Pushing the Limits by Open Standards: Enabling Larger, Faster, and More Credible System Simulations

Oliver Lenord, Bosch Research

Keynote at the American Modelica Conference, Oct. 12-14, 2026, Atlanta, USA

Public C-SC0

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Pushing the Limits by Open Standards
Content

- Part 1:
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  - Objectives
  - Achievements:
    - M&S Scalability
    - Process Scalability
- Part 2:
  - Agentic Model-based Systems Engineering

- Summary/Conclusions/Outlook

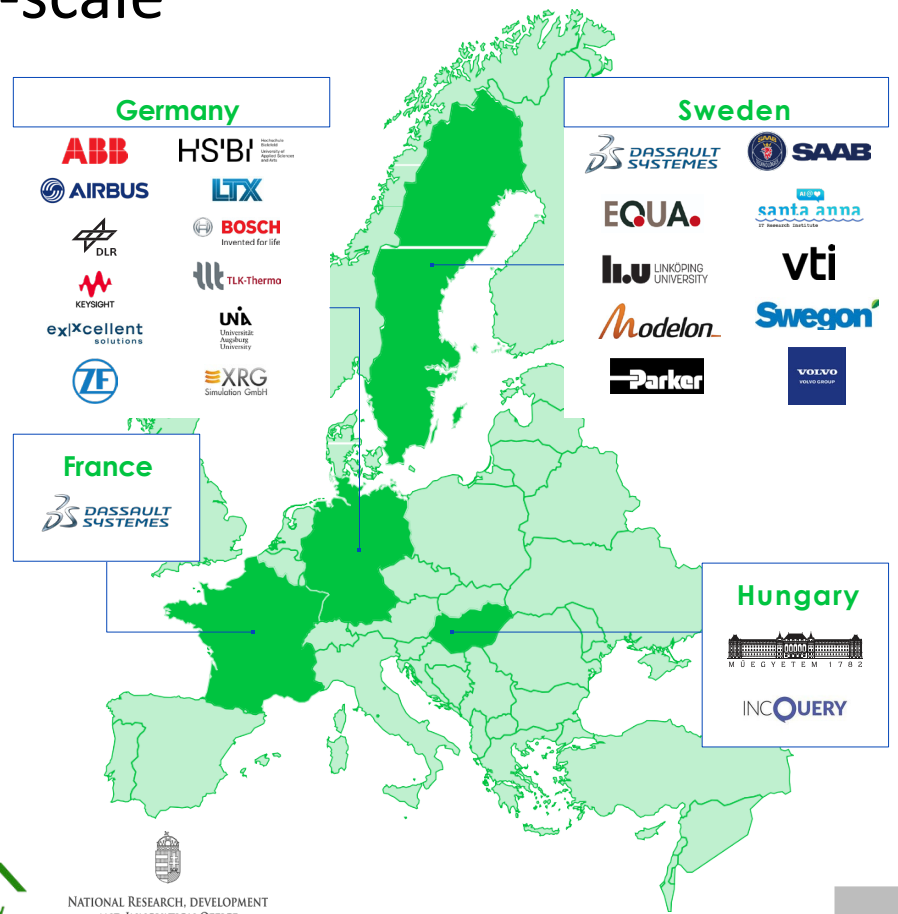
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ITEA4 22013 OpenSCALING

Open standards for Scalable Virtual Engineering and Operation

Enable credible system simulation on large-scale

- Speed-up simulations by magnitudes
- Scale model size by magnitudes
- Credible and traceable simulation workflows



Start date: November 2023
End date: May 2027*

Project website
https://openscaling.org/

*Final approval of cost-neutral extension pending

Funded by:

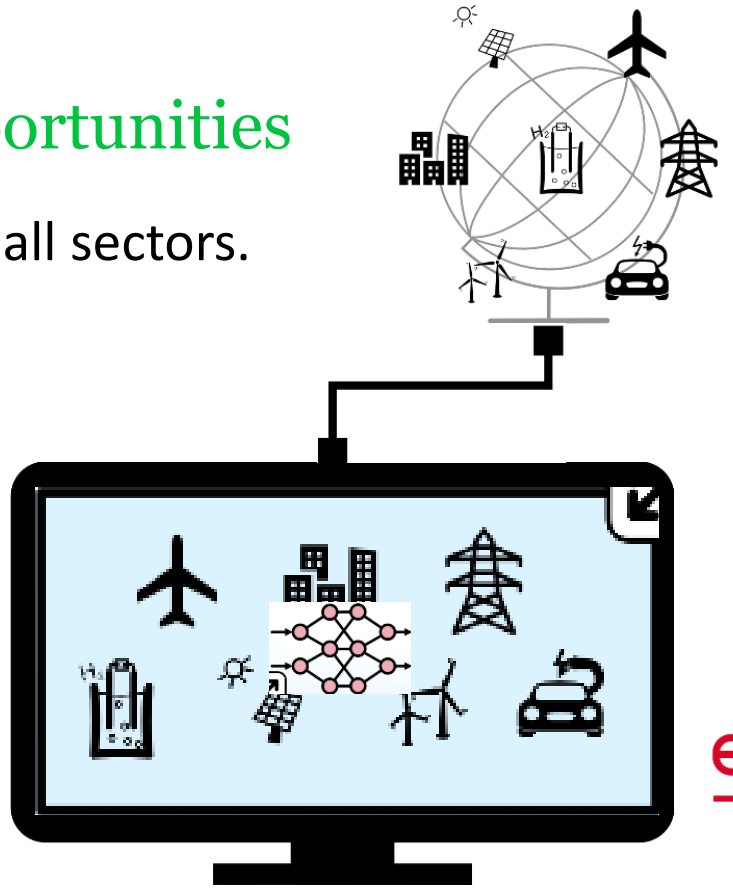
Federal Ministry of Research, Technology and Space

VINNOVA Sweden's Innovation Agency

National Research, Development and Innovation Office Hungary

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Problem Statement – Solutions – Opportunities



- Urgent need for sustainable solutions across all sectors.
  - Demand for new technologies, redesign and wholistic optimization
- Enable scalable virtual engineering
  - Simulation methods, tools
  - processes, standards, exchange formats
- Exploit
  - Modeling & Simulation tool USPs ➔ Increase market share, open new markets
  - Sustainable product development ➔ Gain productivity and reduce time to market

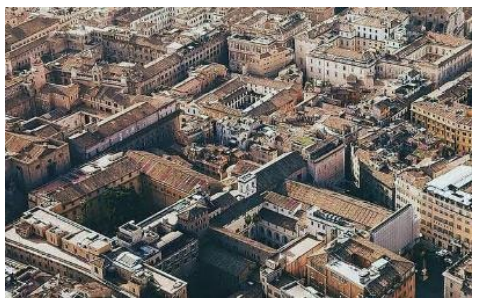
The Scalability Challenge – System of Systems

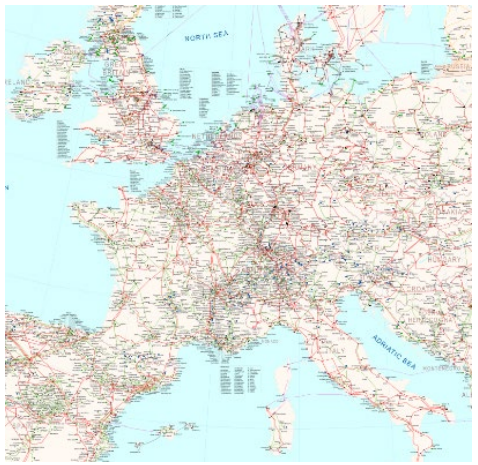










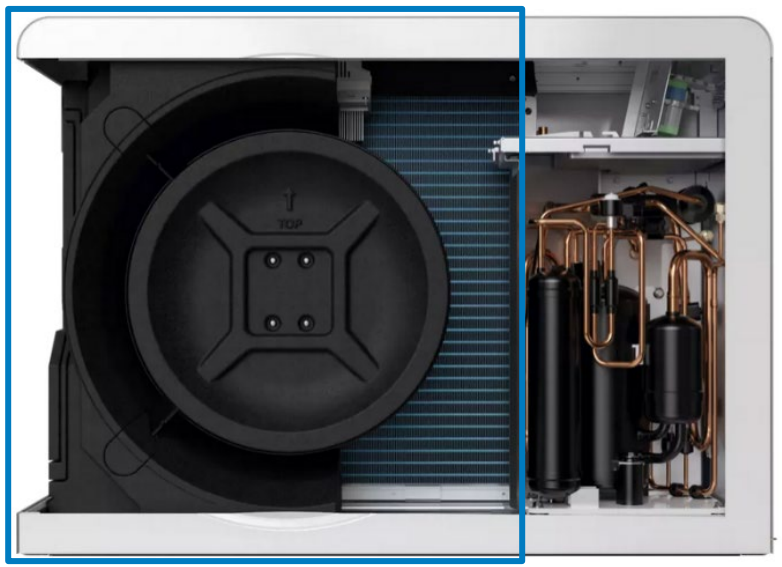


Casella, Francesco. “Simulation of Large-Scale Modelica Models with Array-Preserving Technology: Early Results and Perspectives.” Keynote presented at the OpenModelica Annual Workshop 2023, Linköping, February 6, 2023.

