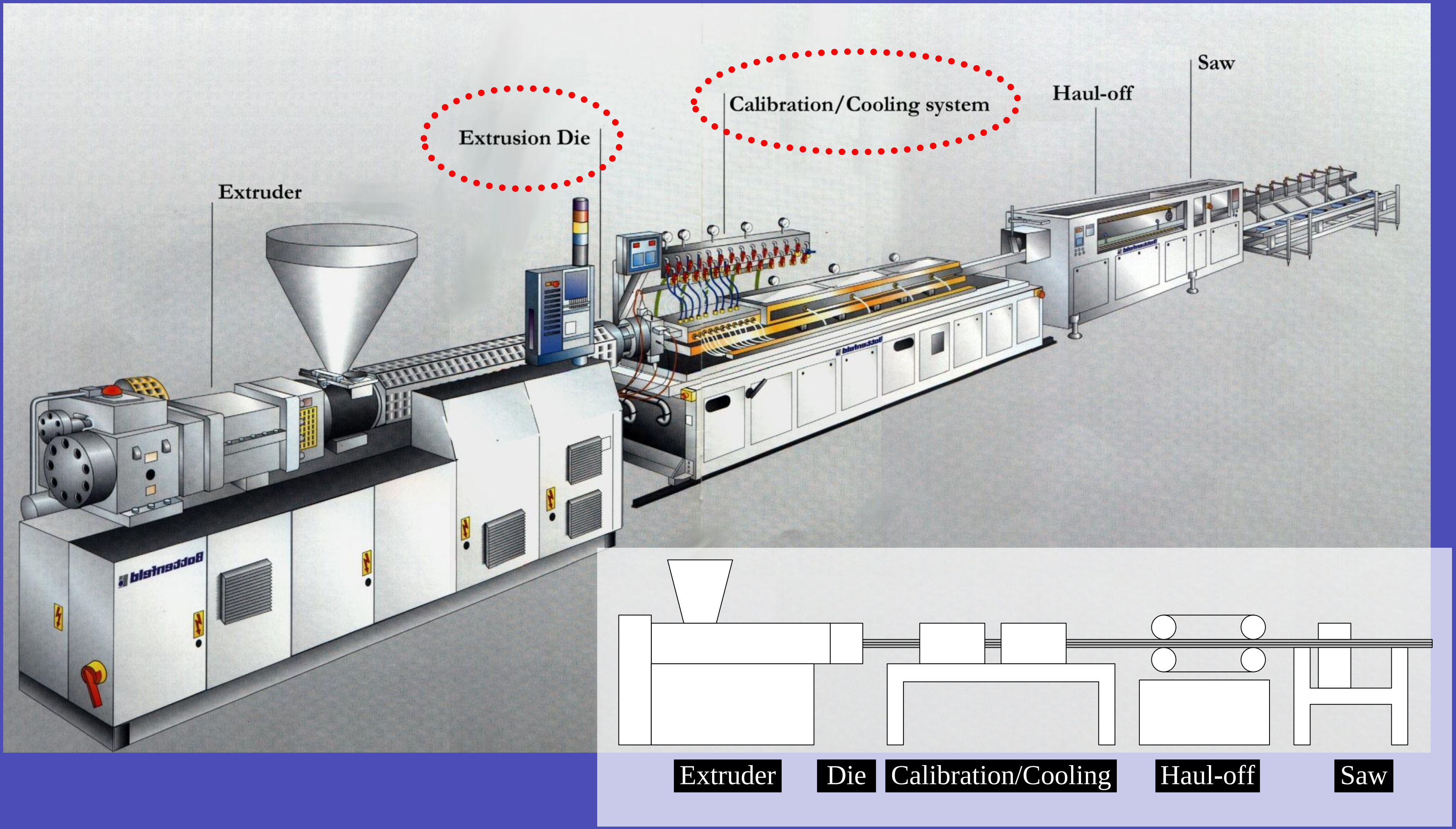
Introduction - *Profile Extrusion*



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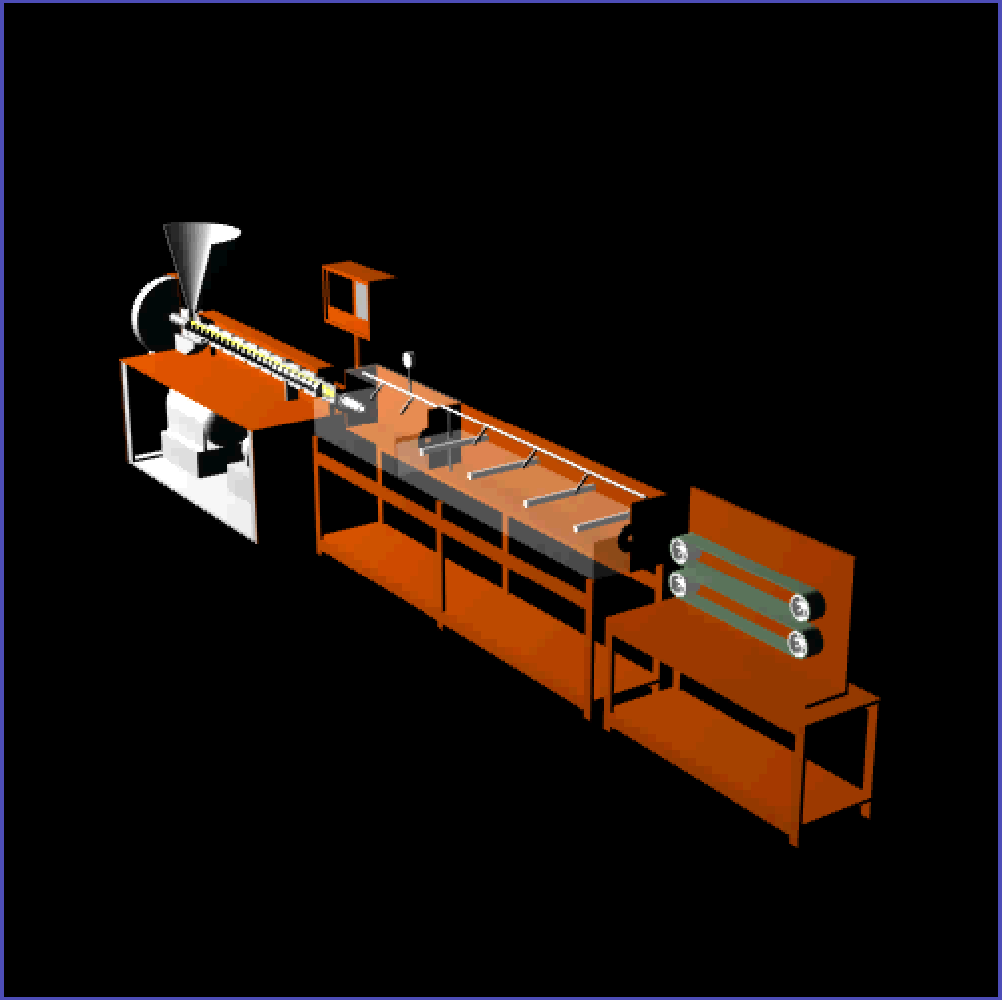
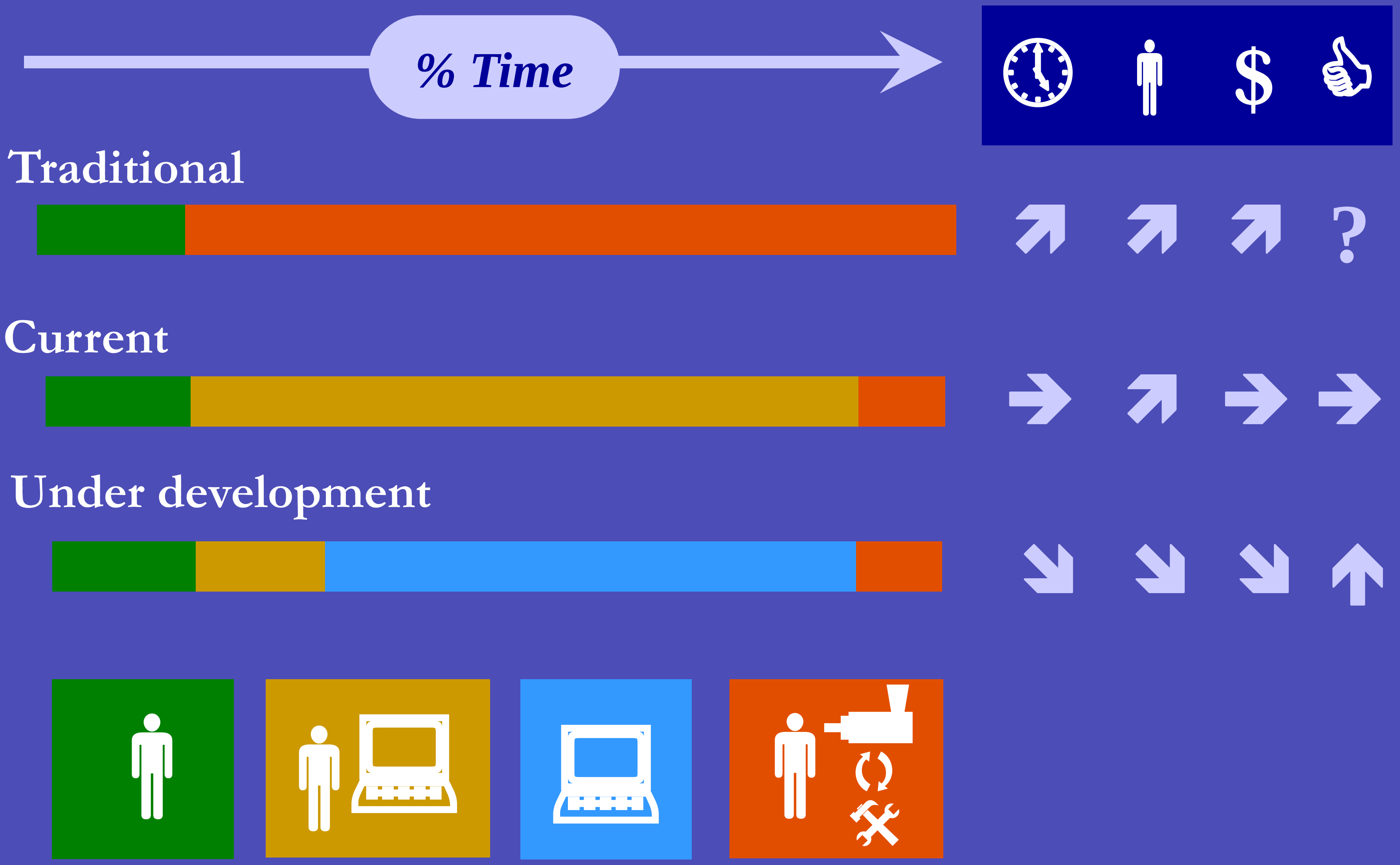


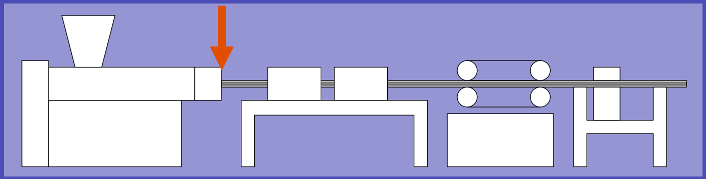
Introduction - *Design Approaches*



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

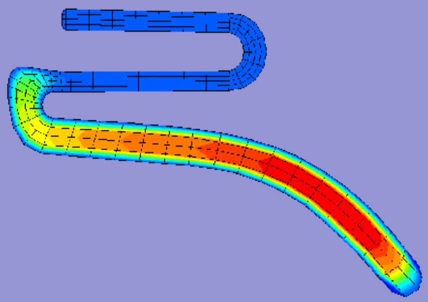
Extrusion Dies – *Problem Statement*

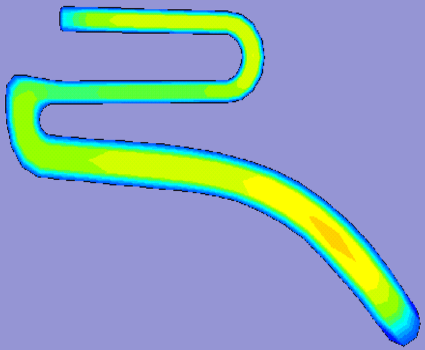


Unbalanced | **Balanced**

Extrusion run

Numerical Velocity contours

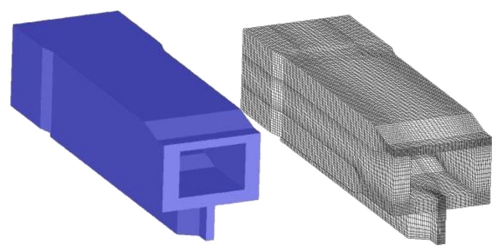




Extrusion Dies – *Flow Distribution Optimisation*

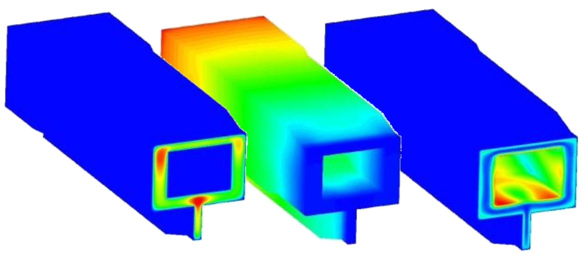
Trial Parameters

Pre-Processor



Geometry Mesh

3D non-isothermal flow field calculation (FVM)

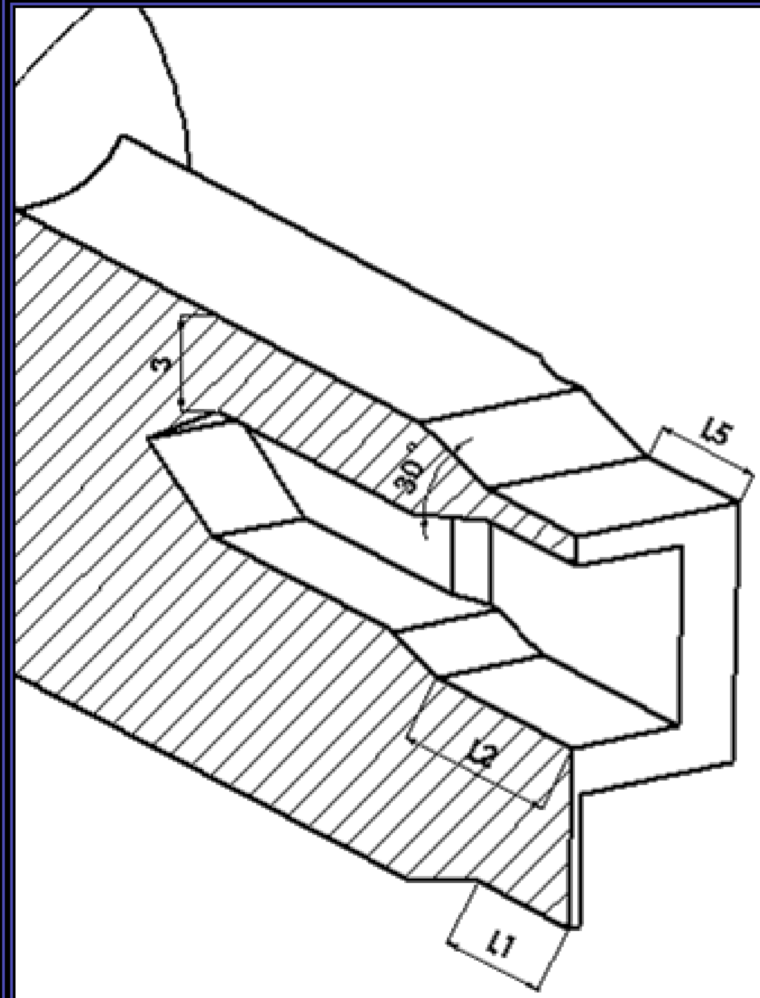


Velocity Pressure Temperature

Performance Evaluation

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

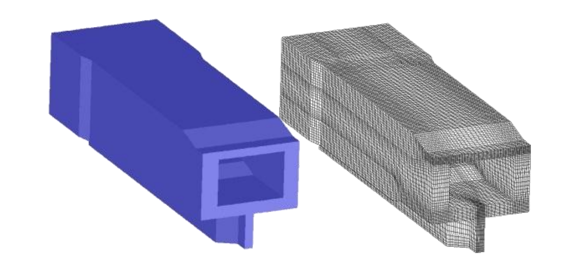
Modification of the controllable geometrical parameters until the optimum is reached



Extrusion Dies – *Flow Distribution Optimisation*

Trial Parameters

Pre-Processor



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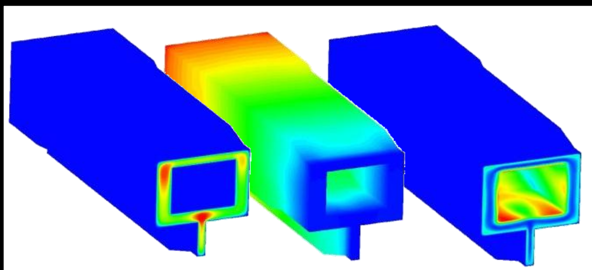

