Powering Innovation That Drives Human Advancement

Innovating Semiconductor Manufacturing with ML-augmented Digital Twins

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EDPS, 2024

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Agenda

Challenges of Digital Twin in Semiconductor Manufacturing

Emerging Digital Twin and Co-optimization Technologies

Manufacturing Digital Twin in Omniverse and Use Cases

Summary

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Digital Twins for Semiconductor Manufacturing Requires Partnerships

- NSTC Funding one Digital Twin Manufacturing Institute at $285 million over 5 years as consortium of universities and companies from US Chip Act
  - CHIPS for America Announces $285 Million Funding Opportunity for a Digital Twin and Semiconductor CHIPS Manufacturing USA Institute | NIST

- Rockwell and NVIDIA provide process automation tools, and DT models of factories with the Industrial Metaverse: Emulate3D, FactoryTalk, Omniverse

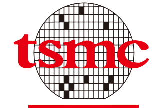
- MSFT and AWS provide IOT connections and compute on the cloud for data-analytics based Digital Twins: AzureTwin, AWS Twinmaker

- Equipment and Foundry companies like Applied Materials, Lam Research and TSMC can create Digital Twin models of their equipment, e.g. Applied Twin

- Ansys, PTC, Autodesk, etc. could provide simulation-based digital twins and hybrid (AI plus physics) digital twins

- Ansys is one of the 8 founding members of the digital twin consortium

Semi Digital Twin ECO Partners



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SoC/3DIC Manufacturing Process Overview

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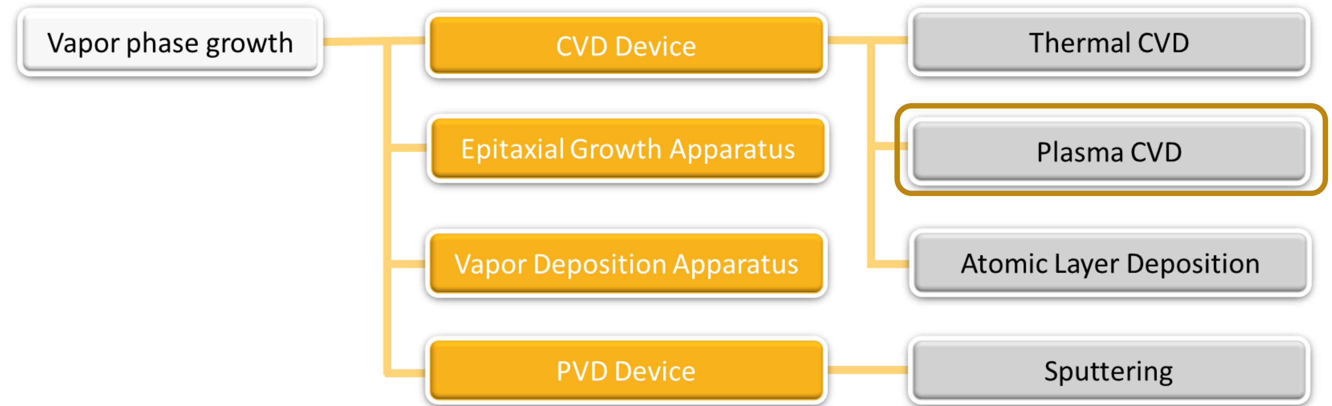
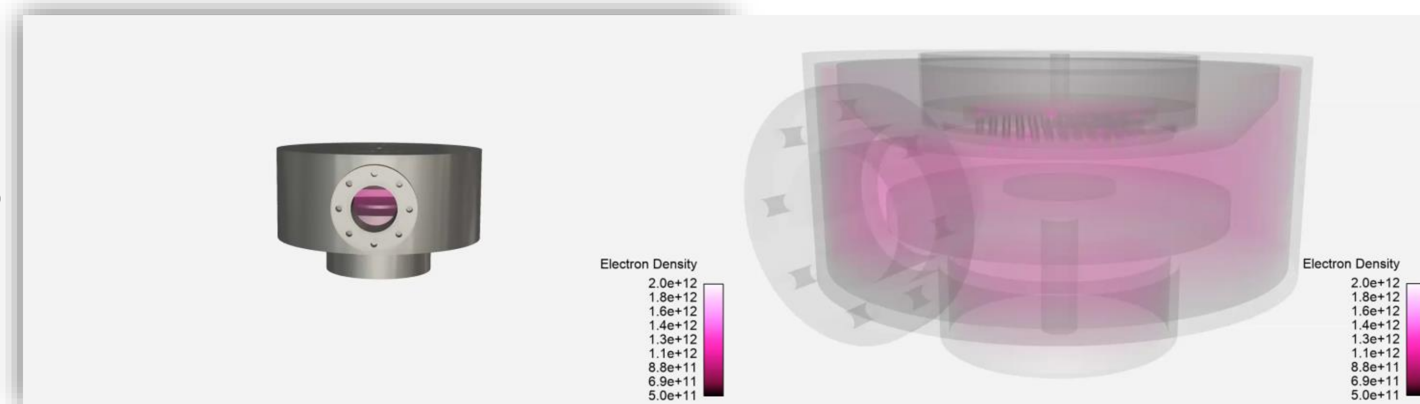
Film Forming - PECVD

- **Engineering Goals**
  - **Uniform** flow and temperature distribution for accuracy of film thickness across wafer
  - **Prevents** particle generation defects in the chamber
  - **Predict** non-uniformity of process results due to manufacturing equipment



- **Multiphysics Solutions**
  - **Chemkin Pro**: reaction mechanisms, material properties, etc.
  - **EMA3D and Fluent solvers**: Species transport, surface reaction considering the particle physics effect for plasma dynamics
  - Multiphsysics simulation with ROMs considering time-domain electrodynamics, electromagnetics, particle in cells (PIC) and CFD
  - Native GPU-enabled fast CFD and mechanical solvers



- **Benefits**
  - **Improve** product quality and yield rate by optimizing design of equipment and process
  - **Save** engineering cost and **reduce** rework