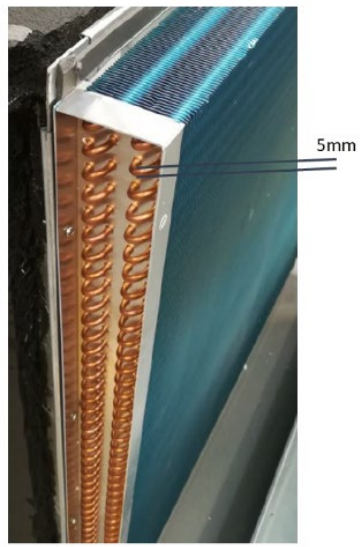
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The Scalability Challenge – n-Dimensional Discretization

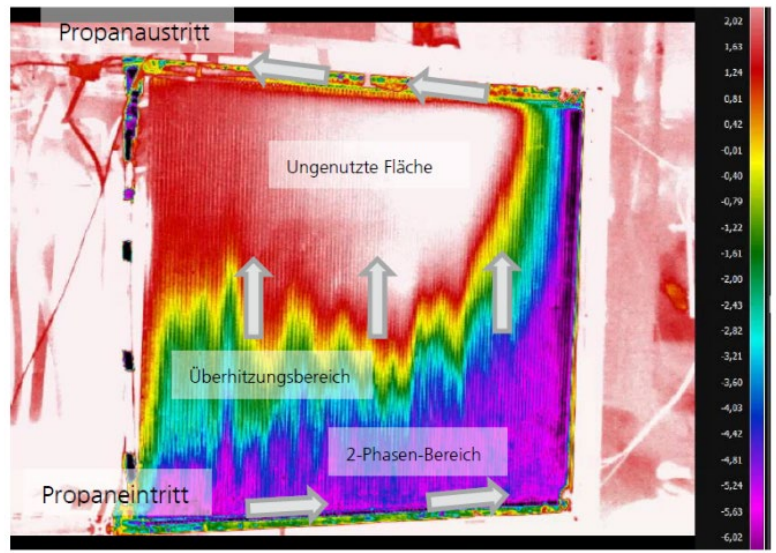
Fan & Evaporator



Heat Exchanger

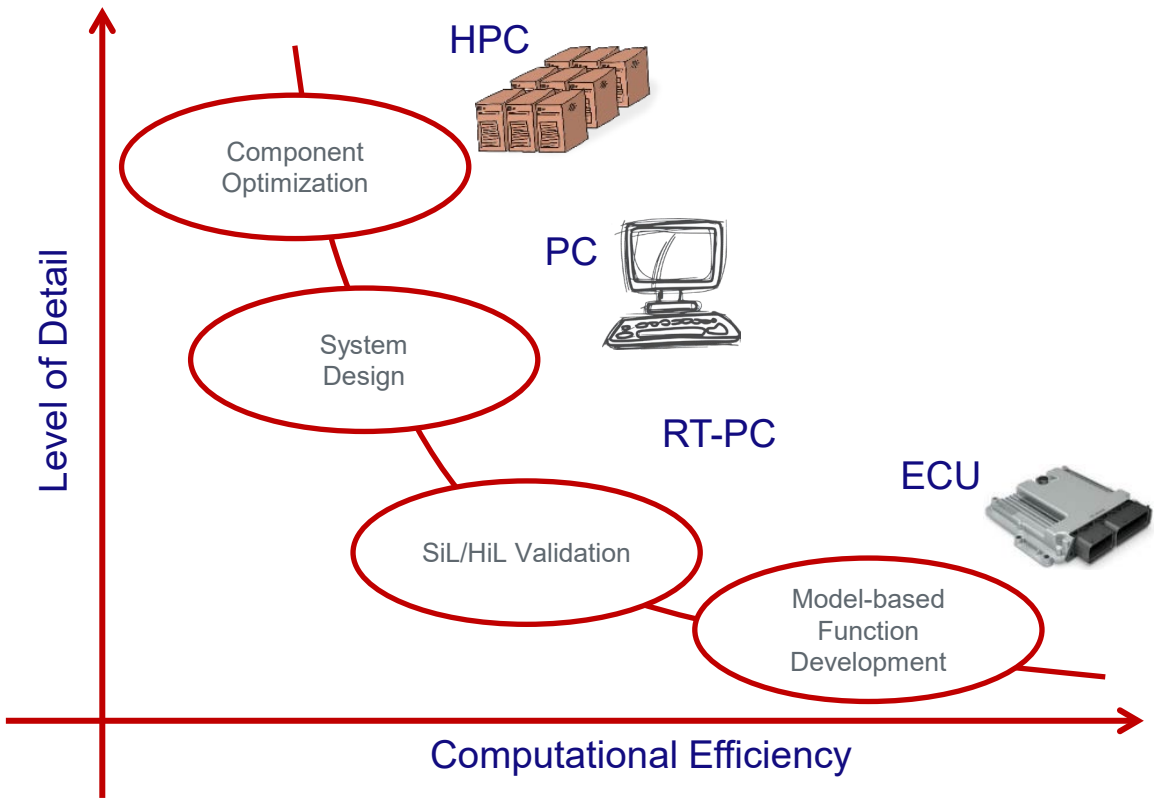


Spatial distribution of Icing



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Scalability Challenge – Computational Down-sizing



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Project Objectives & Challenges

Increase scalability of models

- Tools & methods for large scale system simulation.
- Highly flexible pre-compiled models.
- Efficient model quality assessment and UQ* for large and/or high dimensional systems.
- Built-in simulation AI* support.

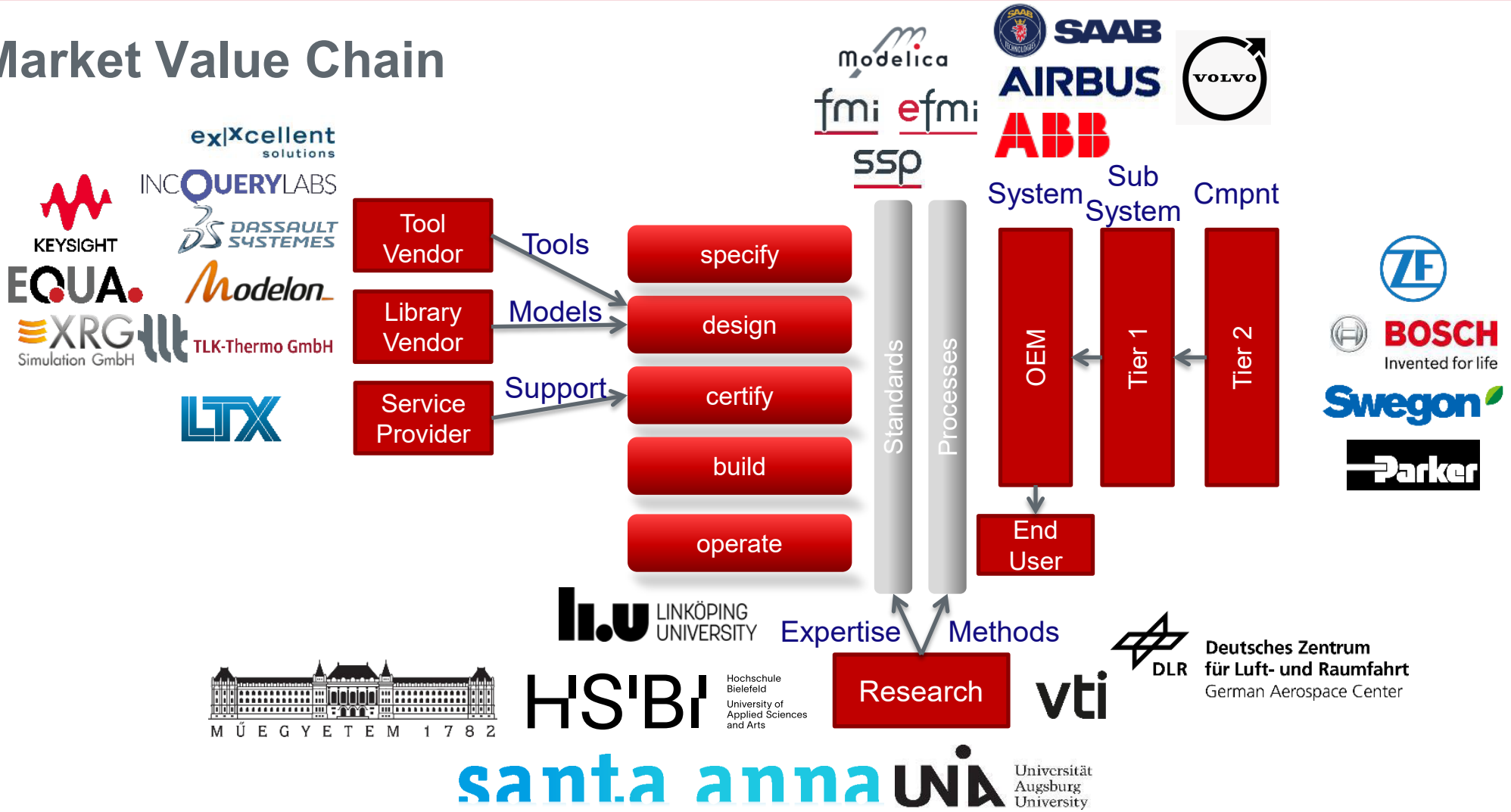
Increase scalability of processes

- From manual modeling to model generation.
- Meta data enriched model exchange standards.
- Traceable model credibility as integral part of model-based systems engineering

