Final Conference

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Smart injection RTM process based on innovative sensors and hybrid twin

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01

Virtual twin of RTM process

Resin Transfer Moulding process

Flow in porous medium (filling stage)

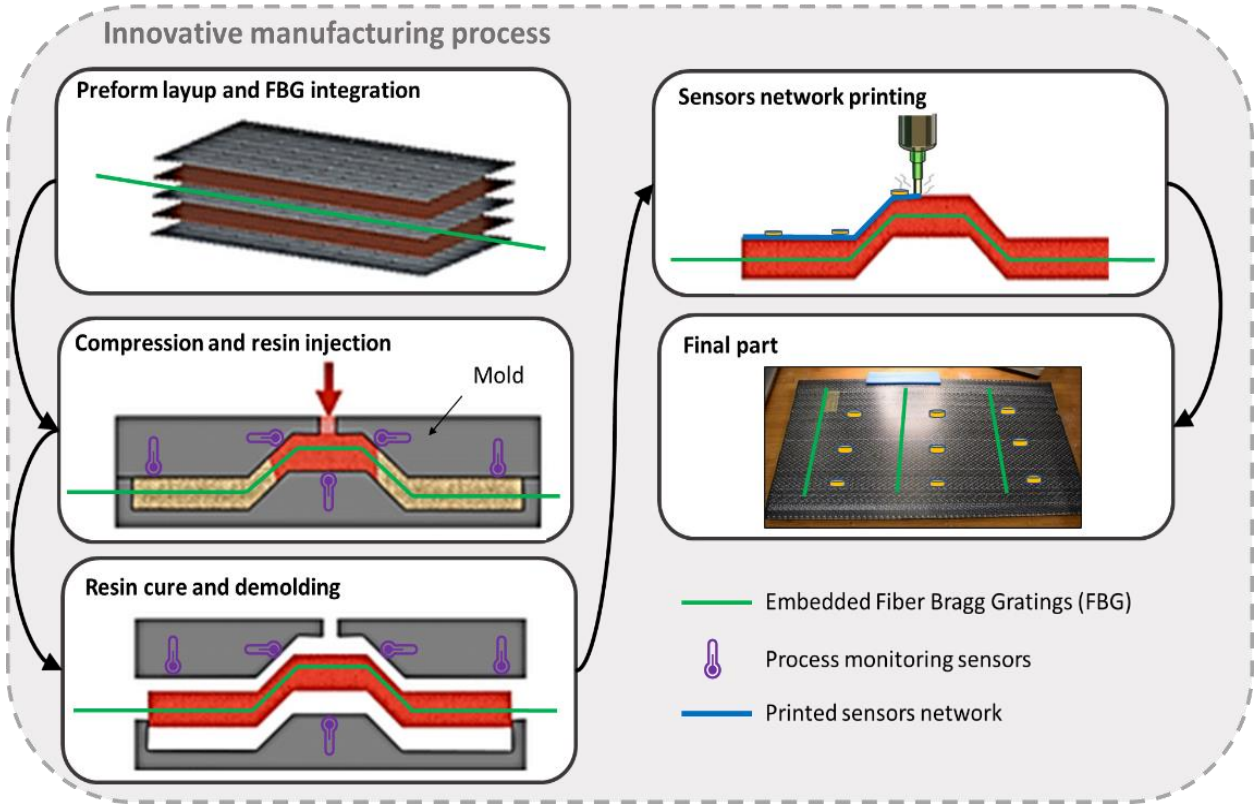
- ✓ 3D woven fabric
- ✓ Newtonian fluid
- ✓ Darcy's law
- ✓ Race tracks

Chemical reaction (curing stage)

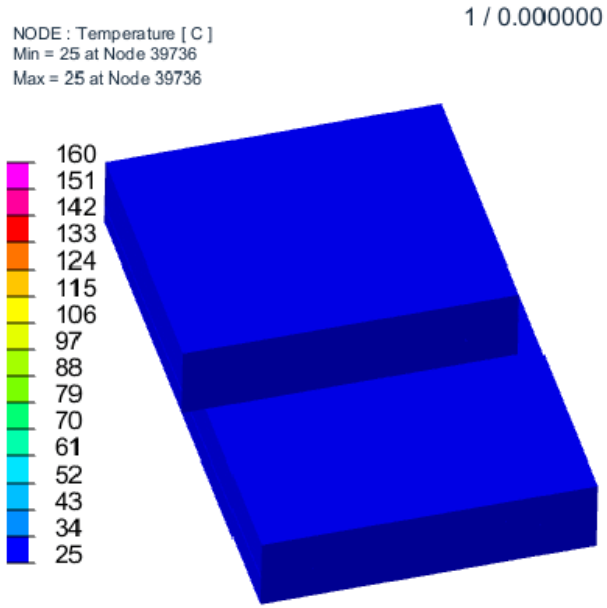
- ✓ Kinetics of polymerization
- ✓ Kamal-Sourour model

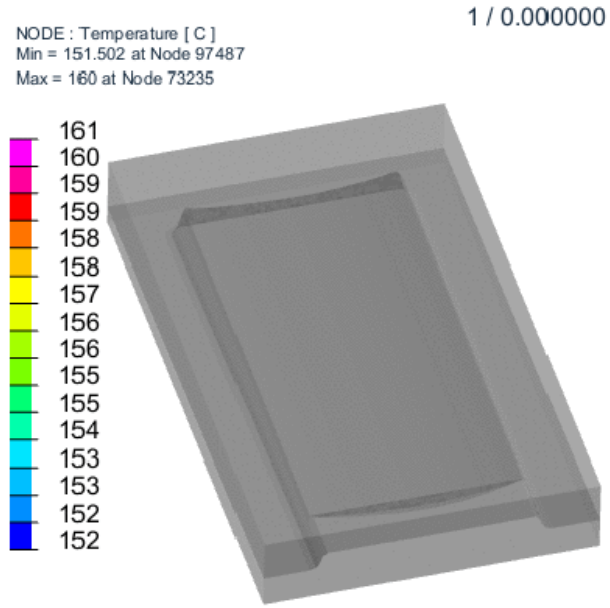
Heat transfer

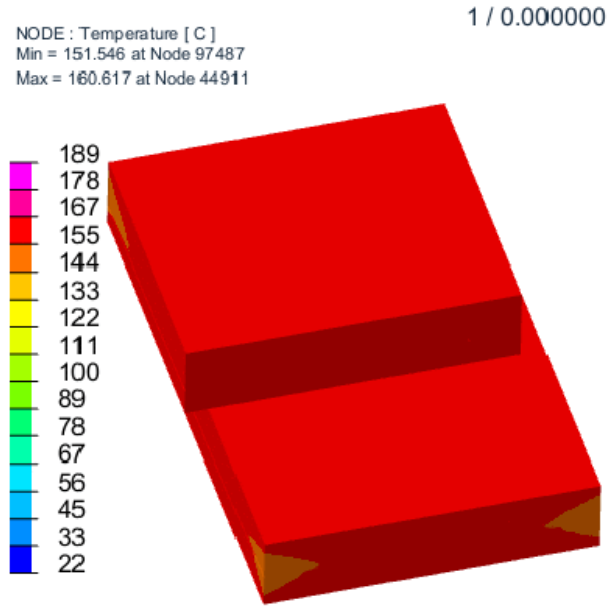
- ✓ Conduction + Convection
- ✓ Thermo-dependent mechanical properties