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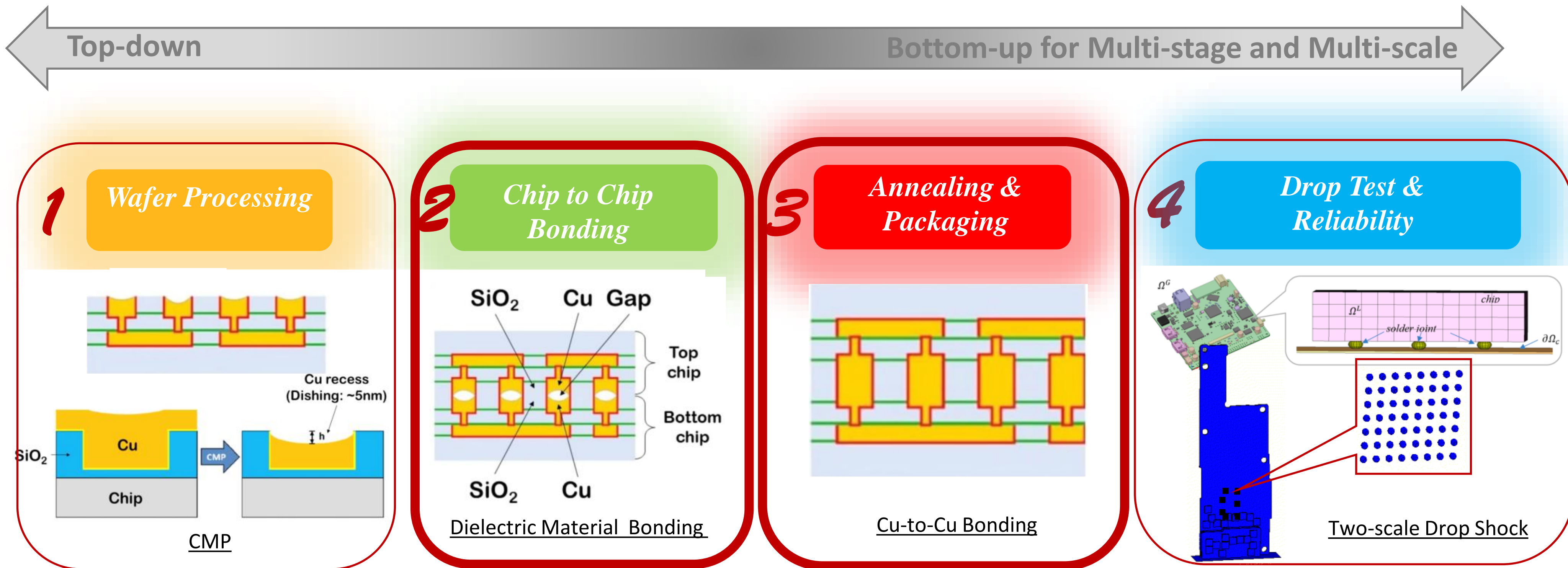
3DHI Process Simulation – CMP and Hybrid Bonding

- CMP analysis followed by adhesion between layers (e.g. Hybrid Bonding) simulation is in a pressing need



“Integrated Process-mechanical Stress Analysis of 2.5D/3D ICs with Two Types of Interconnections in Advanced Packaging”, B. Ren, N. Chang, et al., IIRW, 2023

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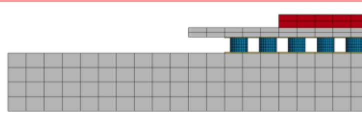
ML-based Multiscale Framework for Solder Joints Reliability

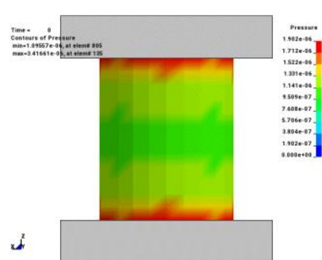
- Incompressible Smoothed Particle Galerkin (ISPG) Method and Two-scale Co-simulation (TSC) were developed in LS-DYNA to meet this need.

Manufacturing-informed Multi-scale Framework

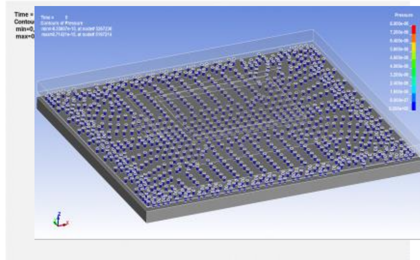
Chip-Scale Solder Reflow Simulation by ISPG Technology

Solder Reflow & Packaging





Single Solder Reflow



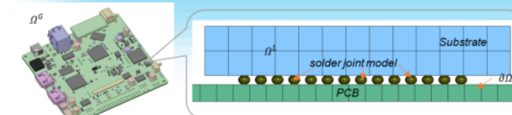
Reflow of 2000 Solder Balls

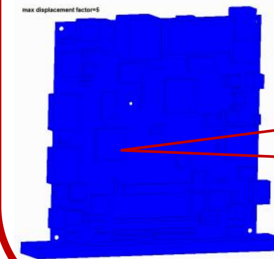
Immerse Modeling Thermal-induced PCB Warpage

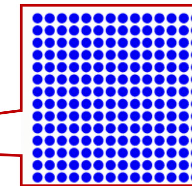
Mask and Pad Geometry Dissimilar Solder Ball Shapes

Two-scale Dynamic Shock Wave Simulation by TSC Technology

Drop and Shock Tests







Linking Chip- and System-Scale in Drop Shock Simulation

Wei H., Wu CT, Hu W., Su TH., et al. (2023). "Machine Learning-based Multi-scale Simulation of Composite Materials with Applications to Electronics Drop Tests", Journal of Engineering Mechanics.

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Semiconductor Manufacturing Process Overview