UQ: Uncertainty Quantification
AI: Artificial Intelligence

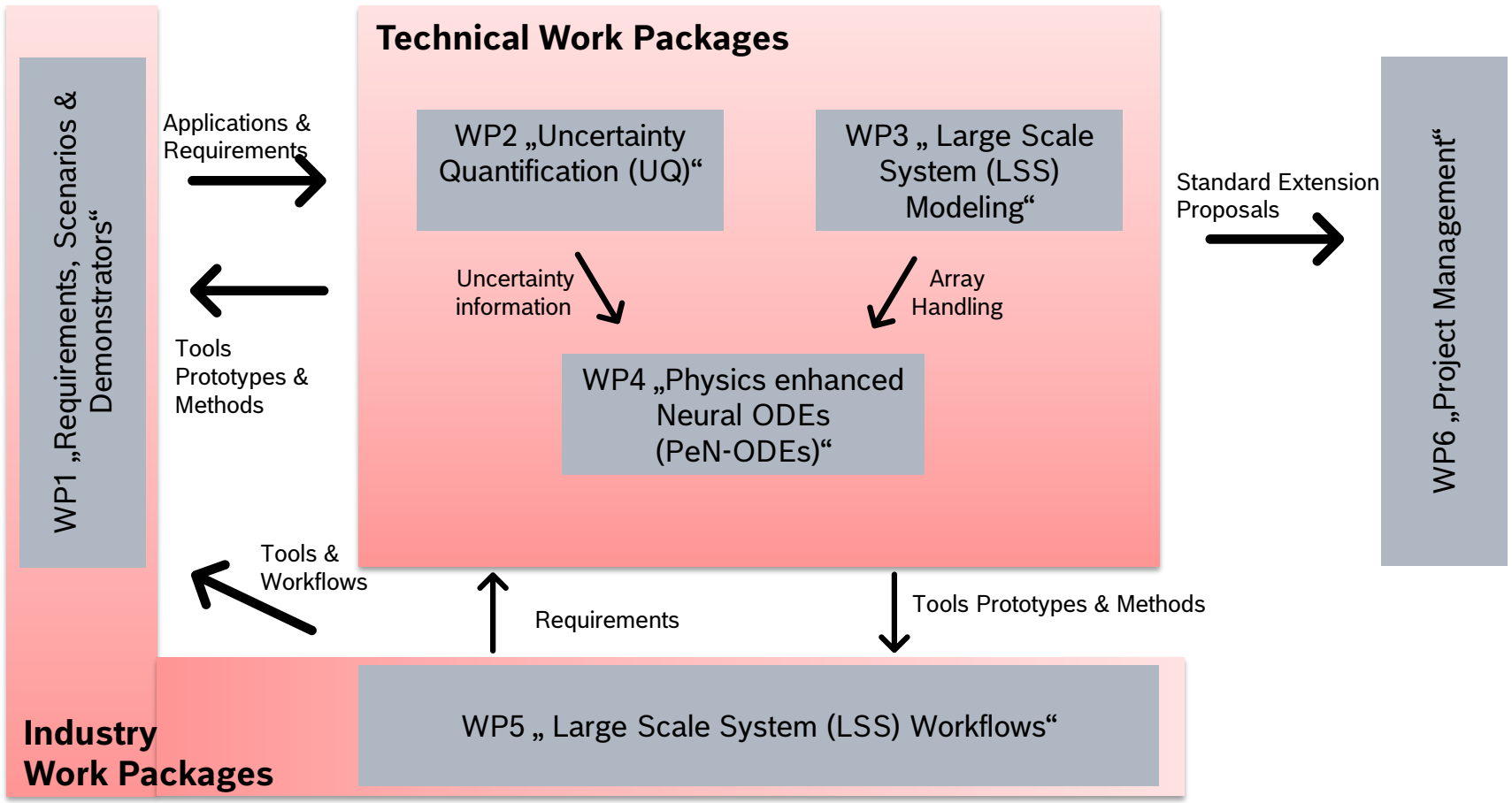
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Market Value Chain



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Recap – Work Structure



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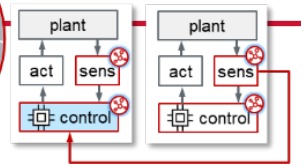
Large-scale green hydrogen

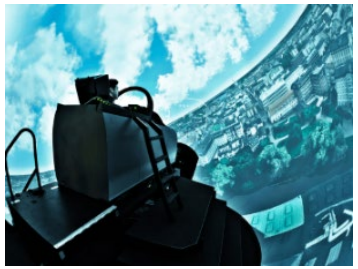




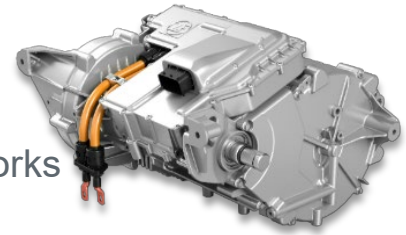
Resource-aware function of distributed control system