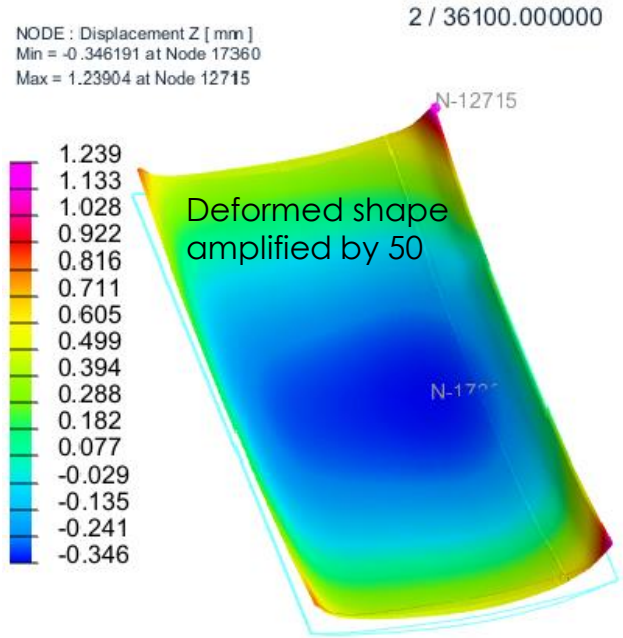


Multiphysics RTM Virtual Twin









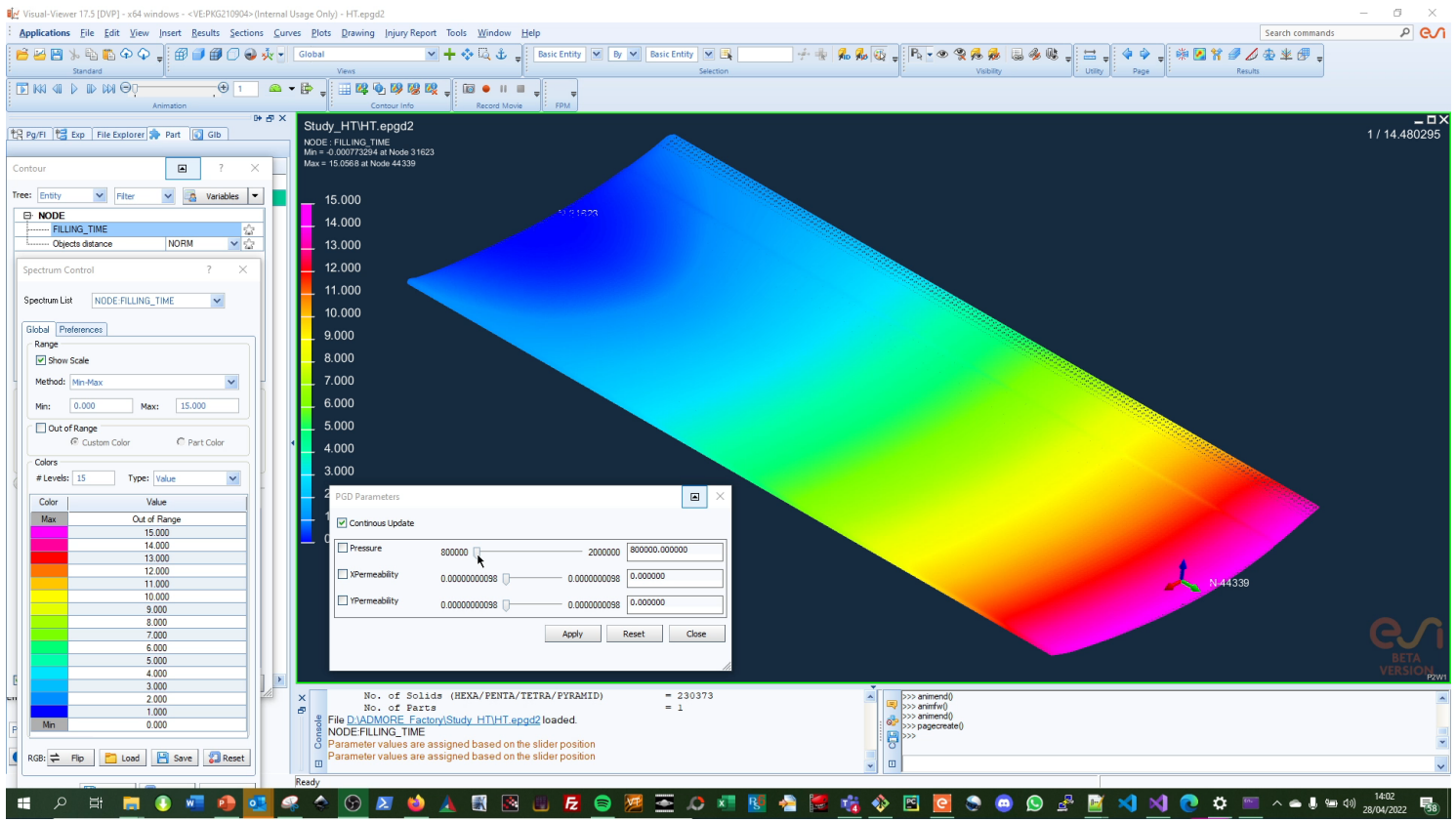
PREHEATING → FILLING → CURING AND COOLING → DEMOLDING

Reduced Multiphysics RTM Virtual Twin

To predict resin arrival time

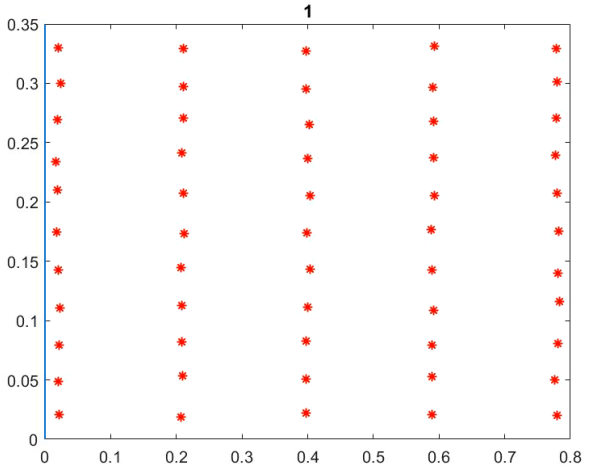
- 3 parameters (in-plane permeabilities/pressure)
  DOE with 3 values/parameter (min/mean/max)
  Dimensions reduction by SVD
- Training phase using 27 offline simulations
  Regression with sparse-PGD
- Validation phase on 23 offline simulations:
  MSE < 1% with cross-validation

More than
1 million combinations
available instantly !



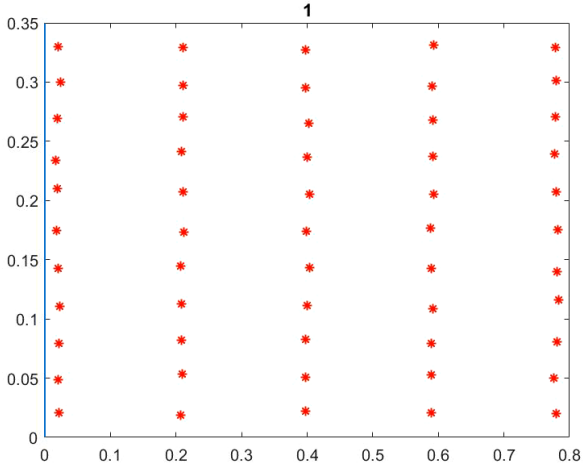
RTM Virtual Twin prediction

Reference result



Emulated experiment

Simulation: error $150[\%]$



Reduced Multiphysics model

- Some material properties are unknown (e.g. permeability, racetrack)
- Some physics have not been modelled
- Model updating is not possible online