Silicon Crystal Growth

Ingot Shaping and Slicing

Wafer Lapping, Etching and Polishing

Oxidation

Coating Application

Photoresist Exposure

Etching

Doping

Inspection

Layering

Wafer Dicing

Lead Frame Mounting

Wire bonding, Soldering

Molding

Trimming and Forming

PCB Modeling

Mechanical Reliability

Shock and Vibration Reliability

Raw Silicon Producers

Equipment Manufacturers and Chip Factories

Outsourced Assembly & Testing

PCB Manufacturers

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Agenda

Challenges of Digital Twin in Semiconductor Manufacturing

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Summary

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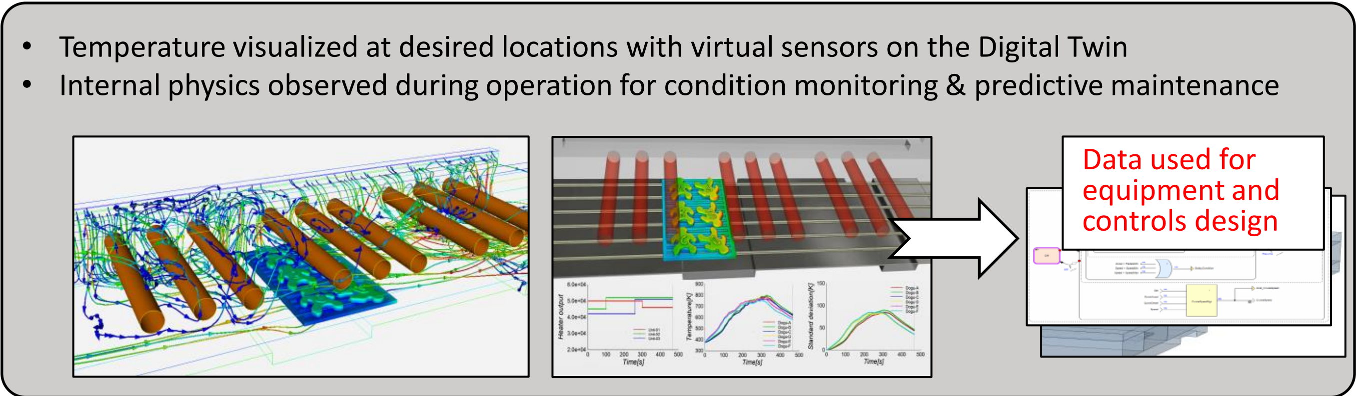
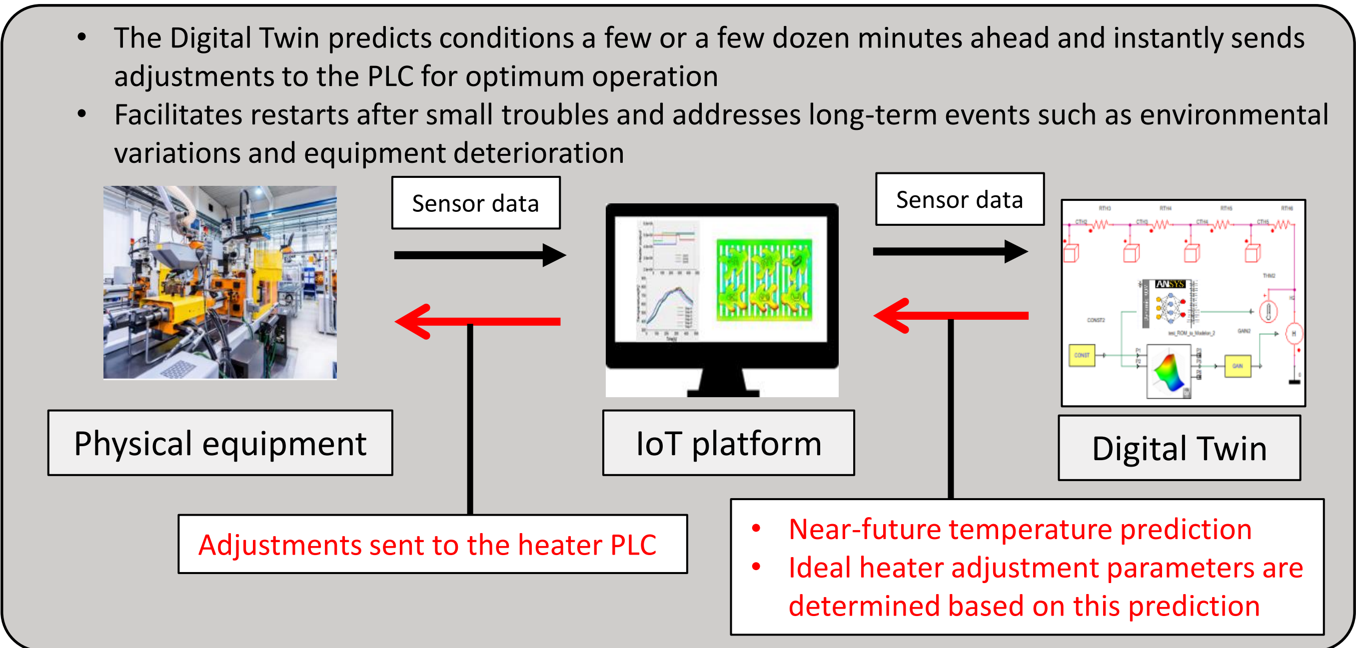
Overview of Digital Twin

- Ansys physics-based Digital Twins virtually emulate production line equipment with fidelity and synchronize the virtual and physical systems to address challenges arising in the production line

  - Digital Twin benefits
    - Predictive and prescriptive maintenance
    - Equipment and operation optimization
    - System construction and troubleshooting

  - Challenges expected in production lines
    - Shorten the line startup period
    - Improve the yield rate
    - Trace the causes of defect and manage data
    - Operate efficiently and autonomously





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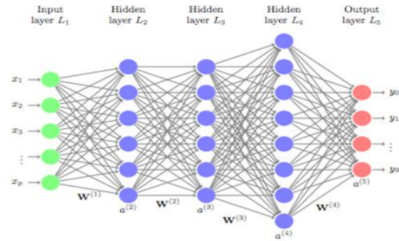
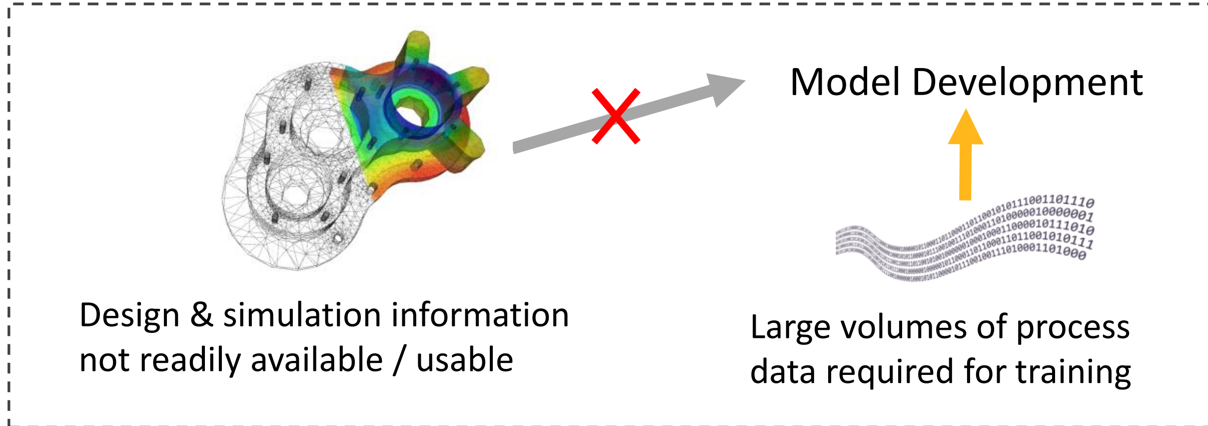
Digital Twin Challenge: Accuracy, Time & Cost