V2X communication between vehicles / infrastructure

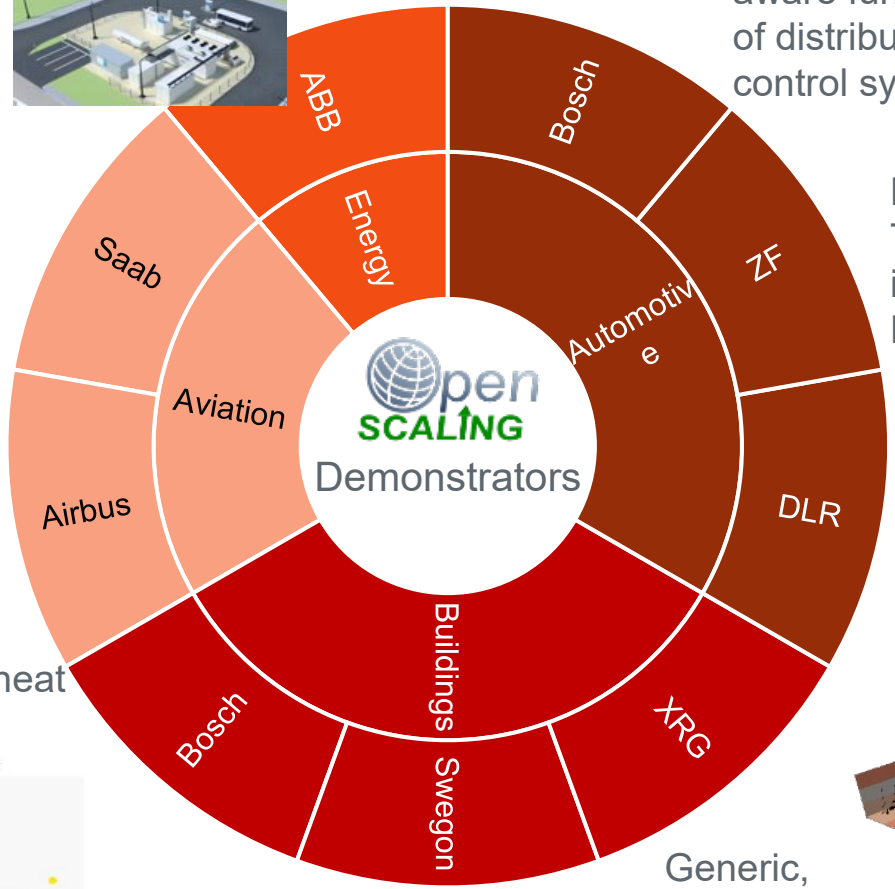




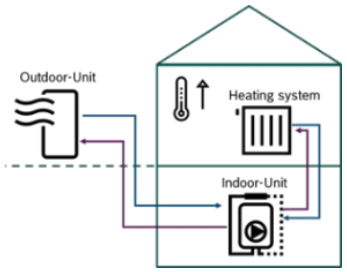
Vehicle systems



PeN-ODEs for Thermal Networks in Power Electronics



Fuel Cell propulsion





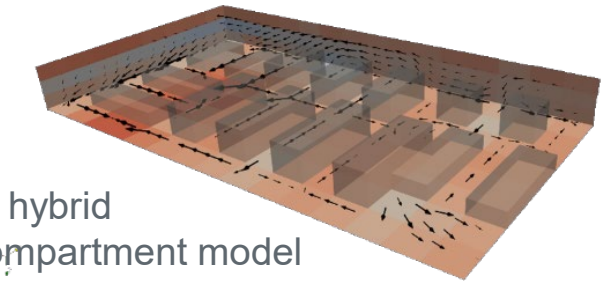
Virtual testing of heat pump systems

PeN-ODEs for Autonomous Vehicle





Precompiled, flexible models for HVAC of buildings

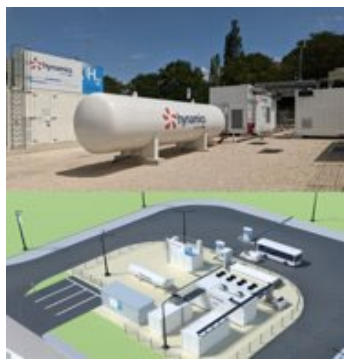


Generic, scalable, hybrid indoor compartment model

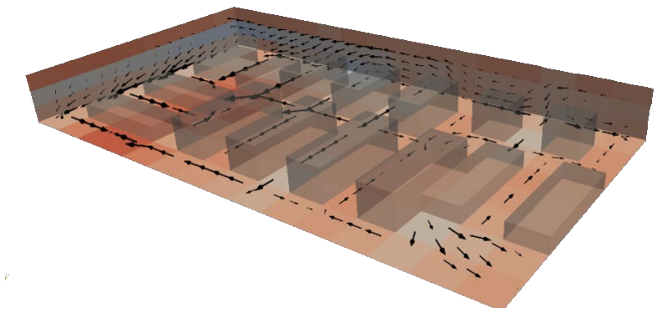
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Scalability of Simulation Methods and Tools

Application examples from demonstrators and benchmarks:



Large-scale
green hydrogen
by ABB



Generic, scalable, hybrid
indoor compartment model
by XRG



Large-scale district heating systems
by EQUA

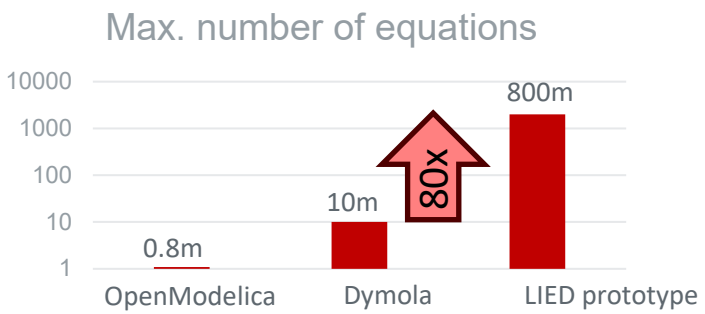
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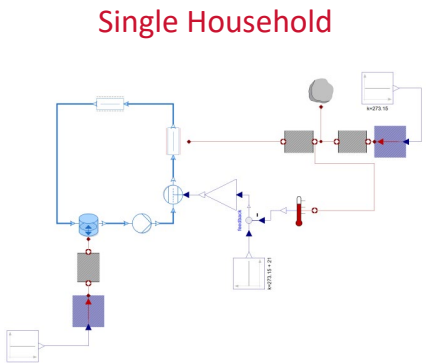
KPI - Larger models (Modelica)

Initial goal 10x larger

Simple benchmark (district heating network)

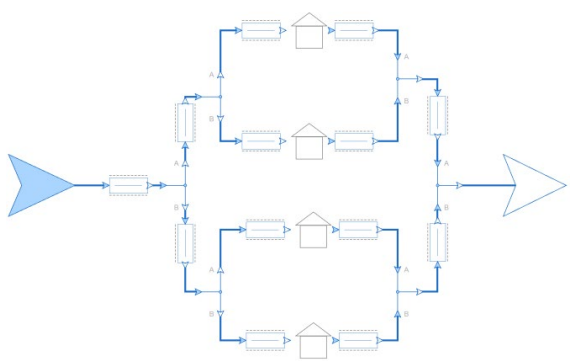


Size limit pushed by magnitudes!



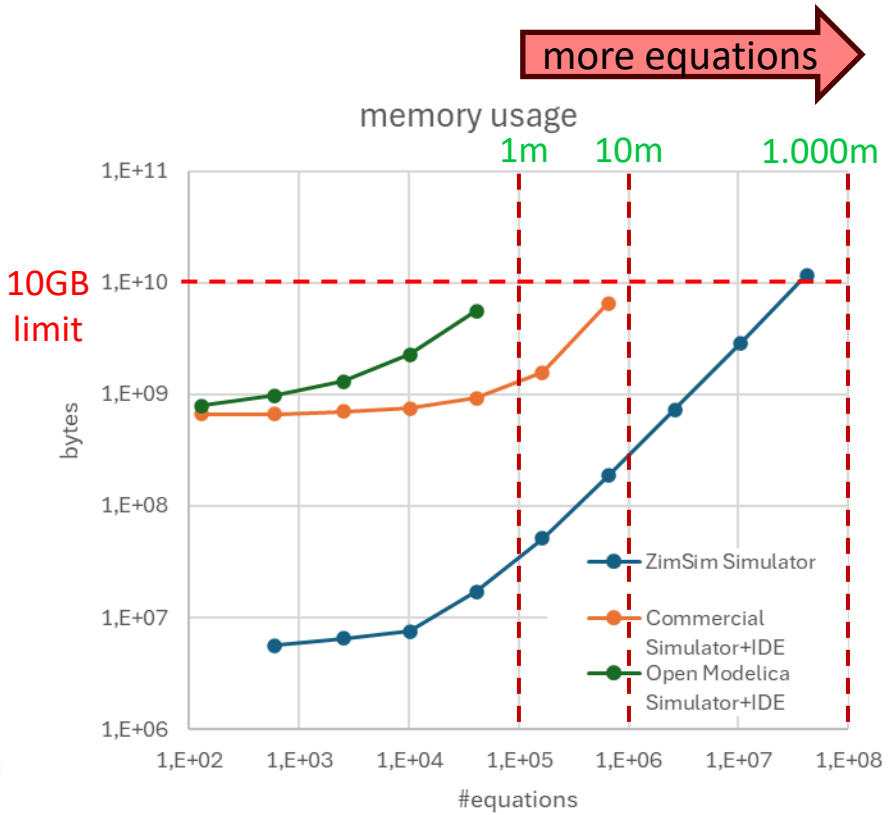
Single Household

4^n



Network of Households

LIED: Linear Implicit Equilibrium Dynamics



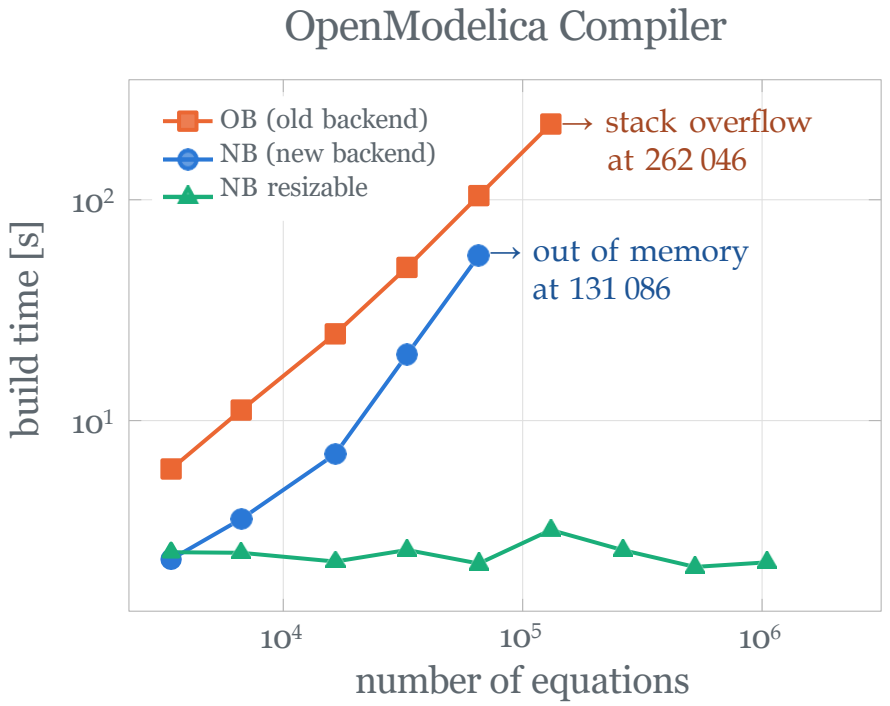
Zimmer, Dirk. “Large Network Examples for the Generation of Modular Simulation Code from Modelica”, In: Asian Modelica Conference, September 21-22, 2026, Hangzhou, China.

