

Hype or Reality?

Scalable Reduced Order Modelling For Digital Twins



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Scalable Reduced Order Modelling For Digital Twins

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Agenda

- 1 Digital Twins**
- 2 Digital Twins @ Work**
- 3 Challenges & Opportunities**
- 4 Reduced Order and Surrogate Modeling**
- 5 The Future**

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Digital Twins



The Digital Twin Paradigm



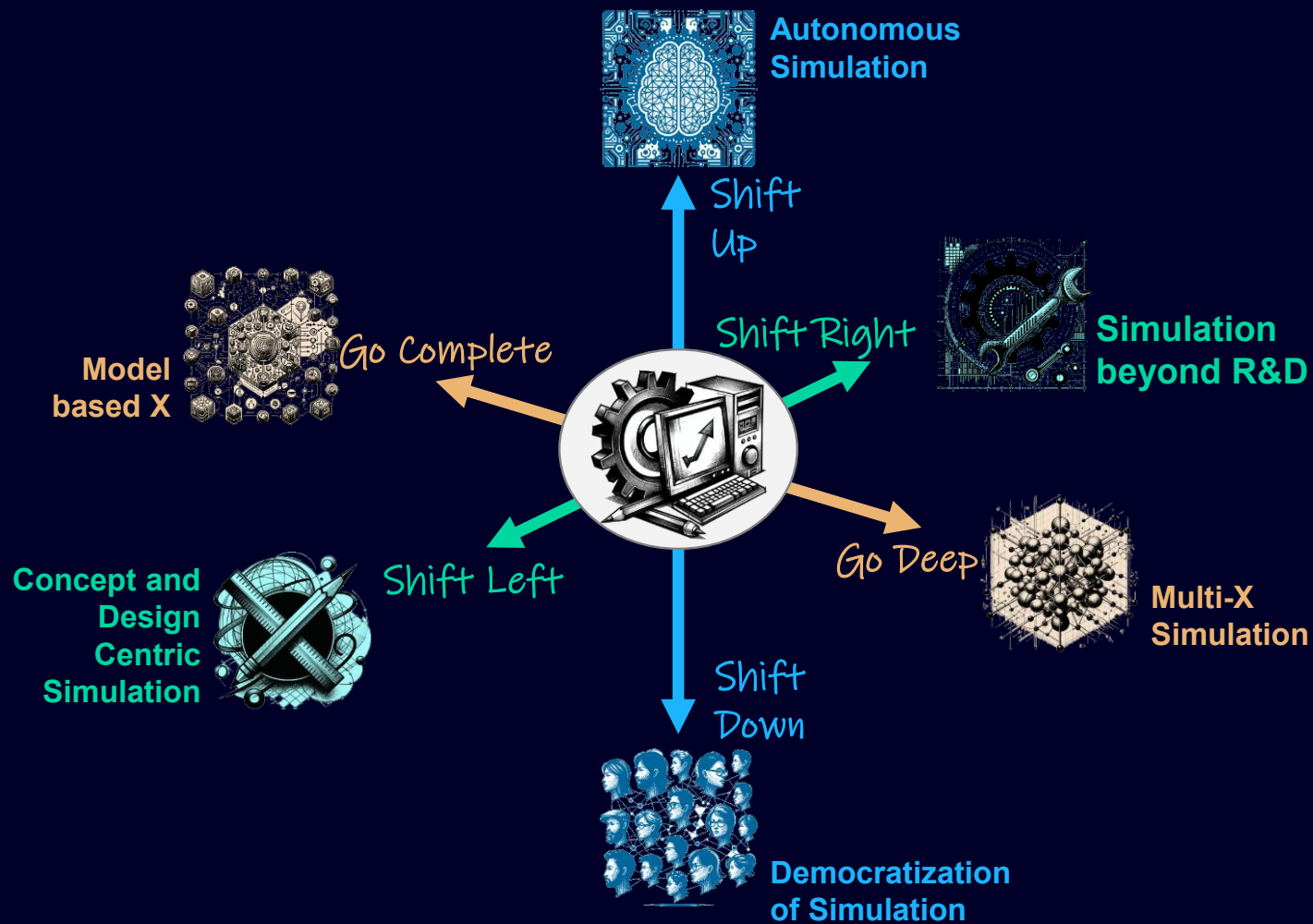
A comprehensive set of digital models accepted as full substitutes for reality to understand, predict, and optimize the physical counterpart's performance characteristics for specific purposes. The bidirectional interaction between the digital and the real is central to the digital twin.

Our Vision

//

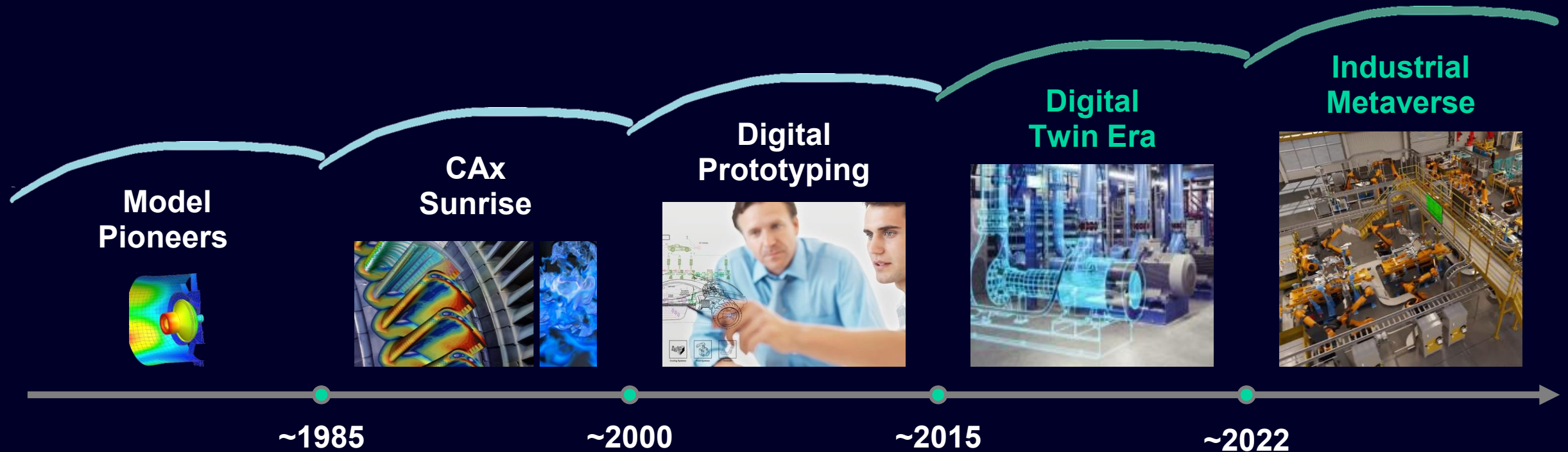
Anyone will be able to easily and robustly predict all relevant behavior of complex systems up to the required realism with compute time and accuracy guarantees.

Digital Twins require a massive expansion of the use of simulation technologies



- ↔ Extending 'use cases'
- ↔ Lifecycle spanning simulation
- ↔ Extending 'user' profiles

Digital Twins - a golden age for industrial mathematics



CAX: Computer Aided Design, Engineering, & Manufacturing

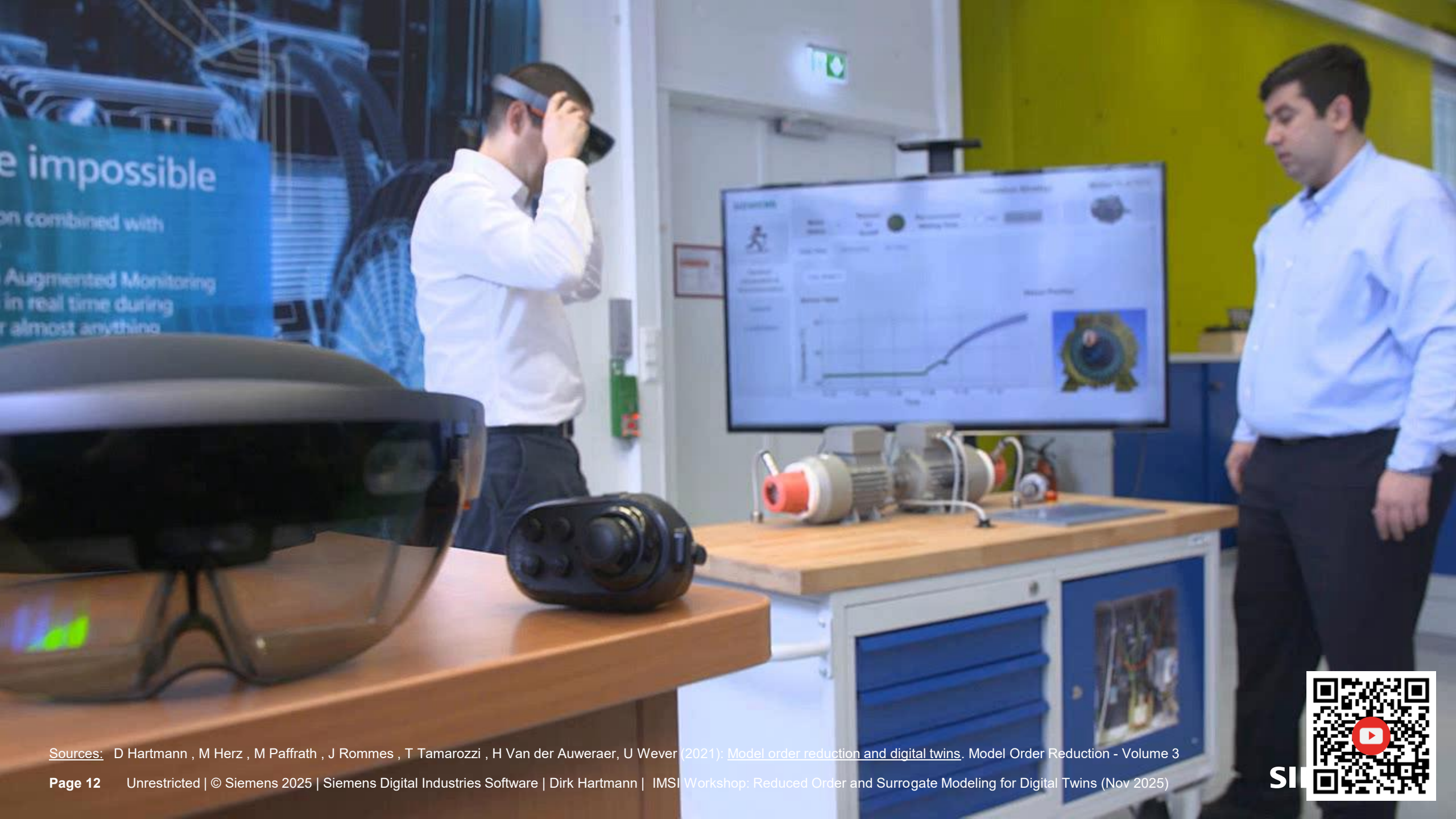
Source: D. Hartmann, H. Van der Auweraer (2025): [Digital Twins - a golden age for industrial](#). Journal of Mathematics in Industry

Digital Twins @ Work

Major categories of Executable Digital Twin applications

xDT Category	Use this application when you want to...	Examples
 Virtual Testing & Commissioning	... prepare for how your asset or system would interact with other assets, systems, or people.	• Testing of automation by virtual commissioning • Testing new control strategies on gas turbines • Operator training
 Virtual Sensing	...measure something in your asset or system, but it isn't feasible to put a sensor there.	• Temperature inside electric rotor • Pressure distribution inside a gas turbine • Free-flow inside a sewage network
 Diagnosis & Identification	...know why your asset or system is behaving the way it is.	• Unbalance detection of large rotors • Leakage detection in a water distribution network • Predictive maintenance for machine tools
 Performance Prediction	...know how your asset or system might behave in future operation.	• Remaining useful lifetime of electric motors • Monitoring of coking in steam cracking furnaces • Movement of people in emergencies
 Performance Optimization	...inform actions on how to control the asset or system (with or without a Human-in-the-Loop).	• Model predictive control of a chemical reactor • Pump schedule optimization of oil pipelines • Operating point setting of catalyst modules

Source: D. Hartmann (2021): [Real-time Digital Twins](#).