Data-Driven Modeling

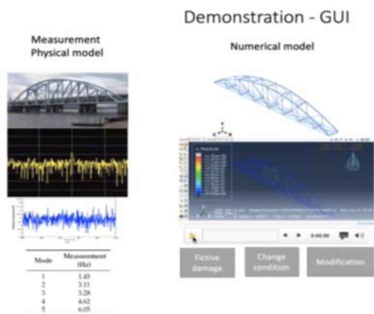


Design & simulation information not readily available / usable

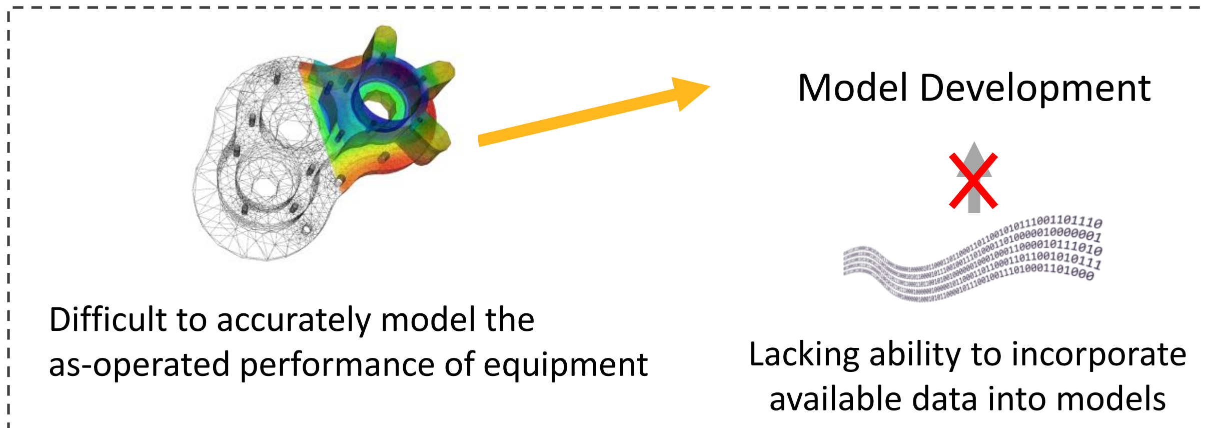
Large volumes of process data required for training

Insufficient accuracy, limited by observed data

Long, expensive time scales to develop & deploy



Simulation-Based Modeling



Difficult to accurately model the as-operated performance of equipment

Lacking ability to incorporate available data into models

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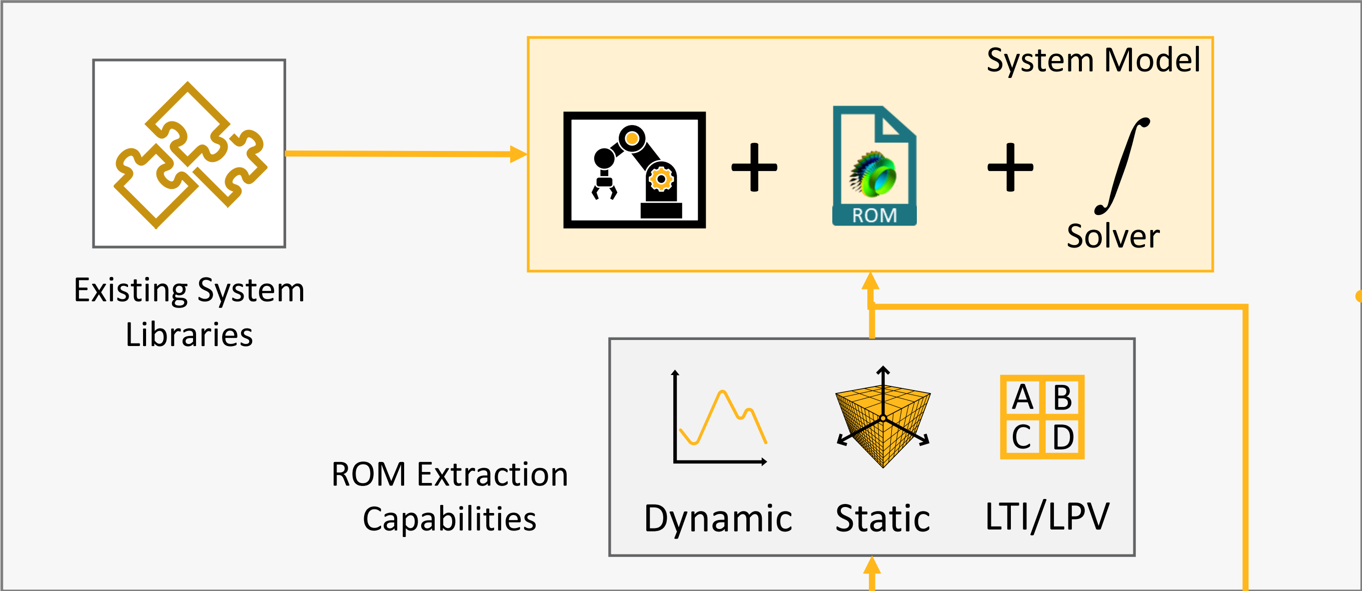
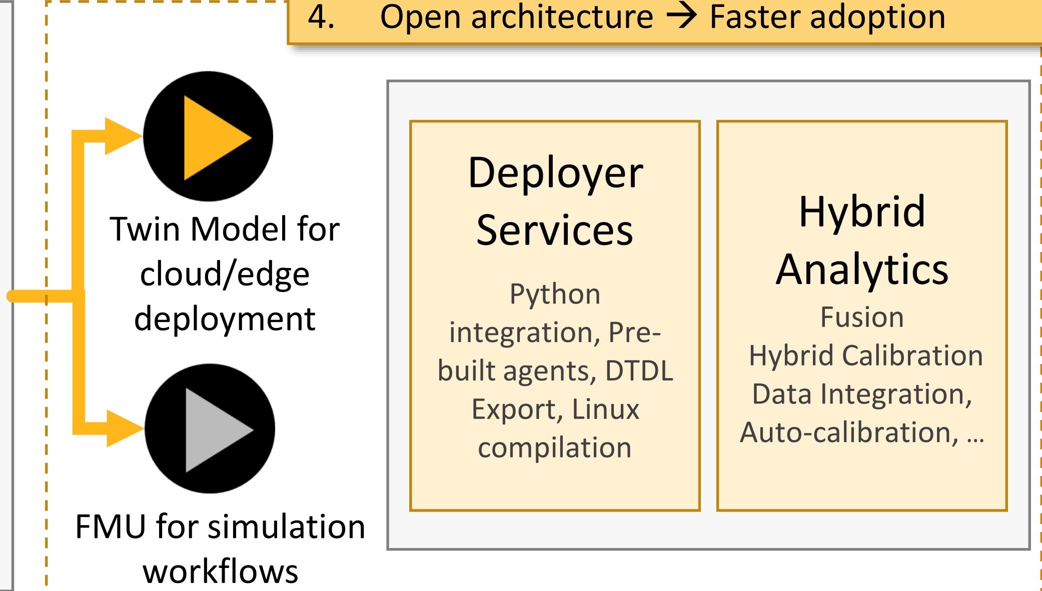
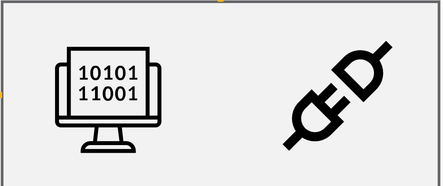
Ansys Digital Twin Architecture

1. Hybrid Calibration → Most accurate Twin
2. Best in class ROM capabilities → Easy Reuse
3. Unique runtime model → Easy Scalability
4. Open architecture → Faster adoption





