Twins:
From concept to success stories

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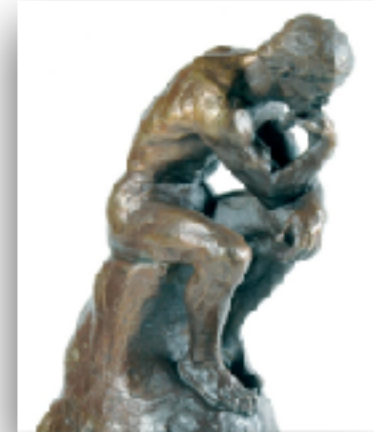
Double trophée @ Teratec 2019

I - CONCEPT



$$\mathcal{L}(u(x,t;\mu)) = f(x,t;\eta)$$

$$\text{B.C. } (x,t;\xi)$$

Calibration

Data

μ

Process

$\eta, \ \xi$

$$u(x,t) \approx \sum_{i=1}^{\mathrm{N}} U_i(t) N_i(x) \rightarrow \mathbf{KU} = \mathbf{F}$$

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Well Experienced Engineering

Nominal calibrated model

Nominal loading

DESIGN

(Nominal)
in service

Virtual Twin

Real-Time Decision Making

Nominal calibrated model

Nominal loading

DESIGN
(Nominal)
in service

Learning

DATA

- Inputs
- Outputs

Deep learning
Tensor learning,
Dictionary learning,
Manifold learning,
Linear and nonlinear regression
Sparse identification
DMD & Koopman operator,
Data-driven operator

$$\mathcal{O}(\mathcal{I})$$

ONLINE

Digital Twin

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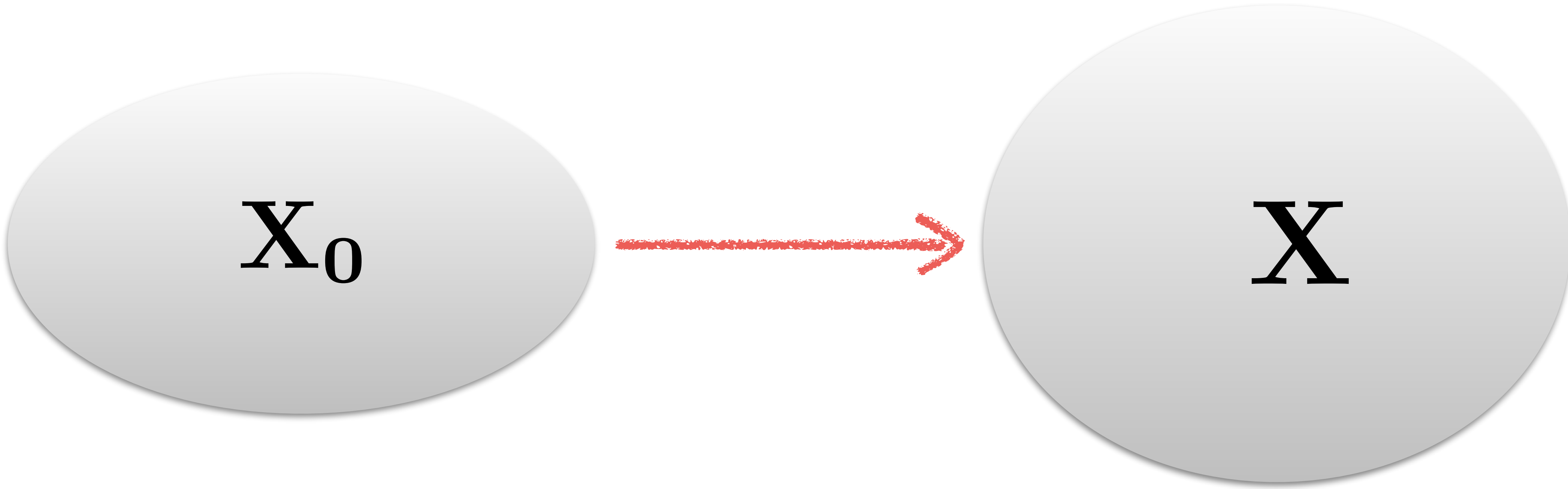
Data-Driven Model Adaptation