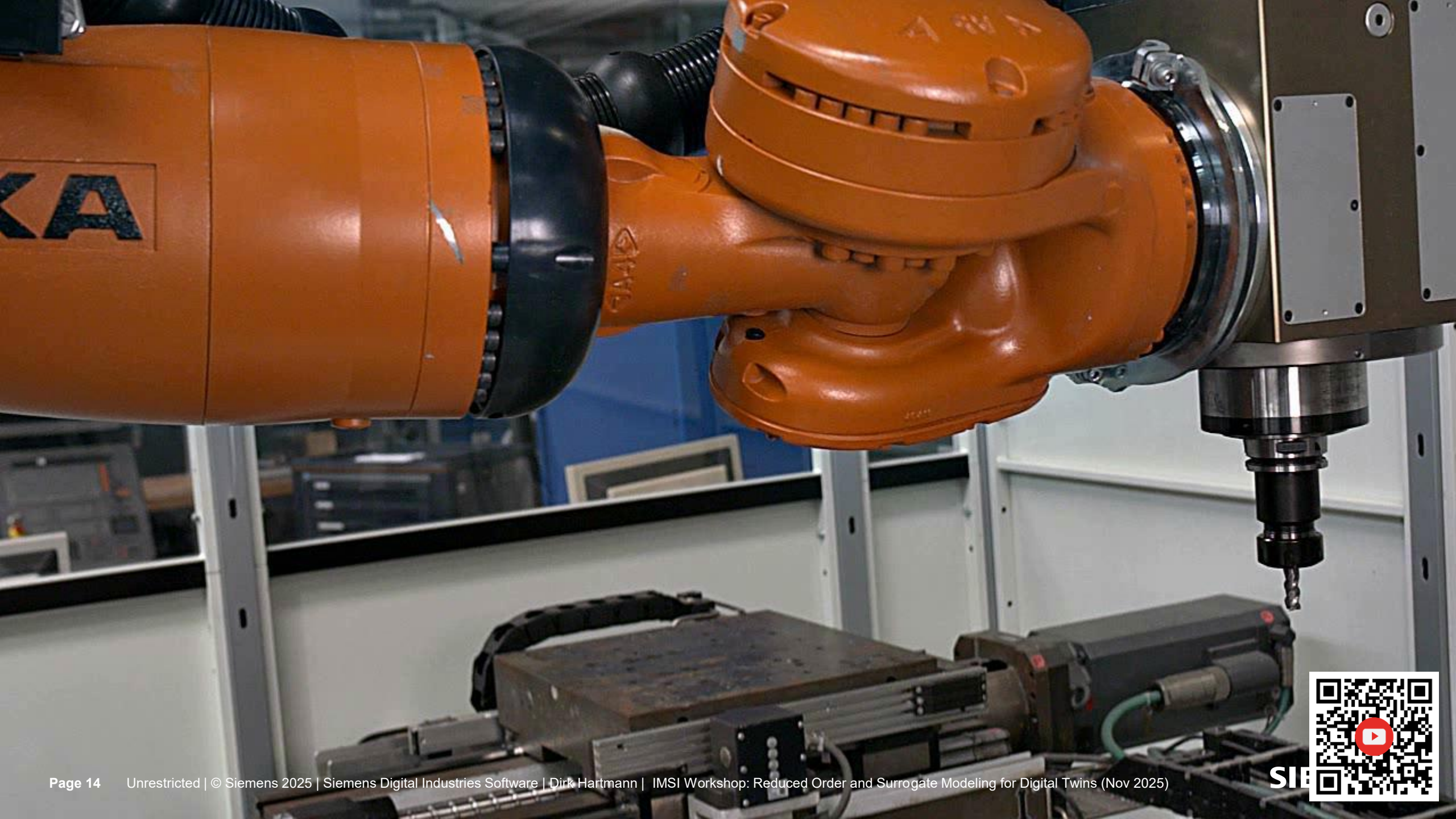
Sources: D Hartmann , M Herz , M Paffrath , J Rommes , T Tamarozzi , H Van der Auweraer , U Wever (2021): [Model order reduction and digital twins](#). Model Order Reduction - Volume 3

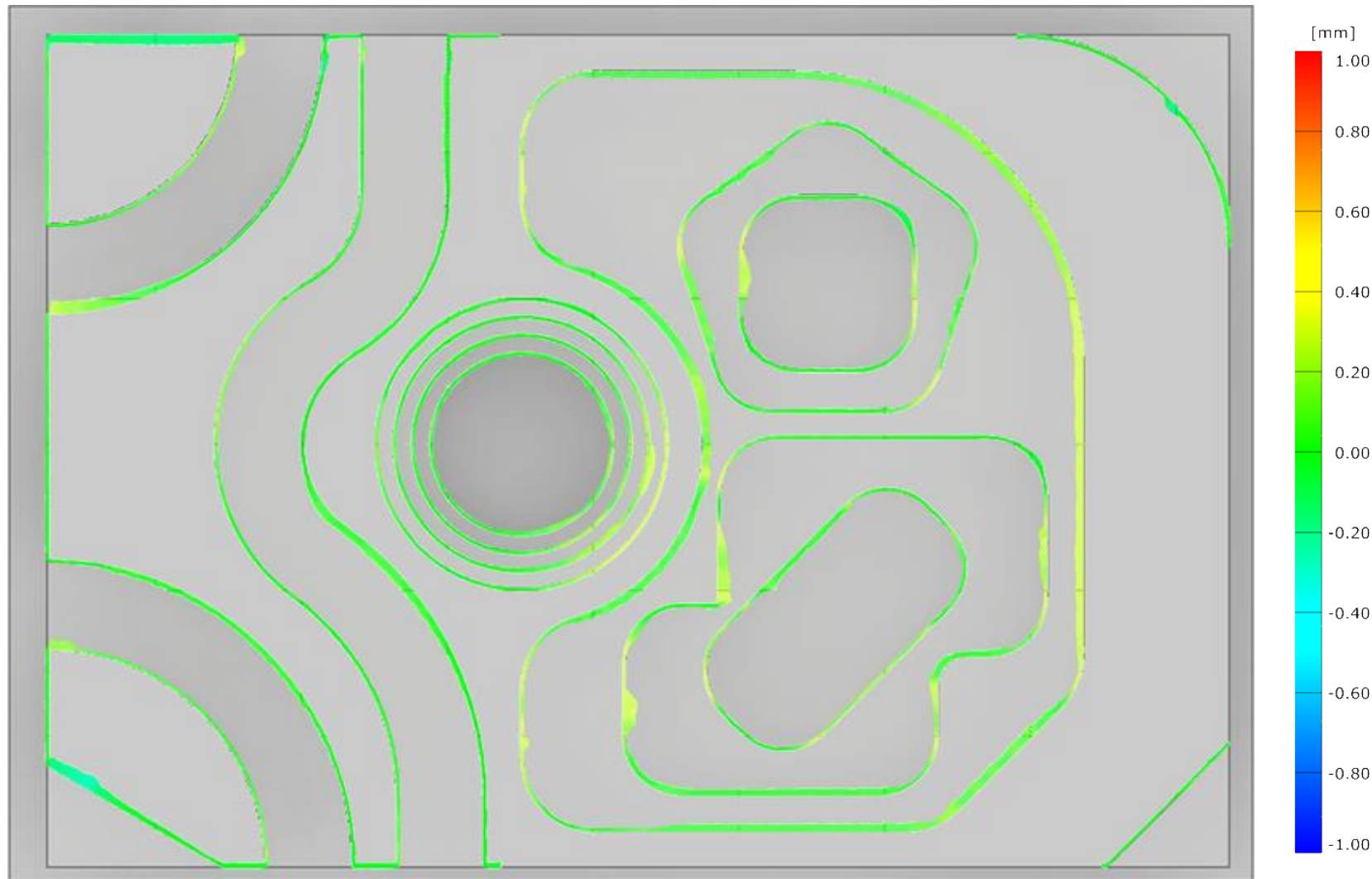


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Source: D. Hartmann (2021): [Real-time Digital Twins](#).





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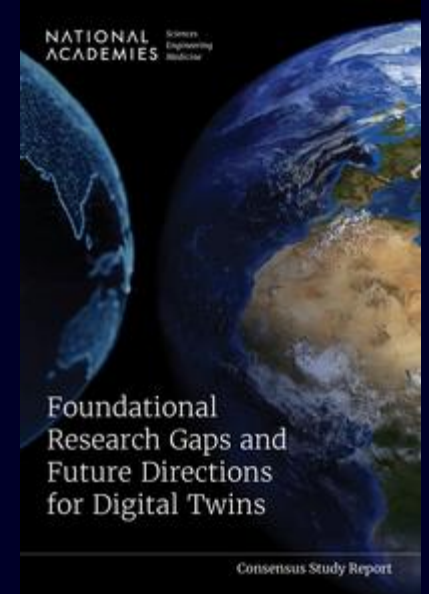
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Sources: F Schnös, D Hartmann, B Obst, G Glashagen (2021): [GPU accelerated voxel-based machining simulation](#). Int. J. of Adv. Manufacturing Tech
M Busch, F Schnös, T Semm, MF Zäh, B Obst, D Hartmann (2020): [Probabilistic information fusion to model the pose-dependent dynamics of milling robots](#). Production Engineering
MF Zaeh, F Schnoes, B Obst, D Hartmann (2020): [Combined offline simulation and online adaptation approach for the accuracy improvement of milling robots](#). CIRP Annals



Why do not we see Digital Twins everywhere?