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KPI – Faster Compilation (Array-preserving compilation)

Benchmark by ABB: Large Scale Green H2-Production





Abdelhak, Karim and Bernhard Bachmann (2025). “Constant Time Causalization using Resizable Arrays”. In: 16th International Modelica Conference 2025, Luzern, Switzerland, September 8-10. URL: https://pretalx.com/16thmodelicafmiconference/talk/XJA98S/ (visited on 2025-09-23)

Abdelhak, Karim. 2026. “Symbolic Methods for Systems of Array-Based Differential-Algebraic Equations.” Application/pdf, July, 1258854 bytes. https://doi.org/10.4119/UNIBI/3018158.

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PeN-ODE Modeling

Johannes Rein, Jonathan Brembeck (2026). “**Physics-enhanced Neural ODEs: Leveraging Modelica for Modular Physics and PyTorch for Efficient Training**”. In: Accepted at the 23rd IEEE Vehicle Power and Propulsion (IEEE VPPC 2026), 5-9 October 2026, in Lyon, France.

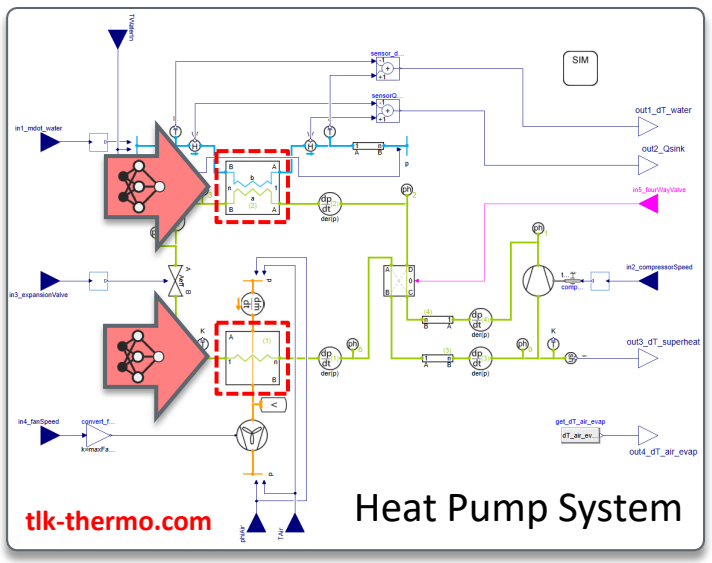
Kamp, Tobias, Christoff Burger, Johannes Rein, and Jonathan Brembeck (2025). “**Hybrid Simulation Models for Embedded Applications: A Modelica and eFMI approach**”. In: 16th International Modelica Conference 2025, Luzern, Switzerland, September 8-10, pp. 555–565. DOI: 10.3384/ecp218555. URL: https://ecp.ep.liu.se/index.php/modelica/article/view/1341/1155.

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KPI - Faster simulation (Modelica)

Initial goal 10x faster

PeN-ODE Heat Exchanger Surrogates



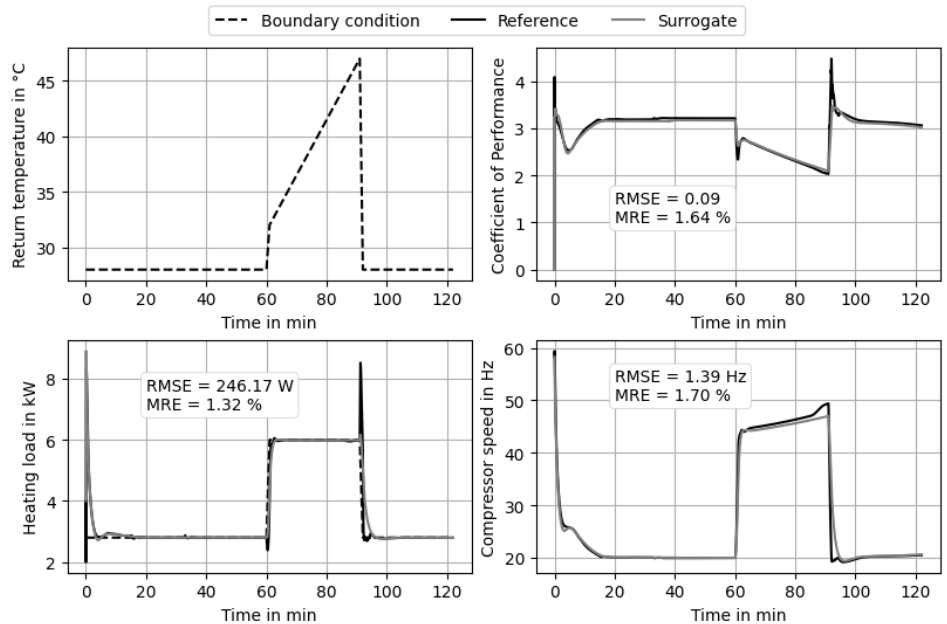
Speed-up >12x
(mean rel. error < 2 %)

- **Dynamic balance equations**
- **Neural network** for transport processes
- Training on **steady-state data**

PeN-ODE
Physics-enhanced Neural Ordinary Differential Equation

Testing scenario

Switch between heating and domestic hot water tank charging with linear return temperature profile



	Reference	Surrogate
Simulation speed	26.7 s	2.1 s

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PeN-ODE Training

Aka, Julius, Johannes Brunnemann, Jörg Eiden, Arne Speerforck, and Lars Mikelsons (2025). “**Balanced Neural ODEs: nonlinear model order reduction and Koopman operator approximations**”. In: The Thirteenth International Conference on Learning Representations. URL: https://openreview.net/forum?id=nA464tCGR5.

Hofmann, Andreas and Lars Mikelsons (2025). “**Towards Integration of PeN-ODEs in a Modelica-based workflow**”. In: 16th International Modelica Conference 2025, Luzern, Switzerland, September 8-10. URL: https://pretalx.com/16thmodelicafmiconference/talk/CLGH3S/ .

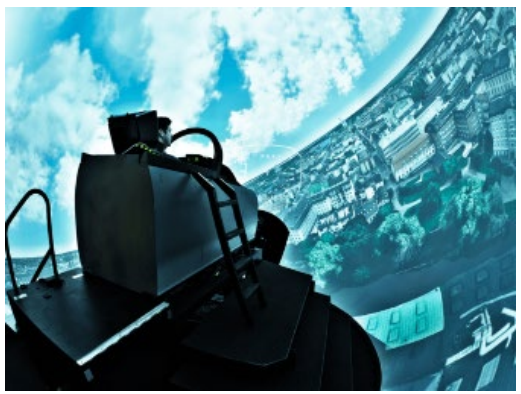
Langenkamp, Linus, Philip Hannebohm, and Bernhard Bachmann (2025). “**Efficient Training of Physics-enhanced Neural ODEs via Direct Collocation and Nonlinear Programming**”. In: 16th International Modelica Conference 2025, Luzern, Switzerland, September 8-10. URL: https://pretalx.com/16thmodelicafmiconference/talk/YTGZHW/.

Thummerer, Tobias, Hans Olsson, Chen Song, Julia Gundermann, Torsten Blochwitz, and Lars Mikelsons (2025). “**LS-SA: Developing an FMI layered standard for holistic & efficient sensitivity analysis over FMUs**”. In: 16th International Modelica Conference 2025, Luzern, Switzerland, September 8-10. URL: https://pretalx.com/16thmodelicafmiconference/talk/RMSZFE/.