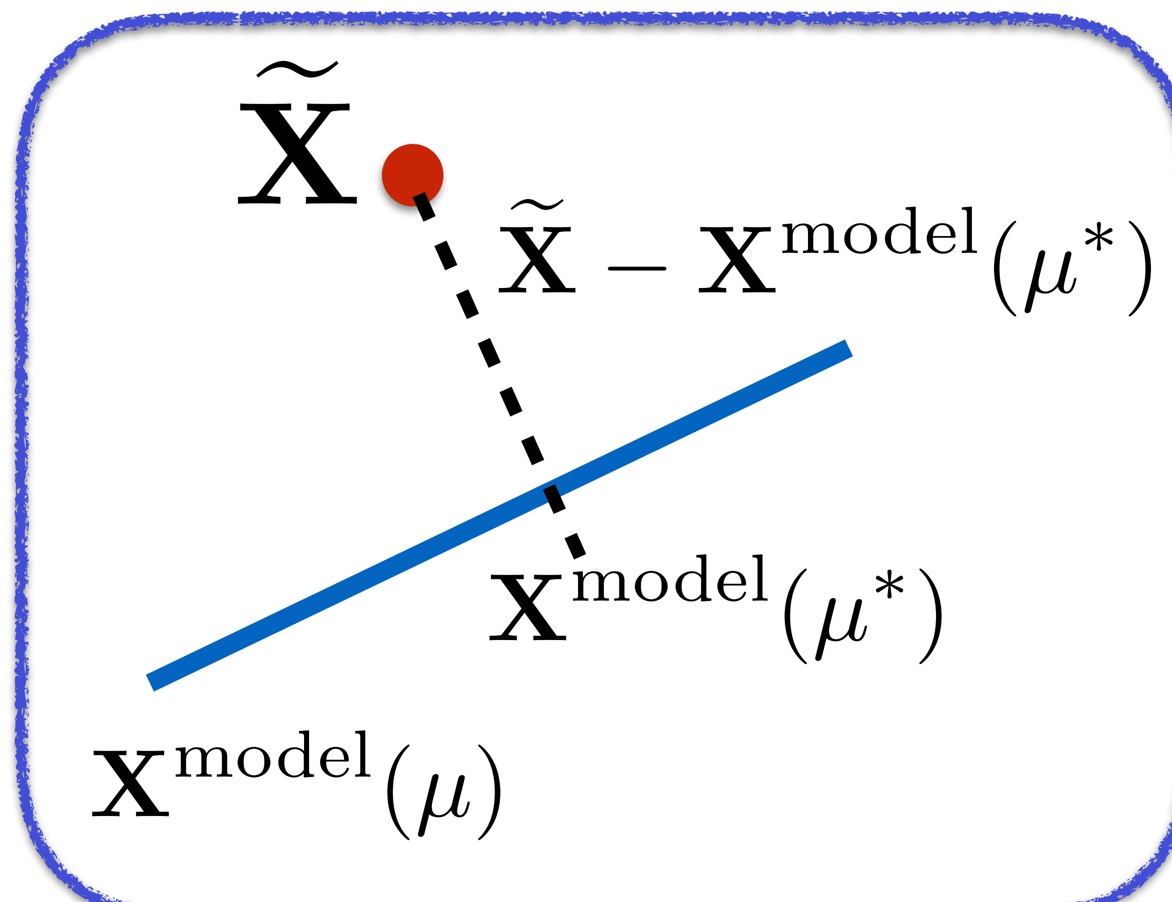


Hybrid Twin

Parametric model $\mathbf{X}^{\mathrm{model}}(\mu)$

Ignorance $\widetilde{\mathbf{X}} - \mathbf{X}^{\mathrm{model}}(\mu^*)$

Data-Based
Divergence Model



HYBRID-TWIN

$$\left\{\begin{array}{l} \dot{\mathbf{X}} = \overbrace{\mathbf{A}(\mathbf{X},t,\boldsymbol{\mu})}^{\text{Parametric deterministic contribution PGD}} + \overbrace{\mathbf{B}(\mathbf{X},t)}^{\text{Data-Driven correction}} + \overbrace{\mathbf{C}(\mathbf{X})}^{\text{Control}} + \overbrace{\mathbf{R}}^{\text{Noise}} \\ \left.\begin{array}{l} \mathbf{Y} = \mathbf{D}(\mathbf{X}) + \mathbf{R}' \\ \mathbf{Z} = \mathbf{G}(\mathbf{X}) + \mathbf{R}'' \end{array}\right\} \text{Measures involving noise} \end{array}\right.$$

Filters:
Kalman,
Bayesian,
…

If the physics-based model is accurate enough, the deviation remains small, and its associated data-driven model results almost linear (or moderately nonlinear). Thus, little data suffices to infer it (the model correction).

Data is expensive to collect and to assimilate !