Validated Ansys Physics



Test Data, 3rd Party Software

Open Ecosystems and Key Announced Partners

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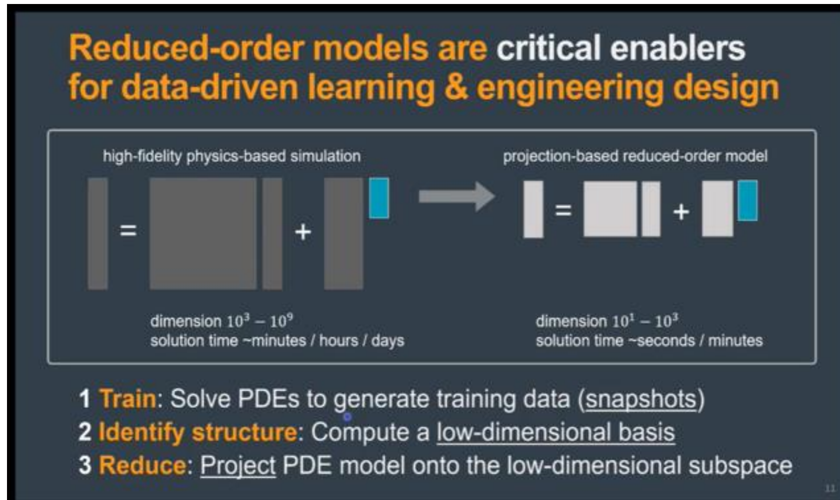
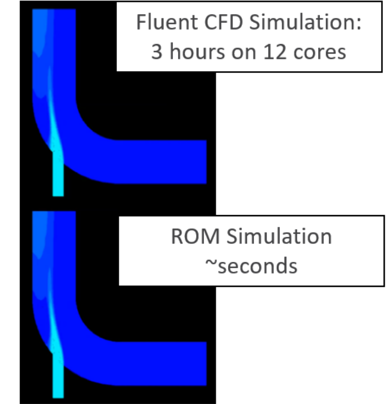
Reduced Order Models (ROM) in Hybrid Digital Twin

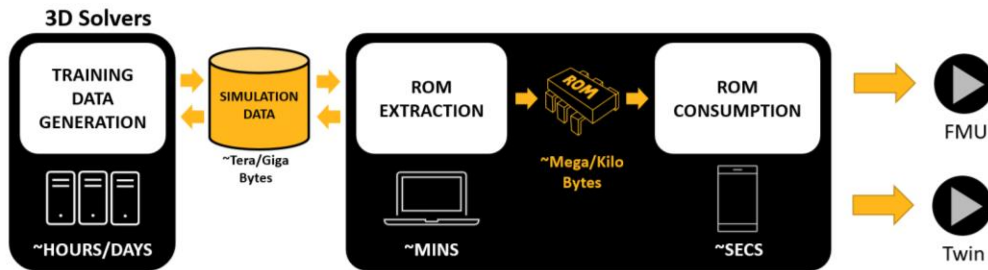


ROMs are compact, auto-generated representations of full-3D models that are useful for control design/validation

- ROMs are usually compute and license intensive to create but fast once built
- ROMs have well-defined inputs and outputs (electrical ports, parameters, etc)
- ROMs match the steady-state and/or dynamic responses of the original model, within specified tolerance
- Benefits
  - Reuse: Easily and automatically generate accurate & validated component models
  - Process Compression: Simulate accurate models in 1/10th to 1/100th of the time
  - System Verification and Optimization: Perform rapid design optimization and tradeoff analysis at system level



ROM Generation Workflow



- All ROMs can be exported as FMUs for use in other tools for scalar inputs and outputs
- ROMs with field inputs/outputs are exported in a proprietary Ansys format (Twin)

ROM Type	Training Data Generation		ROM Extraction		Consumption Format	Ease of Use	Complexity
	Type of Data Required	Source Tools	ROM Technique	Tools			
Response Surface	Parameter Sweep/DoE	All/Any	Lookup table + interpolation	OSL, MC, TB	FMU for Scalars, Twin for Fields	Integrated end-to-end workflow	No states/steady-state only
LTI/LPV/State-space ROMs	Response to step inputs	Mech, CFD and EM	State-space Model with Interpolation	TB, Fluent	FMU for Scalars, Twin for Fields	Mostly integrated. Manual transfers.	Linear or weakly non-linear and stateful
DynaROM	Response to various input waveforms	All/Any	Nonlinear ODE	TB	FMU for Scalars, Twin for Fields	Experience needed to generate training	Non-linear and stateful

OSL : optiSLang MC : Model Center TB : Twin Builder FMU : Functional Mockup Unit

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Enabling ML-augmented Hybrid Digital Twin

Coexistence

Physics Model | Data Model
AI/ML
Physics | Data

Simulation Enhancing Data

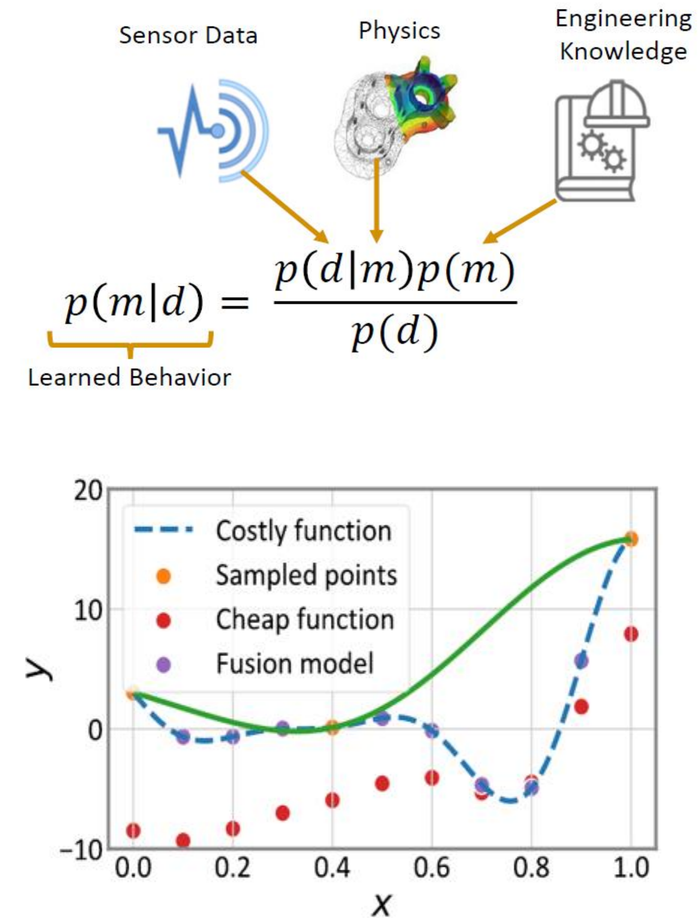
Virtual Sensor
Data Model
Training
Physics Model
AI/ML
Physics | Data