Need experimental data in real time

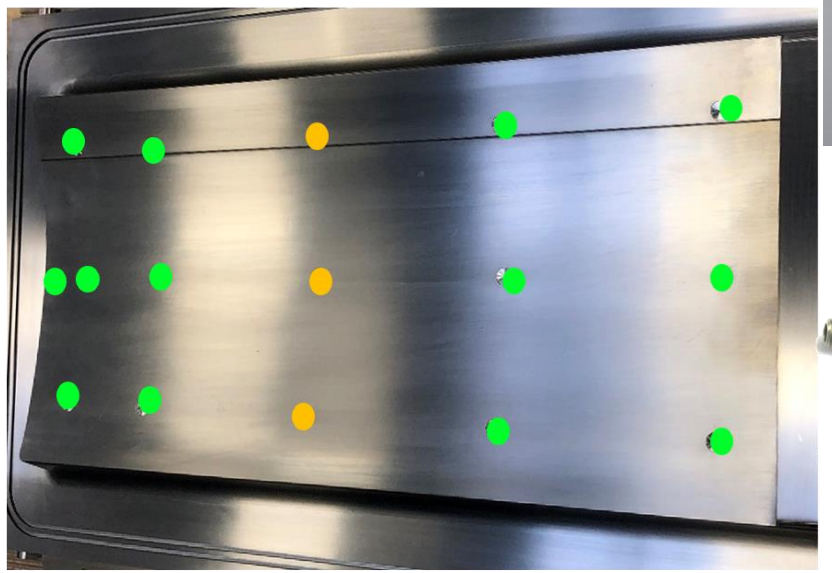
Comparison of flow front position

02

Intelligent sensors and systems in composites manufacturing

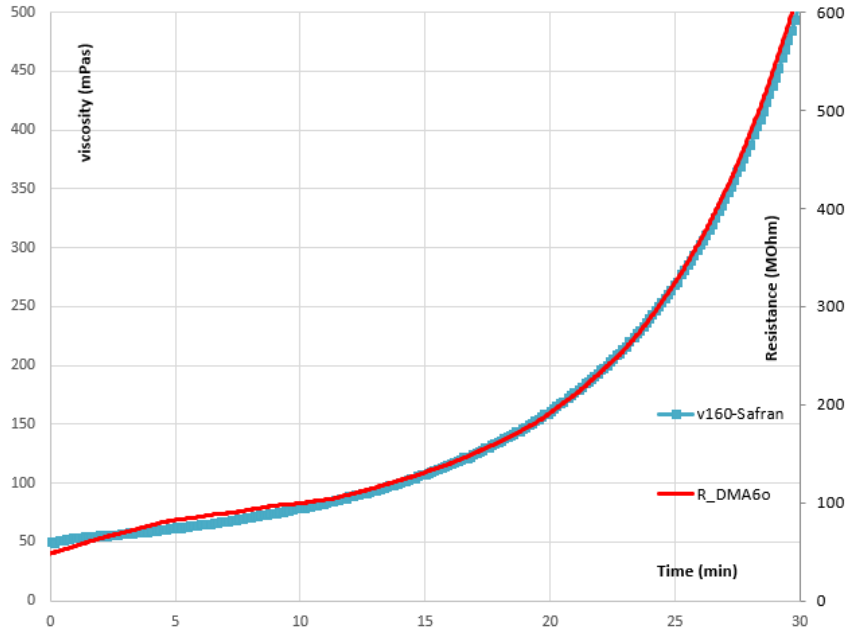
Hardware for real-time process monitoring

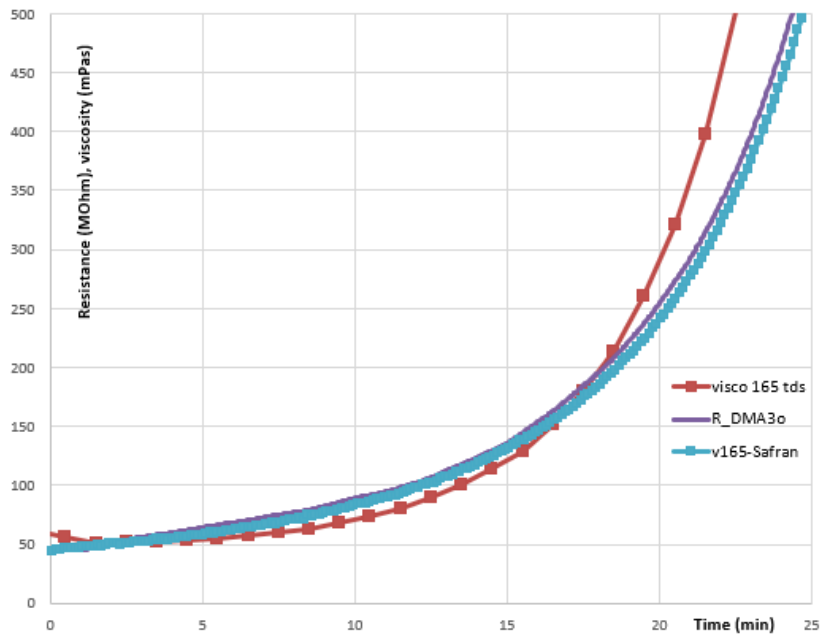
1 Cure Simulator
3 Optiflows
4 Optimolds



1X Tg & viscosity (Cure Simulator)
15 X Resin Arrival (3 Optiflow)
3 X Tg & viscosity (3 Optimold)
UF Resin Arrival (mod Optimold)