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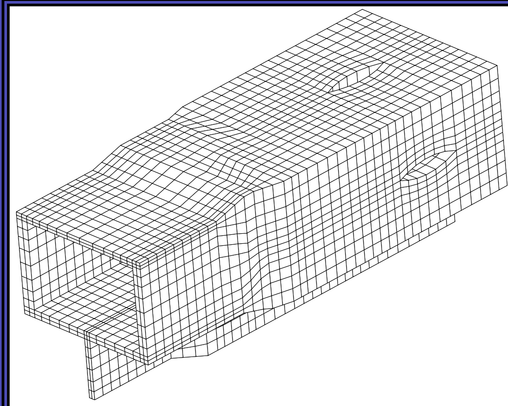
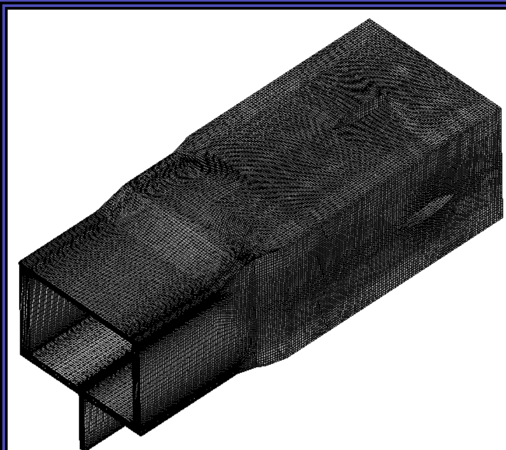
Modification of the controllable geometrical parameters until the optimum is reached

Progressive mesh refinements





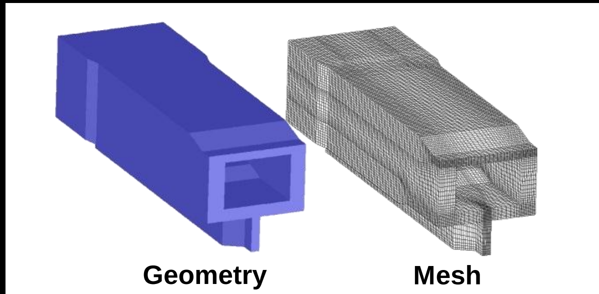
Cells along Thickness	Number of Cells	Time [h:m:s]
2	15 496	0:00:36
4	92 248	0:12:15
6	272 220	1:12:17
8	593 928	4:28:36
10	688 024	6:43:42

PIV / 2.4 GHz

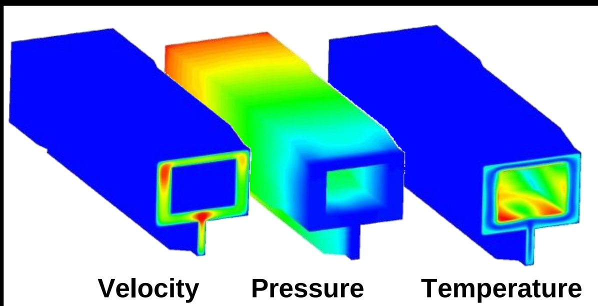
Extrusion Dies – *Flow Distribution Optimisation*

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:

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

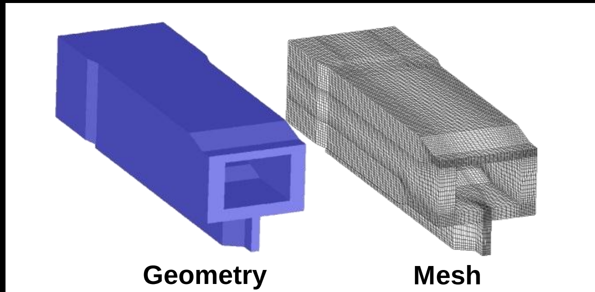
Constitutive equation (Gen. Newtonian):

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

Extrusion Dies – *Flow Distribution Optimisation*

Trial Parameters

Pre-Processor



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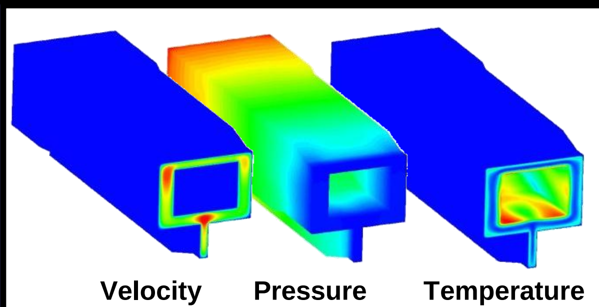

Performance Evaluation

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

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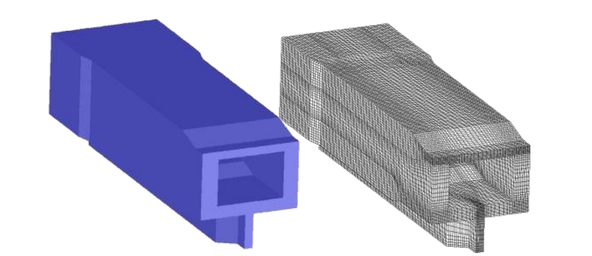
Constitutive equation (viscoelastic):

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

Extrusion Dies – *Flow Distribution Optimisation*

Trial Parameters

Pre-Processor



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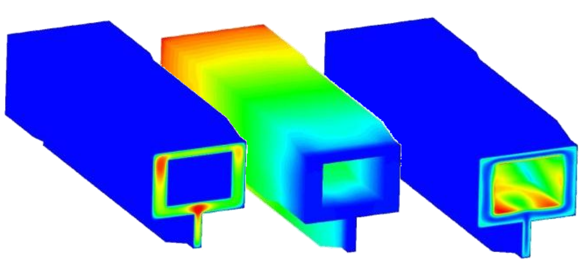


Performance Evaluation

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

Modification of the controllable geometrical parameters until the optimum is reached

Objective Function

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

Area Weighting

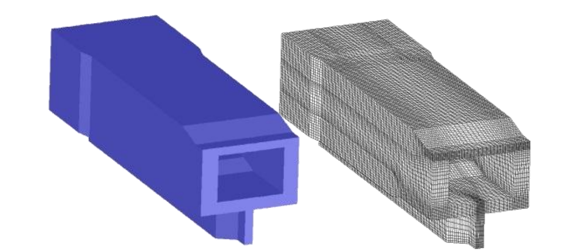
Flow Balance

Admissible L/t value

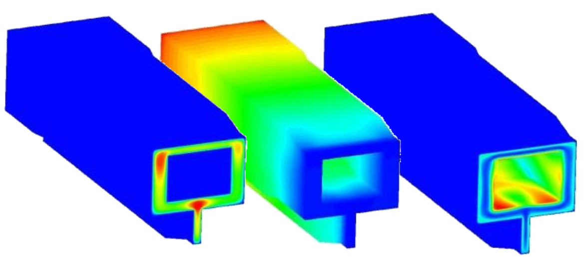
Extrusion Dies – *Flow Distribution Optimisation*

Trial Parameters

Pre-Processor



3D non-isothermal flow field calculation (FVM)



Performance Evaluation

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

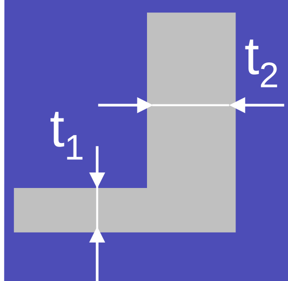
Modification of the controllable geometrical parameters until the optimum is reached

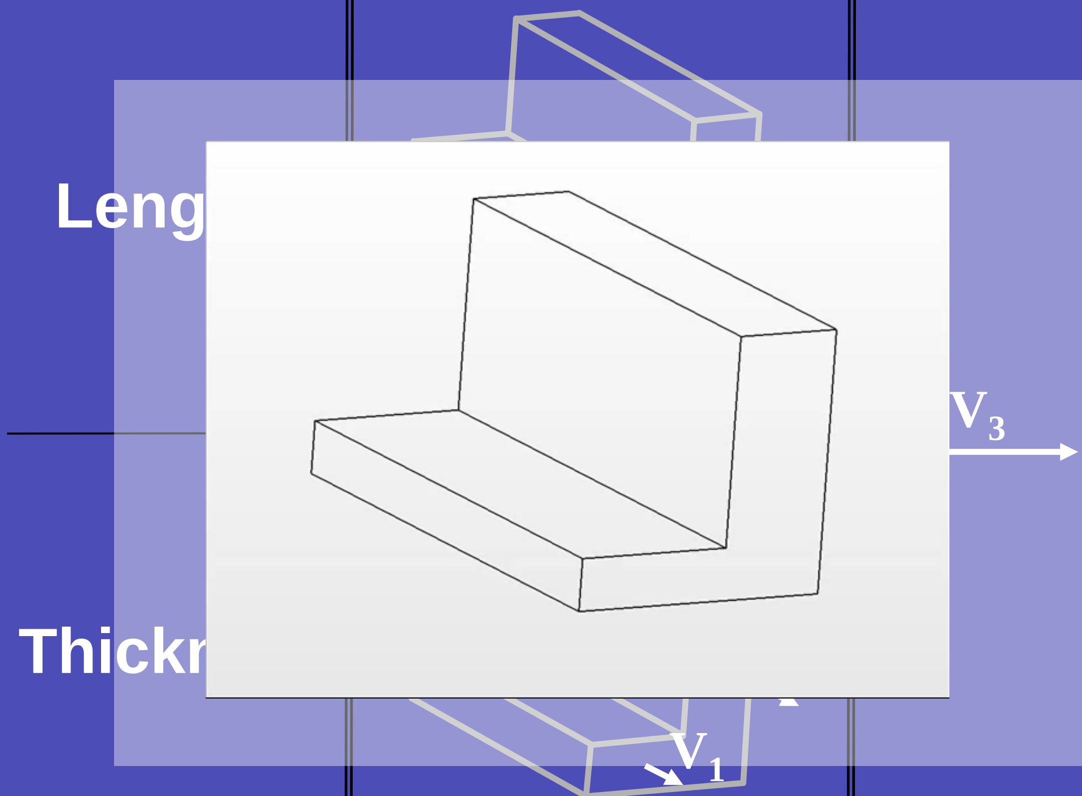
SIMPLEX Method (SM)

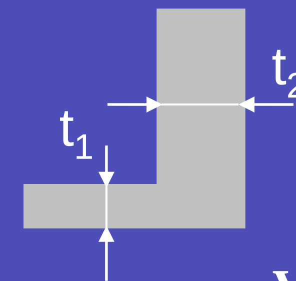
Experimental Method (EM)

Extrusion Dies – *Flow Balance Strategies*

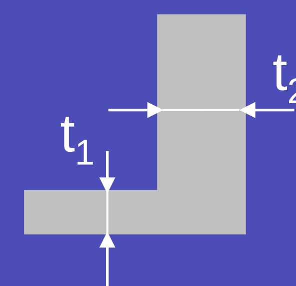
Required Profile	Optimised Variable	Die Flow Channel	Haul-off Speed	Final Profile





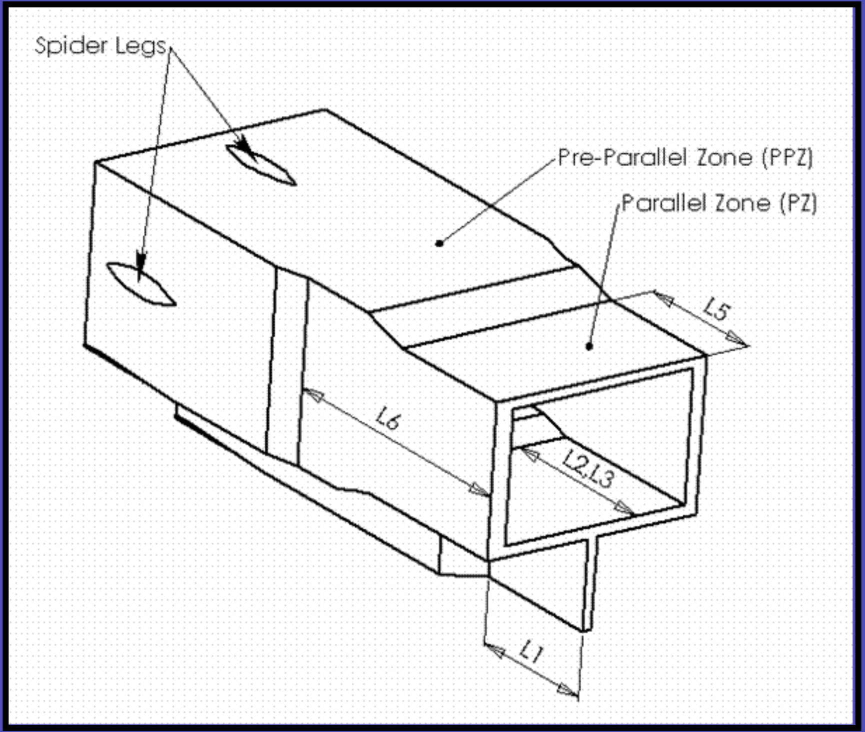


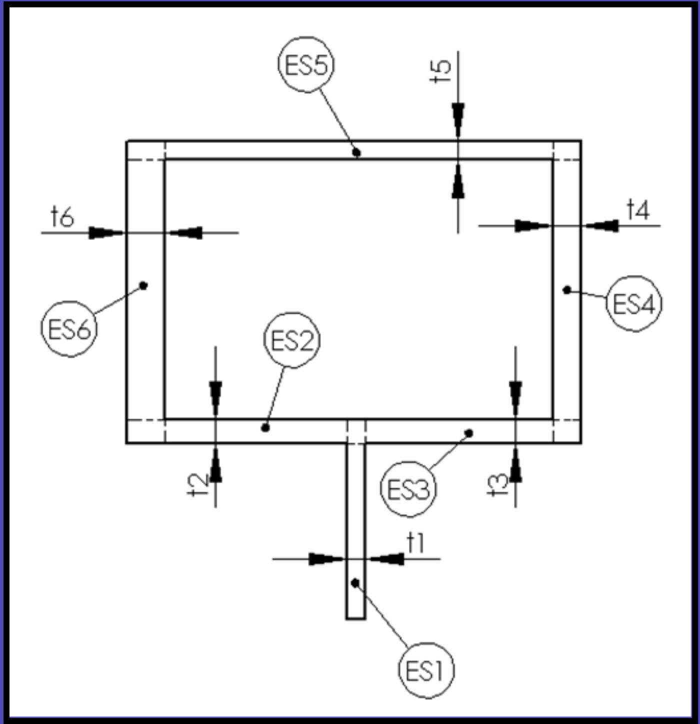
$$\frac{V_3}{V_1} = \frac{V_3}{V_2}$$



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

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*

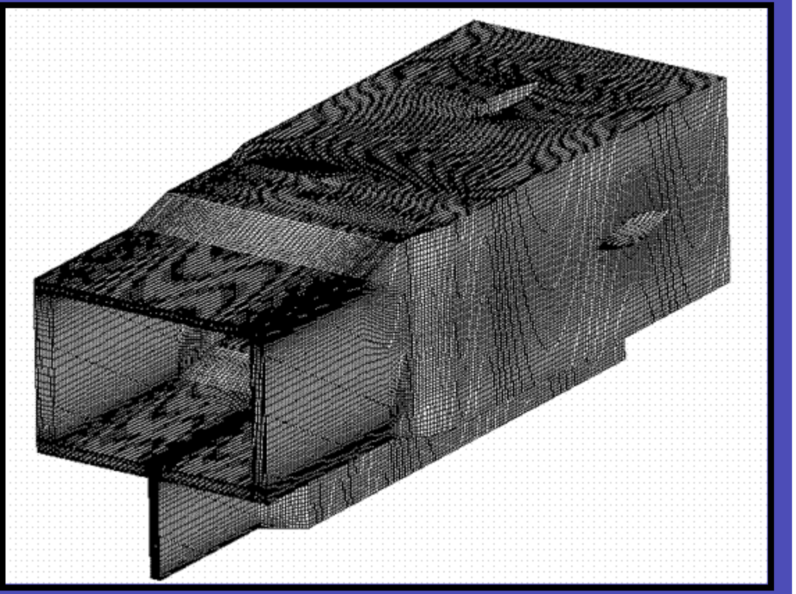
Extrusion Dies – *Optimisation*

Constitutive equation

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

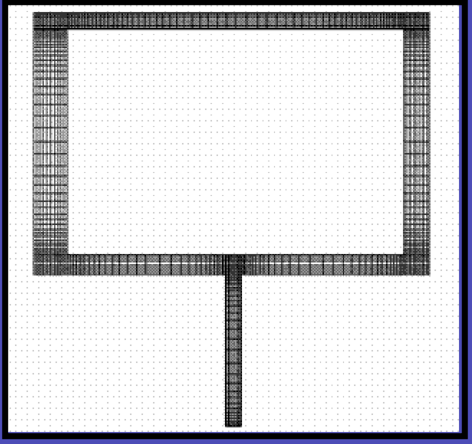
$$F(\dot{\gamma}) = \eta_\infty + \frac{\eta_0-\eta_\infty}{\left(1+(\lambda\dot{\gamma})^2\right)^{\frac{1-n}{2}}} \qquad H(T) = \exp\left[\alpha\left(\frac{1}{T}-\frac{1}{T_\alpha}\right)\right]$$