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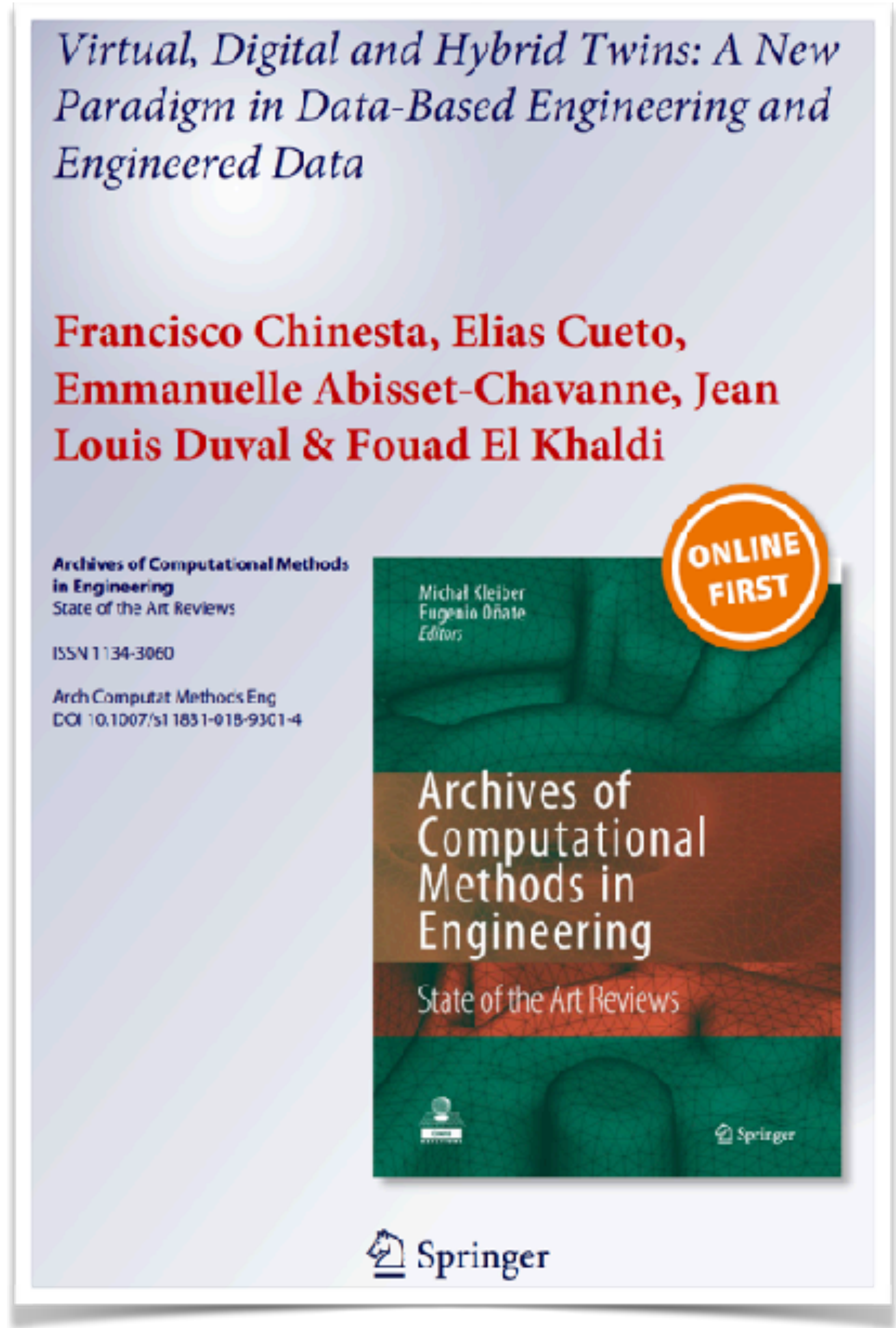
What is needed?

- Real-time simulation
- Real-time calibration
- Real-time data-assimilation
- Real-time data-completion
- Real-time data-analytics
- Real-time data-driven modeling
- Real-time decision making



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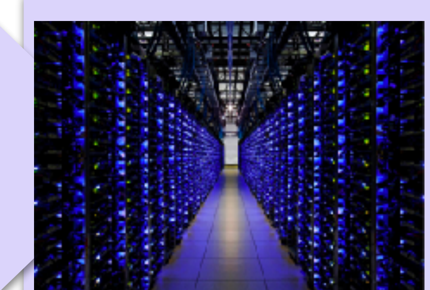
PGD based real-time simulation