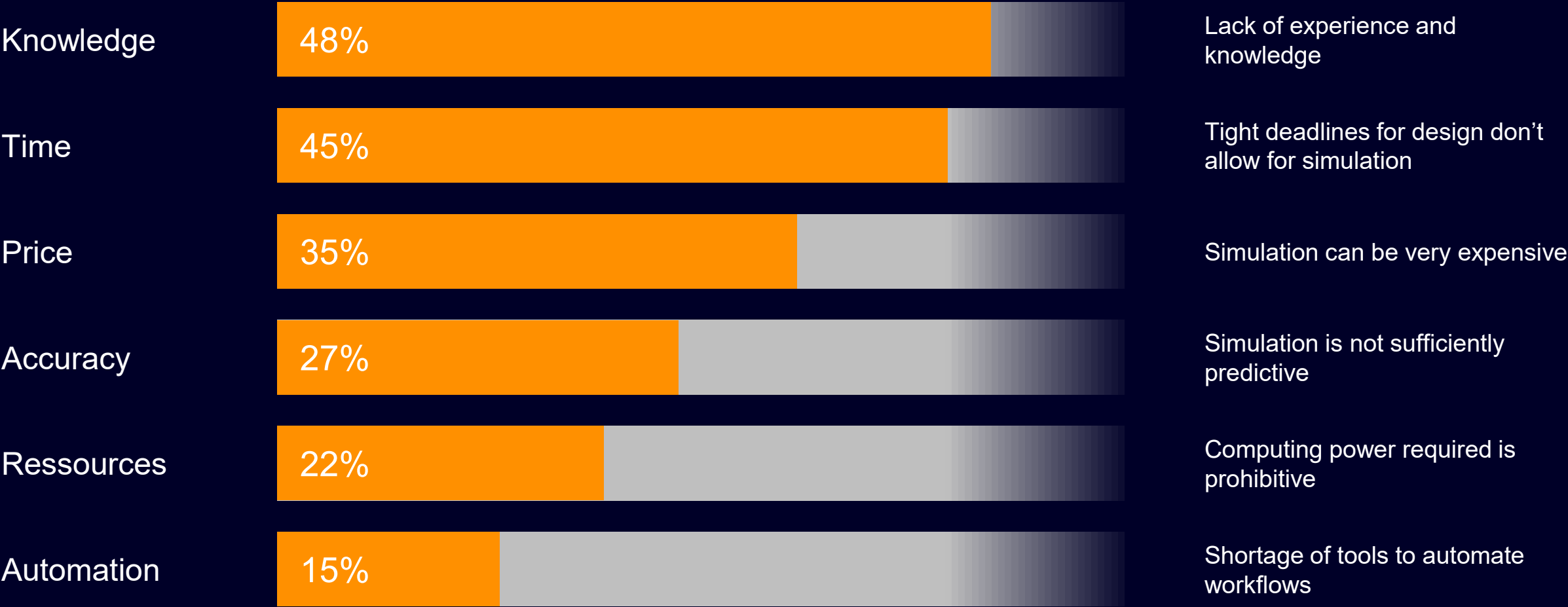
“Despite [...] examples of digital twins providing practical impact and value [...] publicity around digital twins [...] currently outweighs the evidence base of success.”



Source: National Academies (2024): [Foundational Research Gaps and Future Directions for Digital Twins](#).

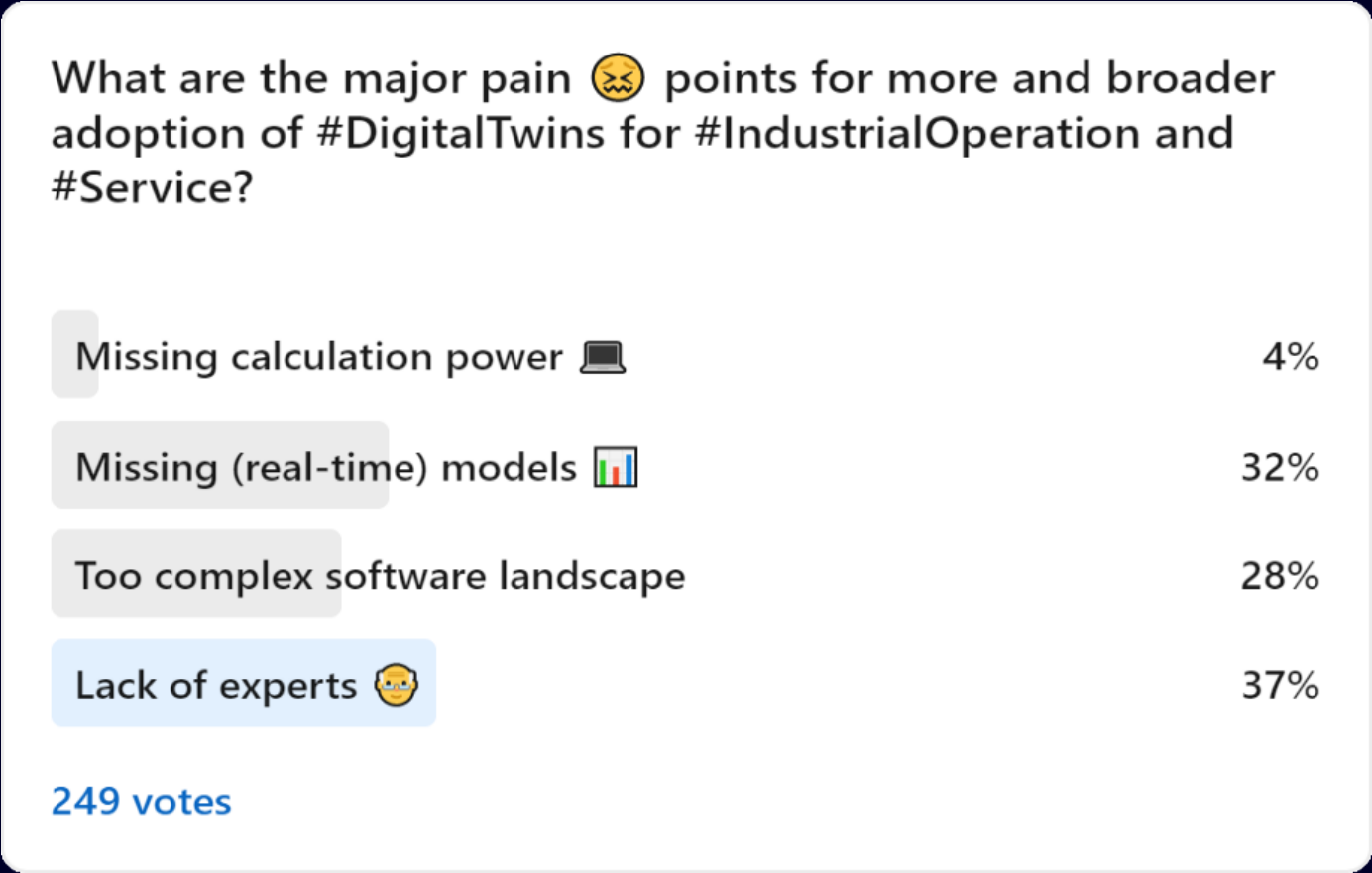
Challenges & Opportunities

Scalability of simulation is limited by the same obstacles since decades.



Source: Engineering.com (2022): [Research Report: The State of Simulation, Prototyping and Validation](#)

Digital Twins are limited by the availability of experts who can realize real-time models in complex software landscapes.



Source: Hartmann D. [What are the major pain points for more and broader adoption of Digital Twins for Industrial Operation and Service?](#) 2022.

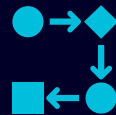
Key Requirements for a Digital Twin Reduced Order Model



Speed



Accuracy



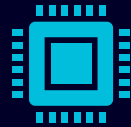
Workflow Efficiency



Trustworthiness



Generalizability



Deployability



Usability

Method innovation in predictive technology is key to scale Digital Twins!

**THE DIGITAL TWIN IN
INDUSTRY AND
INFRASTRUCTURE**

ARC Strategies
March 2023

This report defines the digital twin, providing a common understanding and a basis for discussions among practitioners. The report describes the many dimensions and aspects of digital twins to orient the user, and provide a range of options for building a goal-focused digital twin strategy. It also provides recommendations for implementation and typical use cases across discrete and process manufacturing, and infrastructure such as buildings, electric grids and transportation systems. The report can help readers build a strong foundation for their digital twin program.

By Valentijn de Leeuw and Dick Slansky

ARC
Advisory Group

VISION, EXPERIENCE, ANSWERS FOR INDUSTRY

ARC Strategies • March 2023

A practice of *continuous machine learning and deployment* is emerging (sometimes referred to as “MLOPS”), in which operational data are regularly transferred in batches containing sufficient information to derive model parameters. These (re-)adjusted models can then be deployed to the container or cluster running the real-time application, with minimal impact on operations. This strategy considerably reduces traffic from edge to cloud and back and can be a significant cost saving.

Continuous Machine Learning And Deployment. After Bihuliga, Saudi Aramco, 2019

Hartmann and Van der Auweraer (2020) introduced the concept of the *executable digital twin*. Regardless of the inner architecture of such an executable, such an executable is required to deploy a digital twin in real-time environments, in particular with small time constants and latency requirements, requiring the digital twin to operate fast, and on hardware with limited capability, such as within an edge device. To enable controlled and repeatable deployments, a mechanism of continuous machine learning and deployment in containers or container clusters is a realistic approach.

Separation of data and software is also called *loose coupling*. Both micro-service architectures and loose coupling improve extensibility, scalability, and maintenance efficiency. Extensions can be made by adding additional software components using the existing data or adding new data sources as input to a single software application. Maintenance can be very focused on a particular service without impacting functionality. Software can be extended in functionality by adding microservices without impact on existing services. Application responsiveness can be scaled by running identical microservices in parallel.

A *software agent* has no knowledge of other modules, is loosely coupled and acts autonomously on its environment, based on data from a broker it has subscribed to. It may execute a specific action on that data, for example storing them in a data base. Software agents can adequately work with events that cannot be planned well, as may occur in manufacturing.

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ICIAM 2019 SEMA SIMAI Springer Series 5

Manuel Cruz
Carlos Parés
Peregrina Quintela Eds.

Progress in
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The Industry and the Academia
Points of View

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Digital Twins 13

Fig. 6 Mixed reality setup allowing to measure spatial temperature distributions parallel to operations by means of online simulations. Reproduced with permission. Copyright © Siemens AG

a tremendous achievement [27]. At the same time using model order reduction technologies [28] the concept can be built directly on top of engineering models allowing to achieve the benefits with only little additional efforts. Mathematics enables quasi thermal X-rays for electrical motors allowing to monitor temperature distributions in real time (Fig. 6).¹⁰

5 The Next Wave—Executable Digital Twins

Albeit the previous section has shown four great examples of Digital Twins, a major limiting factor today is the manual work required to realize a Digital Twin, i.e. transfer of the corresponding models between different domains or life cycle phases. Most applications require to provide the models in the right execution environments with the right online capability in particular during the operations phase.