Data Enhancing Simulation

Physics Model
Data Model
Inference
AI/ML
Physics | Data

Full Integration

Hybrid Physics/Data Model
AI/ML
Physics | Data



M. Adams et al. - Hybrid Digital Twins: A Primer on Combining Physics Based and Data Analytics Approaches - IEEE Computer Society, 2022

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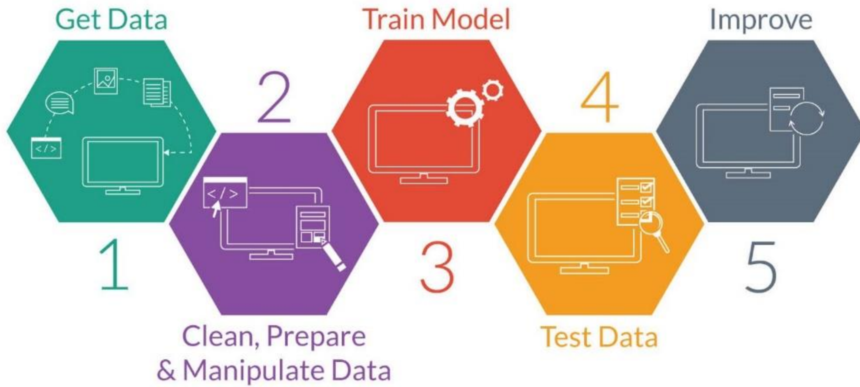
Auto-ML Framework Needed for System Technology Co-optimization



Adaptive Meta-Model of Optimal Prognosis (AMOP) for scalar values:

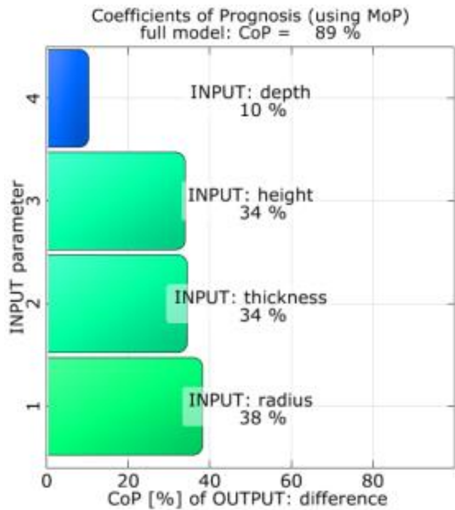
- Objective measure of prognosis quality = Coefficient of Prognosis (CoP)
- Determination of relevant parameter subspace
- Determination of optimal approximation model
- Approximation of solver output by fast surrogate model without over-fitting
- Evaluation of variable sensitivities

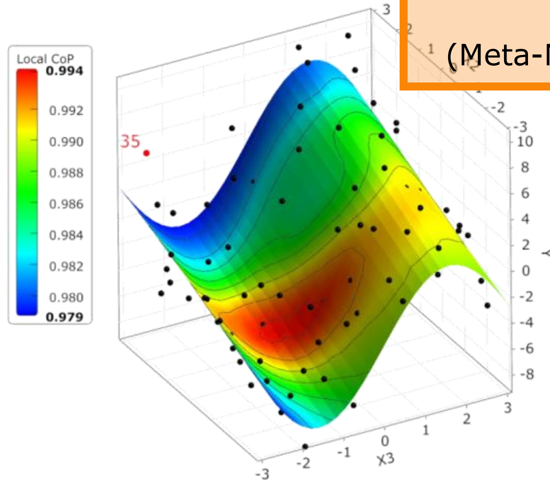
Calculate forecast quality using **CoP** (Coefficient of Prognosis)

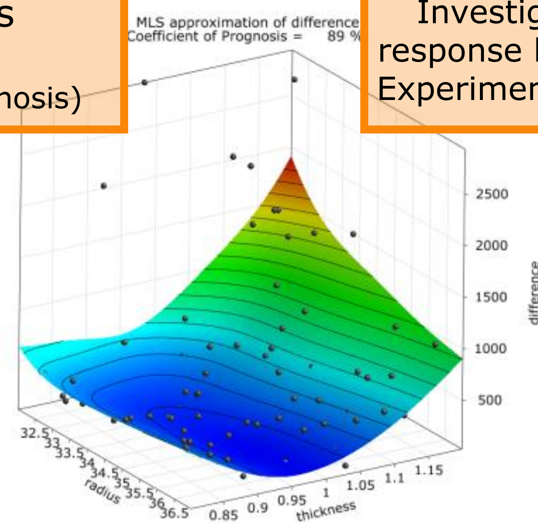
The winner is … **MOP** (Meta-Model of Prognosis)

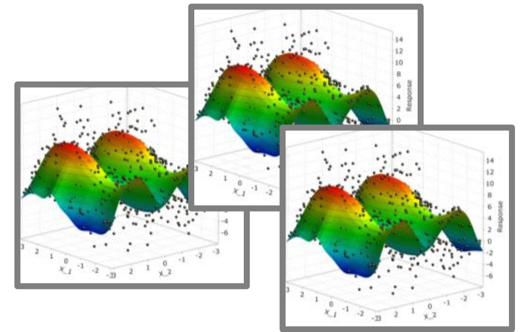
Investigate response by response based on Design of Experiments (DOE) sampling

Generate competing meta-models









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Agenda

- **Challenges of Digital Twin in Semiconductor Manufacturing**
- Emerging Digital Twin and Co-optimization Technologies
- Manufacturing Digital Twin in Omniverse and Use Cases
- Summary