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



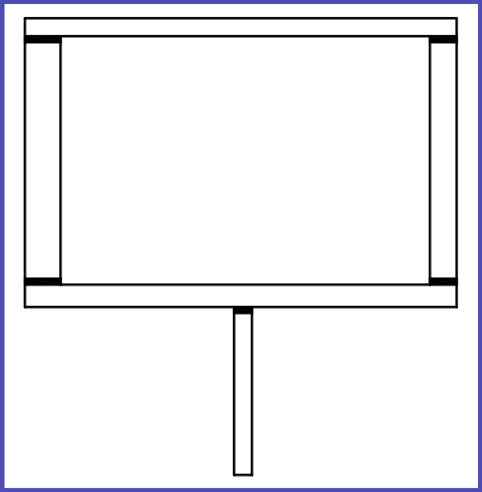
DieINI – Initial trial

Optimizations performed

DieL – Length optimisation

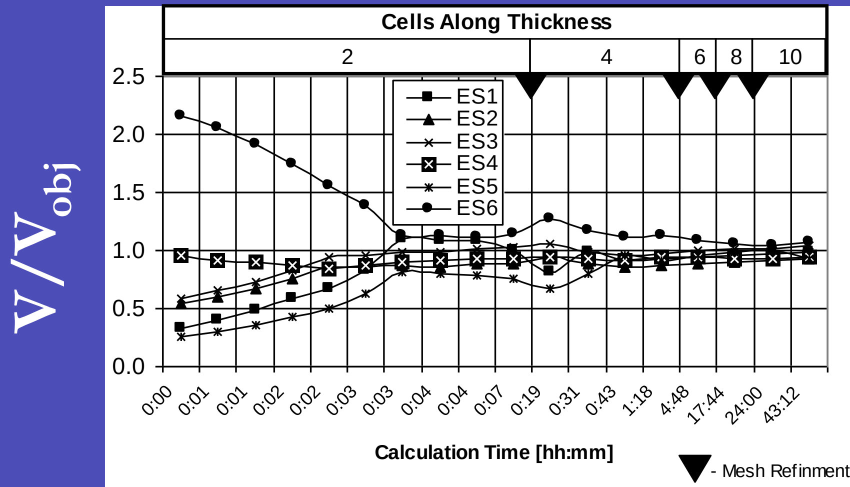
DieT – Thickness optimisation

DieLS – Length optimisation + Flow separators

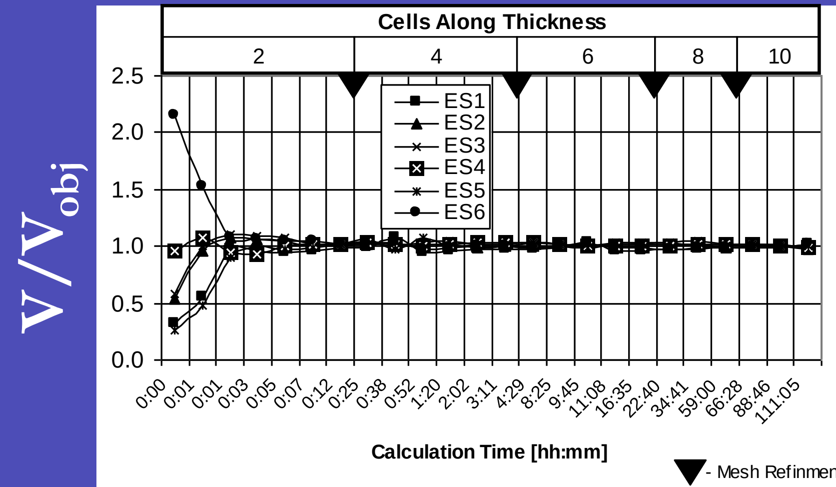


Extrusion Dies – *Optimisation*

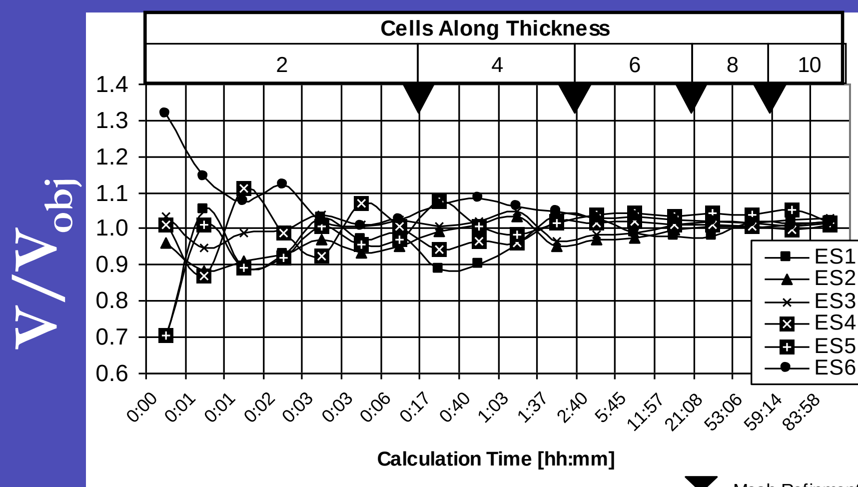
DieL



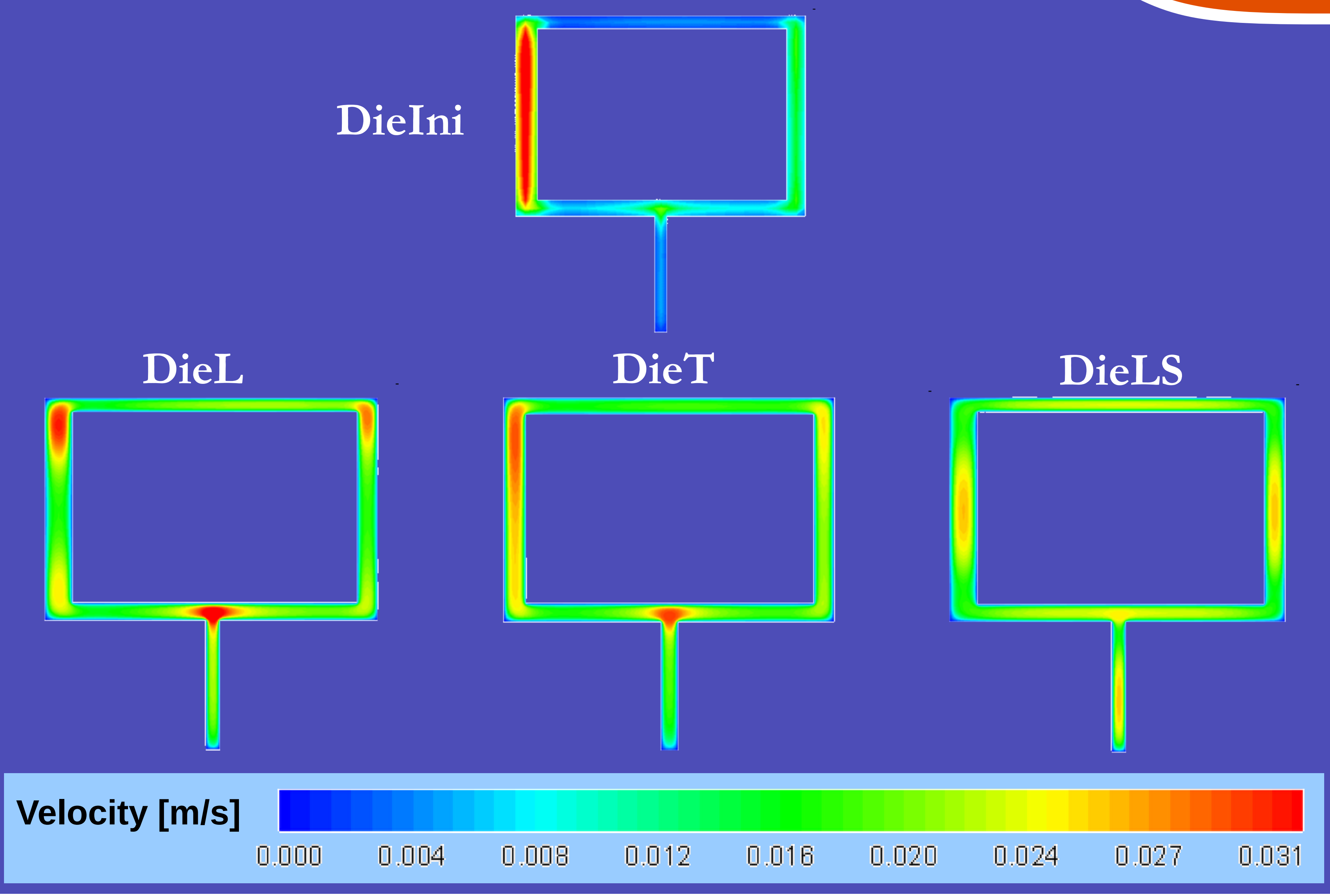
DieT



DieLS



Extrusion Dies – *Optimisation*



Extrusion Dies – *Optimisation*

DieIni

DieL

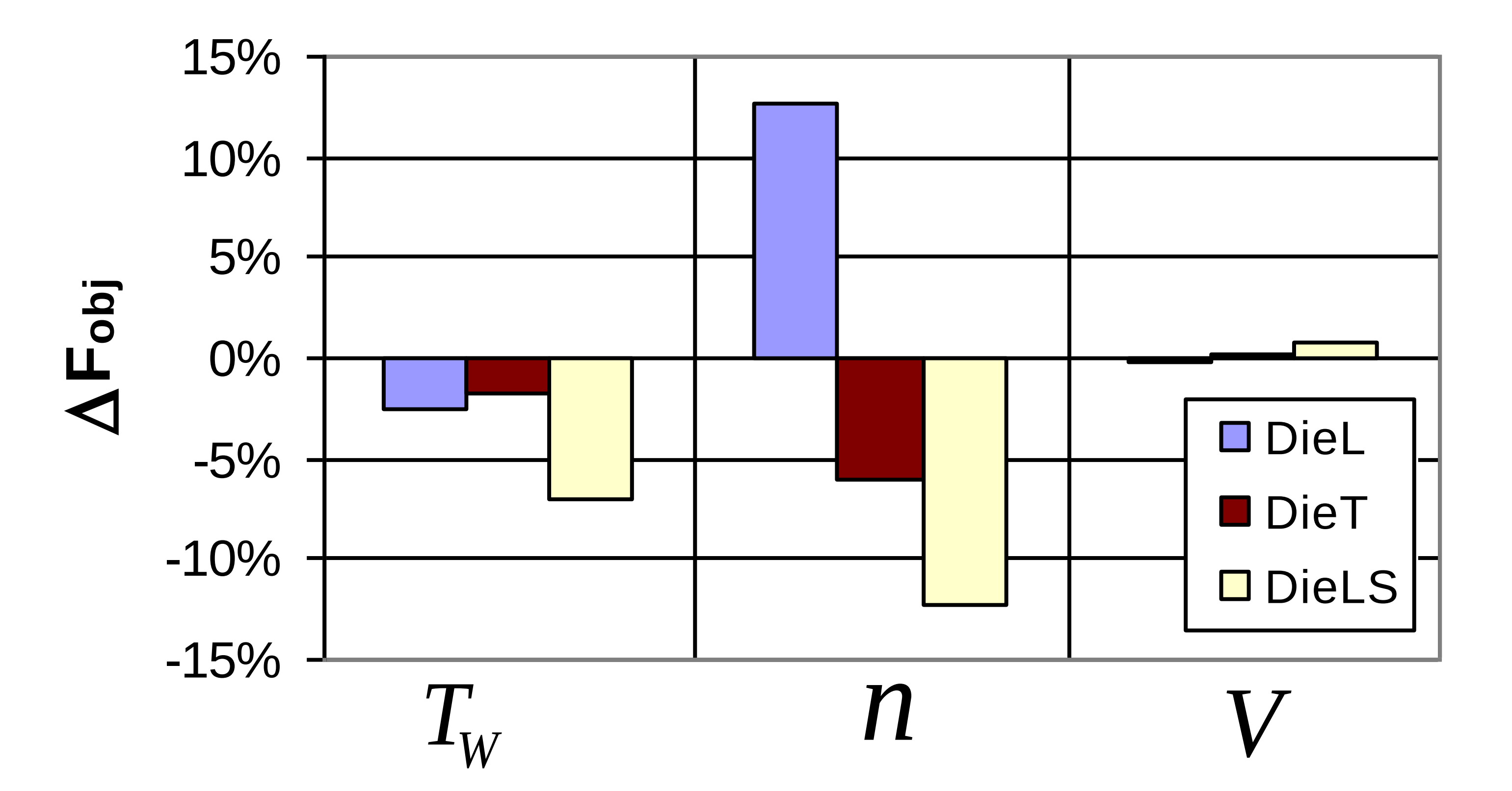
DieT

The factors considered can be divided in two different groups:

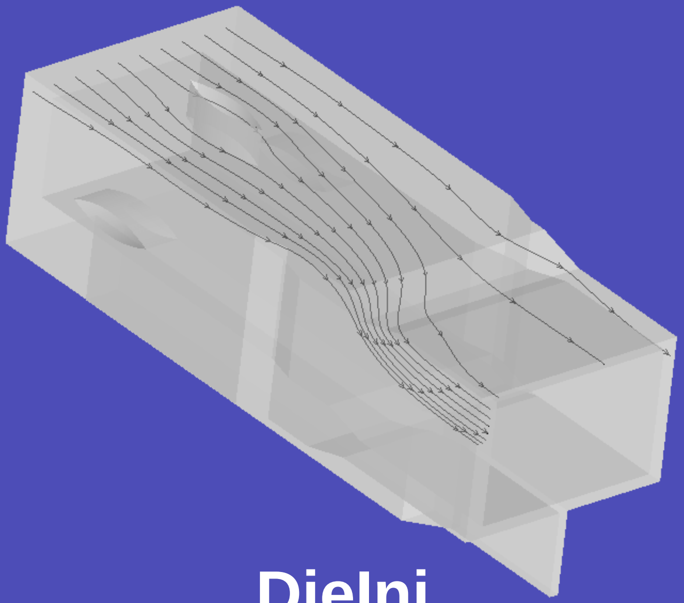
i) processing conditions: V, T_w
ii) melt rheological properties: n

The experiments (simulations) performed were defined by a statistics Taguchi technique, considering three levels for each factor

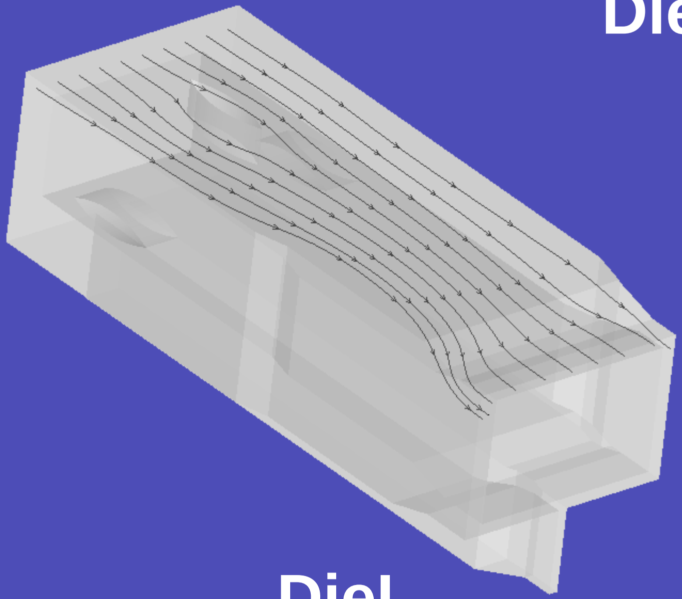
Extrusion Dies - *Length vs Thickness Optimisation*



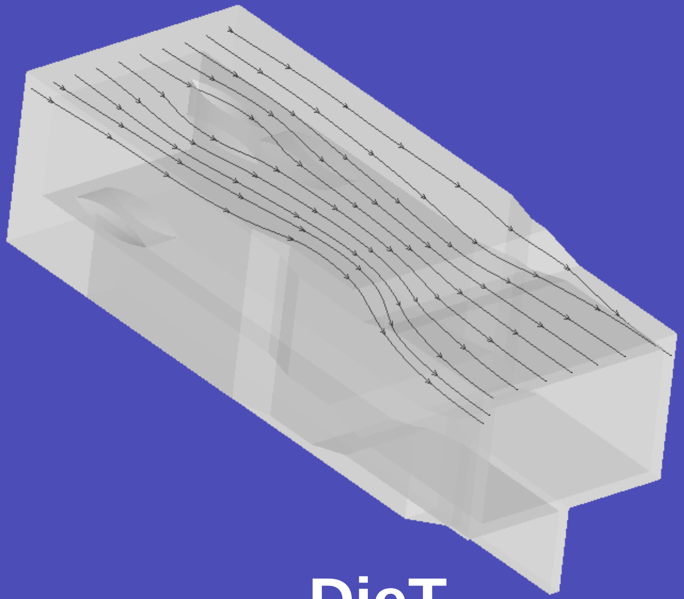
Extrusion Dies - *Length vs Thickness Optimisation*