We therefore introduce the concept of an Executable Digital Twin, which will be from our point of view a key aspect in any future Digital Twin driven application.

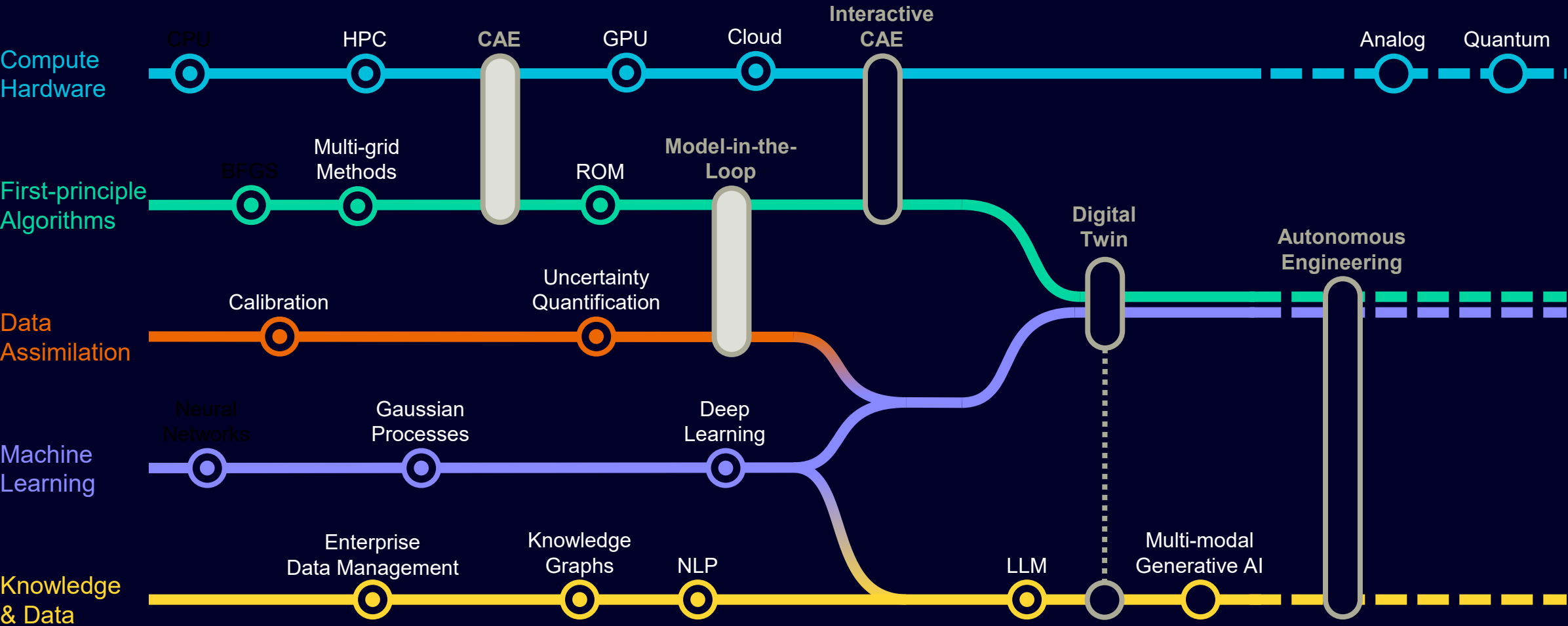
Definition (Executable Digital Twin) An Executable Digital Twin is a specific encapsulated realization of a Digital Twin with its execution engines.¹¹ As such they enable the reuse of simulation models outside R&D. In order to do so, the

¹⁰ Virtual X-ray for large motors <https://youtu.be/96vkjykhIRM>.

¹¹ Typically models today are distributed separately from their execution/simulation tools.

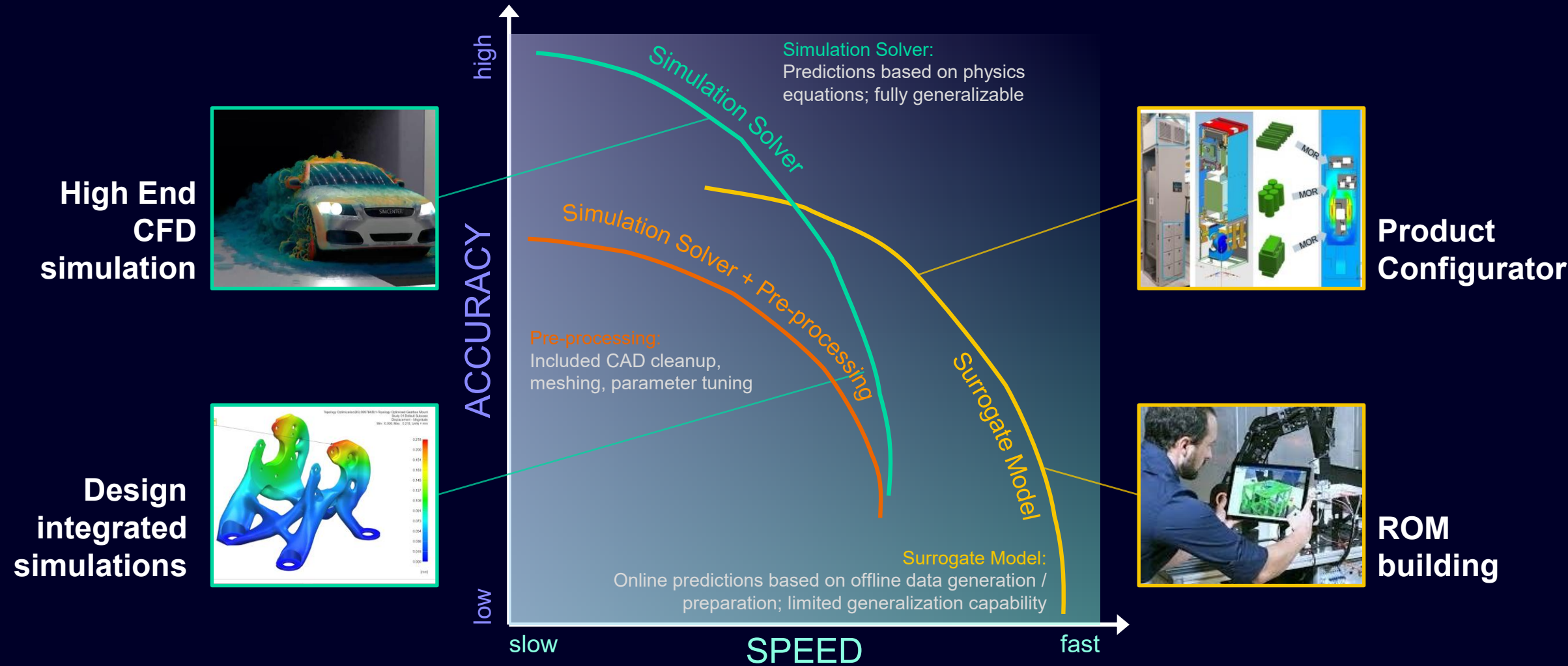
Sources: V De Leeuw, D Slansky (2023): The Digital Twin in Industry and Infrastructure, ARC Advisory Group Industry Report
D Hartmann, H van der Auweraer (2020): Digital Twins, Progress in Industrial Mathematics: Success Stories

The convergence of technology has driven and will continue to drive innovation – Mathematics is a core element of this!



Reduced Order and Surrogate Modeling

Goal: Acceleration of Predictions

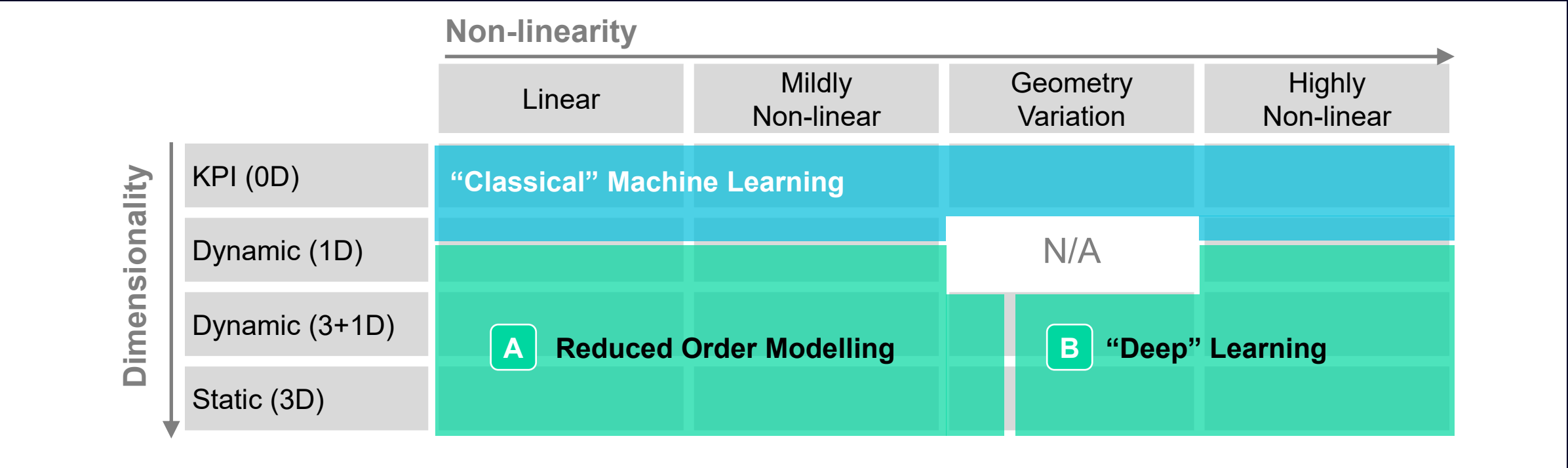


Reduced Order and Surrogate Modeling

Technology Opportunities



There is **no one to one mapping** between technology and use cases, but the problem categorization in terms of **dimensionality & non-linearity** can give **good guidance**.