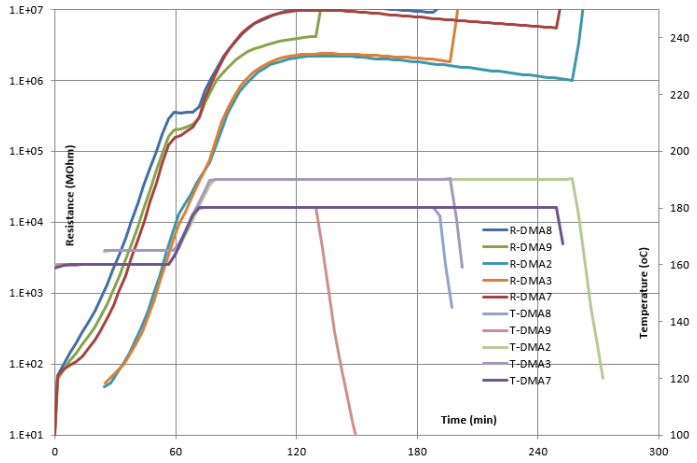
Viscosity vs Resistance



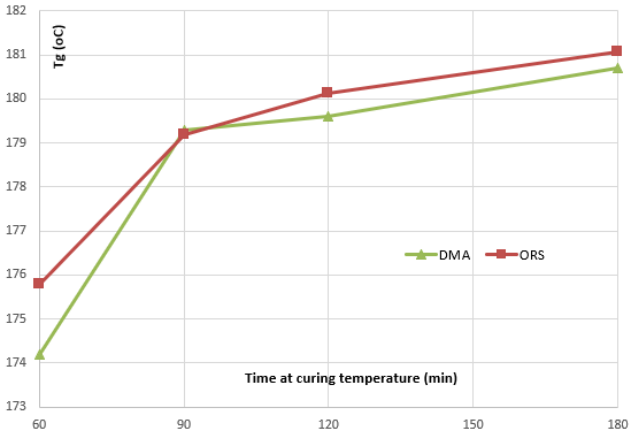


Correlation between viscosity and resistance @160 and 165ºC

Online Tg

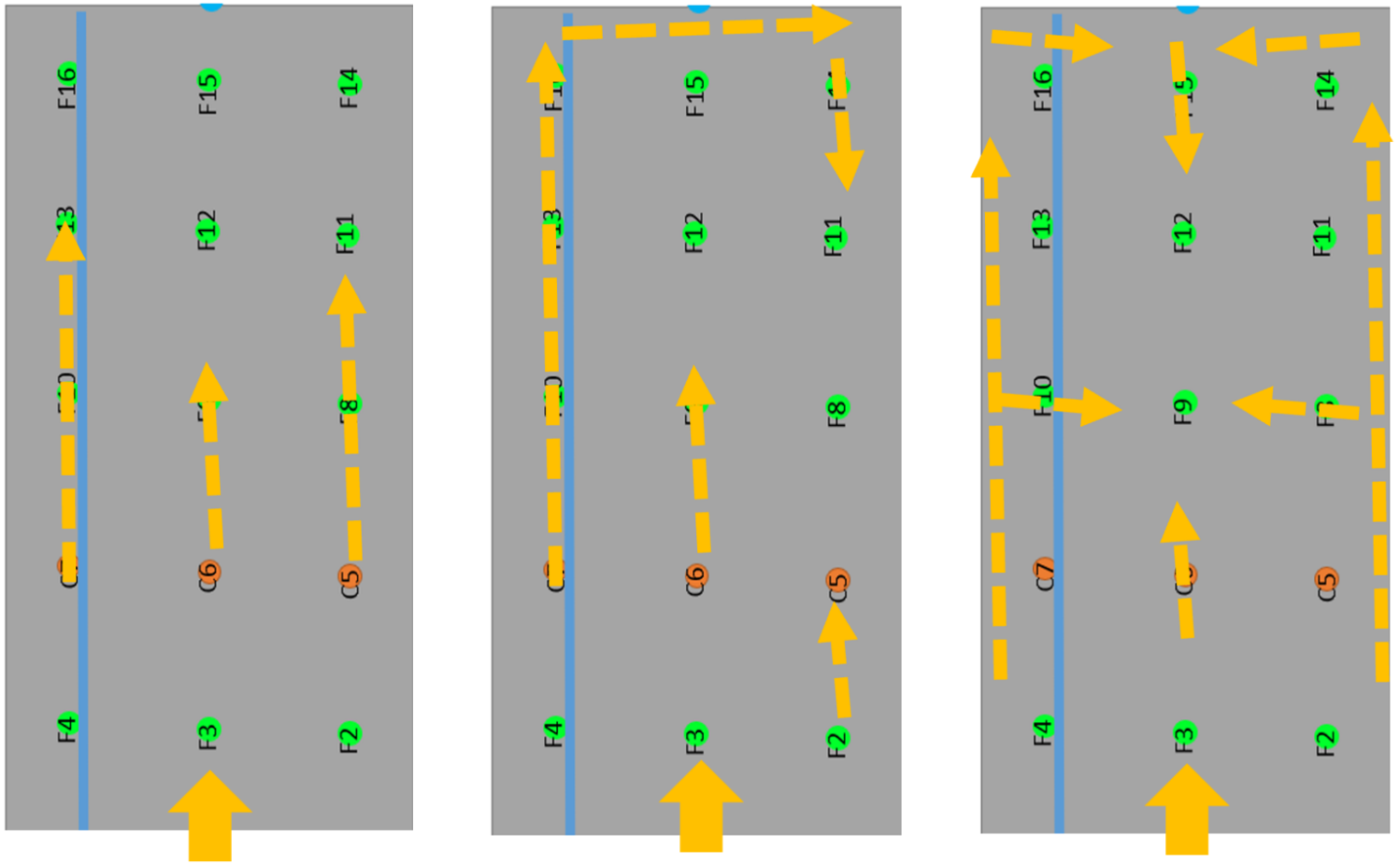


	Temp (time)/Heating rate/ Temp (time)/ Cooling rate	Tg (DMA)
DMA1	160(60)/2/190(180)/1	178.0
DMA2	165(40)/2/190(180)/1	180.7
DMA3	165(40)/2/190(120)/1	179.6
DMA4	165(60)/2/190(90)/1	179.3
DMA5	165(60)/2/**190(60)**/1	**174.2**
DMA6	165(60)/2/**190(45)**/1	179.5 ?
DMA7	160(60)/2/180(180)/1	177.7
DMA8	160(60)/2/180(120)/1	179.6
DMA9	160(60)/2/**180(60)**/1	**175.2**

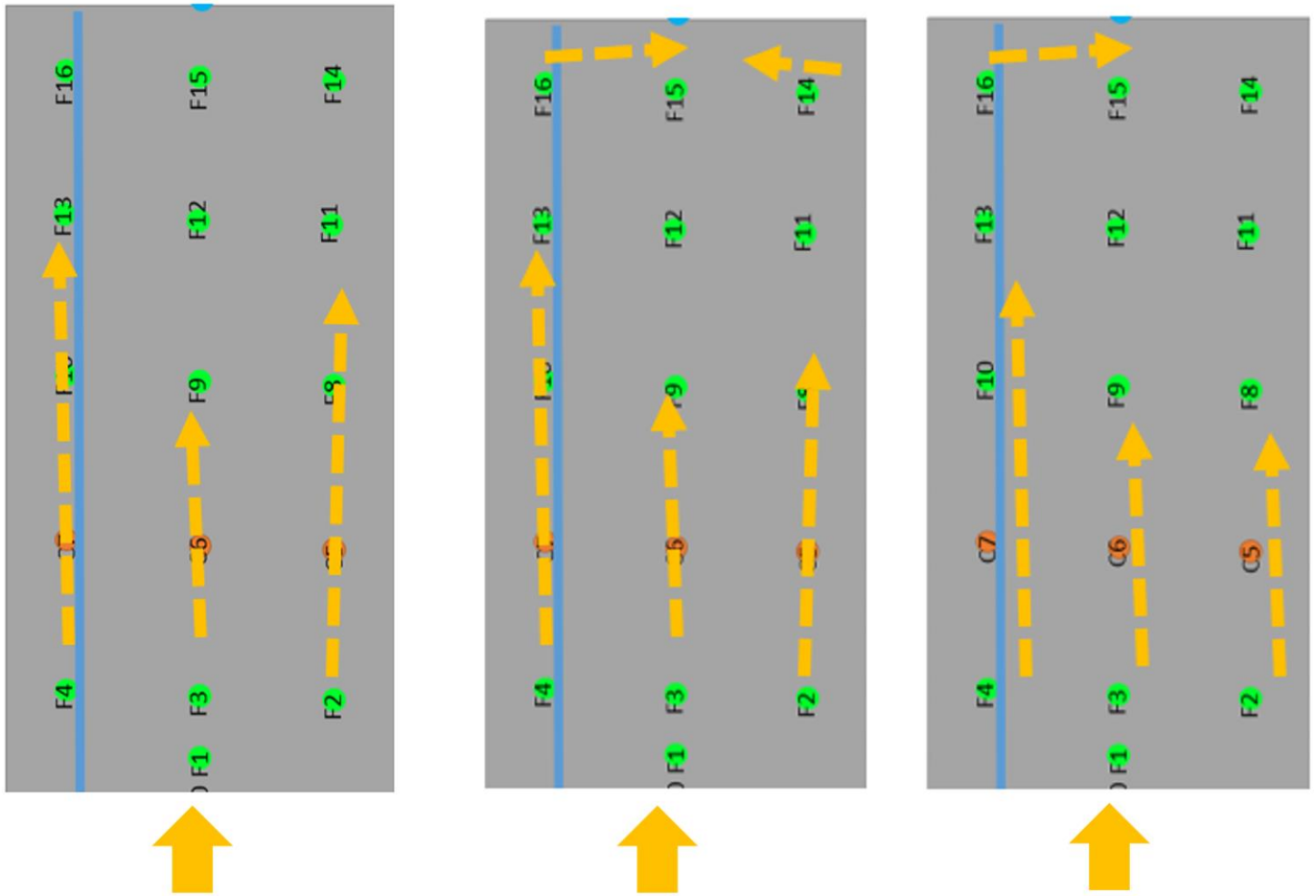


Resistance vs Tg (DMA)
injection@160 or 165ºC, curing@180 or 190ºC for 45',60',90', 120' and 180'