DieIni



DieL

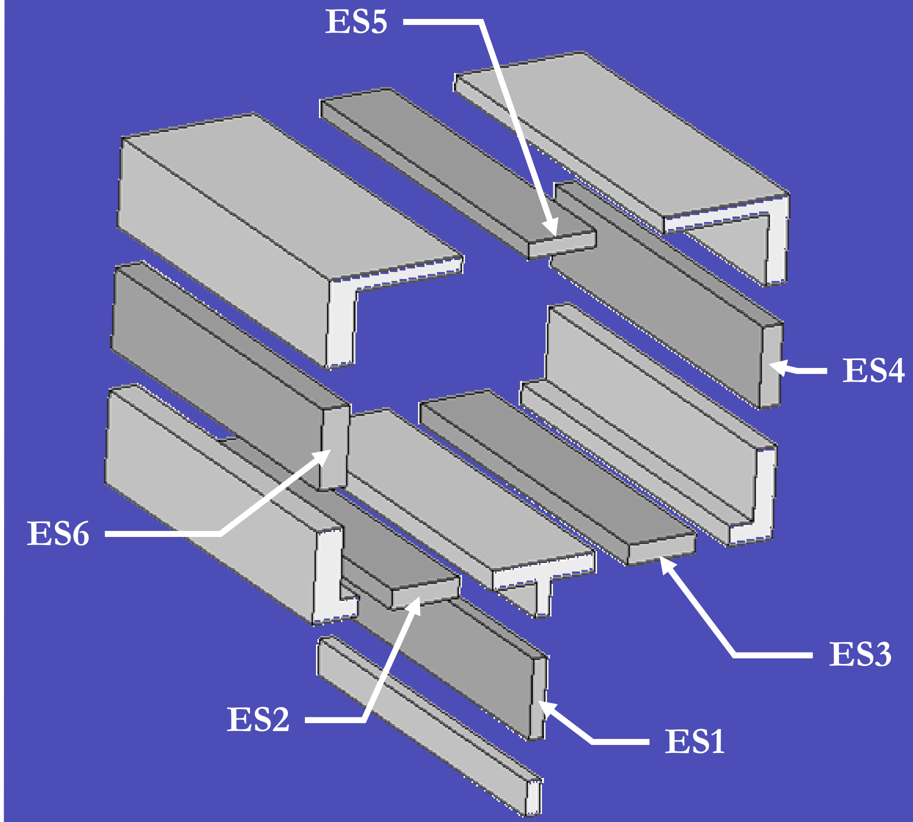


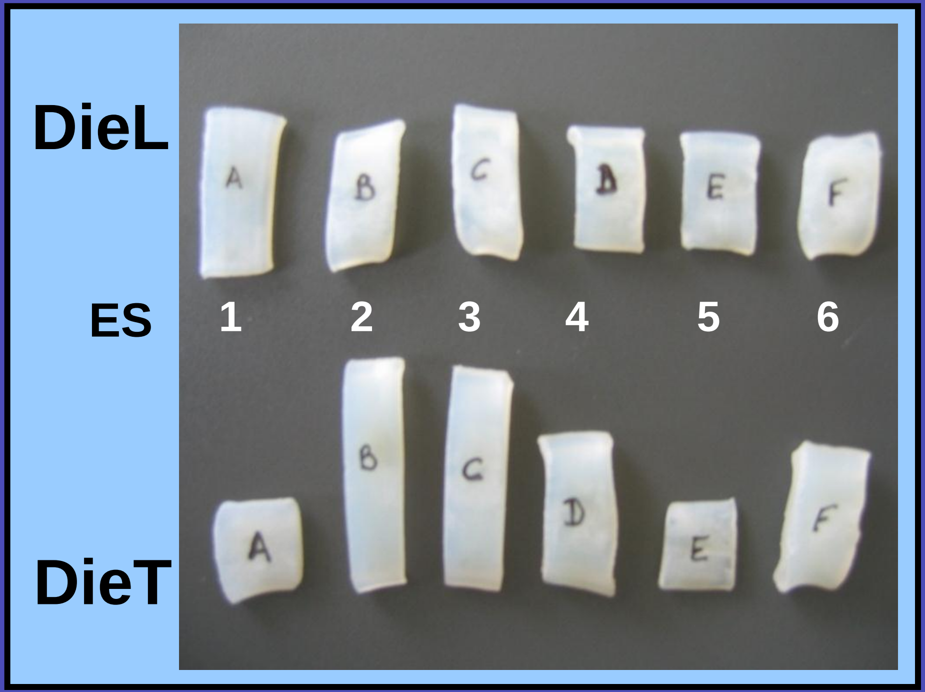
DieT

Extrusion Dies - *Length vs Thickness Optimisation*

Ratio $\overline{V}_{max}/\overline{V}$

Extrusion Die	ES1	ES2	ES3	ES4	ES5	ES6
DieINI	6.20	3.72	3.39	2.18	7.46	1.00
DieL	1.08	1.15	1.03	1.12	1.15	1.00
DieT	1.68	1.38	1.33	1.24	1.56	1.00

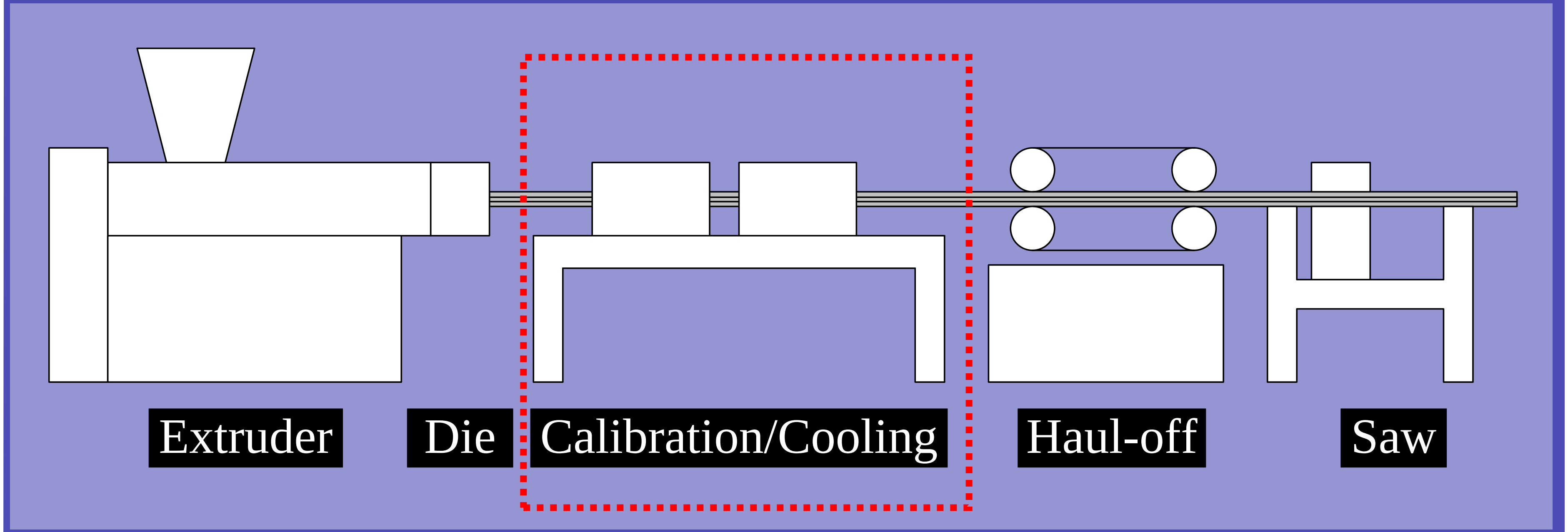




Extrusion Dies - *Conclusion*

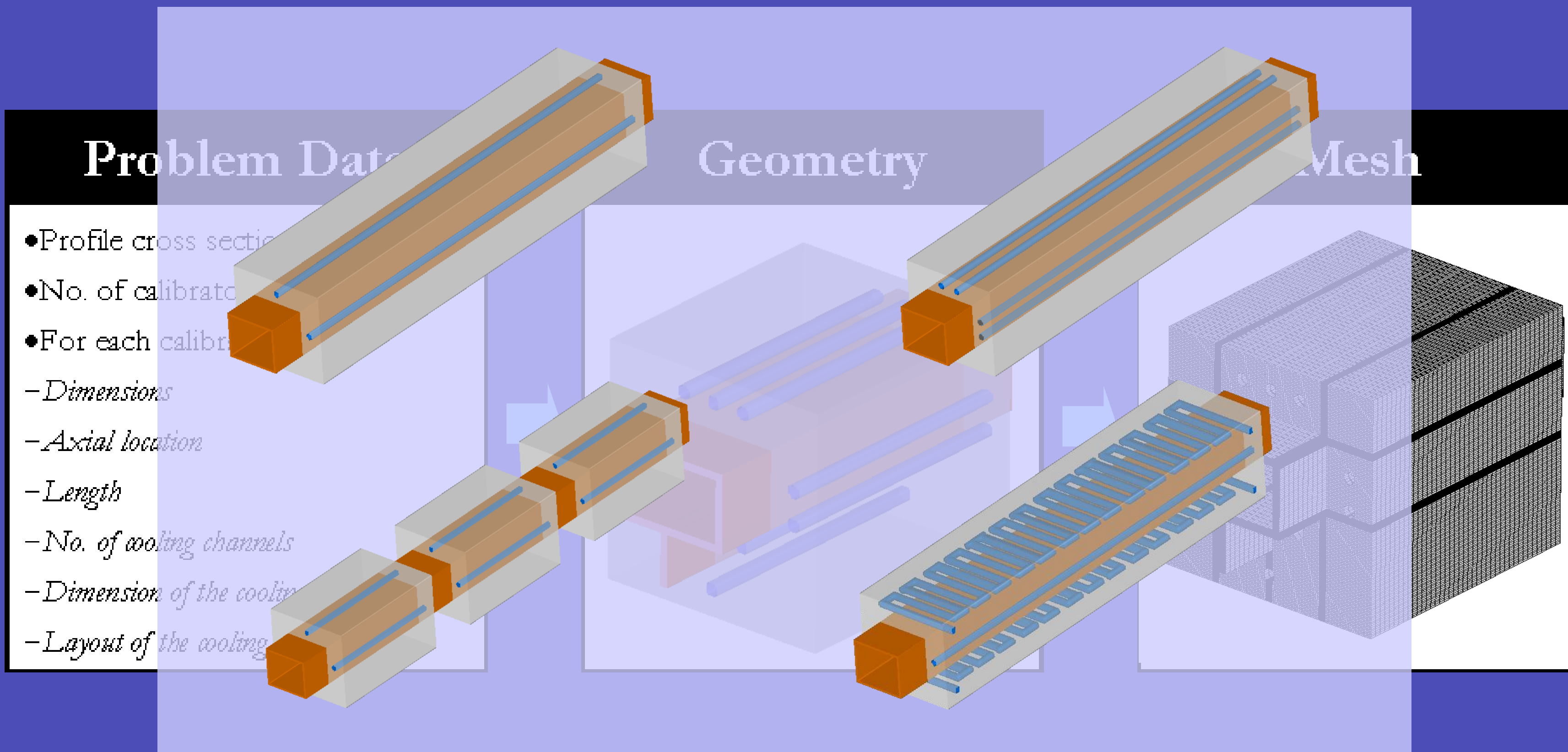
- *Length control* is difficult to apply in geometries with different flow restrictions and leads to dies with higher sensitivity to processing conditions than thickness control;
- *Flow separators* had a positive effect in the flow distribution but affect negatively in the die sensitivity;
- *Thickness optimised dies* produce extrudates that have higher propensity to distort.

Calibrators – *Problem Statement*

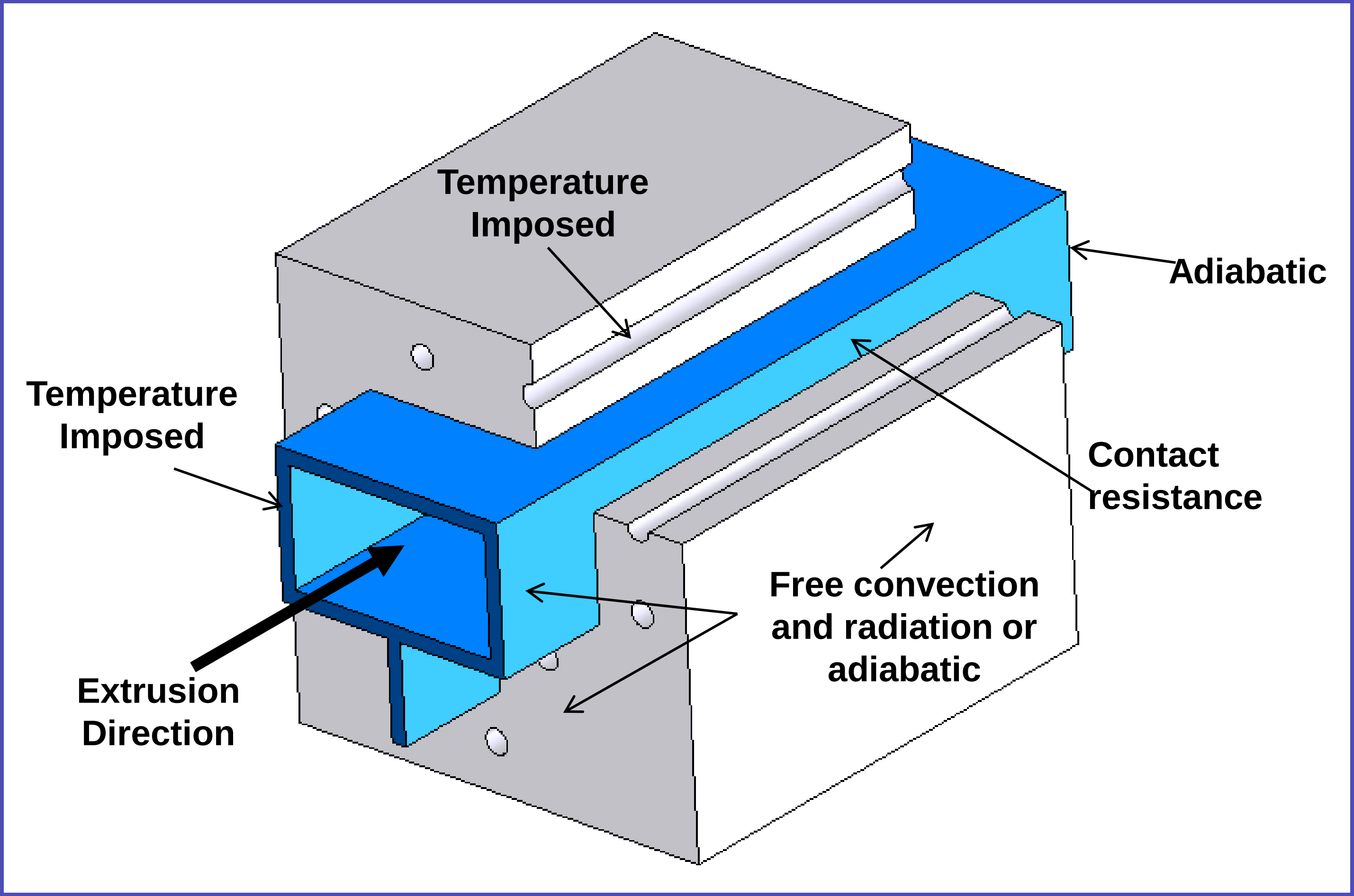


$$\bar{T} < T_s \qquad \downarrow \sigma_T$$

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

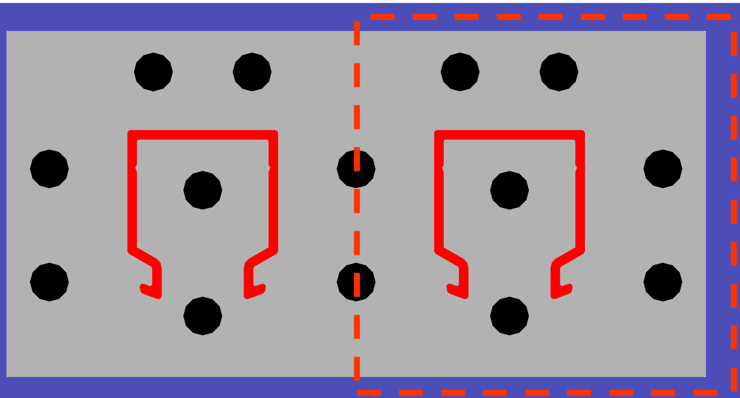
$$\frac{\partial}{\partial x}\left(k_c \frac{\partial Tc}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_c \frac{\partial T_c}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_c \frac{\partial Tc}{\partial z}\right)=0$$

Polymer-calibrator interface

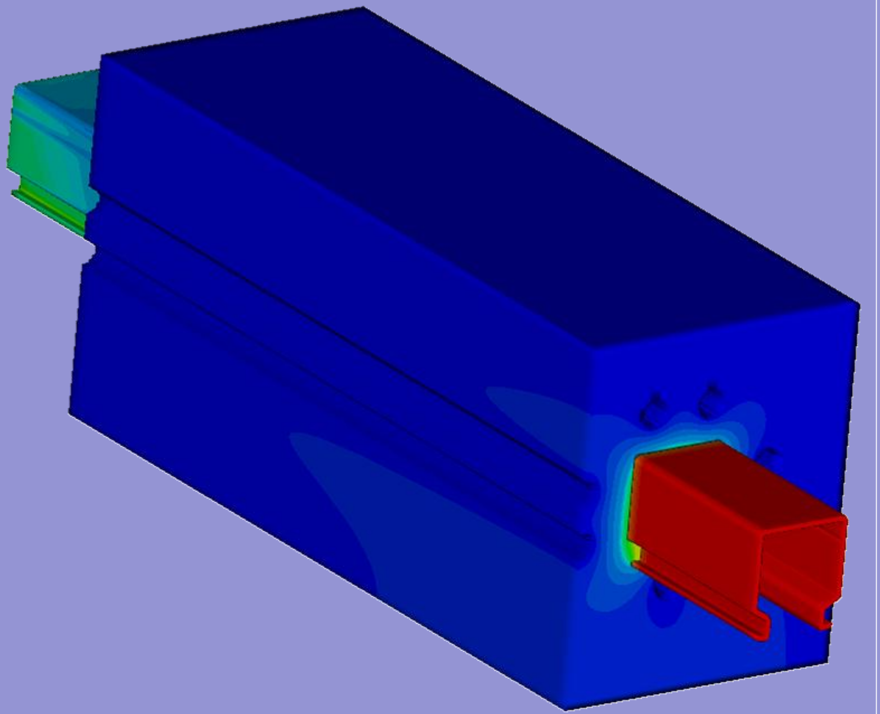
Contact Resistance

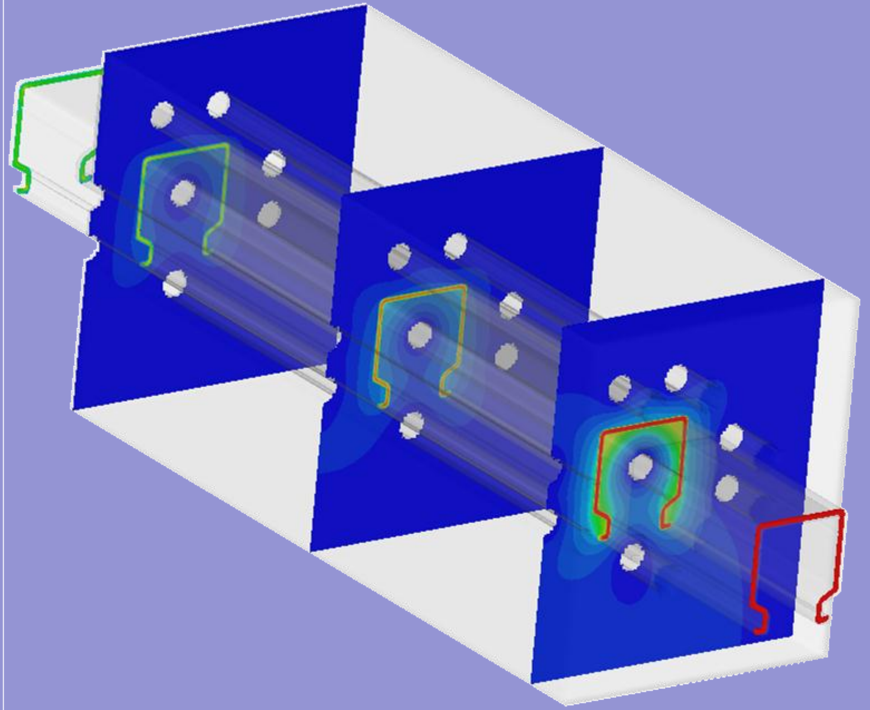
$$k_c\left(\frac{\partial T_c}{\partial n}\right)_{\text{interface}}=-k_p\left(\frac{\partial T_p}{\partial n}\right)_{\text{interface}}=h_i\left(T_p-T_c\right)_{\text{interface}}$$