Parametric solutions

Intrusive constructor, or

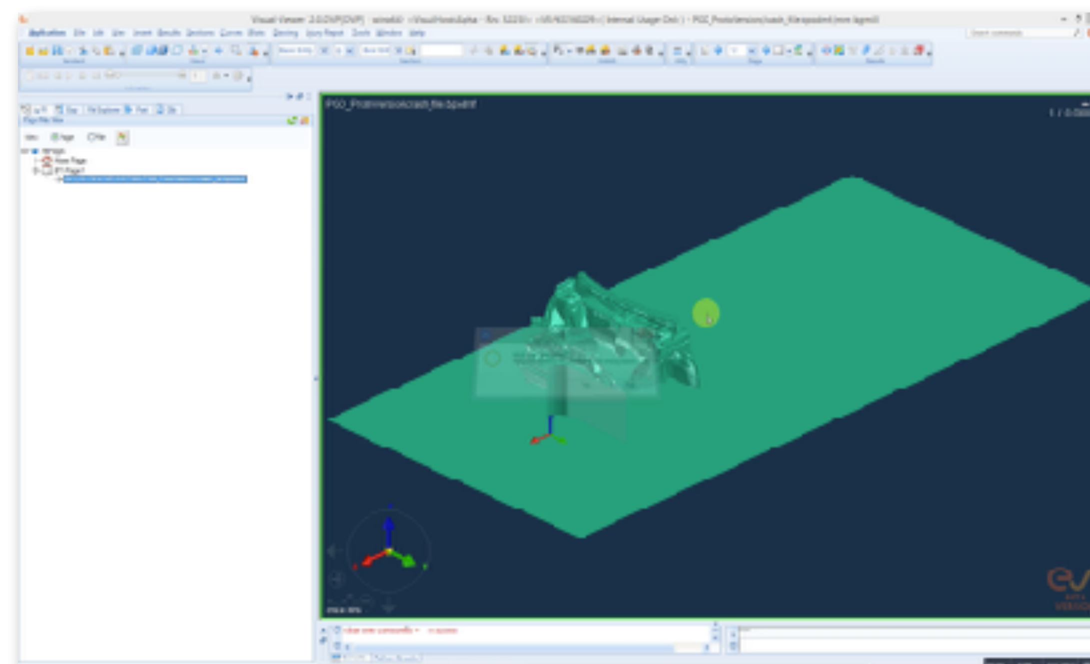
Non-intrusive: SSL, sPGD, …



OFFLINE

$$u(x,t,p)$$

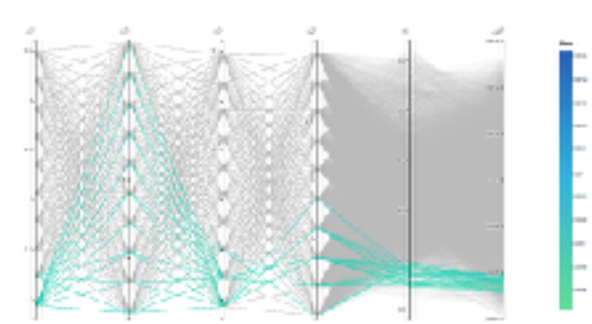
$$u(x,t,p) \approx \sum_{i=1}^{\mathtt{M}} T_i(t) X_i(x) P_i(p)$$



ONLINE

Almost

- Real-time simulation
- Real-time optimization
- Real-time inverse analysis
- Real-time uncertainty propagation
- Real-time control



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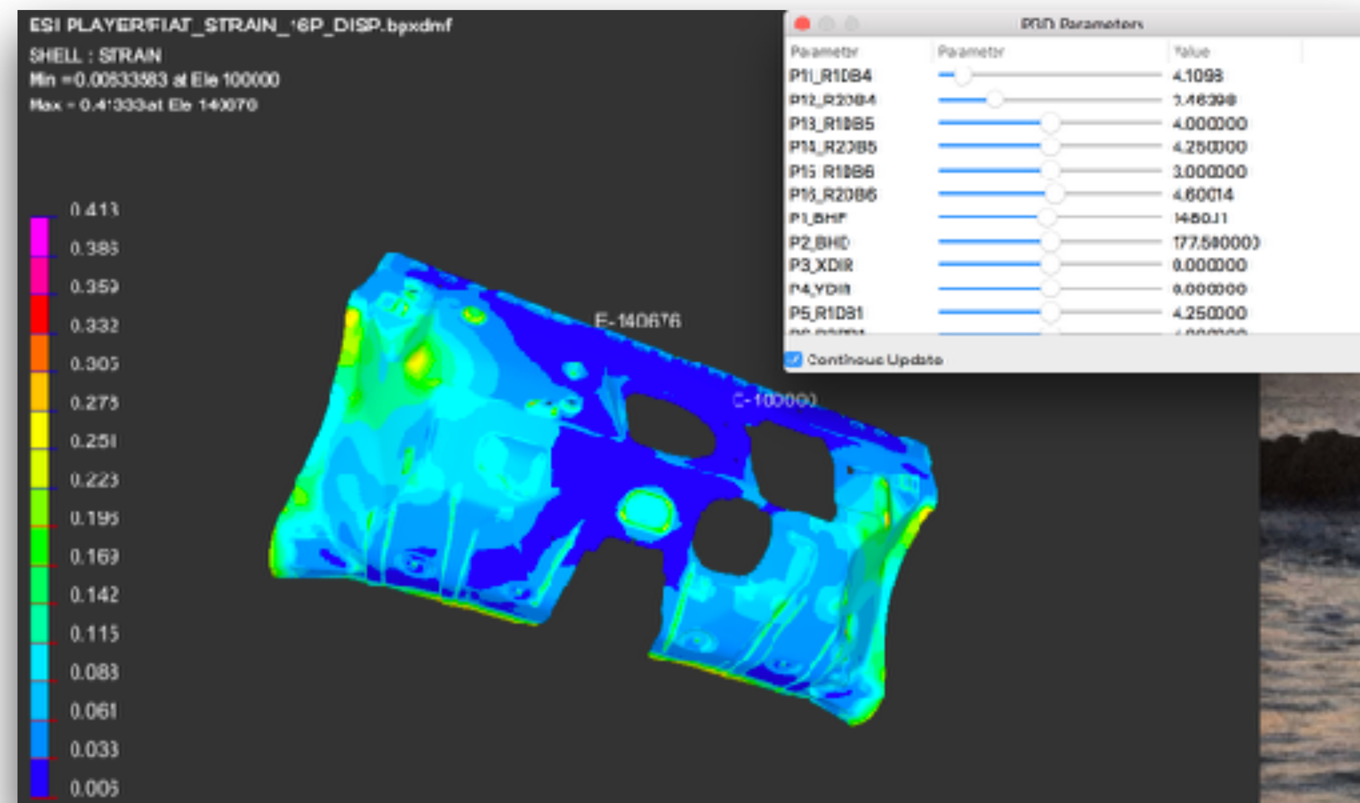
PGD based real-time simulation

PGD (variables separation) + Sparse Sensing + Kriging

15 parameters / 14 runs



PROS:

Non-intrusive

P parameters P runs

Is being validatied

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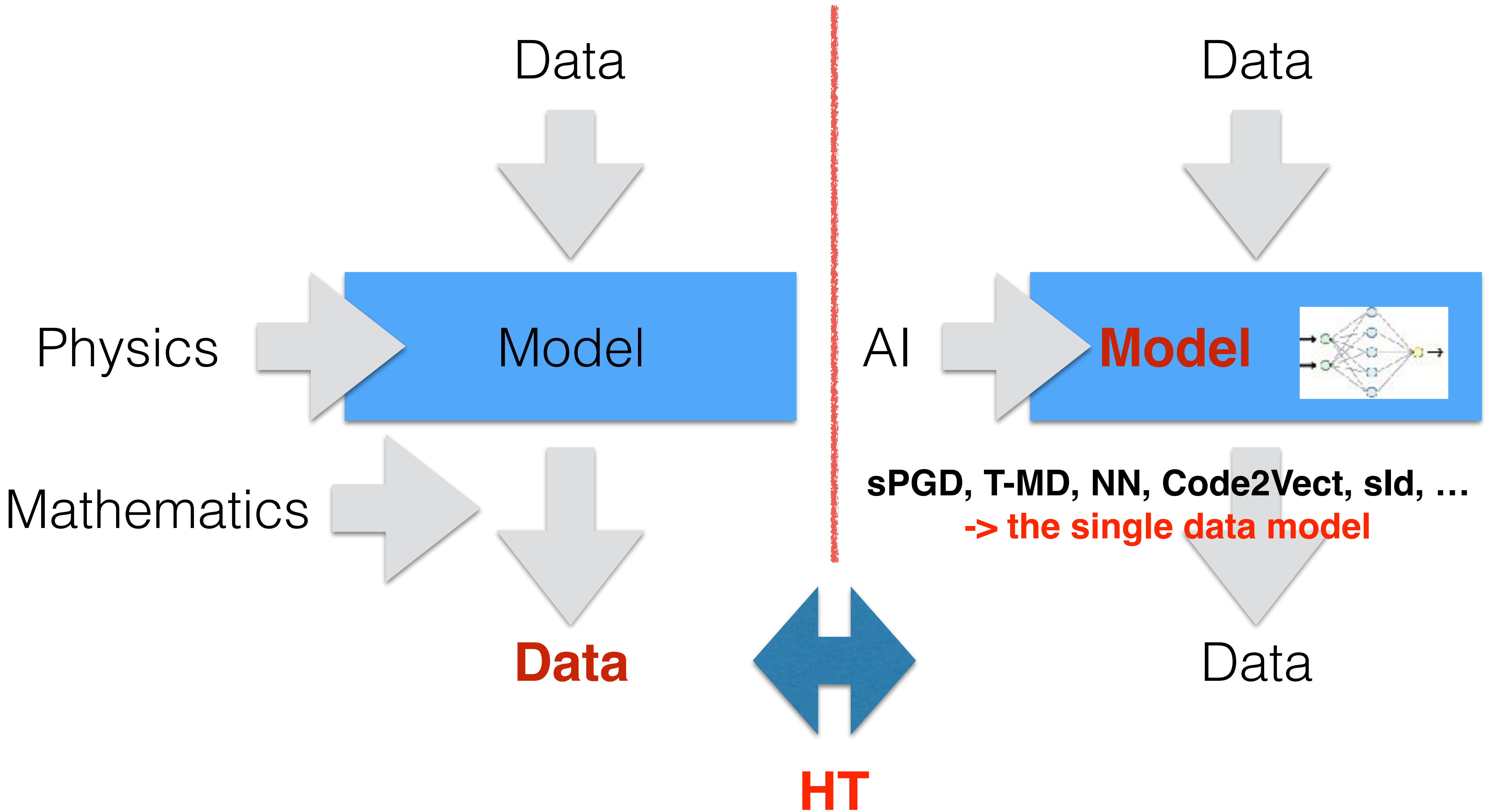
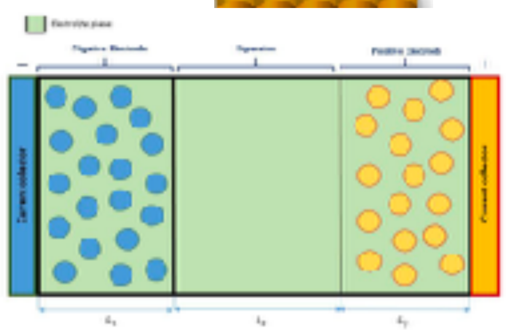
Data-Based Physics & Data-Driven Modelling