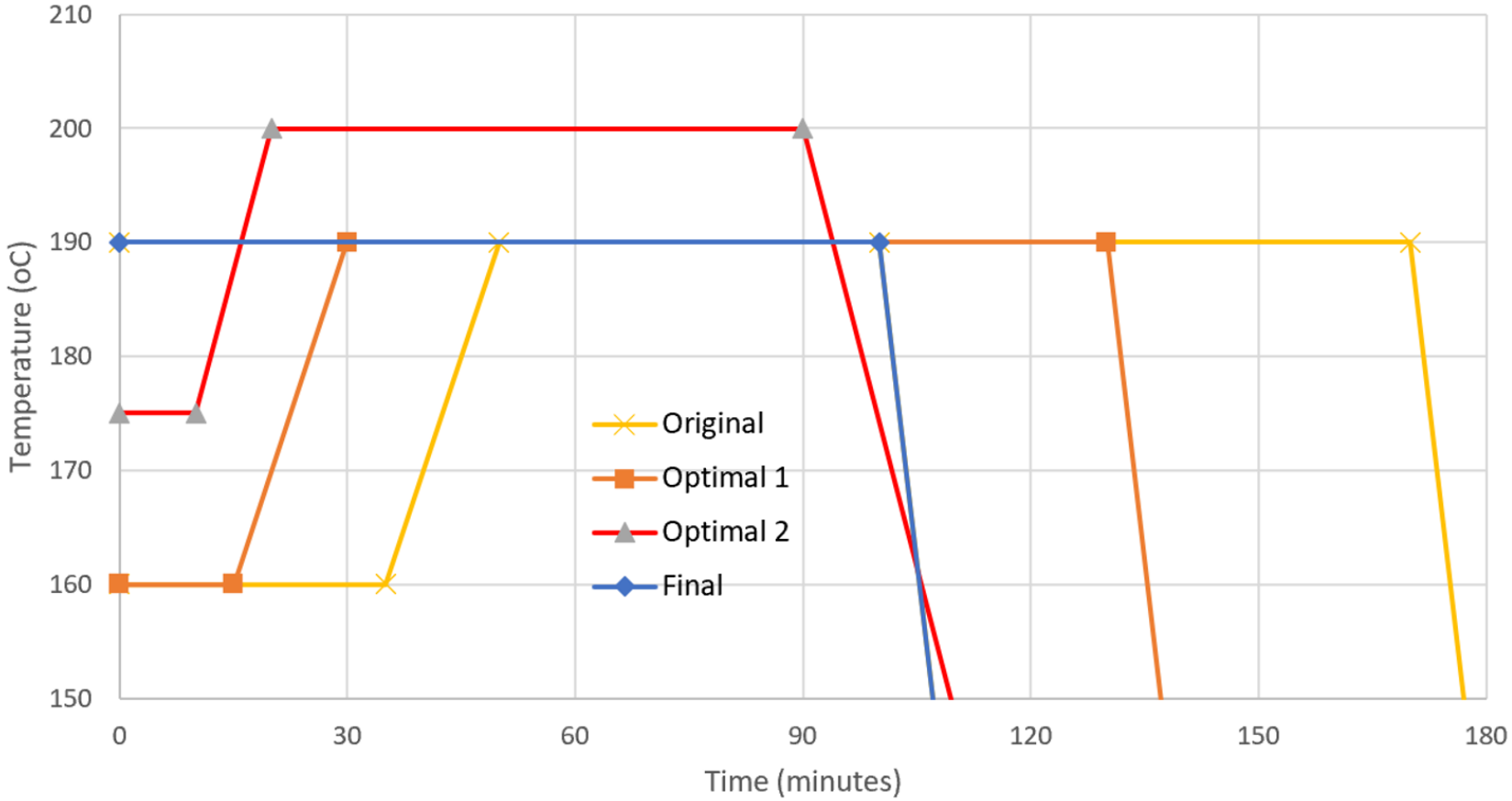
Flow patterns (first injections)



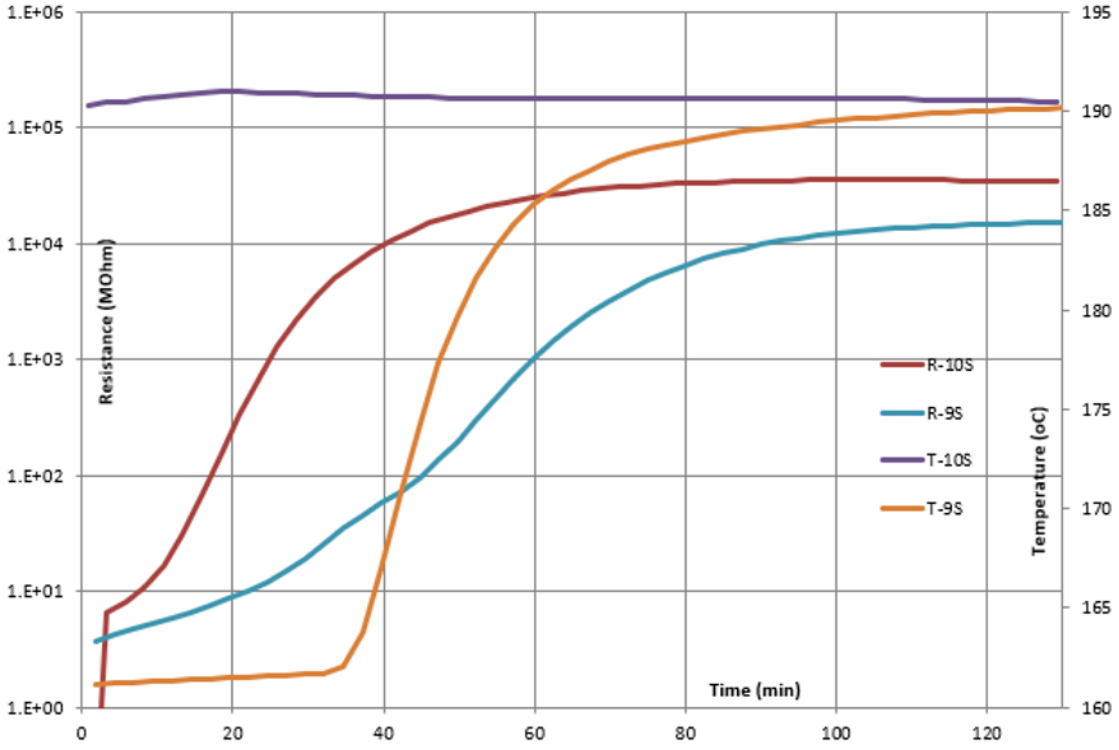
Flow patterns (final injections)