Calibrators - *Typical result*



3D Temperature field calculation (FVM)





Calibrators - *System Behaviour*

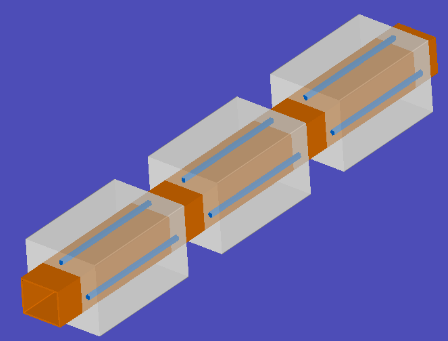
Influence of boundary conditions, process and geometrical parameters on the system performance (in terms of average temperature and temperature uniformity)

Conclusion:

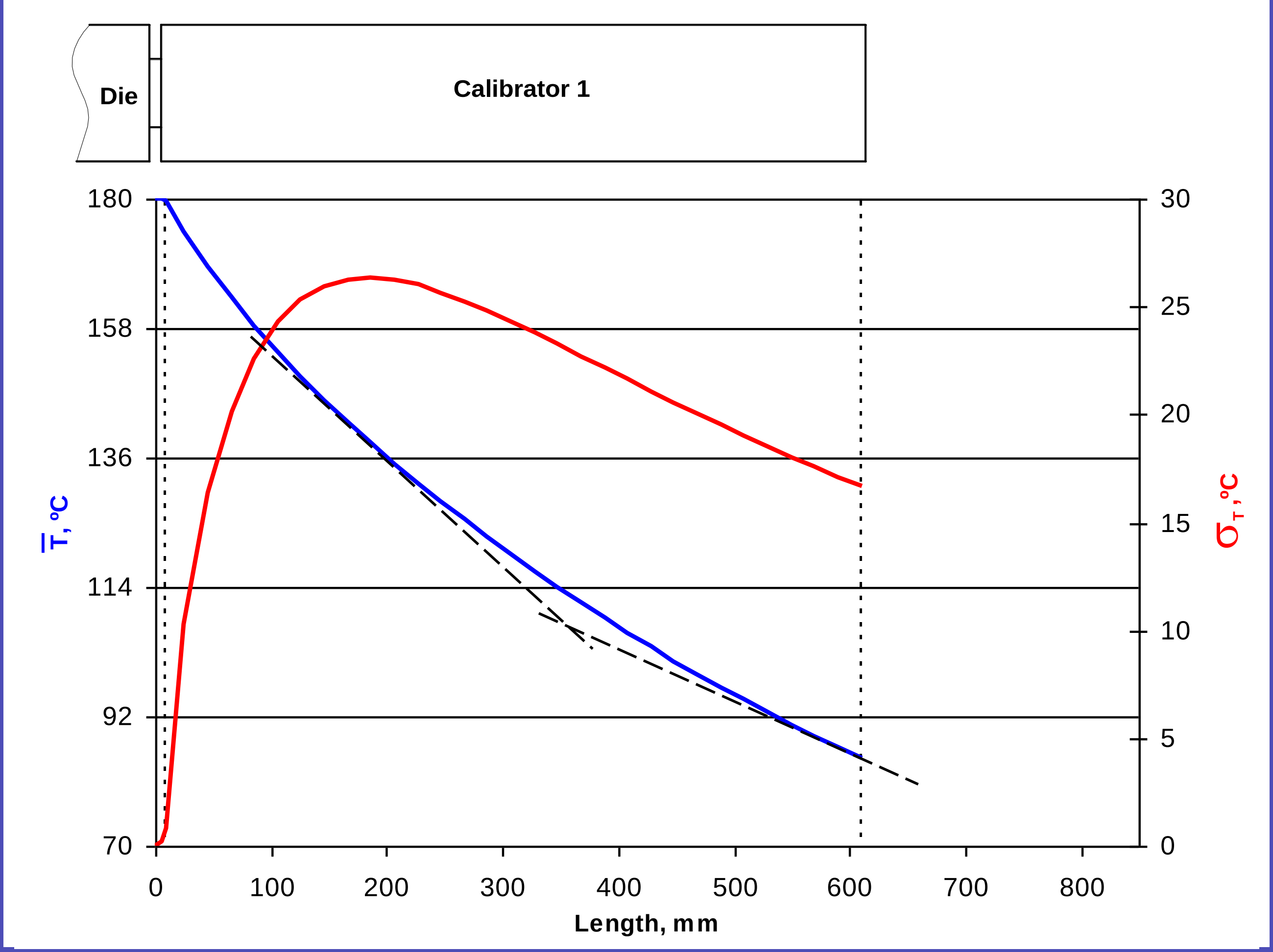
In general

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

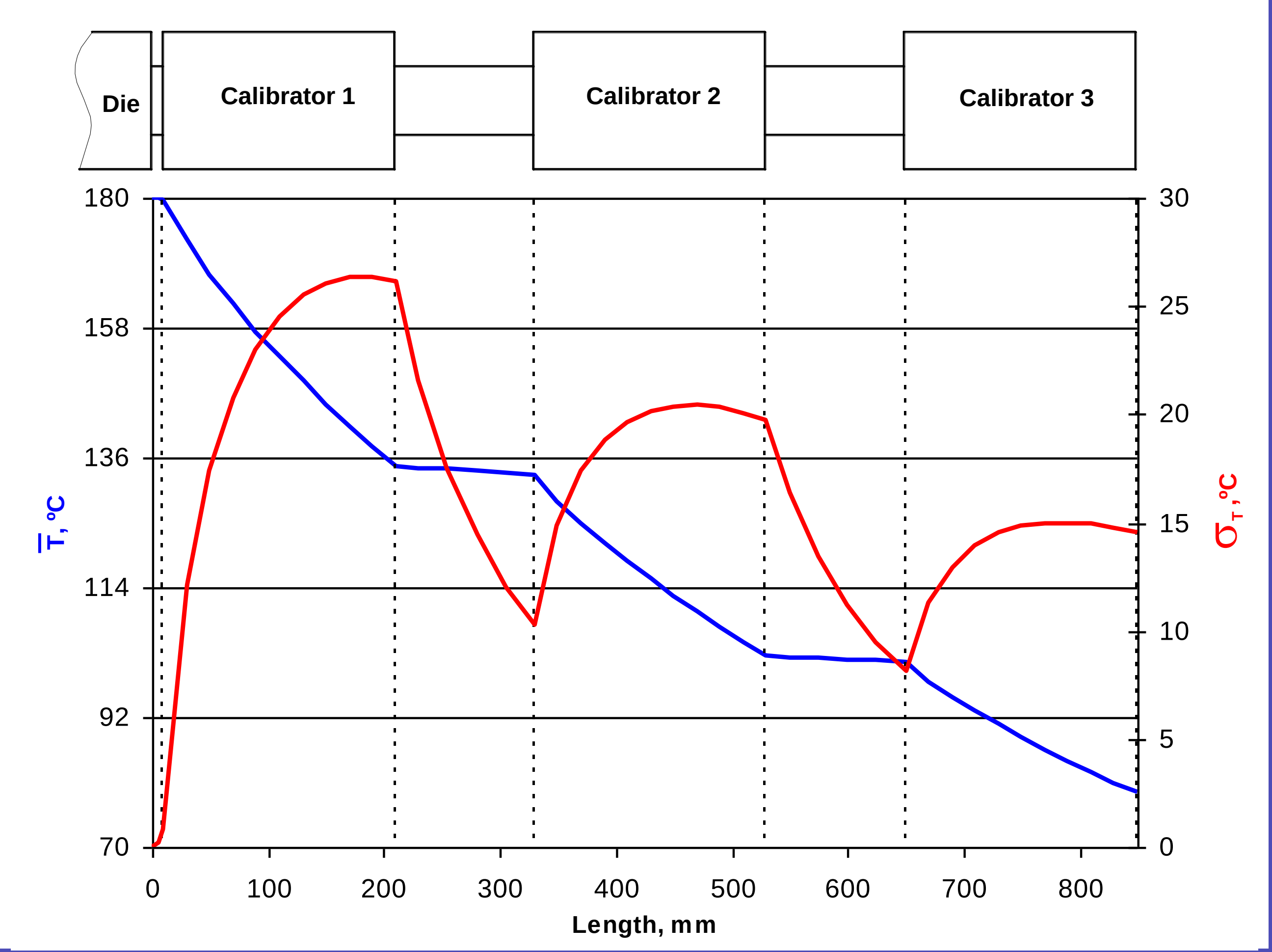
Exceptions



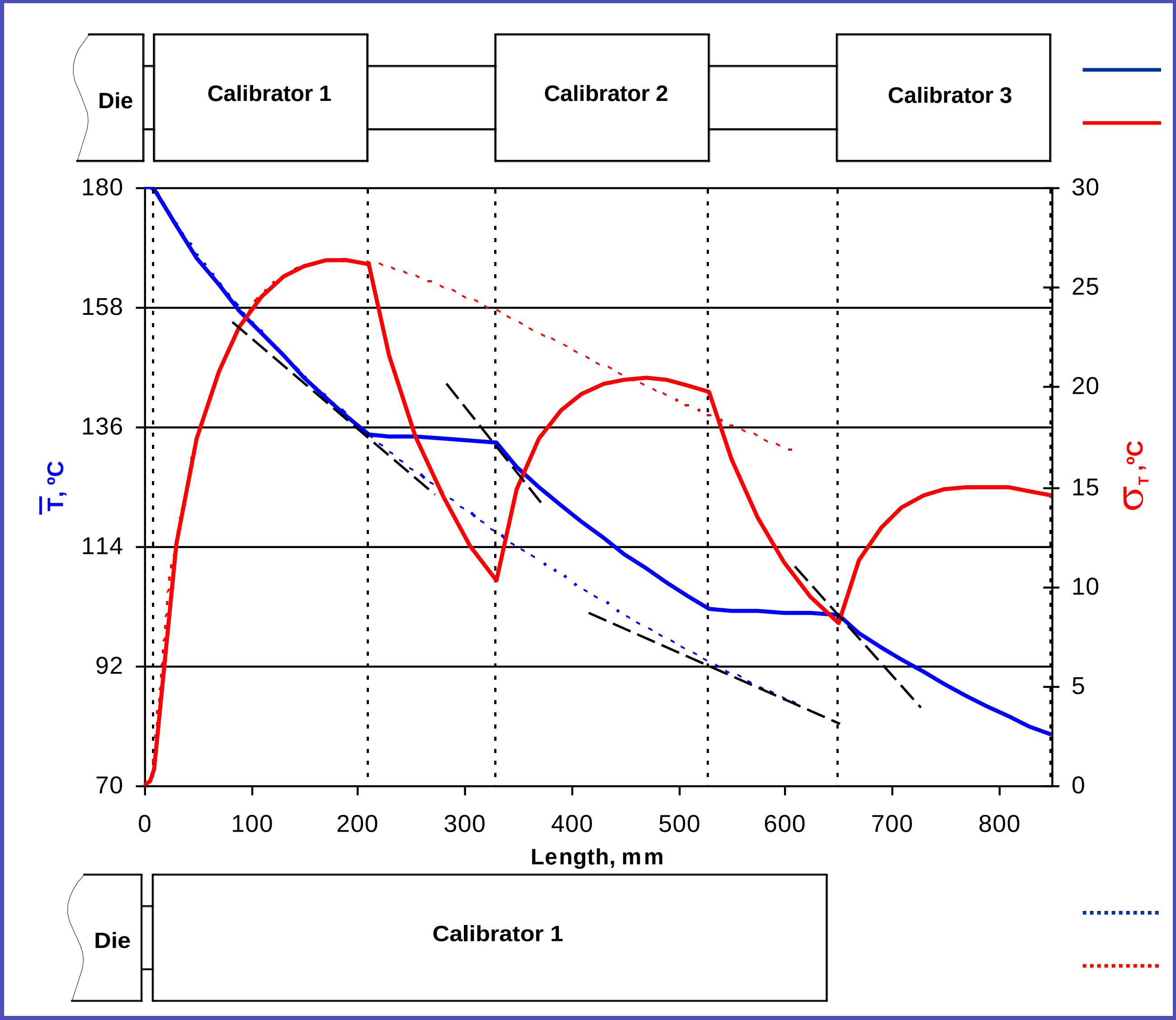
Calibrators - *System Behaviour*



Calibrators - *System Behaviour*

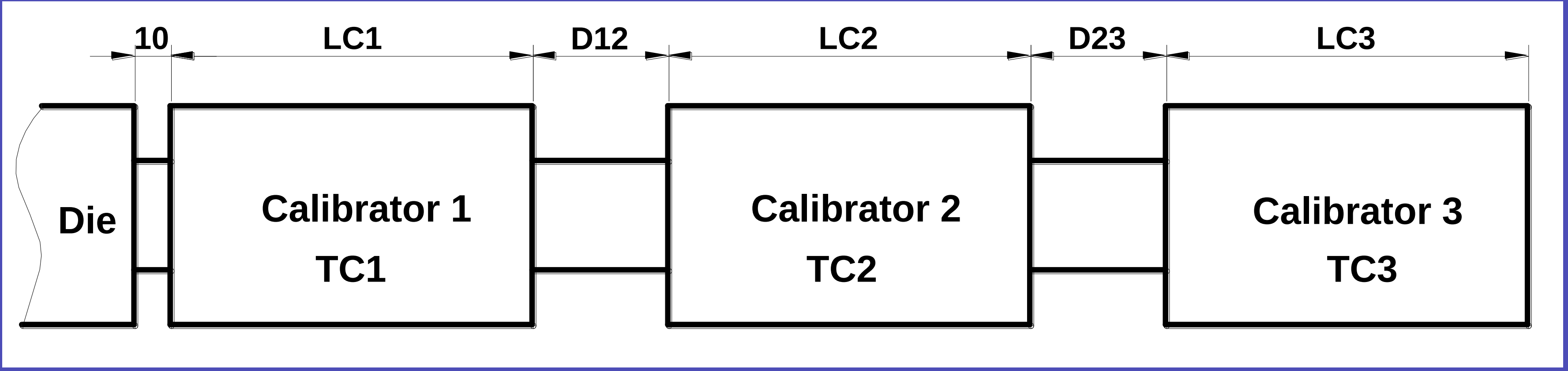


Calibrators - *System Behaviour*



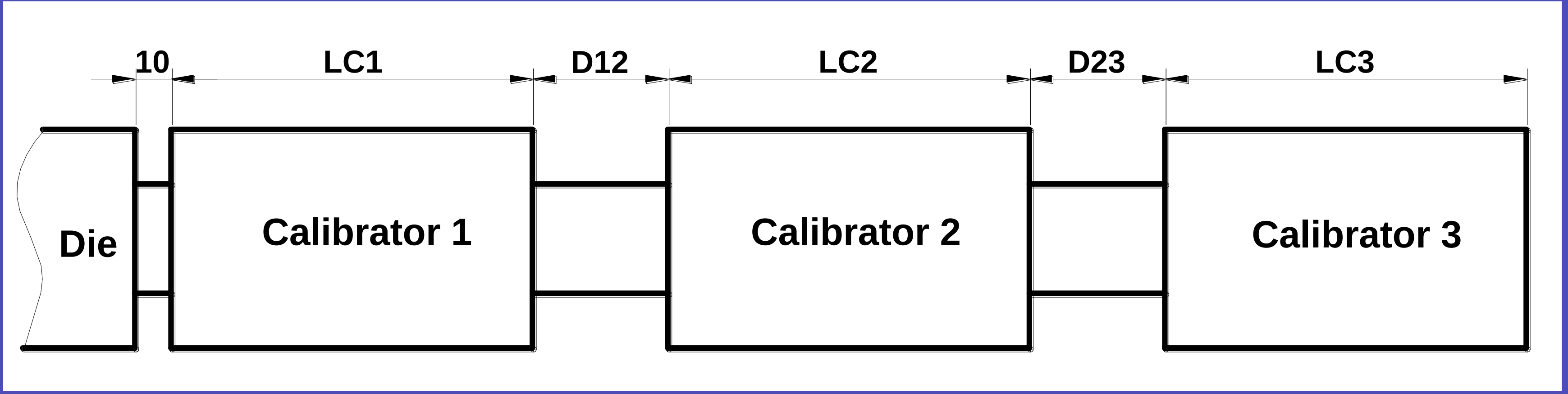
Calibrators - *System Behaviour*

Influence of the cooling units and annealing zones lengths and cooling fluid temperature on the system performance