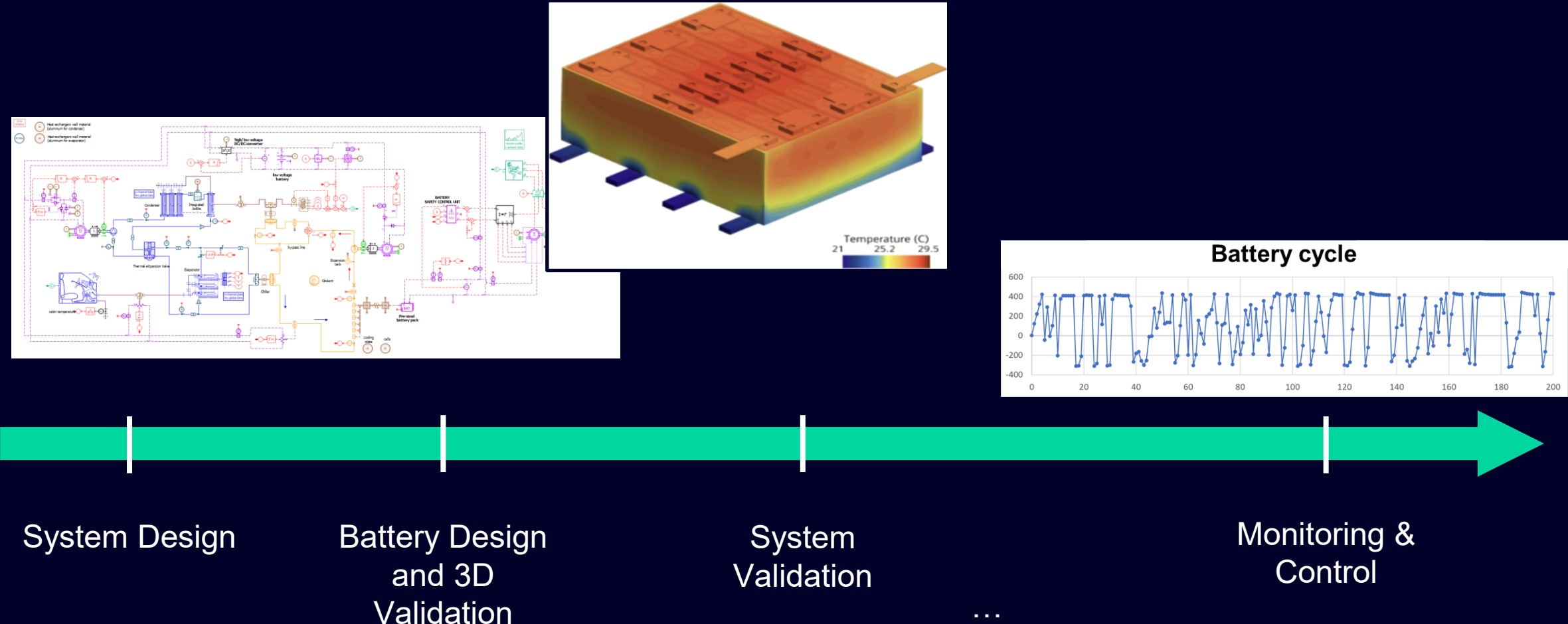


Guideline: Maximize Physical Bias

A

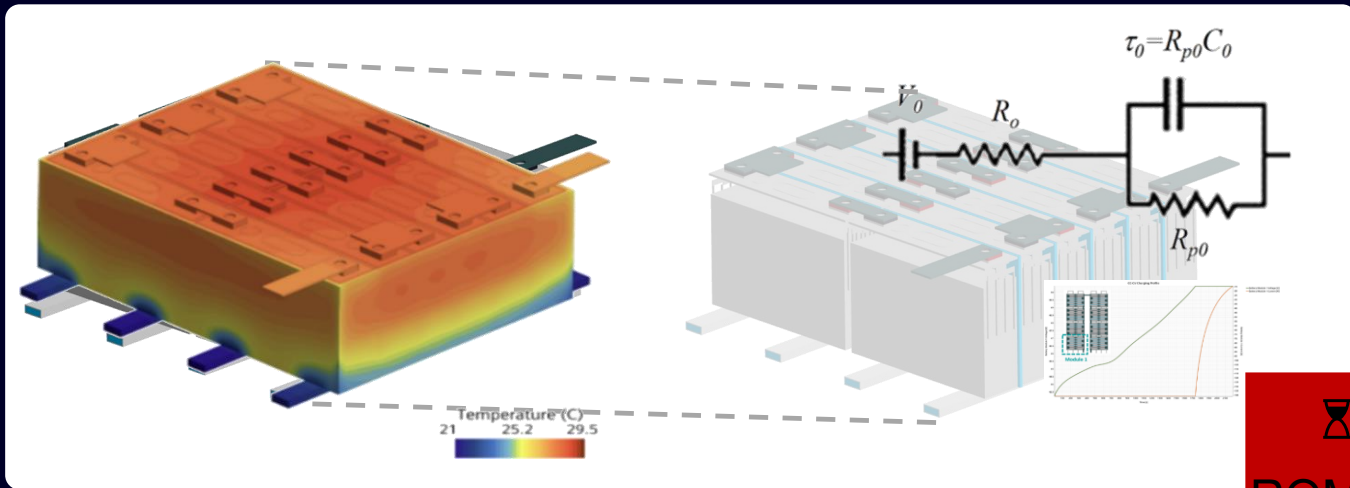
Reduced Order Modelling

Battery Thermal Management along the Life Cycle



Battery Thermal Management

Reduced Order Modelling



Example: Battery thermal management

ROM

Challenge:

Controller embedded real-time thermal simulations

Opportunity:

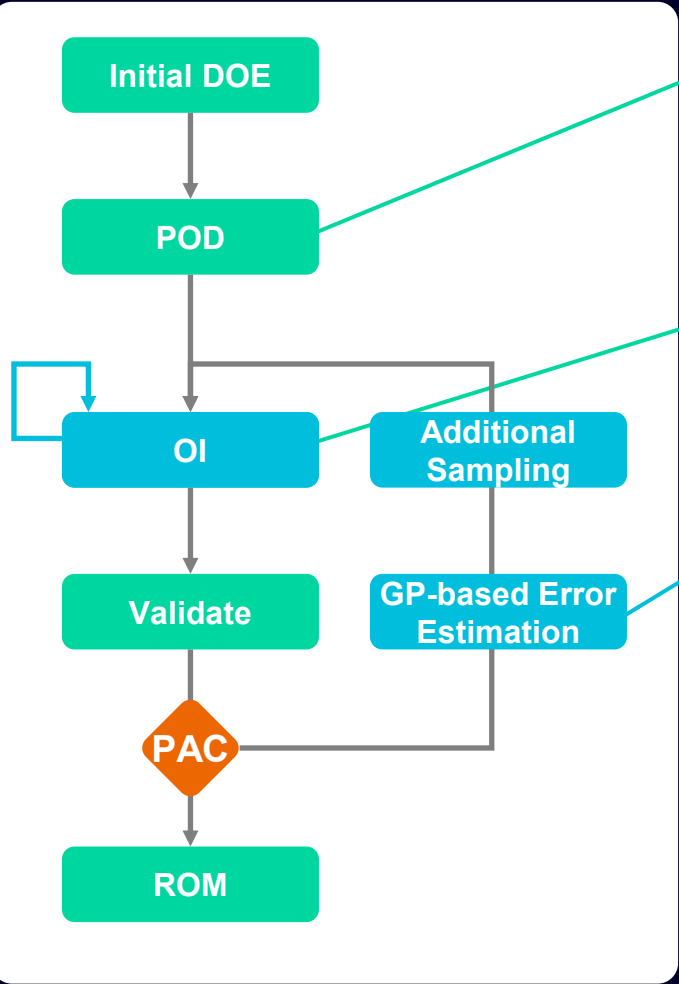
ML-based reduced order modelling technologies

Complex multi-physics model:

- Turbulent fluid flow
- Battery electrochemistry
- Electrical modeling
- ~ 1 million cells

Battery Thermal Management

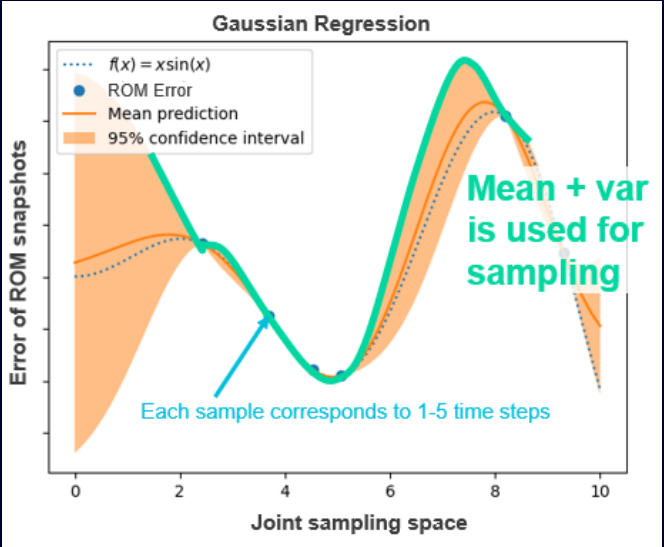
Technical concept



Latent Dimension Identification, e.g., Autoencoder, Diffusion Maps, Dynamic Mode Decomposition, Proper Orthogonal Decomposition (POD), ...

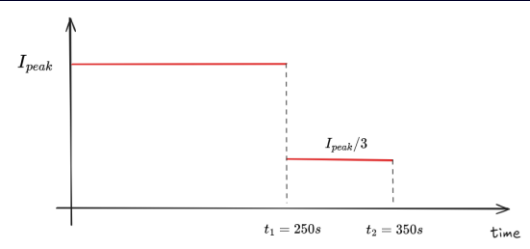
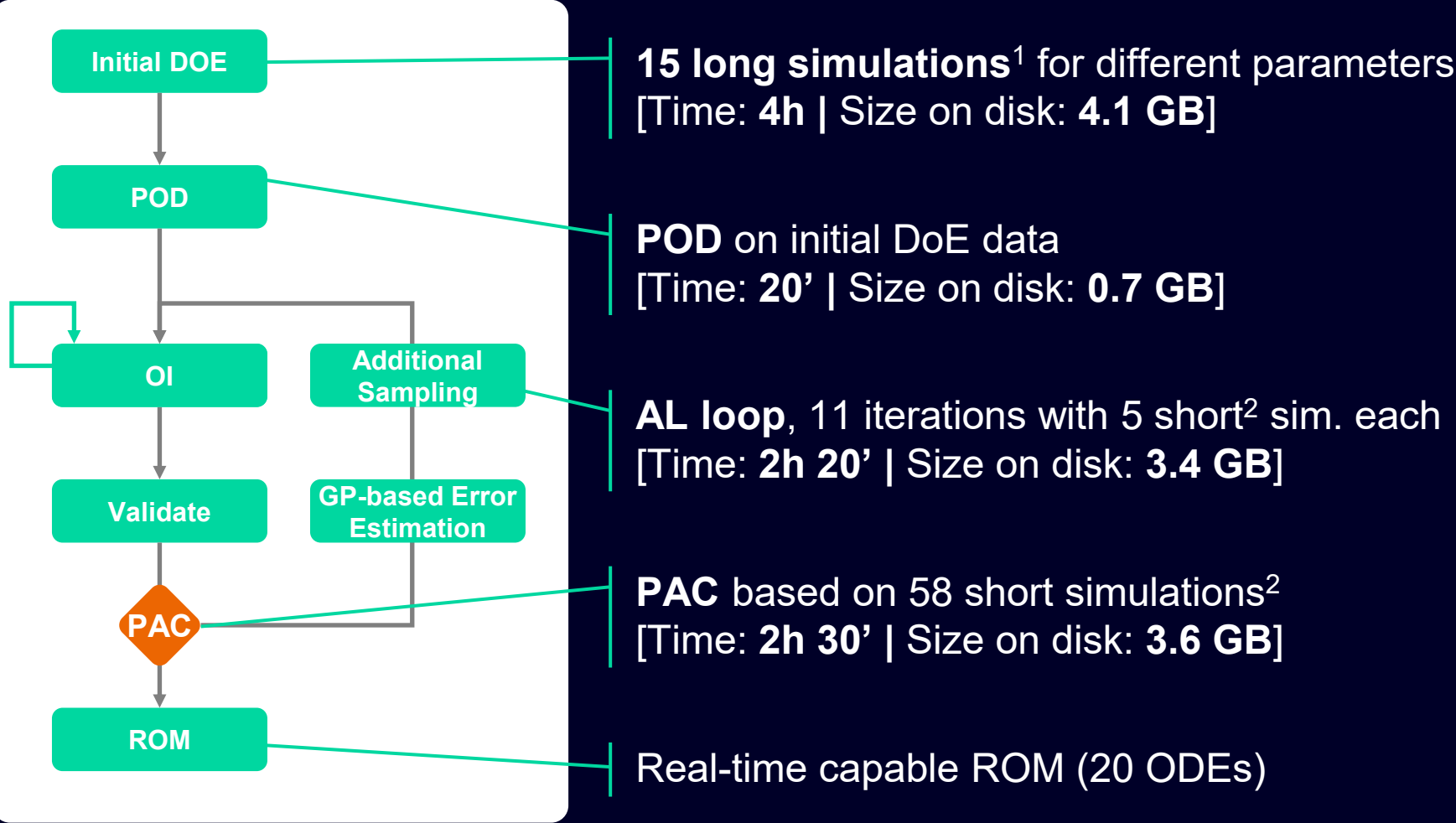
Reduced Model Discovery, e.g., Discrete Empirical Interpolation, Neural Networks, Operator Inference (OI), ...
with **Trajectory Learning**