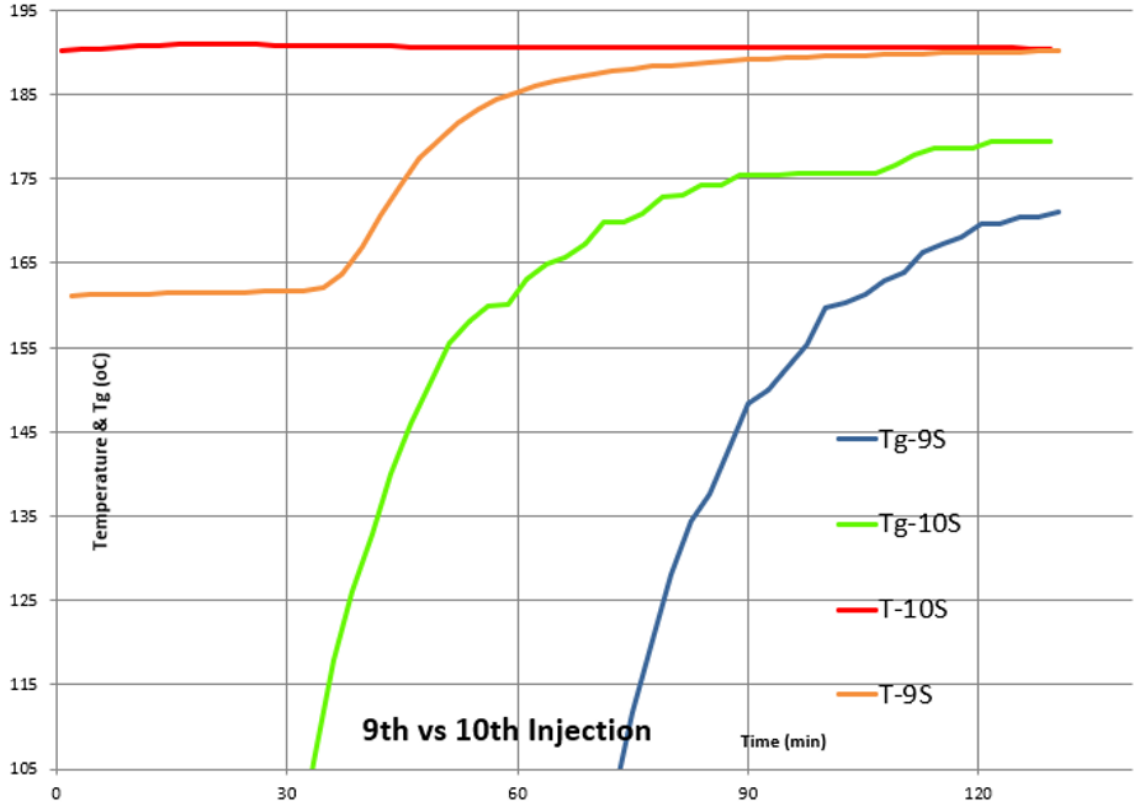


Cycle optimization



Cycle optimization (results)