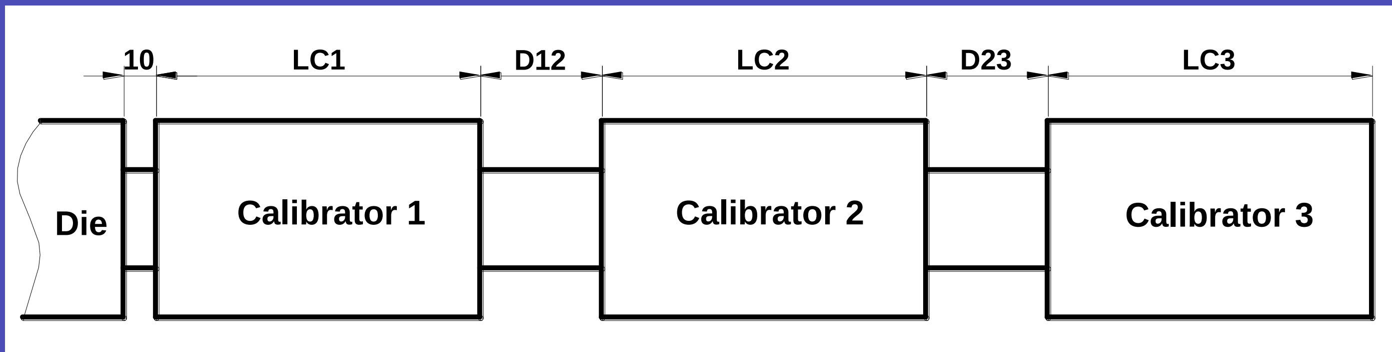


Influence of Length Distribution

LCi and Dij



Calibrators - *System Behaviour*

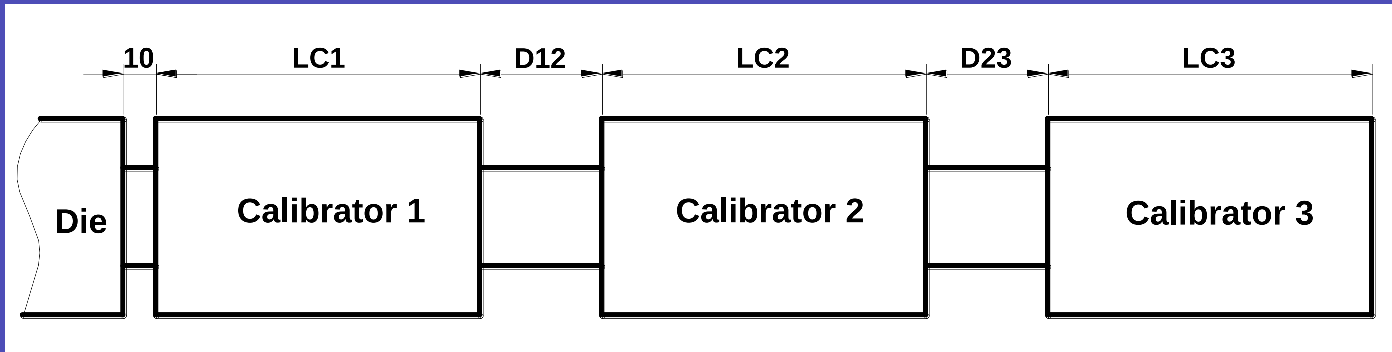


LCi	LC1 [mm]	LC2 [mm]	LC3 [mm]
→	600	-	-
→	300	300	-
→	200	200	200
→	200	200	200
→	200	200	200
↘	300	200	100
↗	100	200	300
↘	300	200	100
↘	300	200	100
↗	100	200	300
↗	100	200	300

Dij	D12 [mm]	D23 [mm]
	-	-
→	240	-
→	120	120
↗	60	180
↘	180	60
→	120	120
→	120	120
↘	180	60
↗	60	180
↘	180	60
↗	60	180

Σ LCi (600 mm), Σ D (240 mm) (system length = 850 mm)

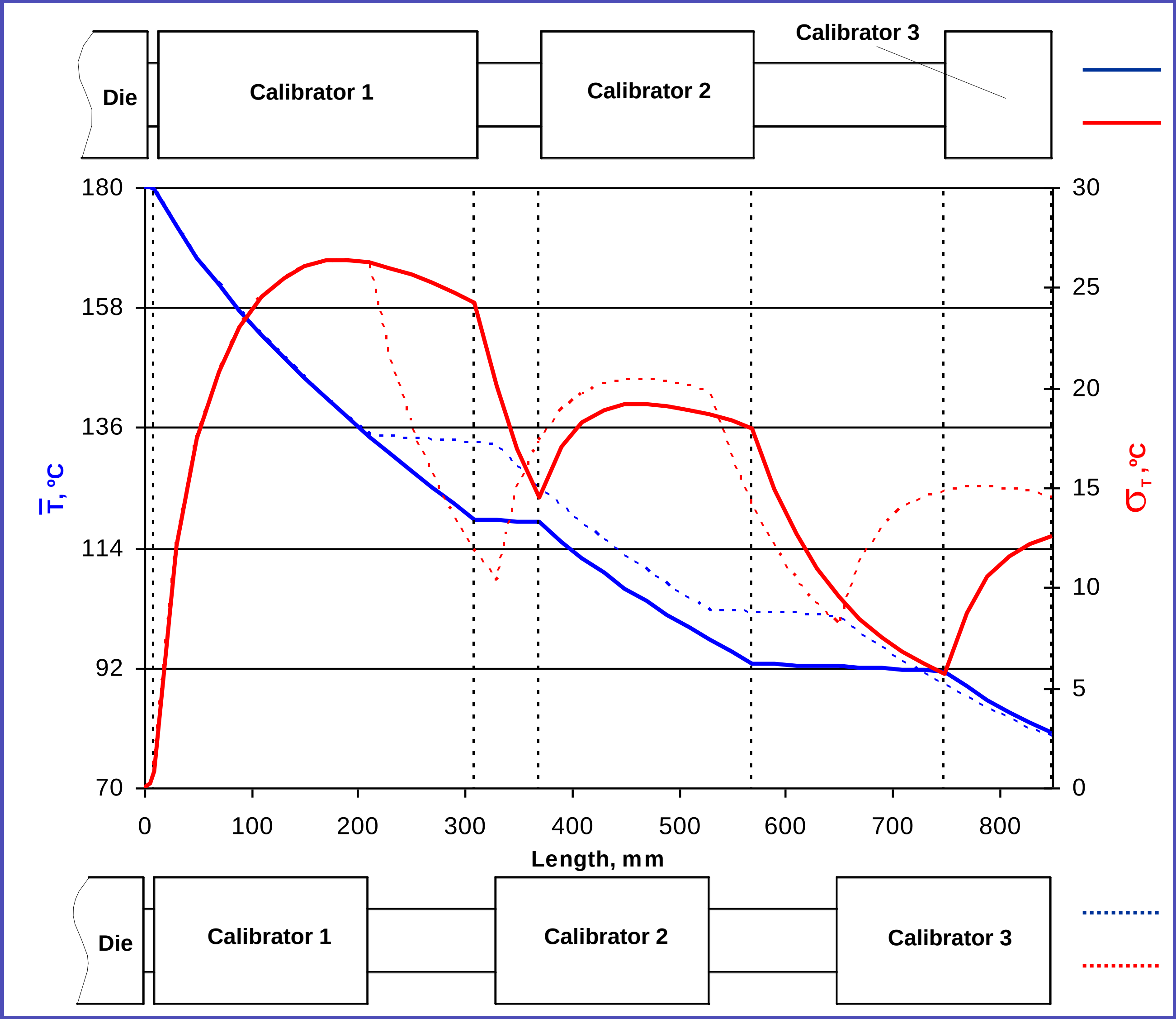
Calibrators - *System Behaviour*



LCi	LC1 [mm]	LC2 [mm]	LC3 [mm]	Dij	D12 [mm]	D23 [mm]	$\overline{T}$ [ºC]	$\overline{T}$ [%]	σ_T [ºC]	σ_T [%]
→	600	-	-		-	-	84.9	0.0%	16.6	0.0%
→	300	300	-	→	240	-	80.3	-5.5%	15.2	-8.6%
→	200	200	200	→	120	120	79.2	-6.7%	14.5	-12.6%
→	200	200	200	↗	60	180	79.5	-6.4%	14.5	-13.1%
→	200	200	200	↘	180	60	79.4	-6.5%	14.8	-10.8%
↘	300	200	100	→	120	120	79.5	-6.4%	13.0	-22.1%
↗	100	200	300	→	120	120	79.4	-6.5%	15.1	-9.3%
↘	300	200	100	↘	180	60	79.6	-6.3%	13.8	-17.3%
↘	300	200	100	↗	60	180	79.9	-5.9%	12.6	-24.3%
↗	100	200	300	↘	180	60	79.7	-6.1%	15.2	-8.4%
↗	100	200	300	↗	60	180	79.5	-6.3%	15.1	-9.4%

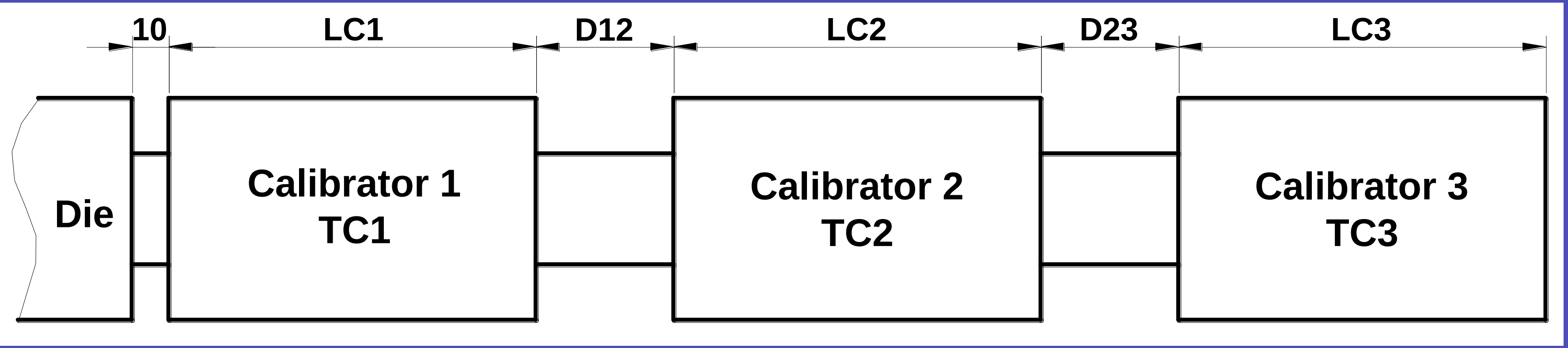
Σ LCi (600 mm), Σ D (240 mm) (system length = 850 mm)

Calibrators - *System Behaviour*

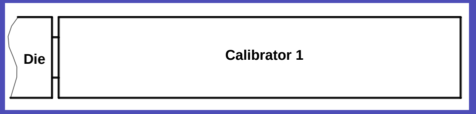


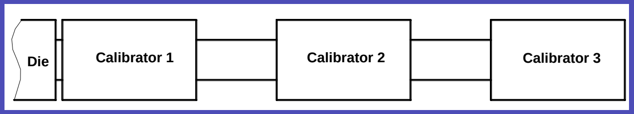
Influence of cooling fluid temperature

TCi

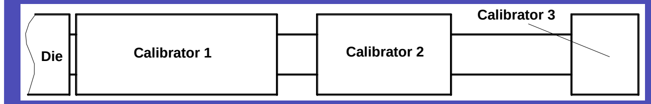


Calibrators - *System Behaviour*





→ LCi + → Dij

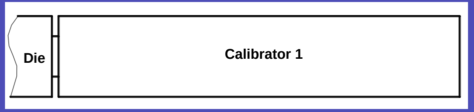


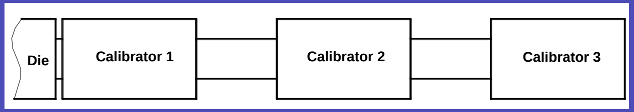
↘ LCi + ↗ Dij

TCi	TC1 [ºC]	TC2 [ºC]	TC3 [ºC]
→	18	-	-
→	18	18	18
→	10	10	10
→	26	26	26
↘	26	18	10
↗	10	18	26
→	18	18	18
→	10	10	10
→	26	26	26
↘	26	18	10
↗	10	18	26

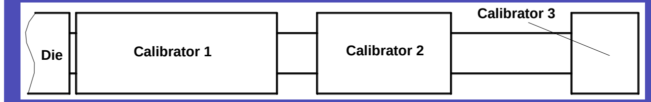
10ºC <= TCi <= 26ºC

Calibrators - *System Behaviour*





→ LCi + → Dij

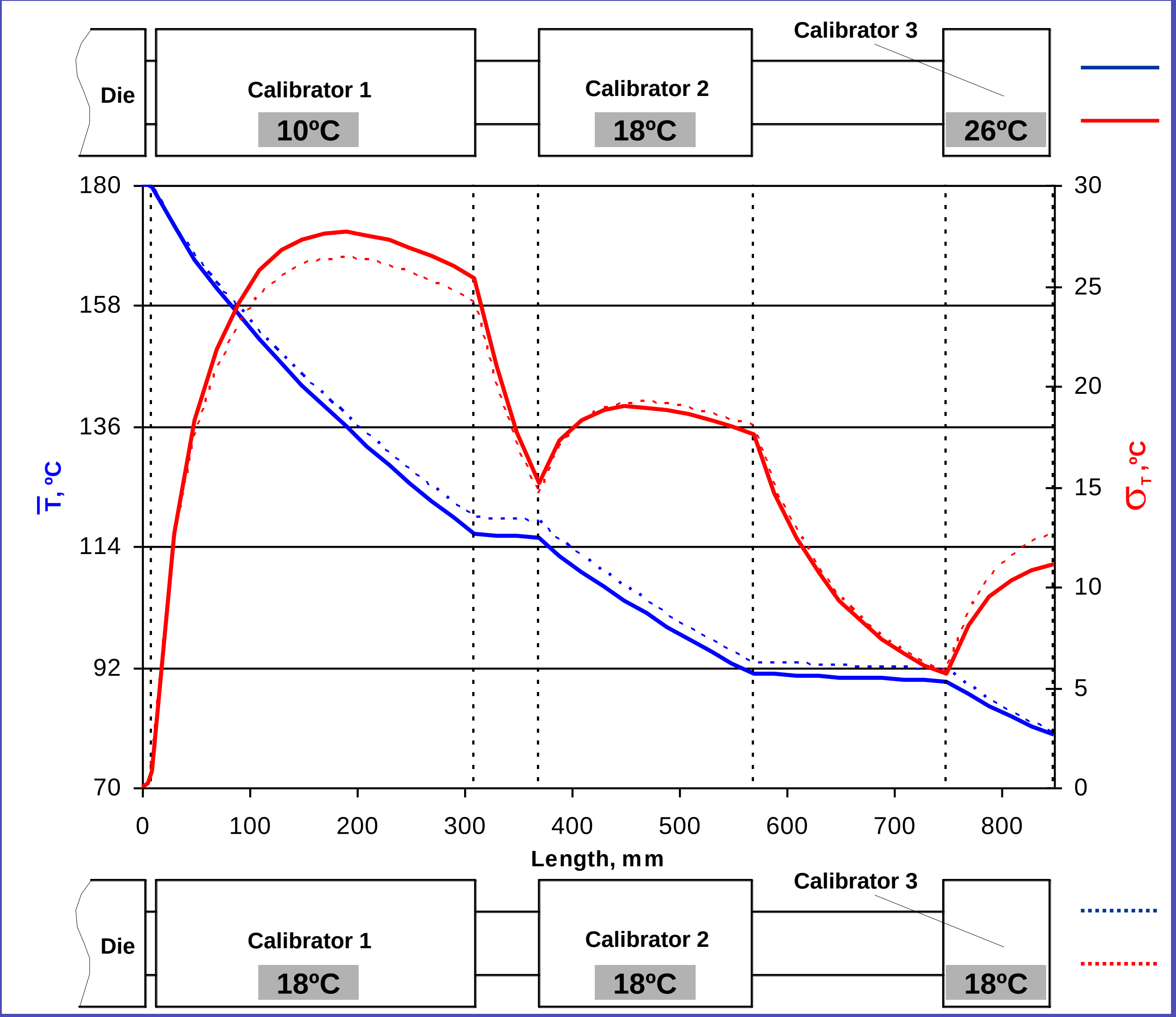


↘ LCi + ↗ Dij

TCi	TC1 [ºC]	TC2 [ºC]	TC3 [ºC]	$\overline{T}$ [ºC]	$\overline{T}$ [%]	σ_T [ºC]	σ_T [%]
→	18	-	-	84.9	-	16.6	-
→	18	18	18	79.2	-6.7%	14.5	-12.6%
→	10	10	10	74.4	-12.3%	15.3	-8.2%
→	26	26	26	83.9	-1.1%	13.8	-17.0%
↘	26	18	10	78.0	-8.1%	16.0	-3.6%
↗	10	18	26	80.3	-5.4%	13.0	-21.7%
→	18	18	18	79.9	-5.9%	12.6	-24.3%
→	10	10	10	75.2	-11.4%	13.2	-20.7%
→	26	26	26	84.6	-0.4%	12.0	-28.0%
↘	26	18	10	80.2	-5.5%	14.1	-15.5%
↗	10	18	26	79.5	-6.3%	11.1	-33.1%