Active Learning, e.g., classical Design of Experiments

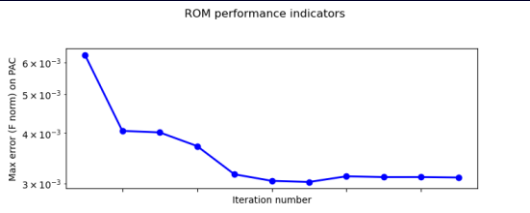


Source: Q Zhuang, D Hartmann, HJ Bungartz, JM Lorenzi (2023): [Active-learning-based nonintrusive model order reduction](#); Data-centric Eng
Q Zhuang, JM Lorenzi, HJ Bungartz, D Hartmann (2021): [Model order reduction based on Runge–Kutta neural networks](#); Data-centric Eng

Battery Thermal Management Results



Heating Profile

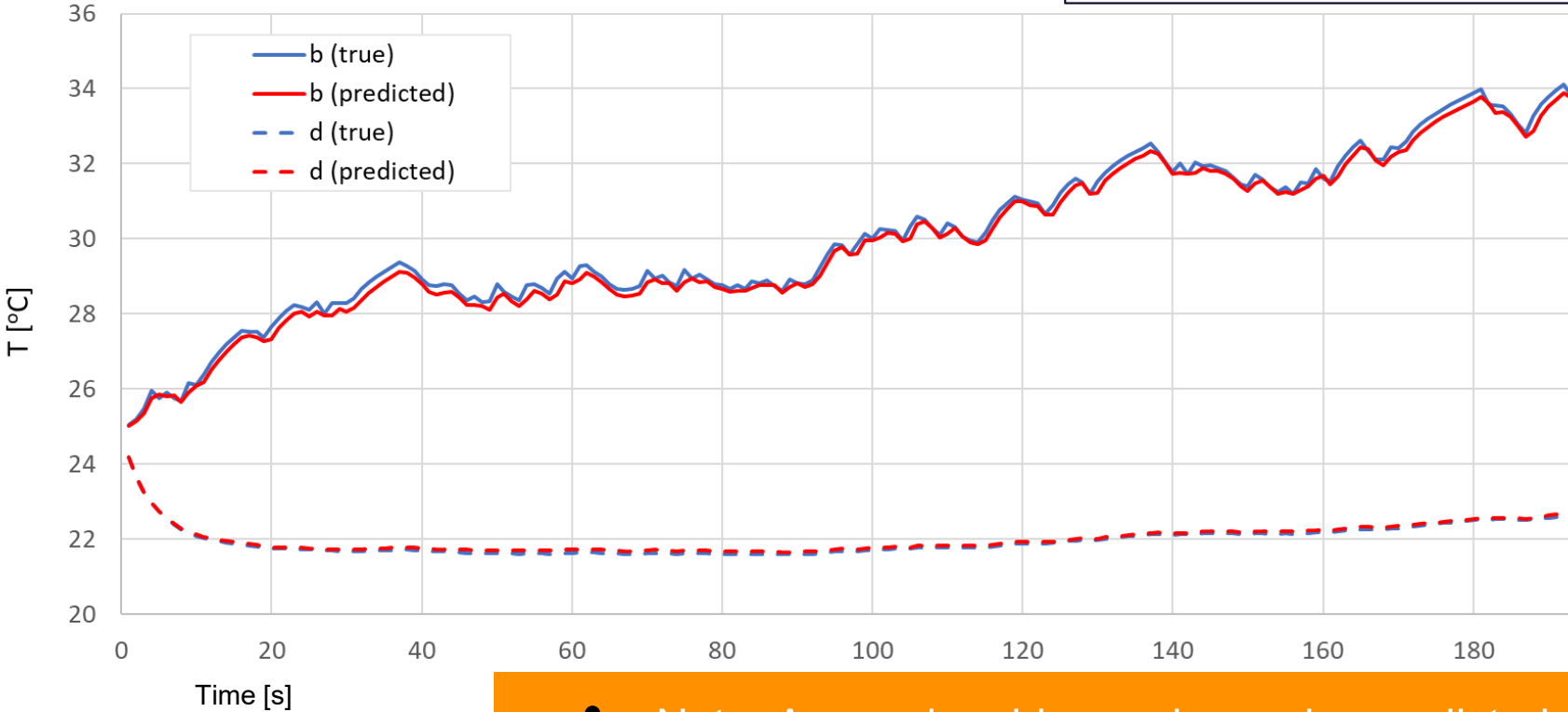


Error improvement

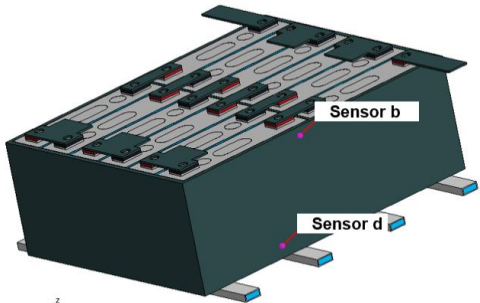
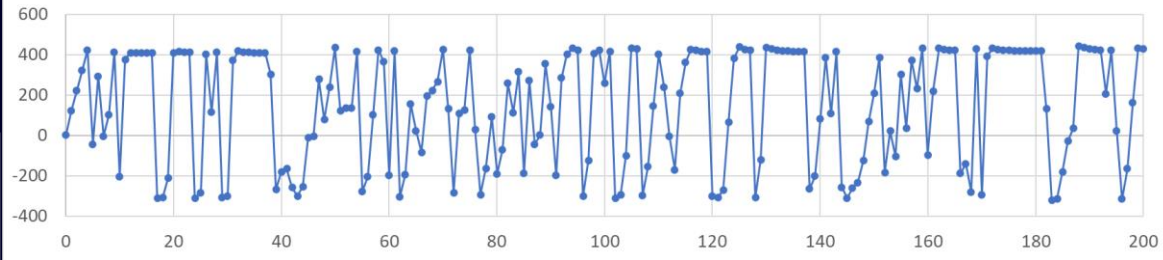
1) 350 time steps per simulation 2) 5 time steps per simulation

Battery Thermal Management Results

Sensors b and d, true vs predicted



Battery cycle for 200 s



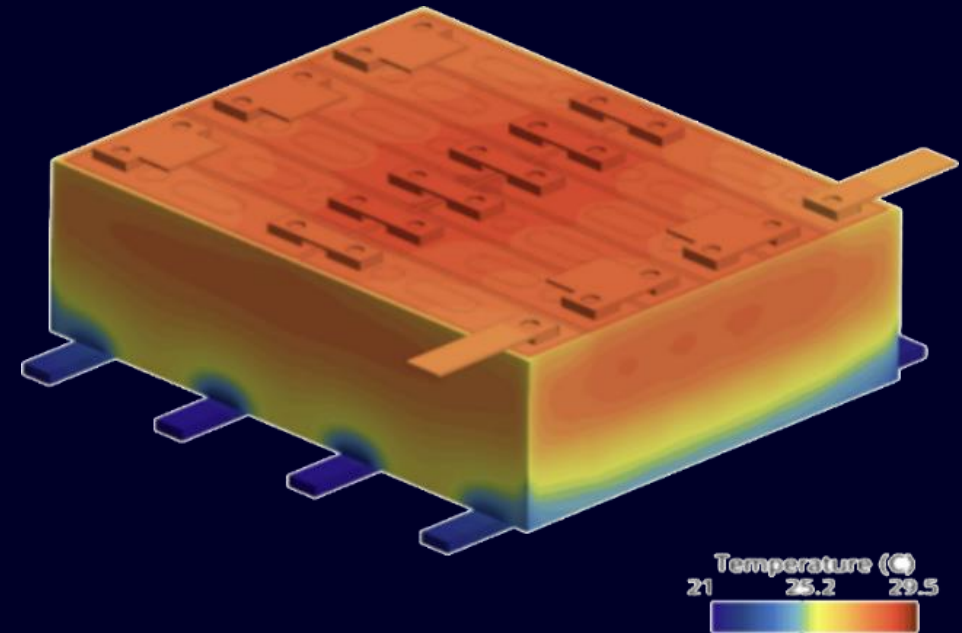
Note: A complex drive cycle can be predicted, albeit the model has seen only simple step functions in the training phase.