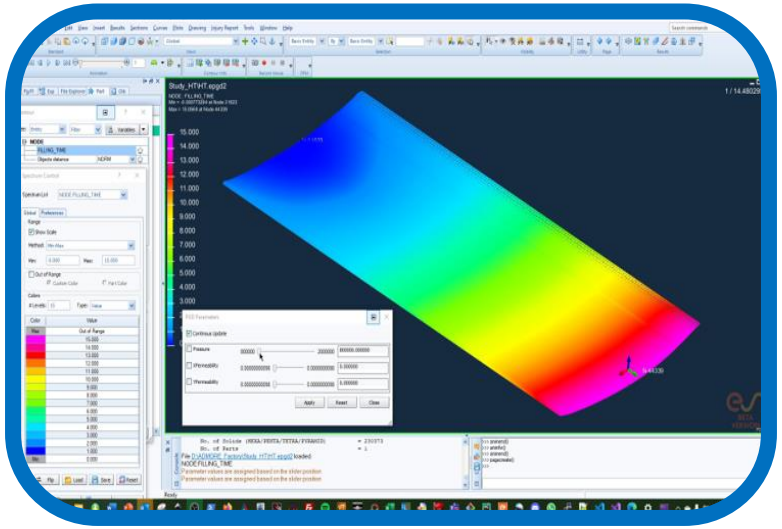


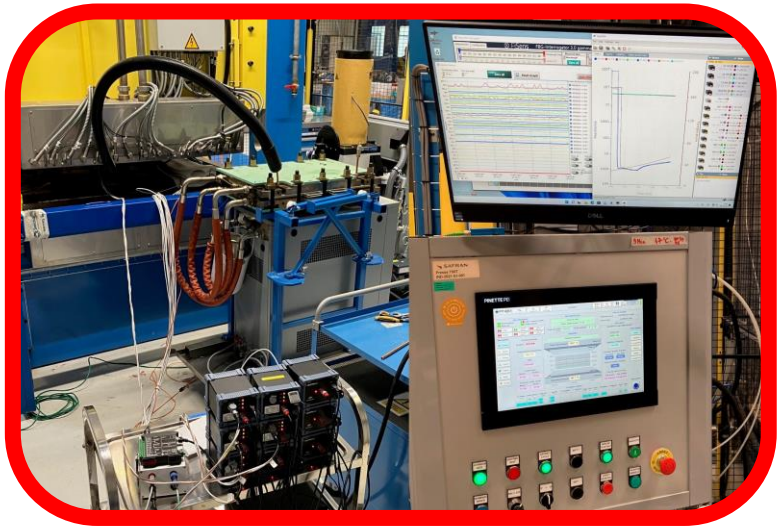


03

Hybrid twin of RTM process

Hybrid Twin concept for RTM





To update FE model

To optimize the process

To control the process

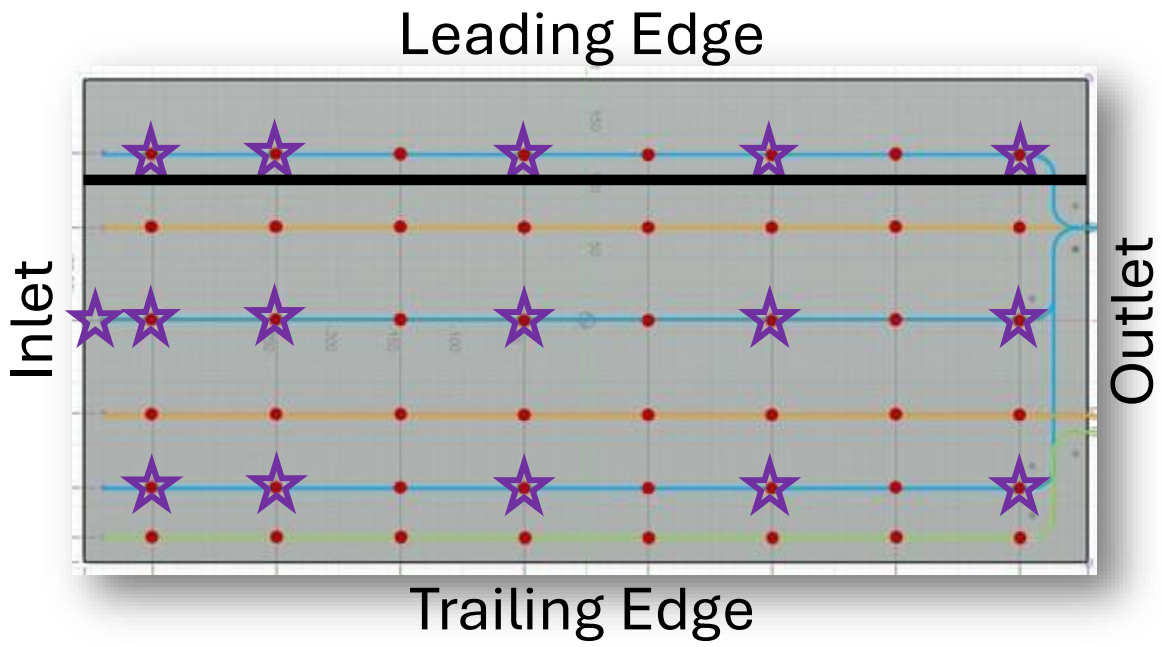
all in real time

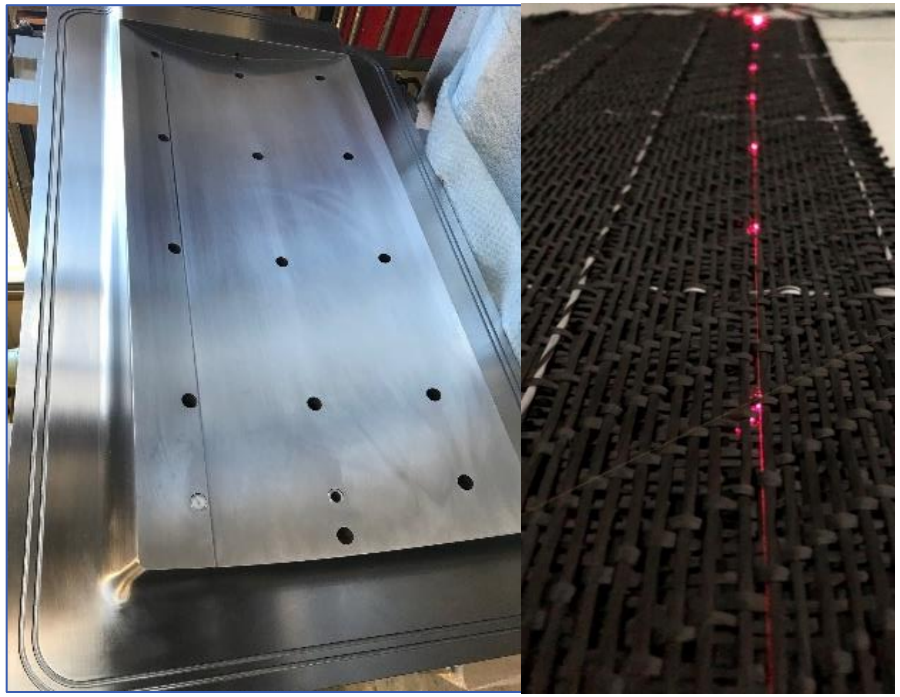
Numerical physics-based model enriched with data coming from real experience in real time

Monitoring RTM process

Adapted new sensors integrated into mould or preform:

- ✓ Resin Arrival Sensors
- ✓ Temperature Sensors
- ✓ Degree of Cure Sensors
- ✓ Strain Sensors



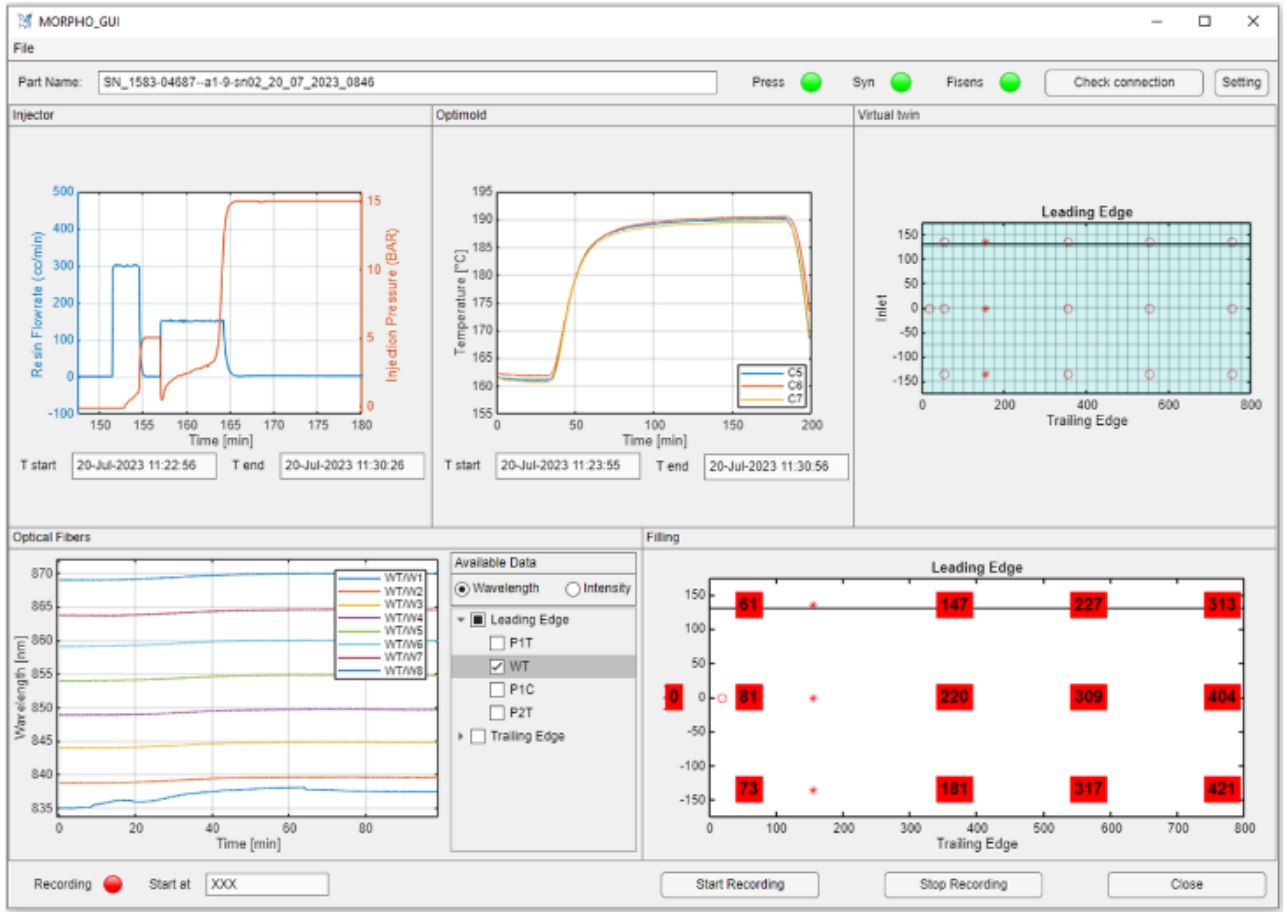


Monitoring RTM process

Developed interface:

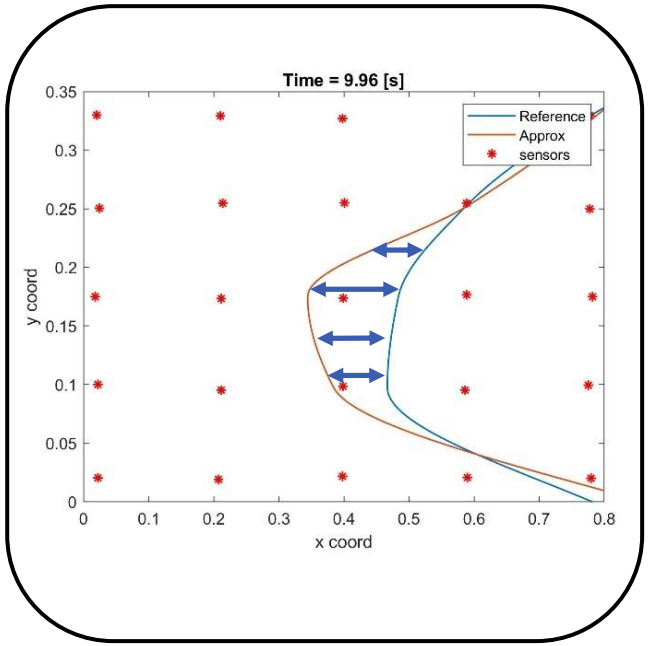
- ✓ Collect data from
  - SAFRAN RTM injector (excel @ 0.2Hz)
  - SYNTHESITE sensors (TCP/IP @ 1Hz)
  - FISENS sensors (UDP @ 5Hz)
- ✓ Use the reduced virtual twin to find best parameters
- ✓ Estimate flow front position
- ✓ Display relevant features of ongoing process