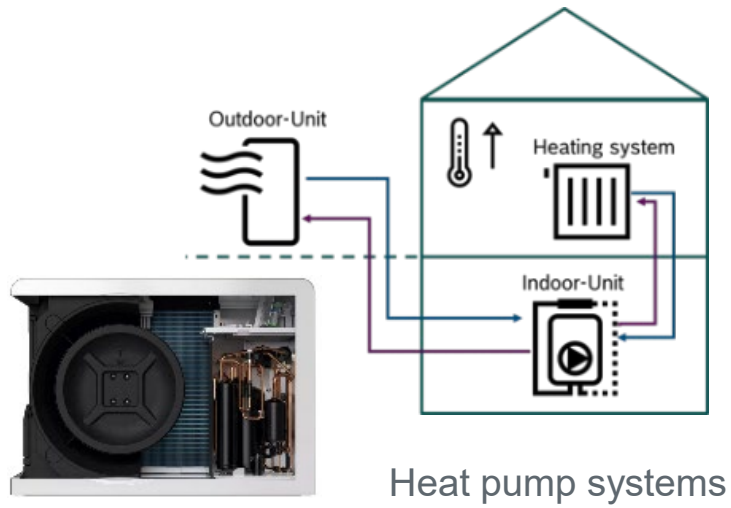
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Scalability of Processes, Standards and Exchange Formats

Application examples from demonstrators and benchmarks:



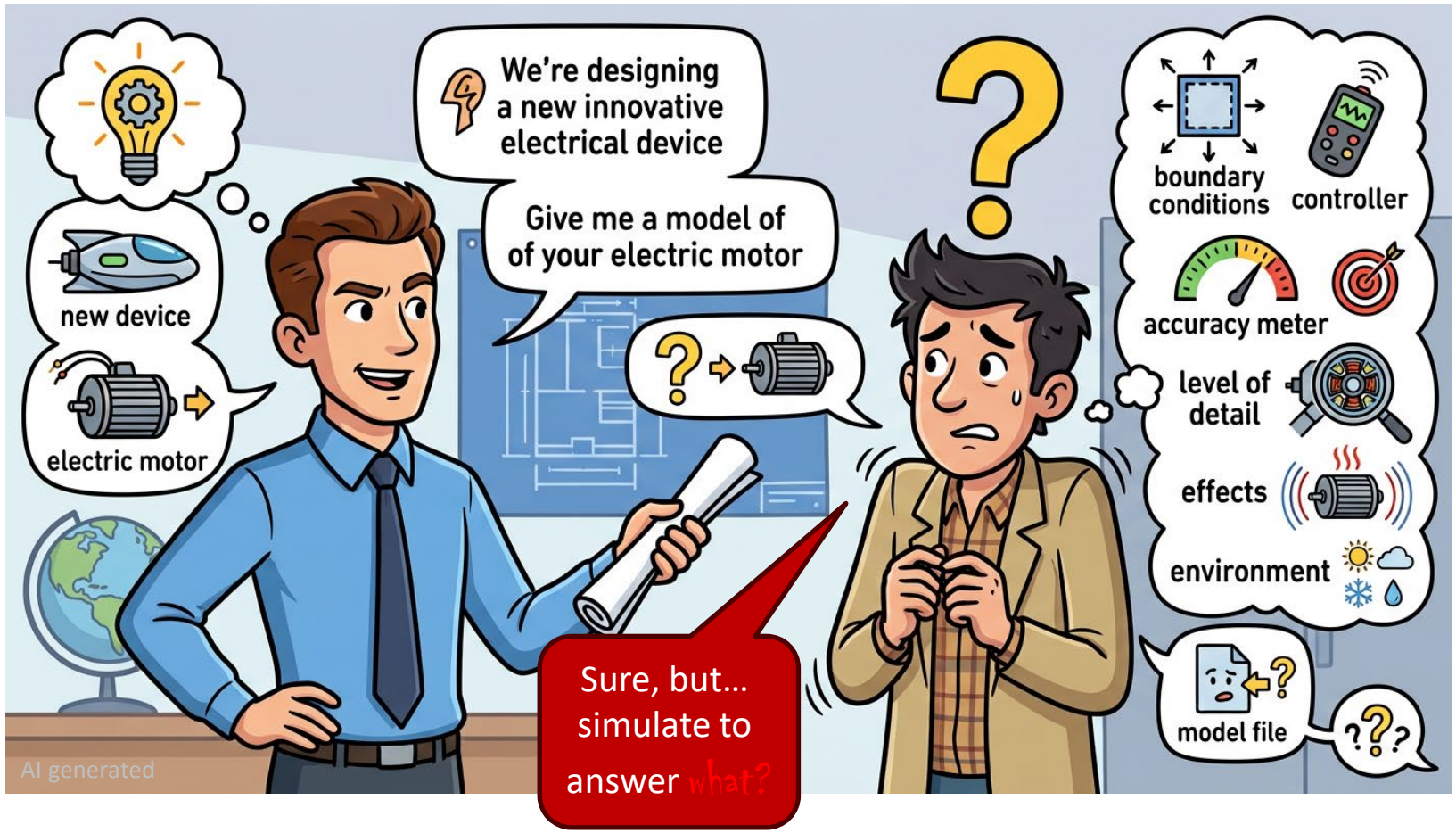
Vehicle systems
by Saab, Volvo



Heat pump systems
by Bosch, TLK-thermo, UNA

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The challenge of Virtual Engineering in a Collaborative Setting



- Vague requirements
- Ambiguous purpose
- Underspecified context of use

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KPI Credible workflows for LSS grounded in open standards



- ✓ Requirements as traceable meta data
- ✓ Specified purpose
- ✓ Defined integration architecture with clear context of use

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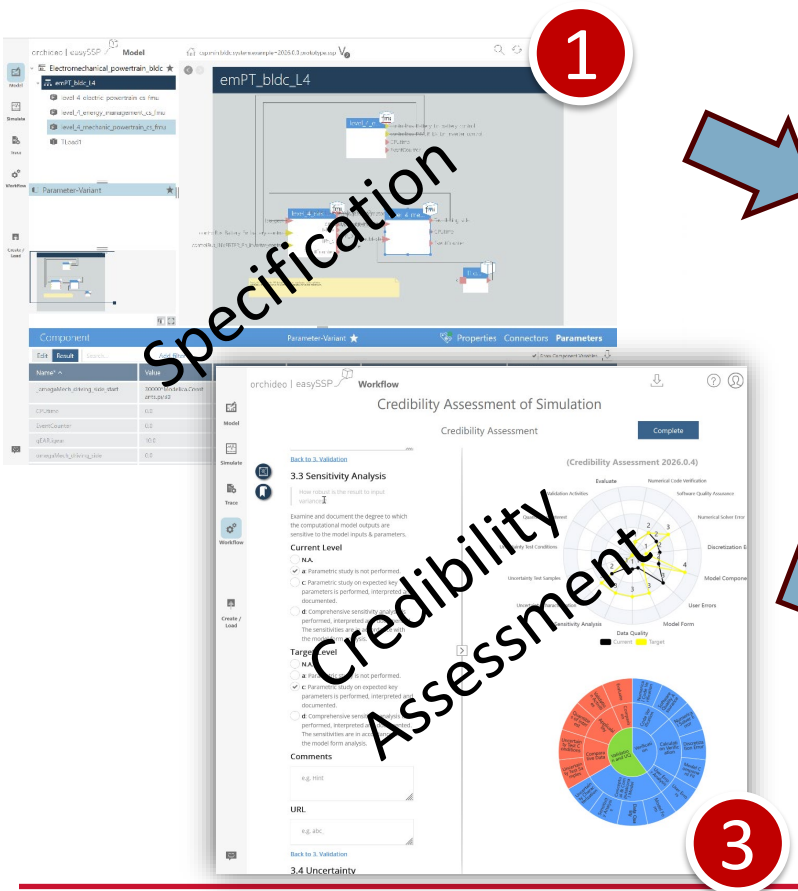
Tool Chain Demo: Credible workflows for LSS



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Tool Chain Demo: Credible workflows for LSS

Workflow-oriented

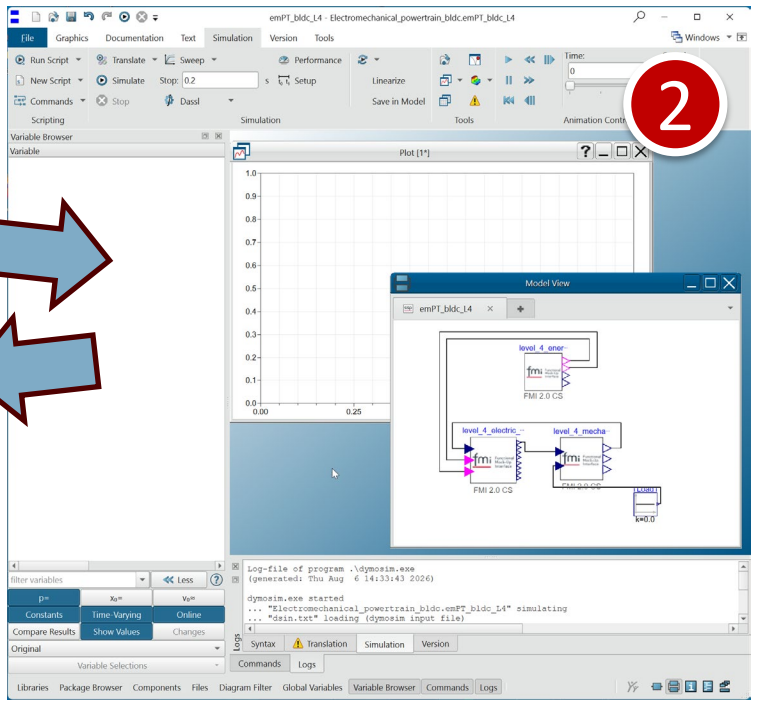








Modeling & Simulation focused



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Layered Standard Validation & Verification, UQ for FMI and SSP

First Draft presented at IMOC 2025:

- Bajand, Amin, Viktor Larsson, Lena Buffoni, Elmir Nahodovic, Robert Hällqvist, Oliver Lenord, Hans Olsson, Martin Otter, and Antoine Vandamme (2025). “Towards a common portable standard for model credibility”. In: 16th International Modelica Conference 2025, Luzern, Switzerland, September 8-10. URL: https://pretalx.com/16thmodelicafmiconference/talk/AMYDFN/ (visited on 2025-09-23)

Release as LS-VVUQ

- In preparation under the hood of the MAP_COORD.