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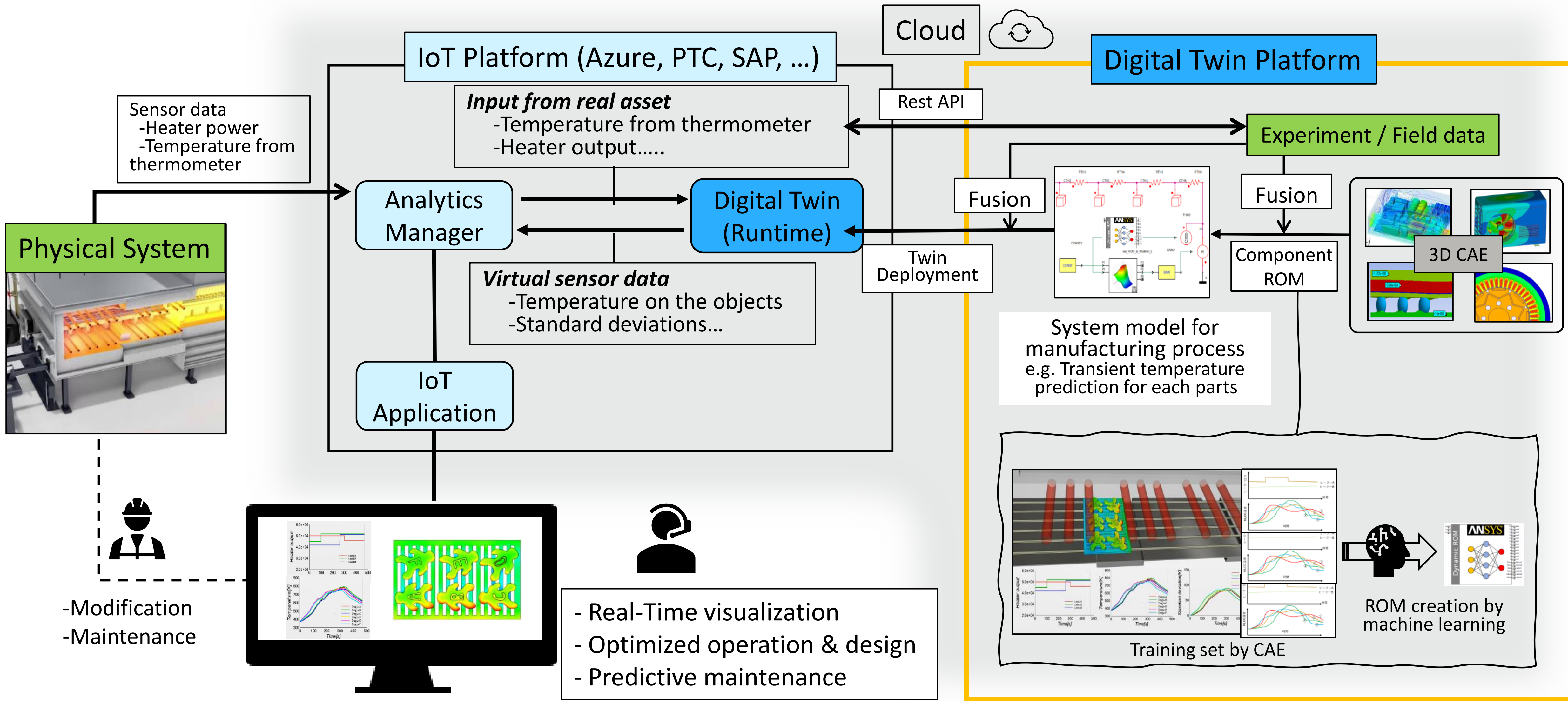
ANSYS Digital Twin for ***Manufacturing Process***



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Digital Twin for Thermal Issue in Data Center

Challenge

- The growing energy consumption in data center is a serious issue. Effective cooling of the data center is a key factor to reduce it, because over 30 % of the energy consumption is from the cooling system.
- Digital Twin operations in real-time for thermal-flow distribution help the optimal operations.

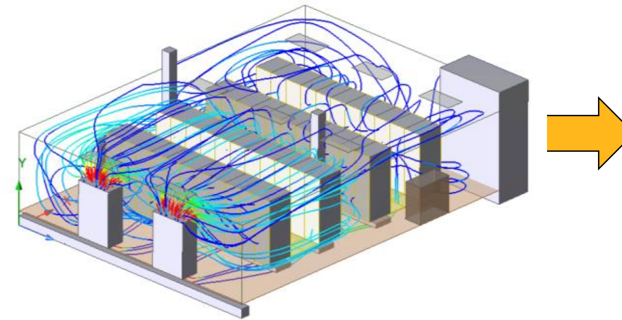
Solution

- Quick training data creation with various operating conditions for Static ROM & LPV ROM by 3D CFD on ***AEDT Icepak***.
- Validated ROM in ***Twin Builder*** can be exported via ***Twin Deployer*** to visualize the temperature fields and the point variables as virtual sensors with dynamics. ***PyTwin*** helps its deployment.

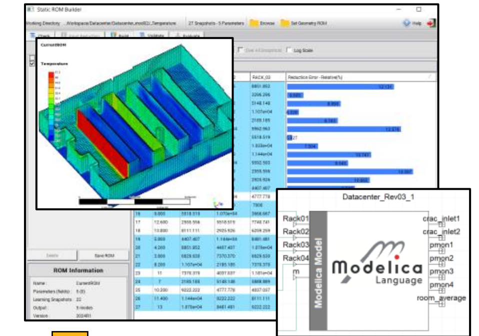
Benefits

- Digital Twin of data center offers:
  - ✓**Real-time visualization** to identify thermal issues.
  - ✓**Immediate alerts** for swift operator response.
  - ✓**What-if analysis** for strategy development and scenario planning.
- Digital Twin enables the optimal operations, reduction of energy consumption and risk management for Data center.

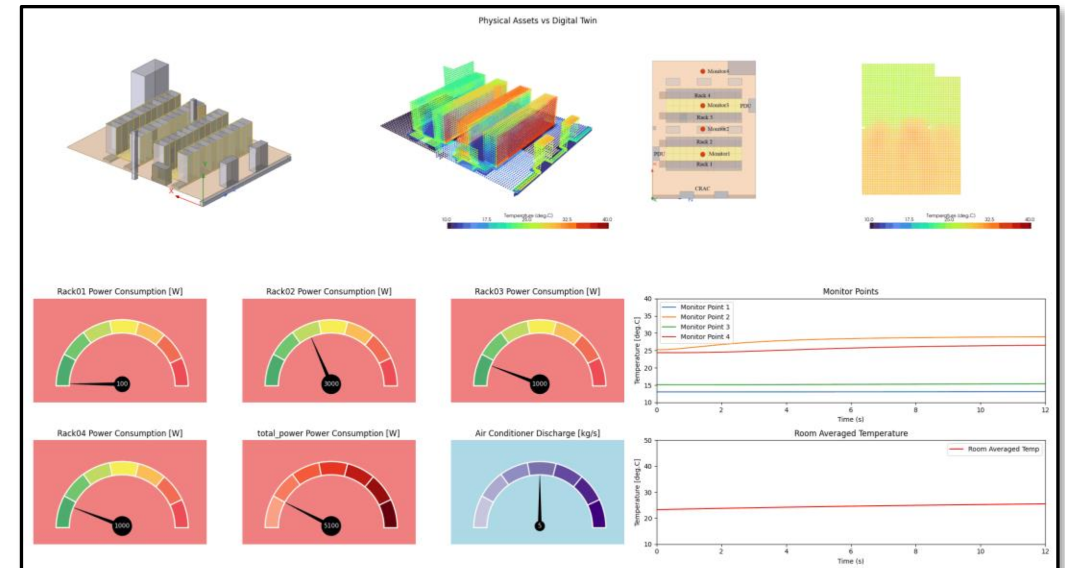
3D thermal flow simulations



Model creation & validation



Twin Deployment & real time visualization



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optiSLang Workflows + 3D ROMs for Virtual Digital Twin

Continental

- 3D ROM function as a virtual twin in a browser-based app
- Able to extract 3D field-data (temperature) out of Icepak
- Prediction quality of 3D field-data is checked and sufficient
- Receive real-time measurements (5-8 thermocouples) and fit/predict to whole corresponding temperature distribution in 4 seconds
- Wide audience of laboratory workers can benefit
- Enables rapid assessment on demand immediately
- A **robust optimal design** can be found early in the process

Digital Twin
Pros and cons of Test and Simulation

TEST DEVICE
- Real Product used
- Measurement itself is in real-time
- Result reliability is huge

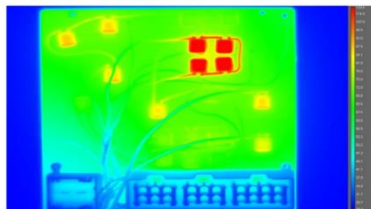
But:
- Physical modification of the product
- Limited measurement points

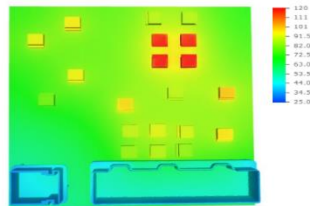
SIMULATION MODEL
- Parametric modelling
- Based on virtual data early in the process
- High resolution

But:
- Dependent on the accuracy of simulation model and the chosen input parameters.