Battery Thermal Management

A fast simulation model isn't everything

There is many more elements to get the Digital Twin working:

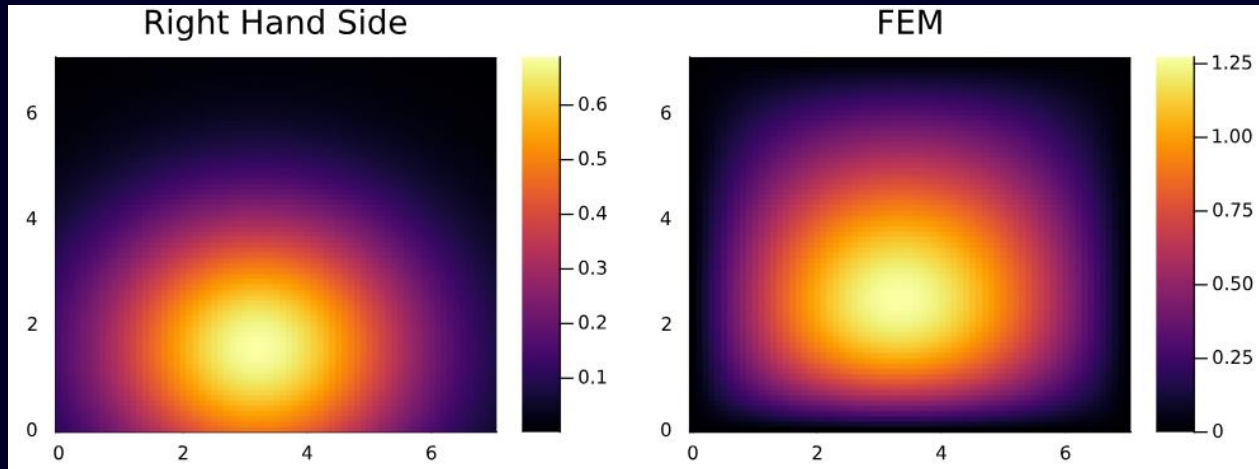
- ▶ Data assimilation
- ▶ Practical uncertainty quantification
- ▶ Integration in control loops
- ▶ Digital rights management
- ▶ “Obscure” compute hardware
- ▶ Required effort & expertise to setup
- ▶ ...



“Brute Force” Surrogate Modelling

Poisson Equation

Brute Force Surrogate Modelling



Challenge:

ML-based surrogate model with limited data requirements, generalizability, trustworthiness

Opportunity:

Domain Decomposition based hybridized Neural Solver

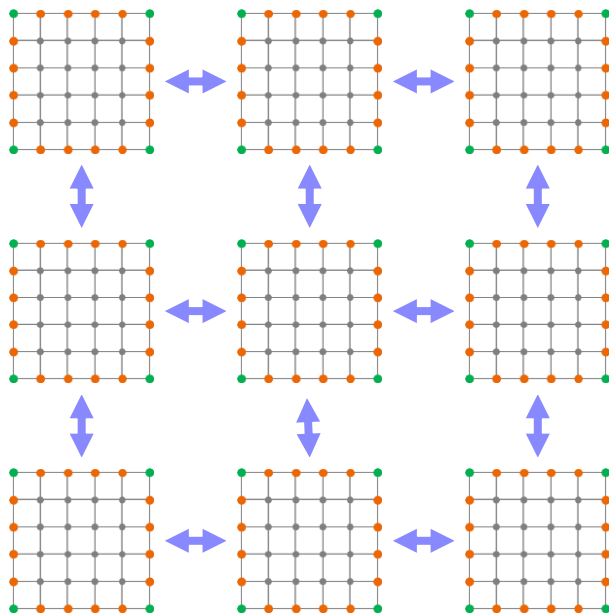
Example: Simple Poisson Model

$$\Delta u = f \text{ on } \Omega, \quad u = 0 \text{ on } \partial\Omega$$

Source: D. Hartmann (2025): Hybridized Data Driven Flux-Conservative Solvers: Towards Foundation Models for PDE-Solving. 1st Workshop on Differentiable Systems and Scientific Machine Learning @ EurIPS 2025

Hybridized Flux Conservative Neural Solver

Ideas



Domain Decomposition



Hybridization (Interface variables as main variables)



Sub-element-based training

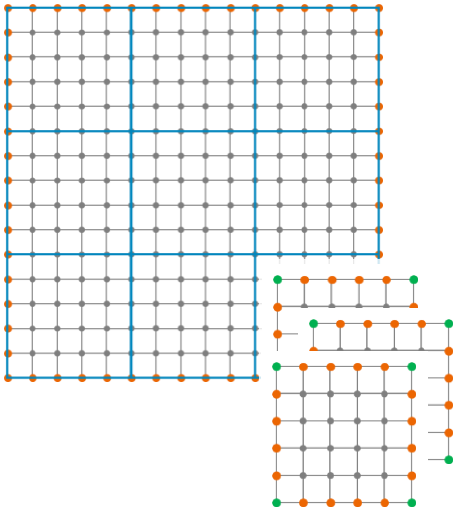


Flux-conservation as coupling condition

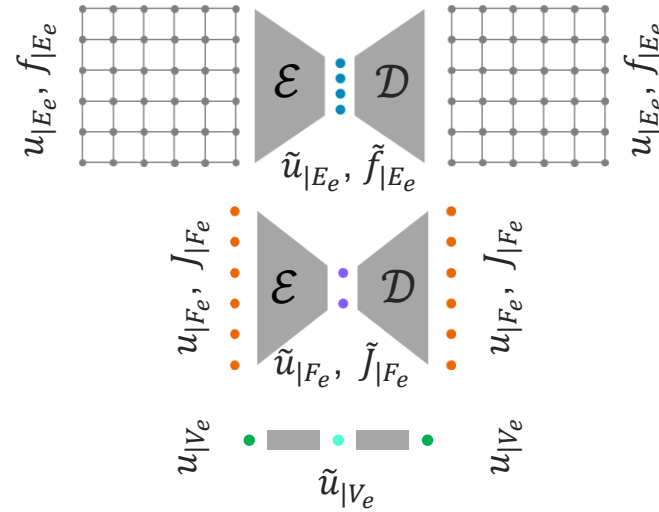
Hybridized Flux Conservative Neural Solver

Training Process

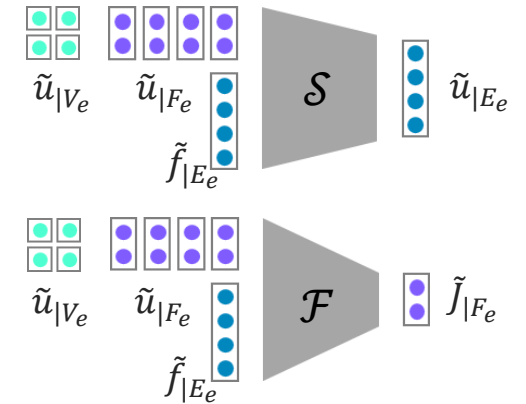
Domain decomposition into
HDD-DG elements



Encoding of vertex, face, and
inner variables



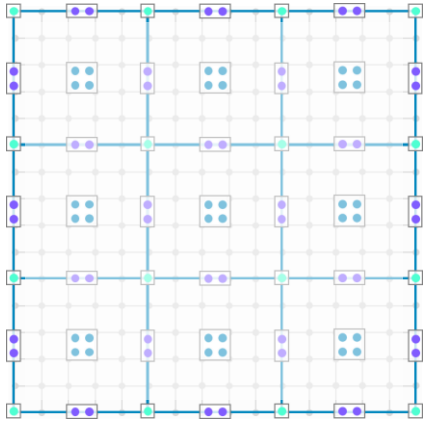
Operator learning of solution
and flux operators



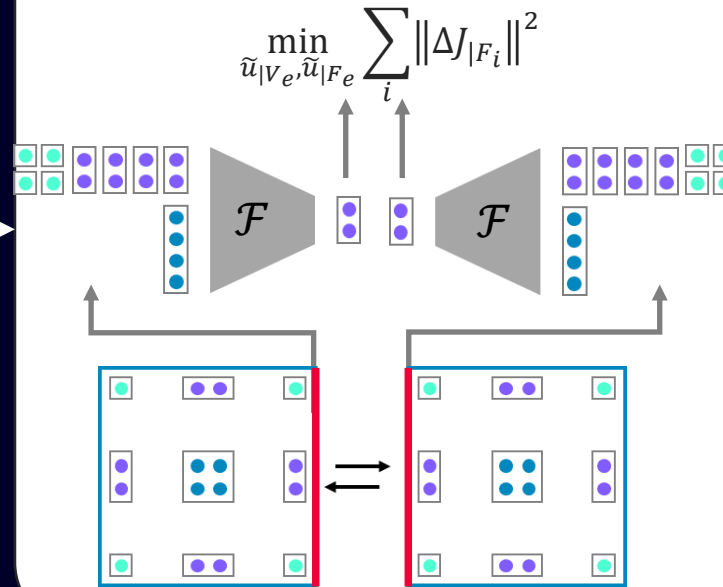
Hybridized Flux Conservative Neural Solver

Inference Process

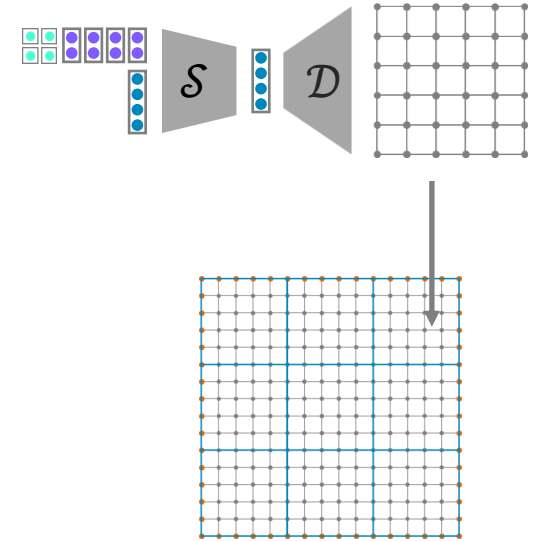
Encode right hand side and boundary conditions



Assemble Δ fluxes
for each **face** and **solve**



Recover latent solution and decode



Hybridized Flux Conservative Neural Solver Results

Setup:

- **Data:** 100 Simulations with 70x70 Finite Elements and random $f = a \exp(-(x - \mu)^2 / 2\sigma^2)$
- **Autoencoders:** PCA with 2 / 4 modes for faces / elements respectively
- **Operators:** 4-layer NN
- **Training:** Adams
- **Solution:** BFGS

Results:

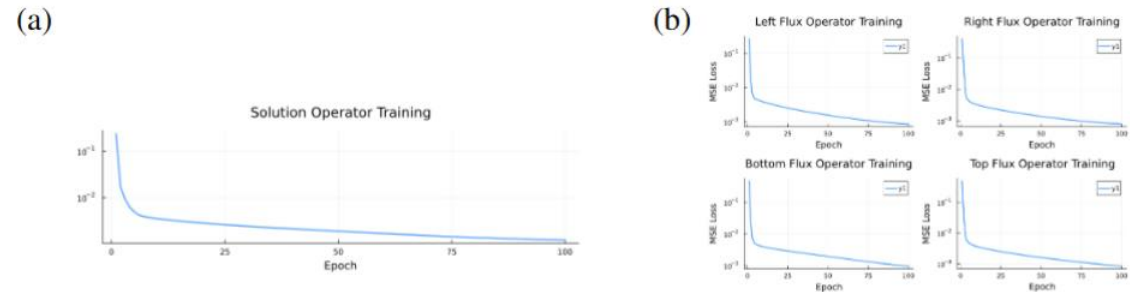


Figure 1: Loss evolution of the operator training (PCA encoding): (a) solution operator, (b) flux operators.