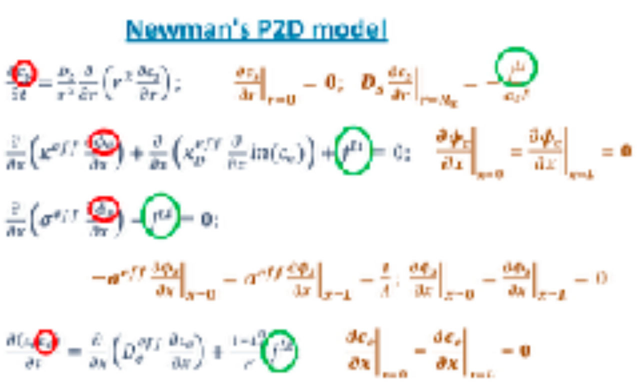


II - INDUSTRIAL SUCCESS

Case-study I: Batteries

Micro



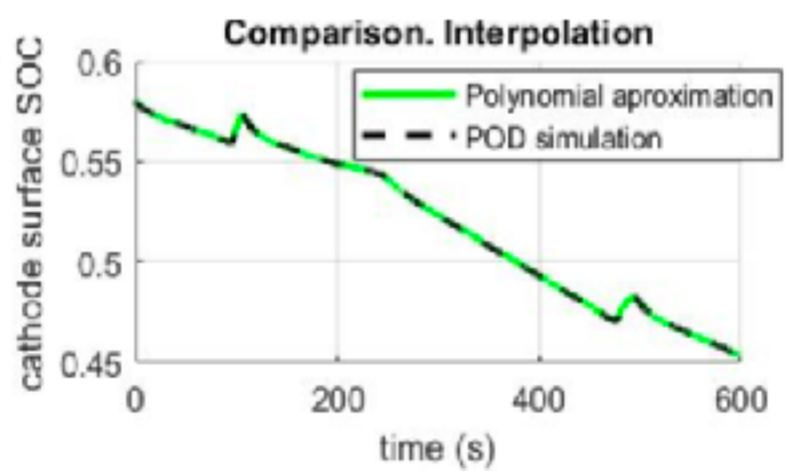


POD
&
PGD

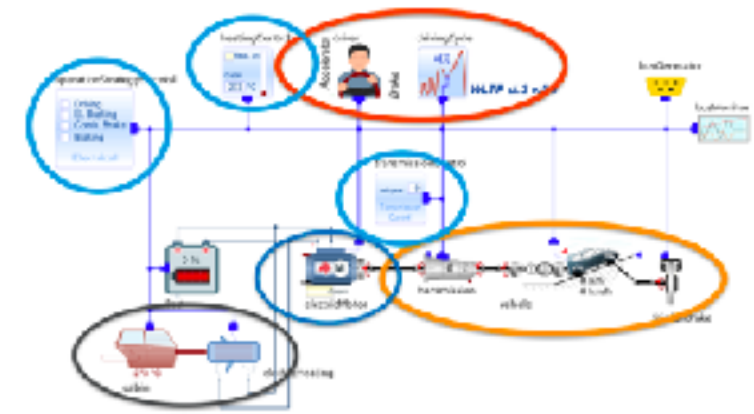
Meso

$$SOC(t) = f(SOC(t=0), Load, Env)$$
$$Voltage(t) = g(SOC(t=0), Load, Env)$$

AI: sPGD & T-MD

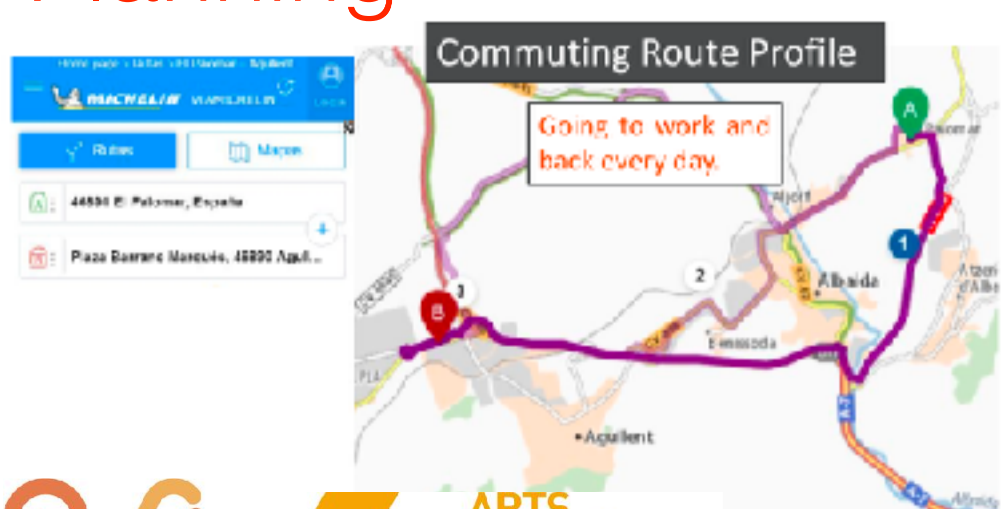