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02

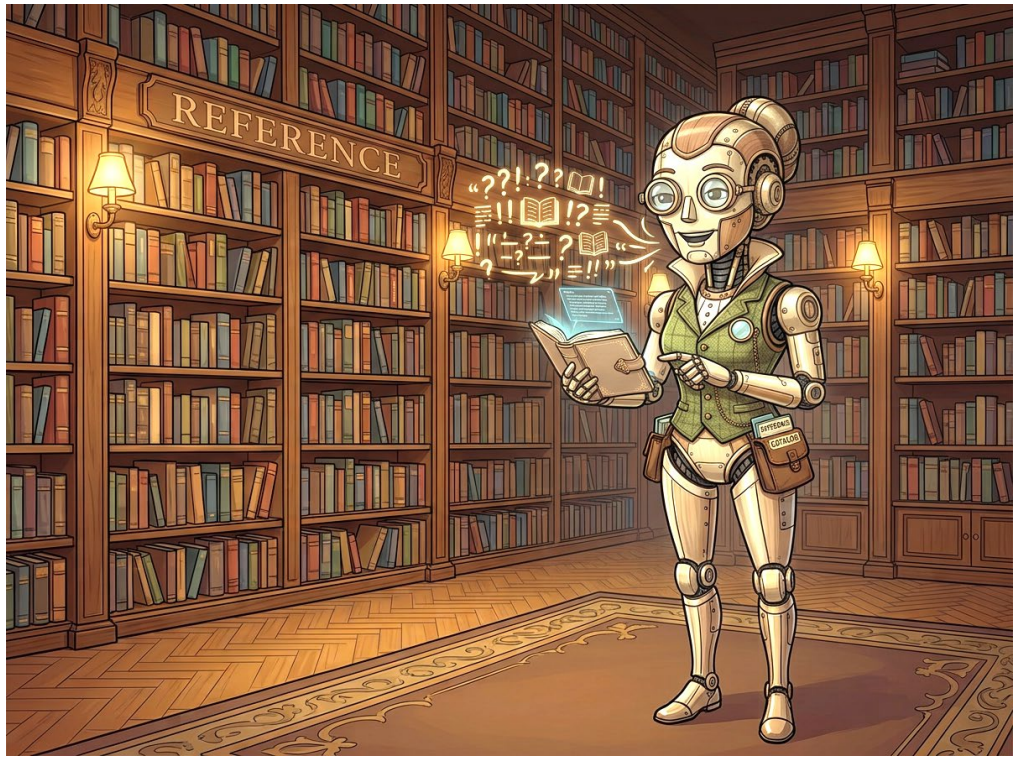
Agentic Model-based Systems Engineering

Public C-SC0

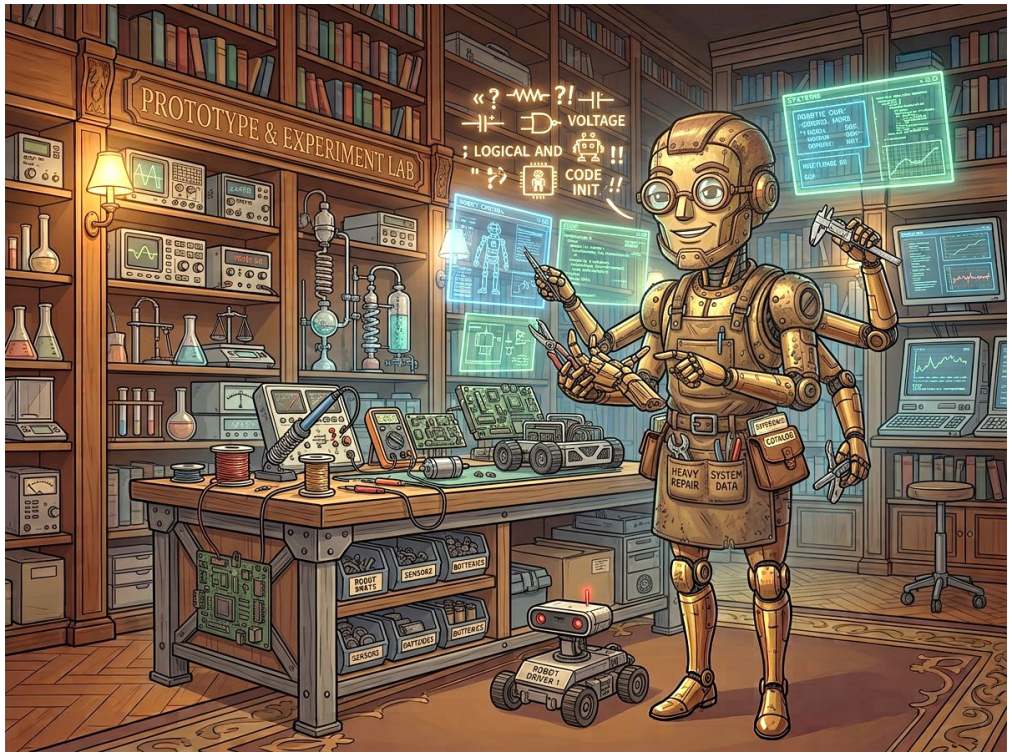
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Agentic Model-based Systems Engineering
From Chat Bot to Agent

- Chat Bot
  - from answer



- AI Agent
  - to action



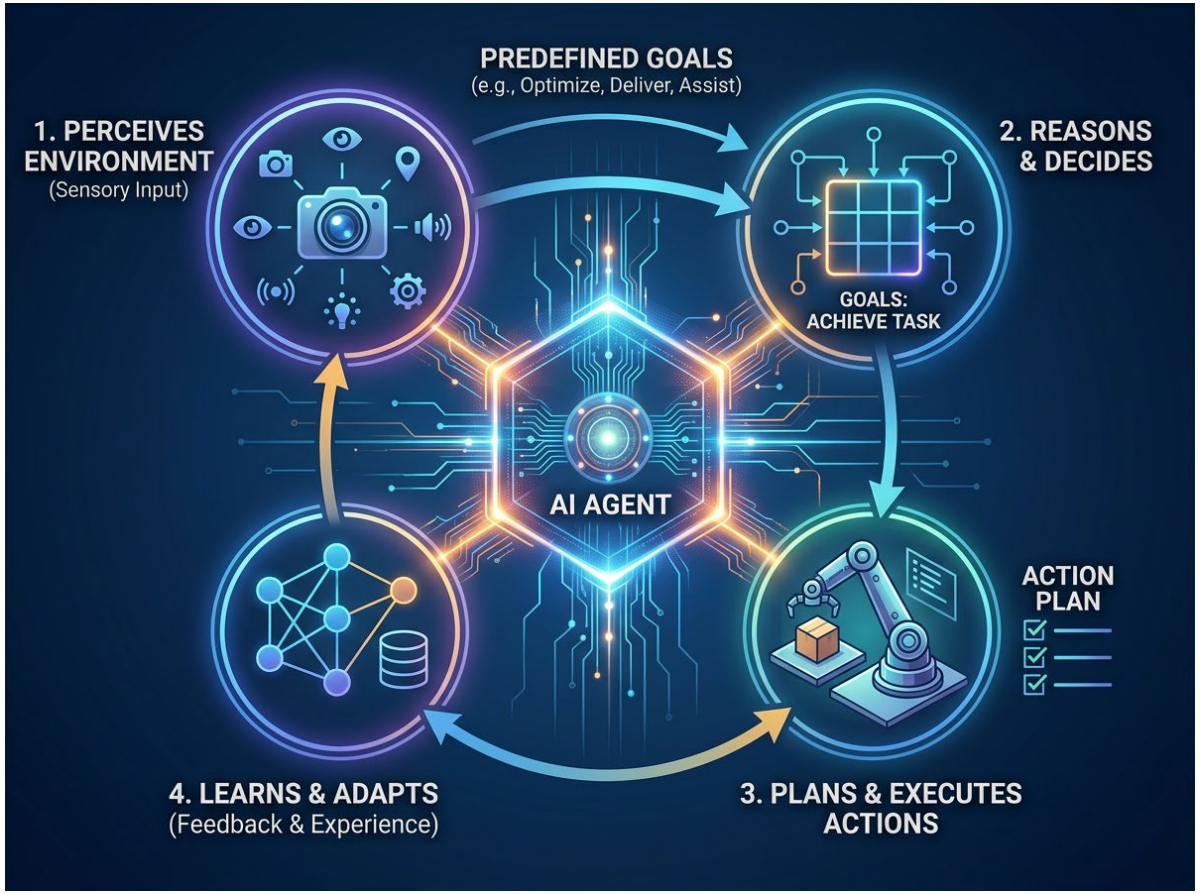
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Agentic Model-based Systems Engineering
What is an AI Agent?