7 processes run in parallel

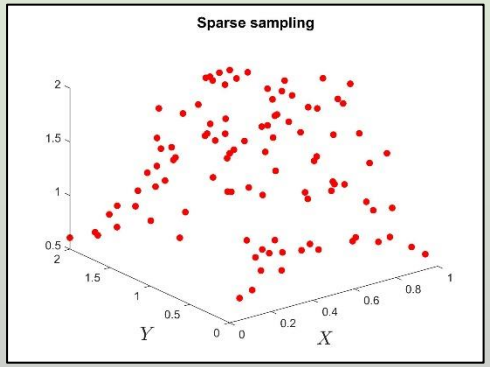


Ignorance model for flow front position

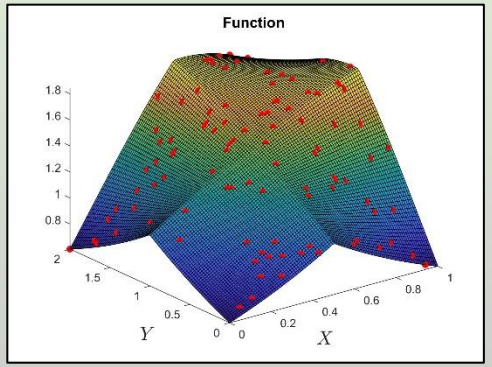
$$\dot{\underline{x}}(t;\underline{p}) = \underbrace{\underline{A}(\underline{x},t;\underline{p})}_{\text{Virtual twin}} + \underbrace{\underline{B}(\underline{x},t;\underline{p})}_{\text{Ignorance model}} + \underbrace{\underline{C}(t)}_{\text{Control}} + \underbrace{\underline{R}(t)}_{\text{Noise}}$$



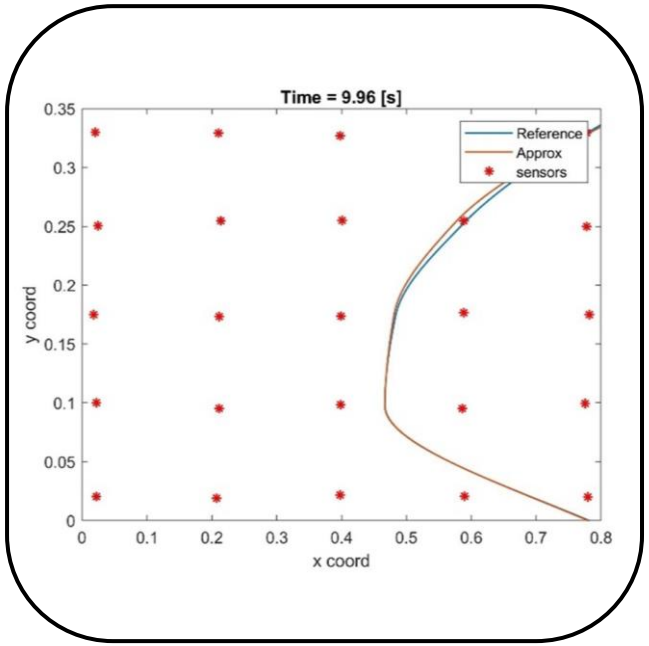
Construction of ignorance model



Sparse ignorance



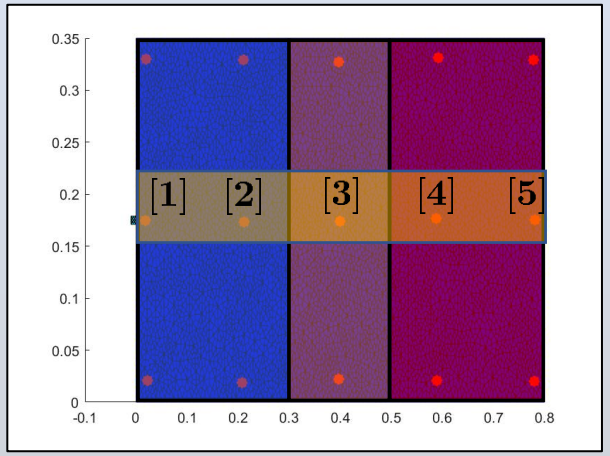
Continuous ignorance

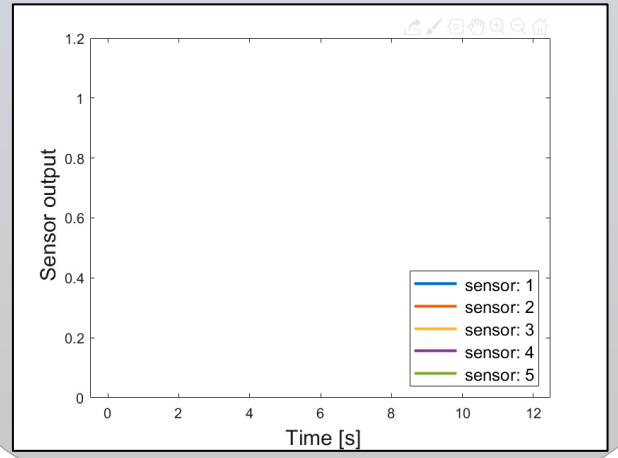


Real Process ≈ Virtual Twin + Ignorance Model = Hybrid Twin

Hybrid Twin for material parameters identification

Emulated experiment





Data store in file

```
27-Apr-2023 13:53:31
42 2 1 2 2 2 2 2 2 2 2 2 2 2 1 1
43 2 1 2 2 2 2 2 2 2 2 2 2 2 1 1
44 2 1 2 2 2 2 2 2 2 2 2 2 2 1 1
45 2 1 2 2 2 2 2 2 2 2 2 2 2 1 1
46 2 1 2 2 2 2 2 2 2 2 2 2 2 1 1
47 2 1 2 2 2 2 2 2 2 2 2 2 2 1 1
48 2 1 2 2 2 2 2 2 2 2 2 2 2 1 1
49 2 1 2 2 2 2 2 2 2 2 2 2 2 1 1
```

Real-Time Identification Tool

Levenberg-Marquardt method:

$$\{\underline{p}\} = \underset{\{\underline{p}\in\mathcal{U}^P\}}{\text{argmin}}\ \chi^2(\underline{p}) = \sum_{j=1}^{\text{Nsensors}} \left[\frac{\text{Arrival-time}^{[j]} - \text{PGD-Arrival-time}^{[j]}(\underline{p})}{\text{Arrival-time}^{[j]}}\right]^2$$

Reference material parameters

Parameter (10^{-8})	1st zone	2nd zone	3th zone
k_x	0.5390	0.0980	0.5390
k_y	0.0539	0.0098	0.0539

	Zone_1	Zone_2	Zone_3
Permeability kx (1e-8)	0	0	0
Permeability ky (1e-8)	0	0	0
Run time [s]	0	0	0

Conclusions

- ✓ The new CF Resin Arrival sensors have been applied successfully for the RTM manufacturing of CFRP aerospace parts at almost industrial conditions.
- ✓ The use of the new CF cure sensors and calibration methods can lead to a significant reduction of the cycle time ensuring part quality.
- ✓ The introduction of the Cure Simulator can considerably facilitate the implementation of this technology in everyday production, reducing considerably the modifications to the existing infrastructure.
- ✓ Hybrid twin allows real-time prediction of flow front position and local material parameters identification.

Next step: real-time control of the RTM process

THANKS

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