Macro

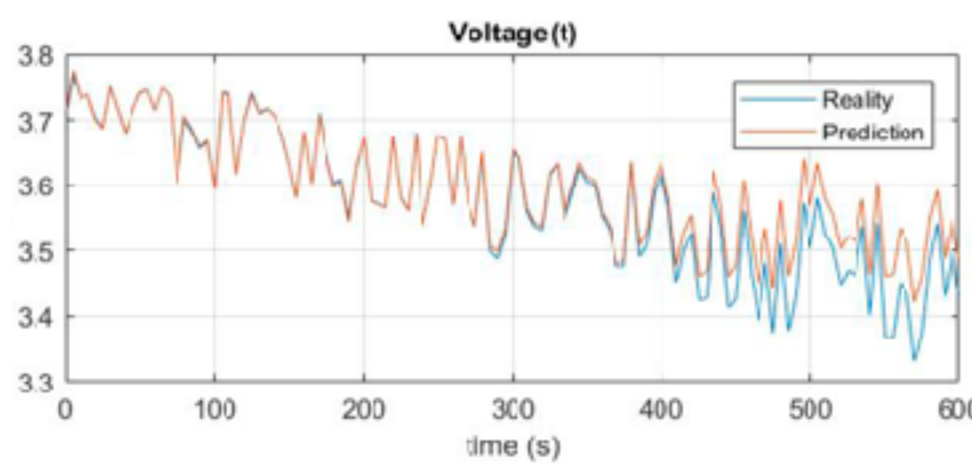


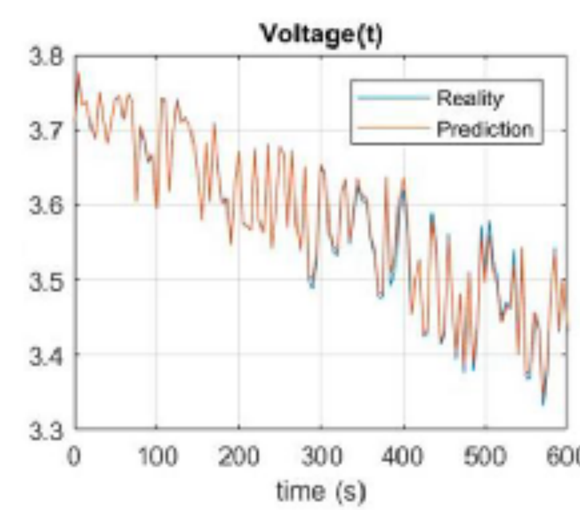
System modelling

Planning



HT





Data-Driven Correction

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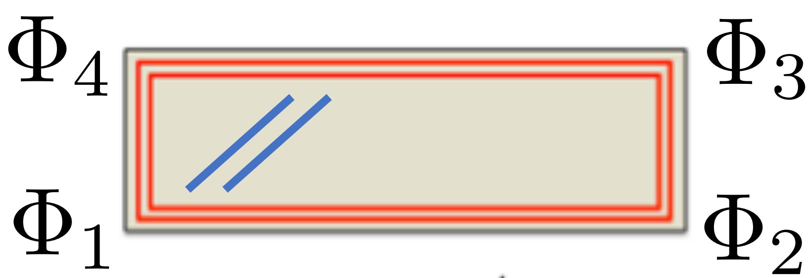
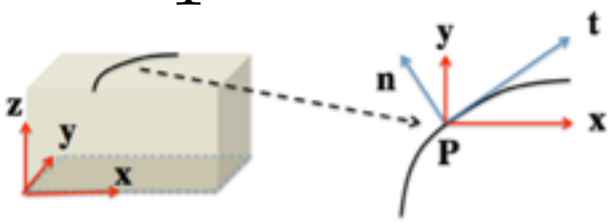
Case-study II: AM