10ºC <= TCi <= 26ºC

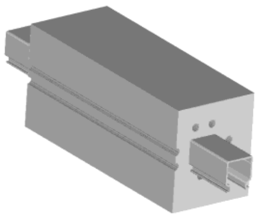
Calibrators - *System Behaviour*



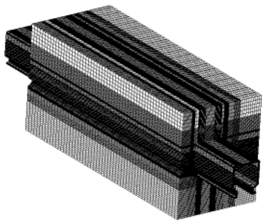
Calibrators - *Optimisation Methodology*

Input Data

Pre- Processor

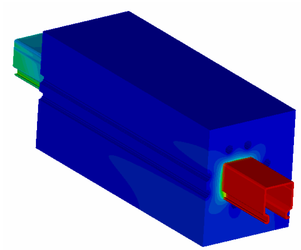


Geometry



Mesh

3D Temperature field calculation (FVM)



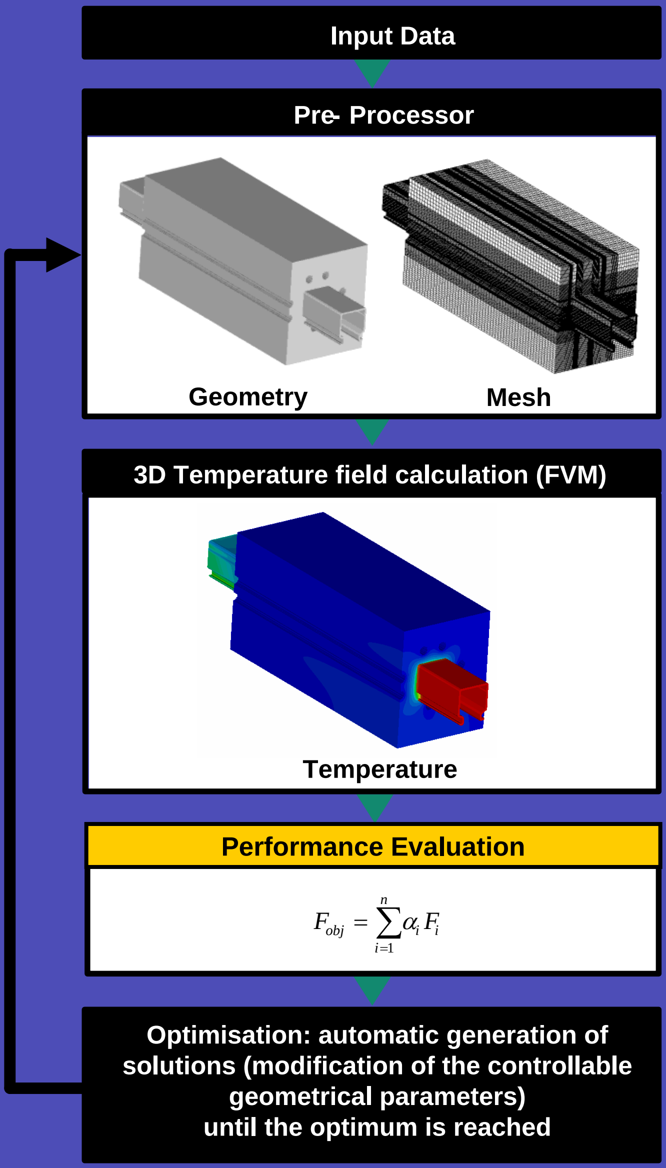
Temperature

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*



Temperature uniformity

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

Cooling efficiency

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

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

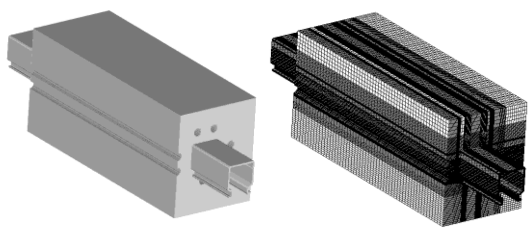
where:

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

Calibrators - *Optimisation Methodology*

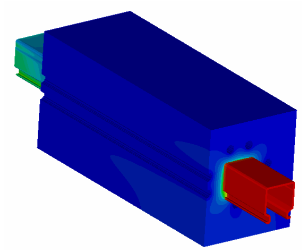
Input Data

Pre- Processor



Geometry **Mesh**

3D Temperature field calculation (FVM)



Temperature

Performance Evaluation

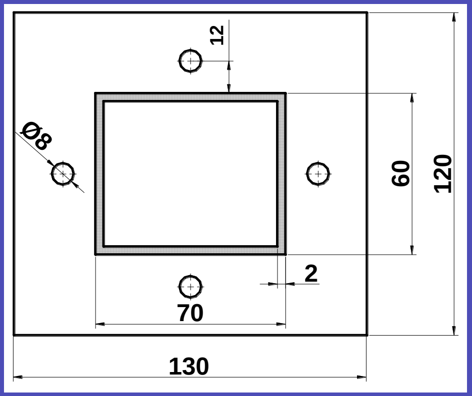
$$F_{obj} = \sum_{i=1}^{n} \alpha_i F_i$$

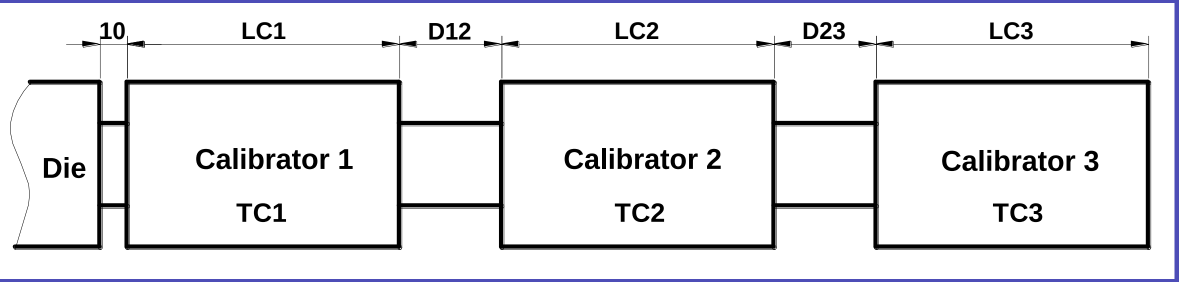
Optimisation: automatic generation of solutions (modification of the controllable geometrical parameters) until the optimum is reached

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

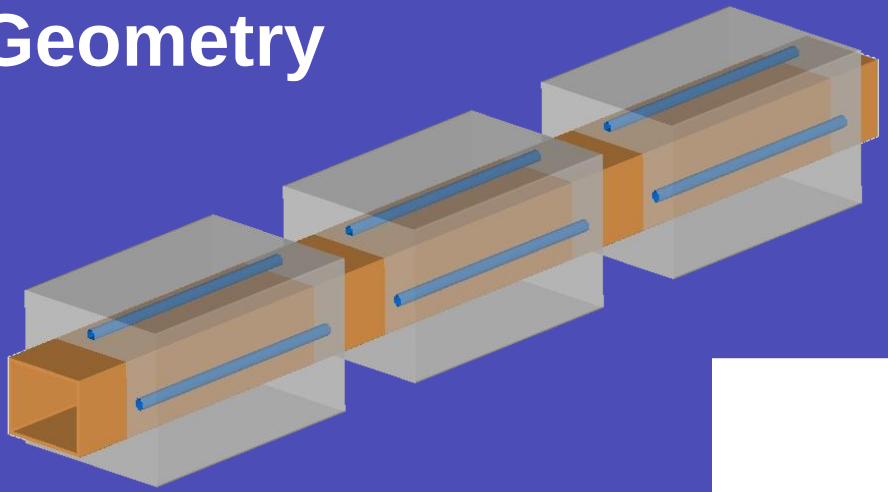
Annealing zones: free convection and radiation

Polymer-calibrator interface: contact resistance

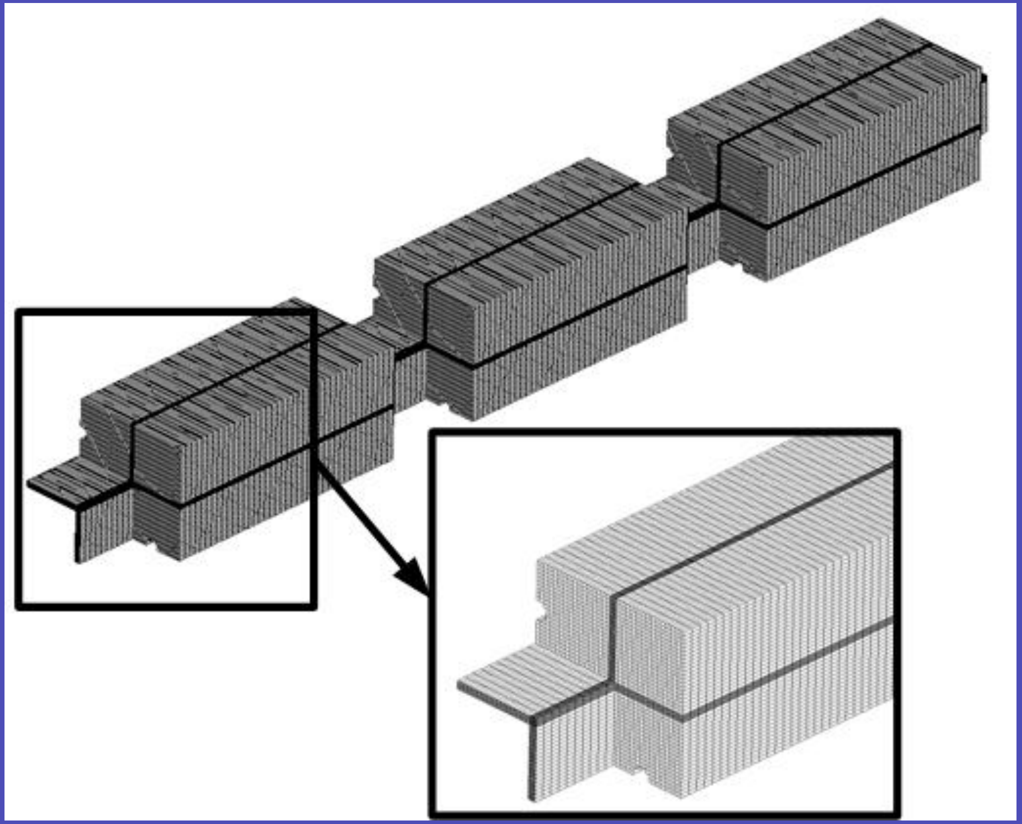
(h_i = 425 W/m^{2}K)