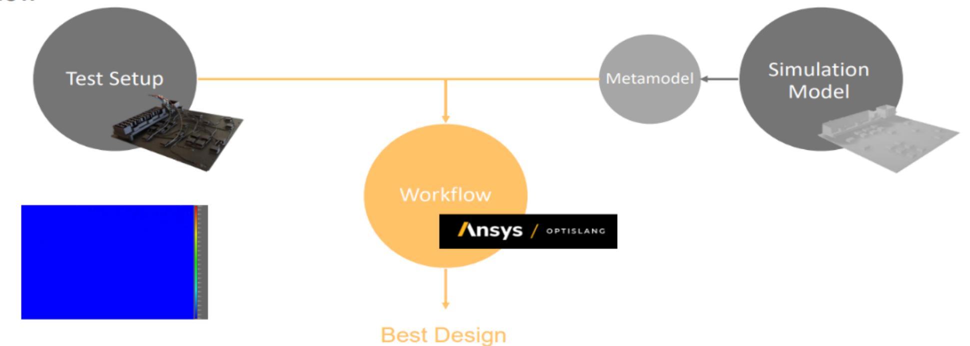
› The **Digital Twin** combines the advantages of test and simulation, eliminating their disadvantages.

Digital Twin
Comparison IR Picture & Digital Twin


Test Setup - IR Picture


Digital Twin Result

Digital Twin
Workflow



Thermal Digital Twin & Virtual Build: A new approach of understanding systems, Laura Lindner, Continental GmbH, WOST2023,

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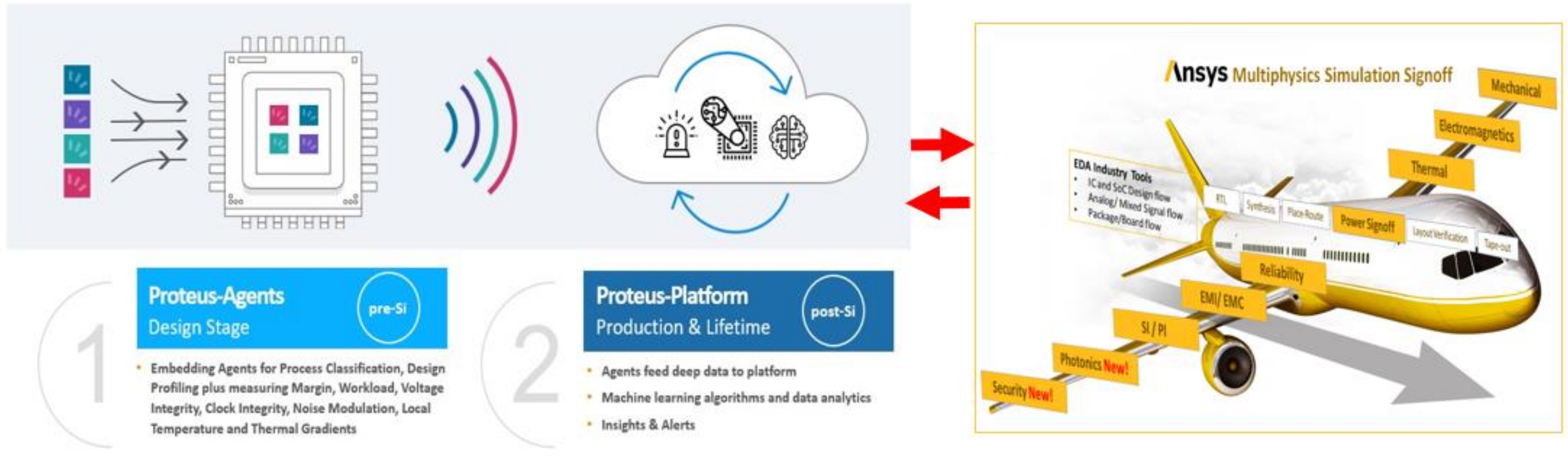
Emerging Model-based Digital Twins with On-chip and System Monitoring Solution (e.g. proteanTecs, Moortec/Synopsys, and PDF)



Key benefits for the application-specific reliability monitoring and digital twins

- Model-based digital twins for application-specific reliability such as aging/wear-out prediction for predictive maintenance with Lifetime Electronics Monitoring
- Can root-cause PI/SI/TI issues during testing/field w/ multi-physics simulation
- Provide on-chip agents feedback on the design with application-specific reliability information
- Optimal locations of on-chip agents can be provided by multi-physics simulation solutions for Thermal/DvD/Workload/Timing, etc.

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Integration with Nvidia Omniverse for Digital Twin Deployment

- Digital Twins runtimes can be executed with Omniverse
  - Input values defined through constant, time series, or streamed from real world
- Results, including 3D ROM visualization can be rendered in Omniverse, and combined with other capabilities of the platform with scene definition, AR/VR, and cloud deployment/streaming, etc.

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Summary

- A robust Hybrid Digital Twin solution is needed that combines the benefits of physics-based simulation with data-based ML techniques to create accurate, evolving representations of real-world assets
- Multiphysics simulation is key to Digital Twin implementations, providing critical capabilities such as virtual sensors, what-if analysis, causality and failure mode analysis
- Hybrid digital twin enables the reuse of existing simulation models (via ROMs, optiSLang, and customized ML solutions), typically created during product design, and makes them fit-for-use during manufacturing operations in combination with measurement data
- ML-augmented Hybrid Digital Twins can be used for Semiconductor Manufacturing real-world use cases

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Acknowledgement

- Thanks to Sameer Kher, Matt Adams, Kalyan Sharma, Srinivasa Mohan, Nima Arkhazloo, Akira Fujii, Bo Ren, CT Wu, and Prith Banerjee for the discussion on hybrid digital twin

- Thanks to Haiyan He, Akhilesh kumar, Jie Yang, Wenbo Xia, and Lang Lin on the discussion of on-chip thermal digital twin

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