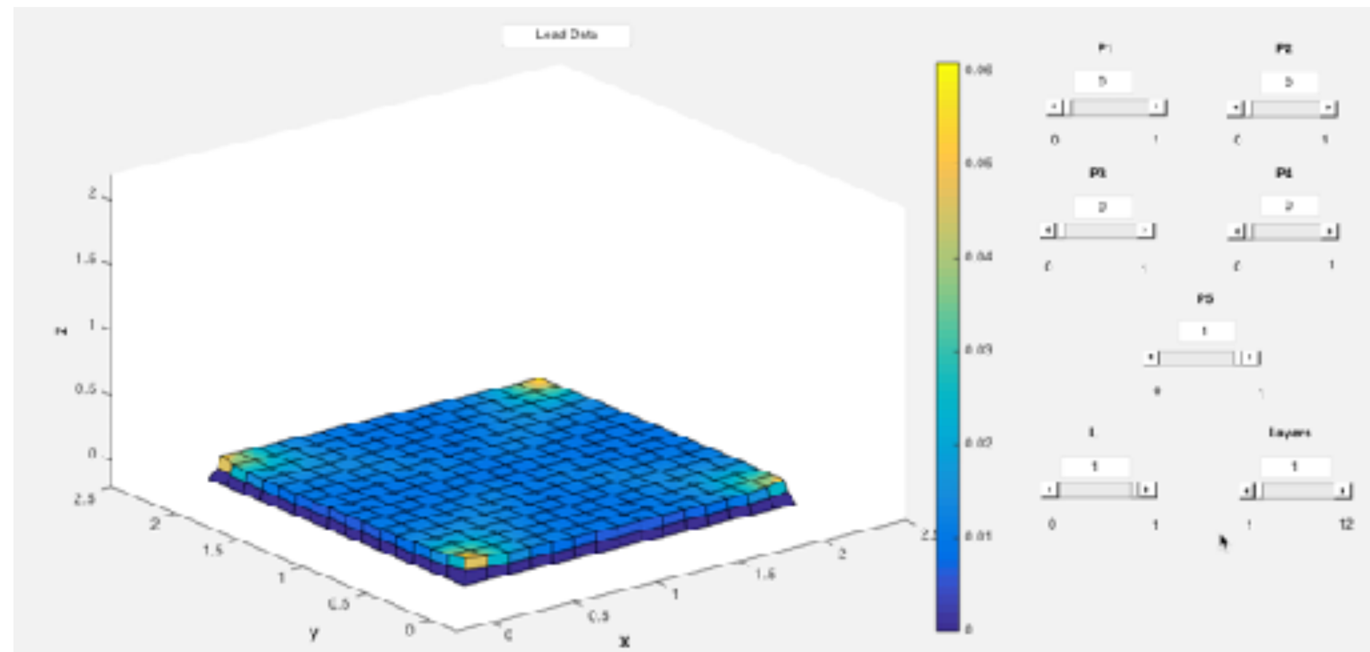
$$\Delta\phi = s$$

$$\phi|_{\partial\Omega} = f(\Phi_1, \Phi_2, \Phi_3, \Phi_4)$$



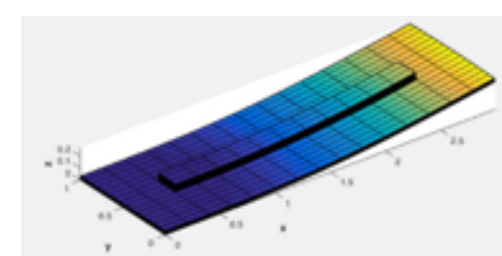


$$\tilde{\sigma}_0(\mathbf{P}) = \begin{pmatrix} \lambda & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

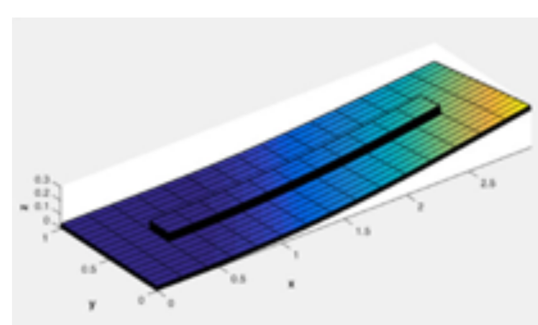


Hybrid Twin

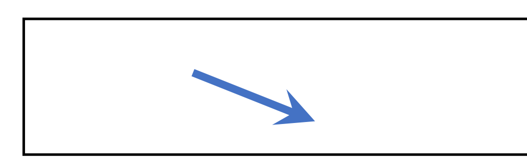
Target



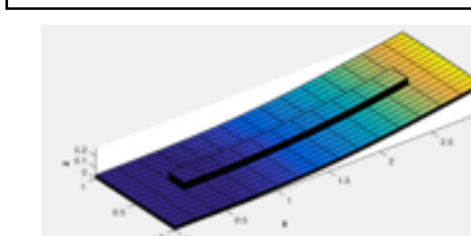
Anticipated based on data



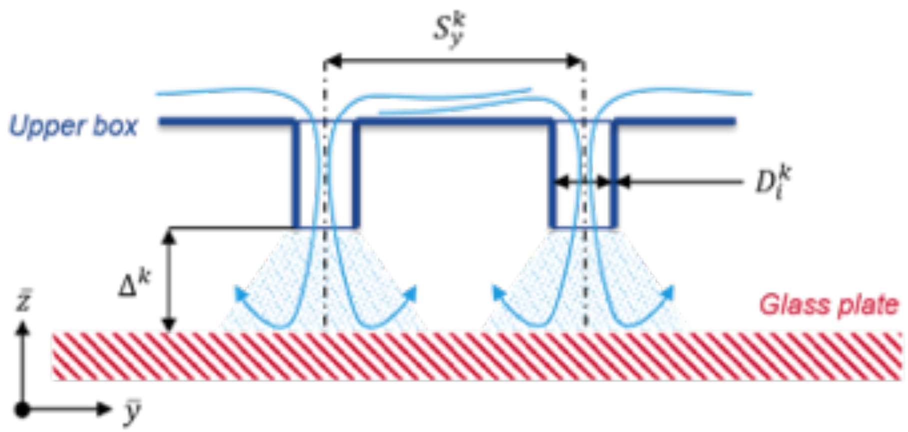
Correction



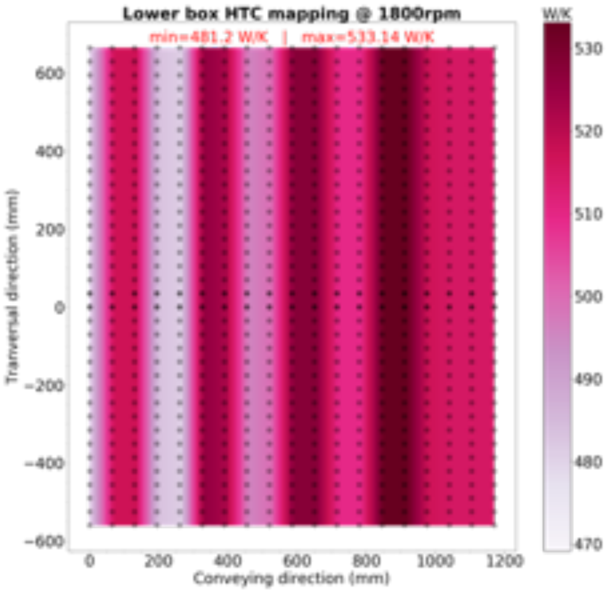
Result



Case-study III: Tempering



$$\Delta h_i^k = f(Re, Pr, D, \Delta, f)$$



HYBRYD TWIN = PHYSICS BASED (REAL-TIME) MODEL (appl. math.) + DATA-DRIVEN LEARNED IN-THE-FLY MODEL (AI)

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