Calibrators - *Case Study*

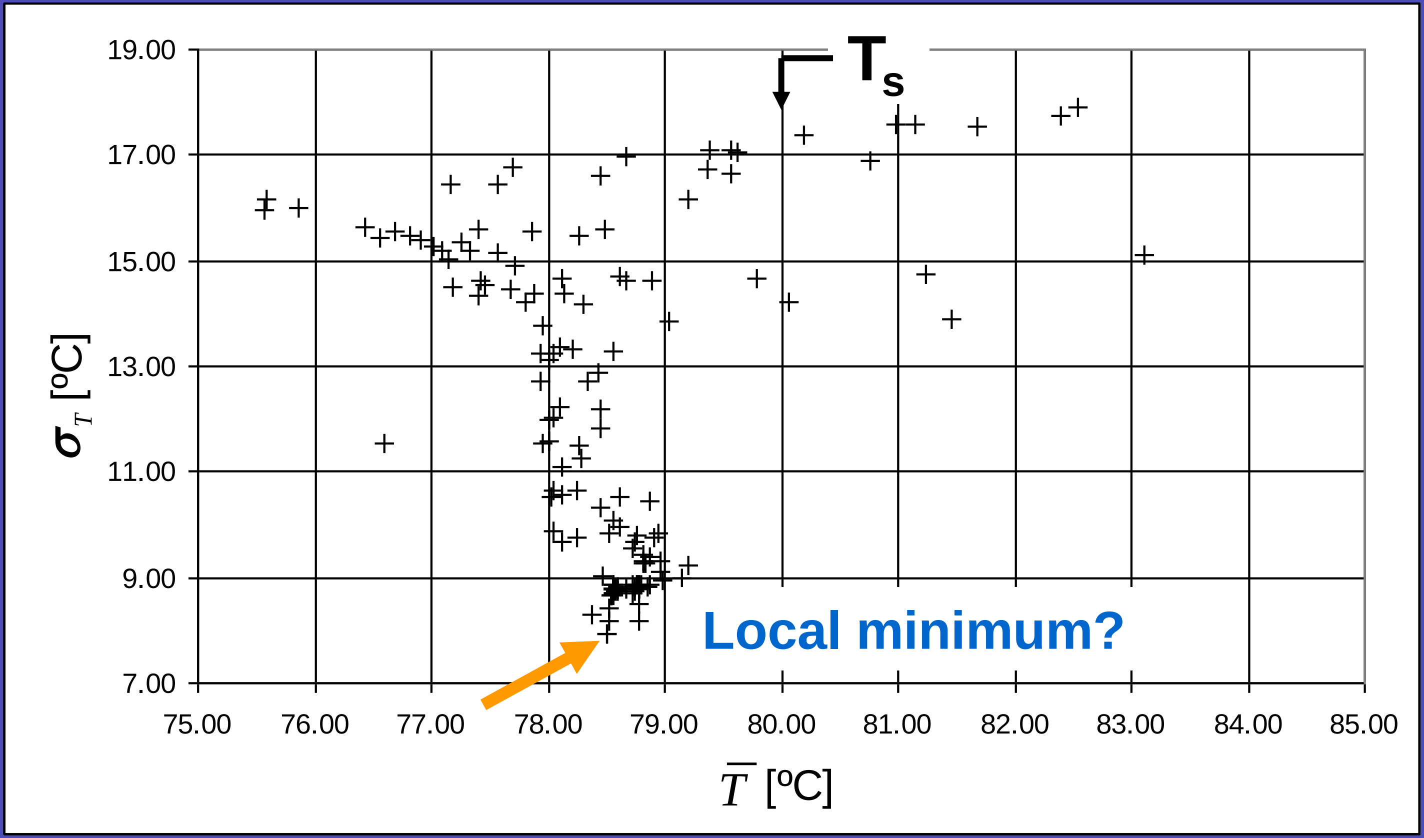
Geometry



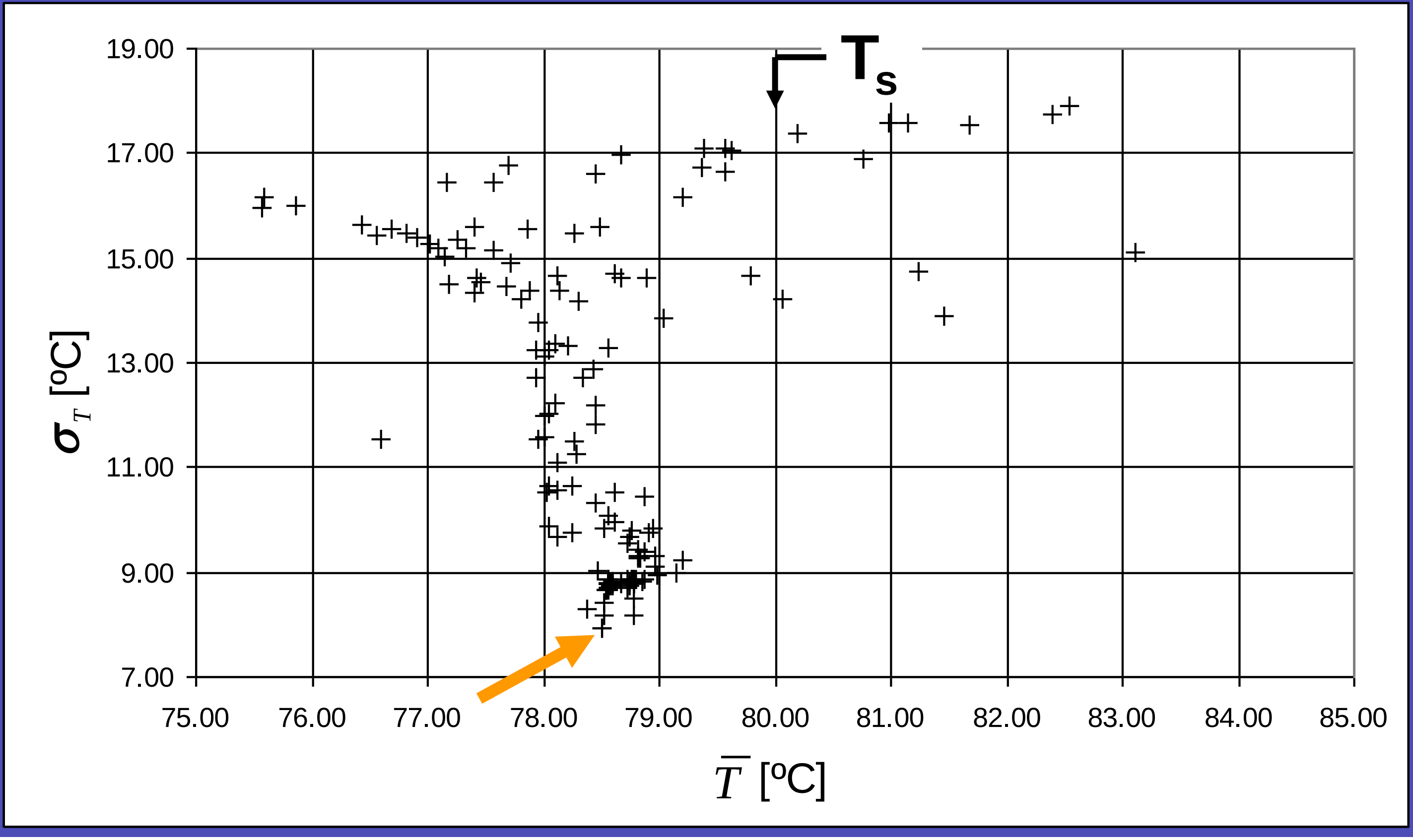
Mesh

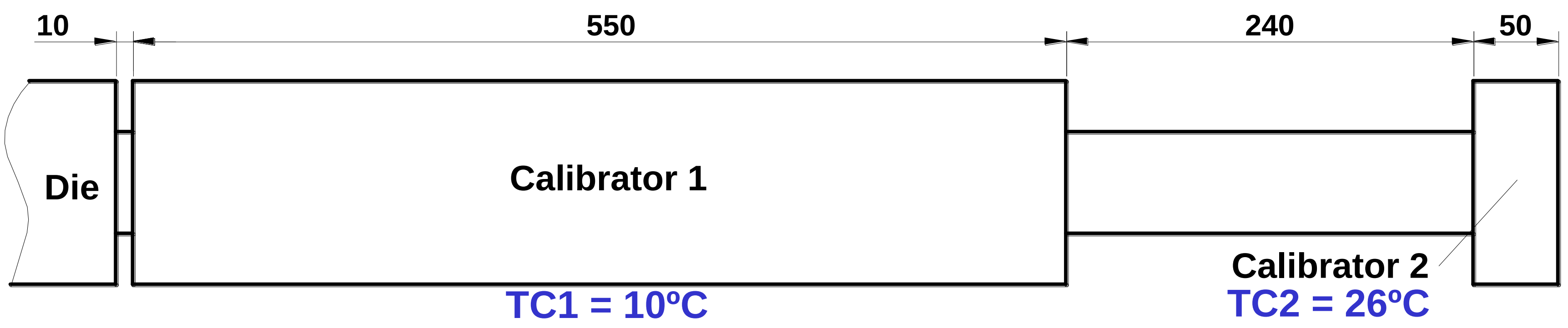


Calibrators - *Case Study*

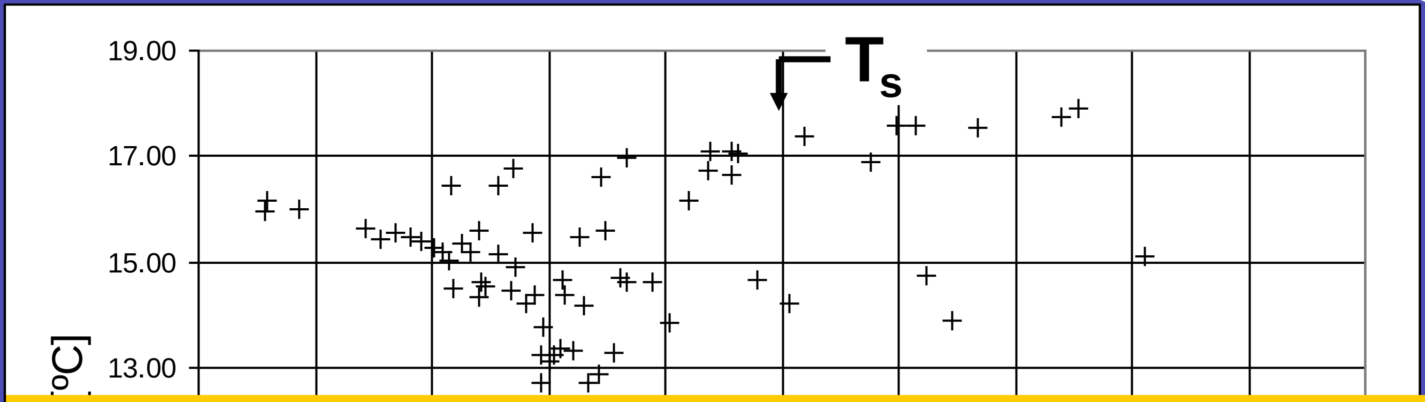


Calibrators - *Case Study*



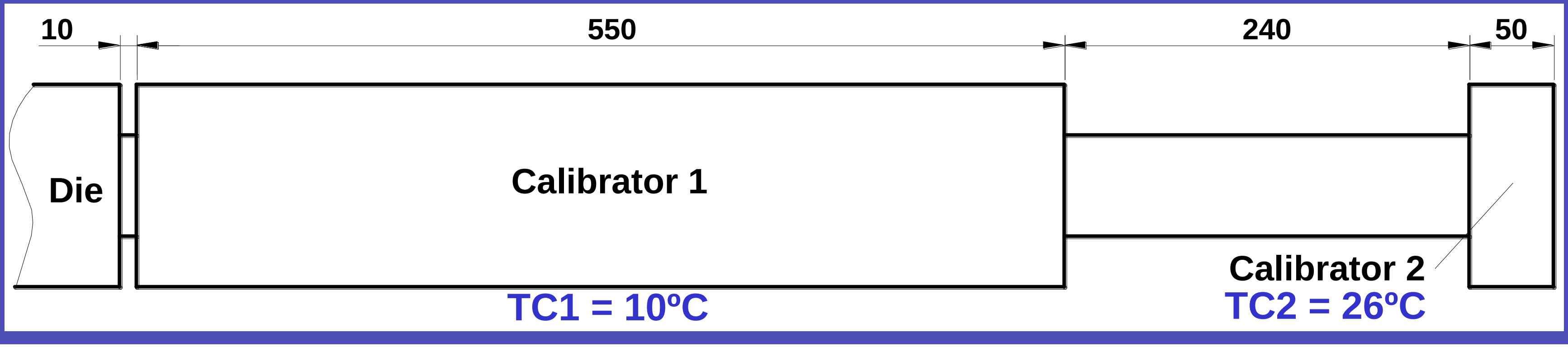


Calibrators - *Case Study*



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

- 52.4%



Calibrators - *Conclusion*

- Cooling systems with

  ascending cooling units lengths

  descending annealing zone lengths

  ascending cooling fluid temperatures

seem to have the best performance.

Conclusion

- The developed optimisation methodologies both for extrusion dies and calibrators were able to improve automatically the system performance;
- The optimisation methodologies are under development;
- The employment of numerical analysis allows a deeper insight of the process.

Ongoing work

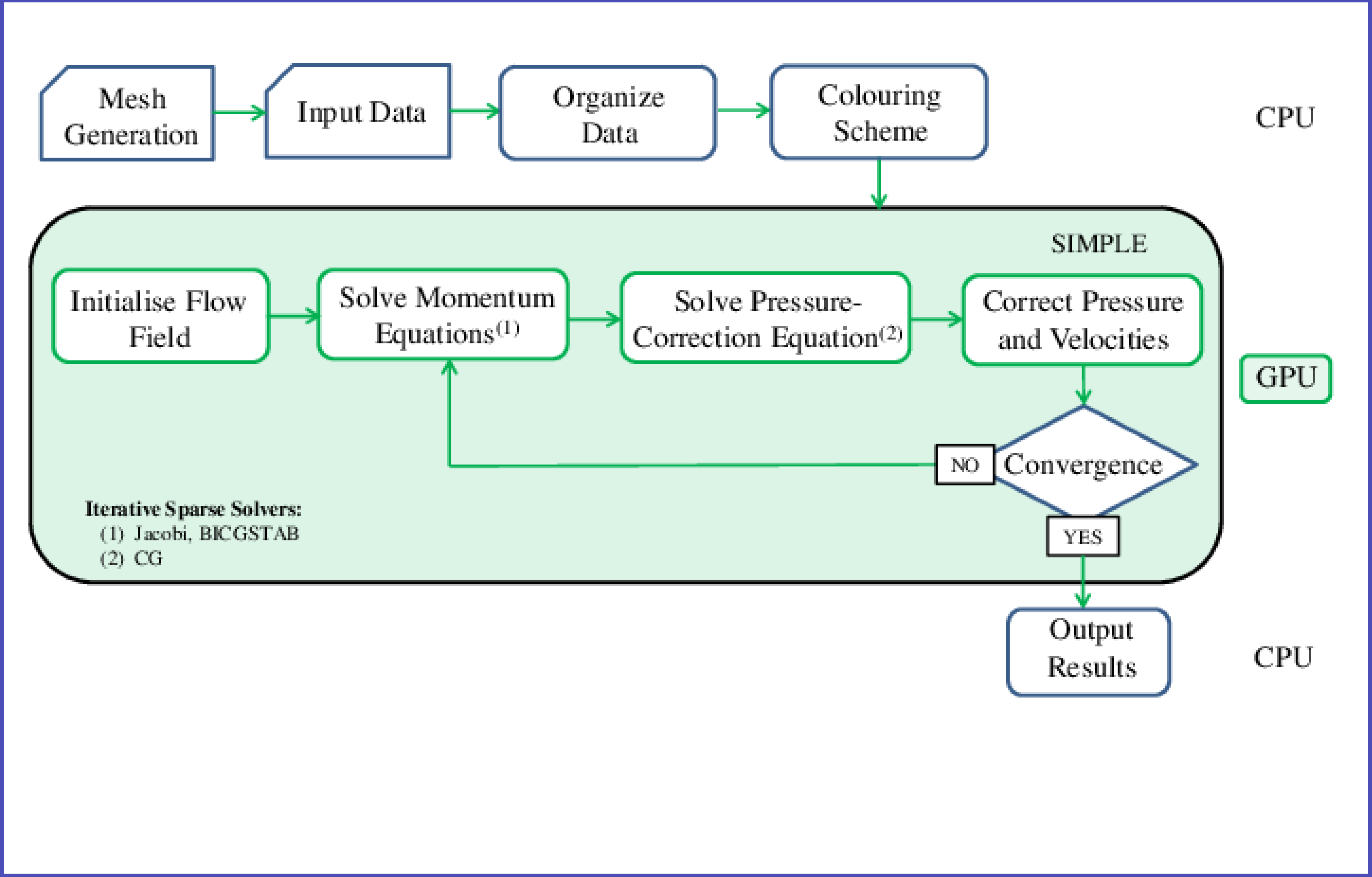
- **Implementation of the wall Slip and free-surface boundary conditions** (L.L. Ferrás, PhD project);
- **Development of unstructured numerical modelling code** (N.D. Gonçalves, PhD project);
- **Implementation of viscoelastic constitutive equations in an unstructured modelling code** (S. Reddy, MSc Eurheo project);
- **Prediction of thermal induced stresses in calibration in OpenFOAM** (S. Reddy, Research Project);
- **Development of high order interpolation schemes** (B. Gubuz, FCT Research Project);

Ongoing work

- **Development of innovative parallelization approaches** (R. Ribeiro, PhD Project);
- **Development of multiscale modelling approaches** (S.T. Mould + S.P. Pereira, PhD Project);
- **Development of SPH numerical modelling code (**D.F. Cordeiro, PhD/Cooperation Project);
- **Development of FSI methodologies for the design of extrusion dies in OpenFOAM** (M.R. Moosavi, Post-doctoral project);
- **Modelling the cooling stage in profile extrusion using OpenFOAM** (R. Ananth, PhD project);

Ongoing work

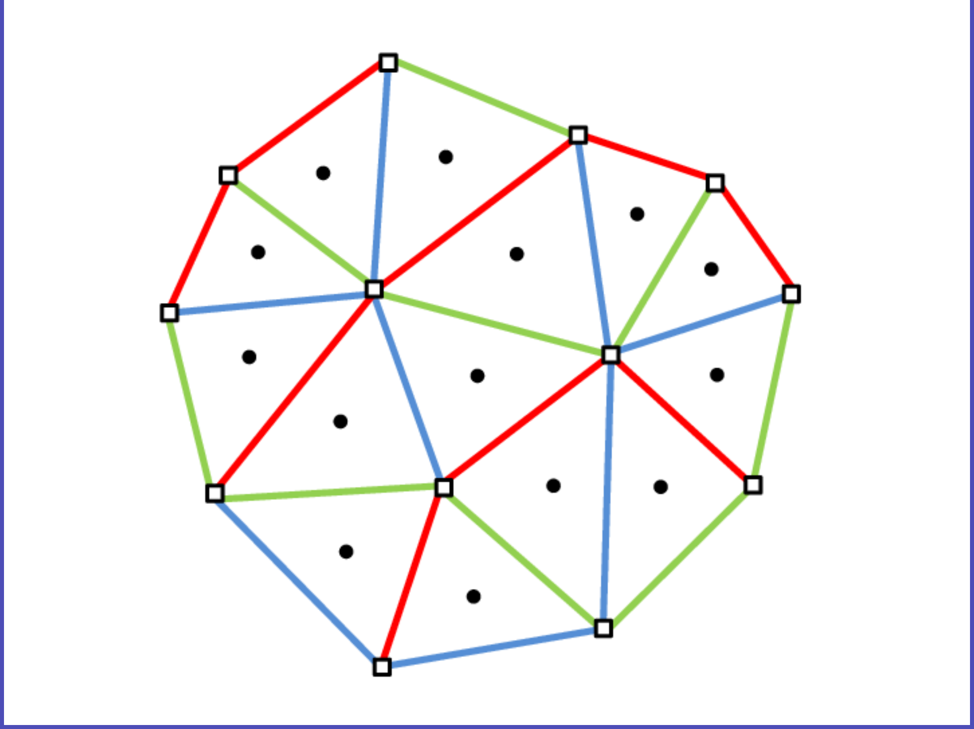
- Numerical code paralelization on GPU (S.P. Pereira, FCT Research Project);



Ongoing work

- Numerical code paralelization on GPU (S.P. Pereira, FCT Research Project);

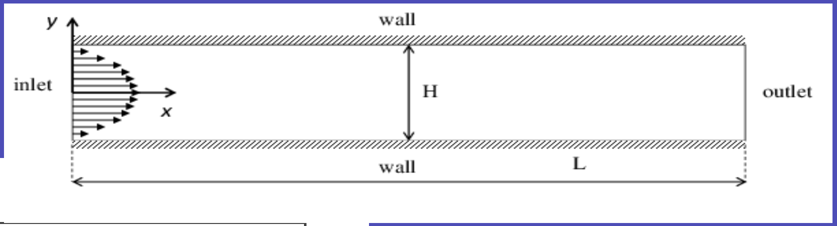
A colouring scheme was used to avoid race conditions

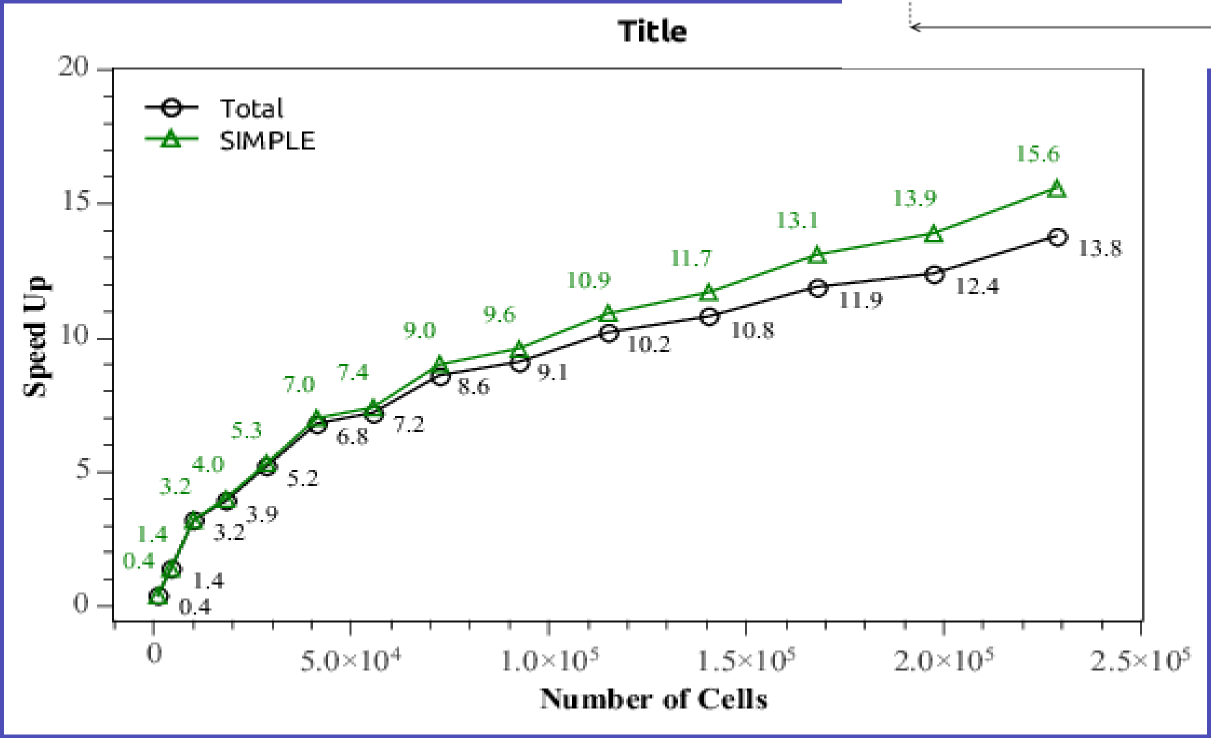


Ongoing work

- Numerical code paralelization on GPU (S.P. Pereira, FCT Research Project);

Poiseuille Flow – Speed Up





Ongoing work

- Numerical code paralelization on GPU (S.P. Pereira, FCT Research Project);

Lid Driven Cavity Flow – Speed Up