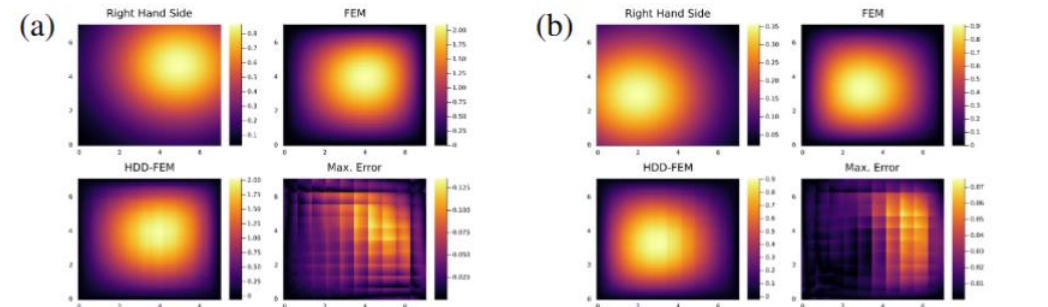


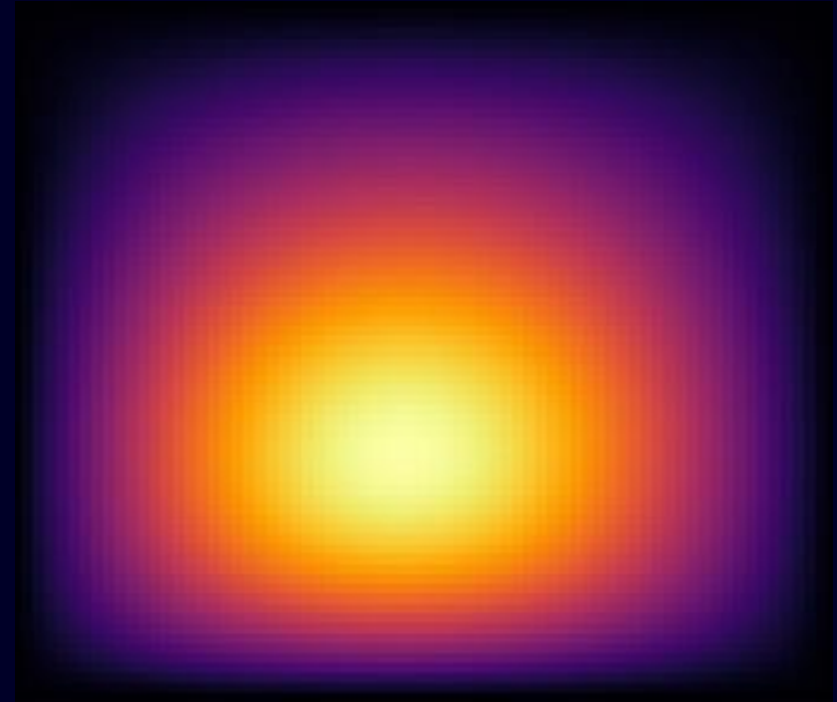
Figure 2: Validation of the method using PCA-encoding for two randomly chosen source functions f which have not been seen during the training.

Hybridized Flux Conservative Neural Solver

Open topics

This is just a first idea, thus there are many open questions

- ▶ More complex non-linear cases
- ▶ Geometry encoding
- ▶ Optimal non-linear solver
- ▶ Optimal architectures
- ▶ Coupling with other methods
- ▶ ...



5

The Future?

Demo: An AI Companion for Design and Engineering



Source: GradCad (2013): [GE jet engine bracket challenge](#)

Aircraft Engine Bracket - Technical Specification

Maximum Size (width x depth x height): 10in x 5in x 3in

Interface 1: 0.75 inch diameter pin.

Fixation / Interface 2-5: 4 0.375-24 AS3239-26 machine bolt: Nut face 0.405 in. max ID and 0.558 in. min OD

Minimum material feature size (wall thickness): 0.050 in.

Material: Ti-6Al-4V

Service Temperature: 75 F

Load Conditions:

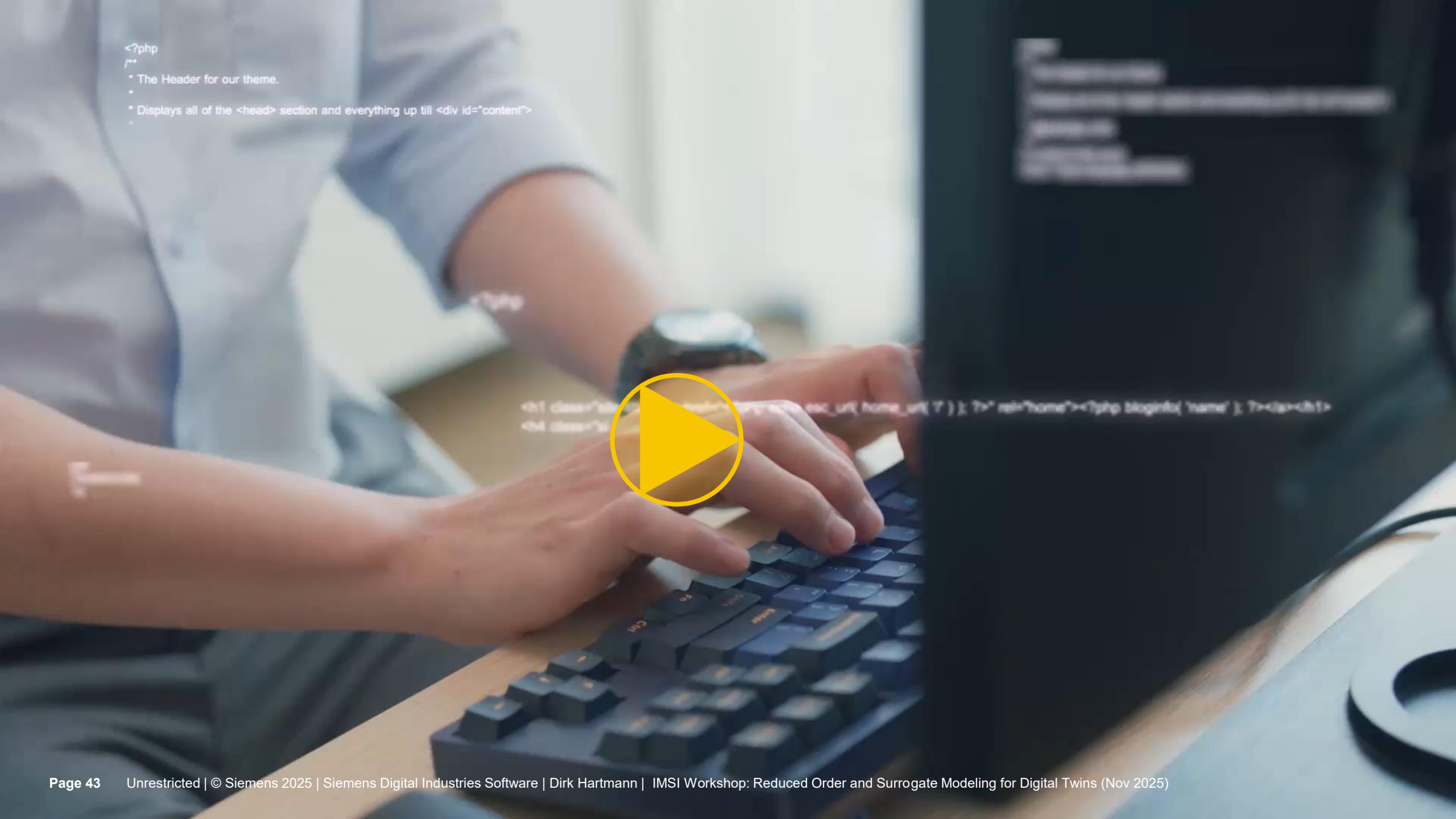
1. Max static linear load of 8,000 lbs vertical up.

Design Goal

- Maximum yield stress below 131 ksi
- Minimum weight



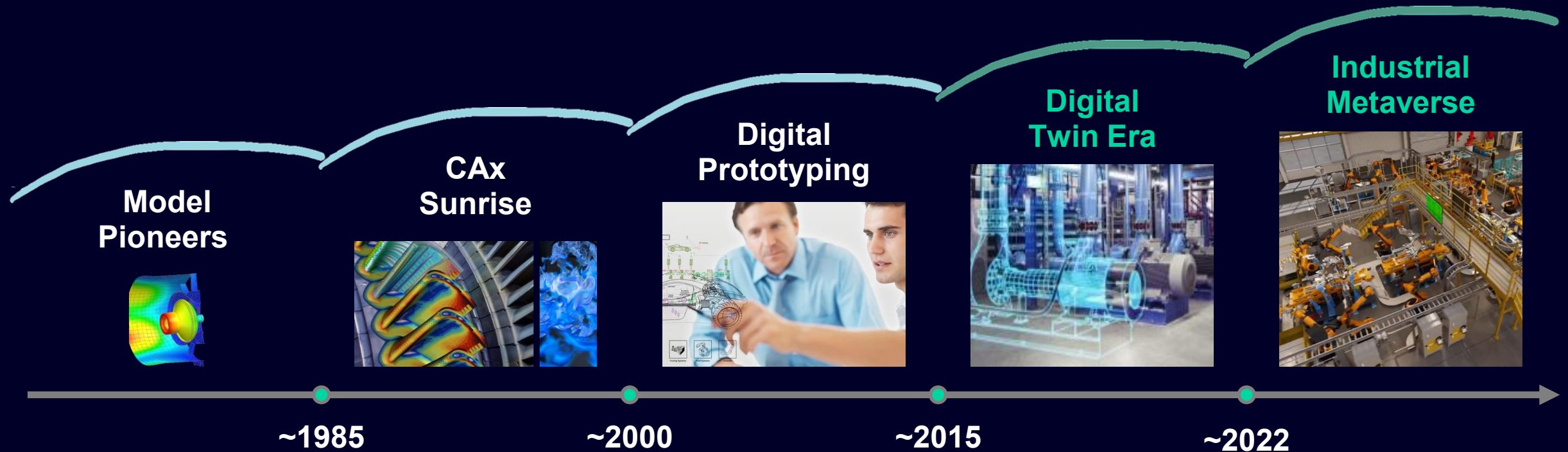
bracket.md



- <?php
- /*
- * The Header for our theme.
- *
- * Displays all of the <head> section and everything up till <div id="content">
- *

<h1 class="site-title"><?php echo esc_url(home_url('/')); ?> rel="home"><?php bloginfo('name'); ?></h1>
<h2 class="site-description"><?php bloginfo('description'); ?></h2>

Digital Twins - a golden age for industrial mathematics



CAx: Computer Aided Design, Engineering, & Manufacturing

Source: D. Hartmann, H. Van der Auweraer (2025): [Digital Twins - a golden age for industrial](#). Journal of Mathematics in Industry

Contact



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The Art of the Possible – Blog

<https://blogs.sw.siemens.com/art-of-the-possible>