- A software-based system that autonomously
  - perceives its environment,
  - reasons and makes decisions,
  - plans and executes actions, and
  - may learn from experience to adapt its behavior,

  in pursuit of predefined goals.



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Agentic Model-based Systems Engineering

Cloud Security Alliance (CSA) Autonomy Level Taxonomy

Autonomy Level	Definition	Measure of success
Level 1 Assisted	The AI executes actions, but each requires explicit, individual human approval .	**Time saved** Hard to measure
Level 2 Supervised	A human approves a plan or batch of actions, and the AI executes autonomously within that scope .	**Value add due to decision quality** Case to case judgement, Impact hard to quantify
Level 3 Conditional	The AI acts autonomously within predefined boundaries and escalates to a human when those boundaries are met or exceeded .	**Effort saved per success** High volume, high success rate
Level 4 High Autonomy	The AI operates with minimal supervision, with humans providing oversight via monitoring and exception handling .	**Value flow increase** Release value earlier; free resources for higher-value tasks
Level 5 Full Autonomy	The AI operates with a broad mandate to pursue goals, including self-modification. This level is not recommended for current enterprise deployments	—

https://labs.cloudsecurityalliance.org/wp-content/uploads/2026/03/agentic-ai-autonomy-levels-control-framework-v2-csa-styled.pdf

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Agentic Model-based Systems Engineering
What is the impact on the engineer's role?

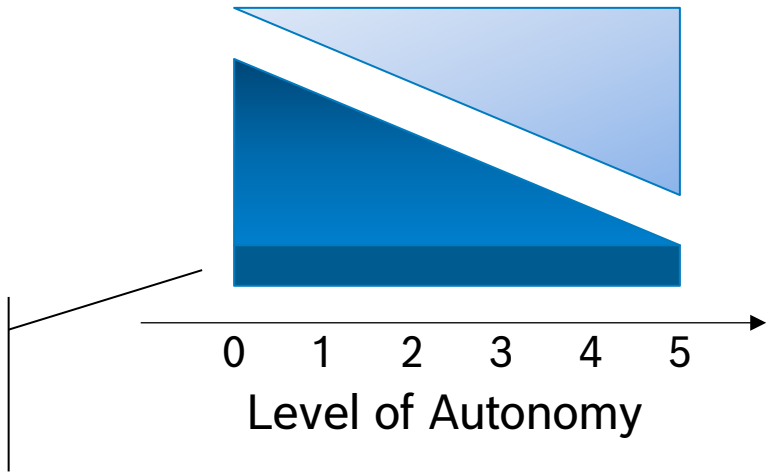


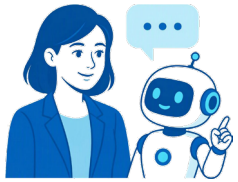
AI

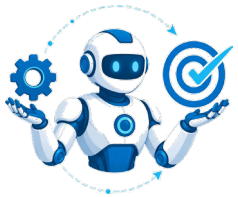


Human

Depends on Legal & Ethical Constraints







from Assistant to Autonomous Agent

from Maker to Approver, Strategist

(Accountability, Goal setting)

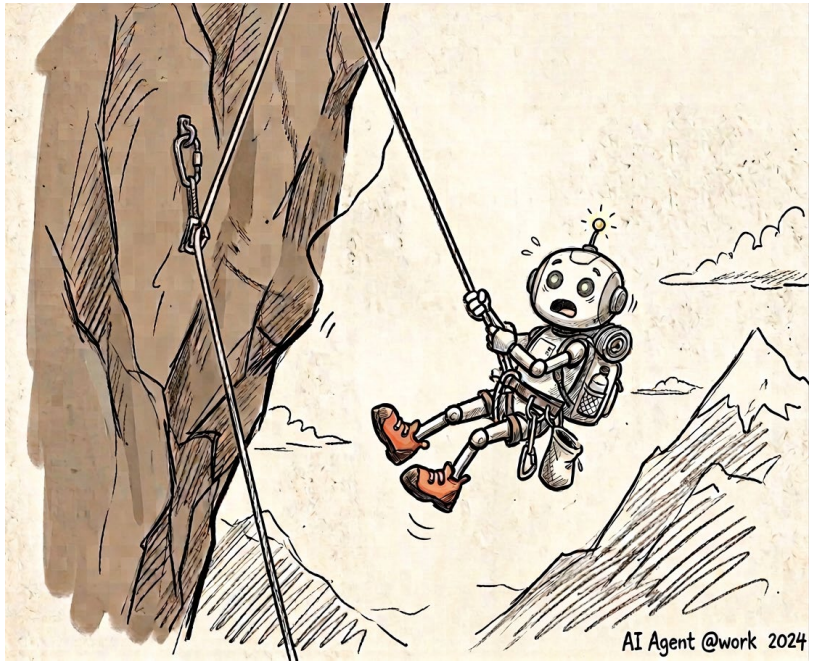


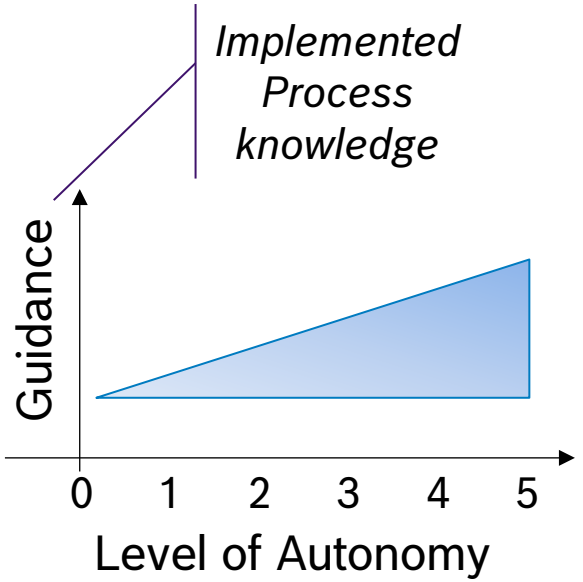


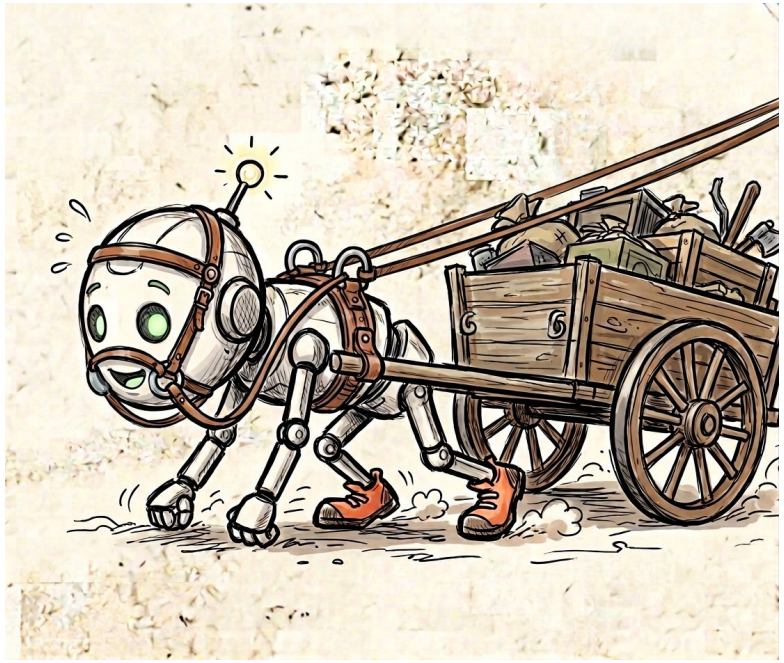
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Agentic Model-based Systems Engineering
How to stay in control?







Security harness:

Prevent serious damage

Bridle harness:

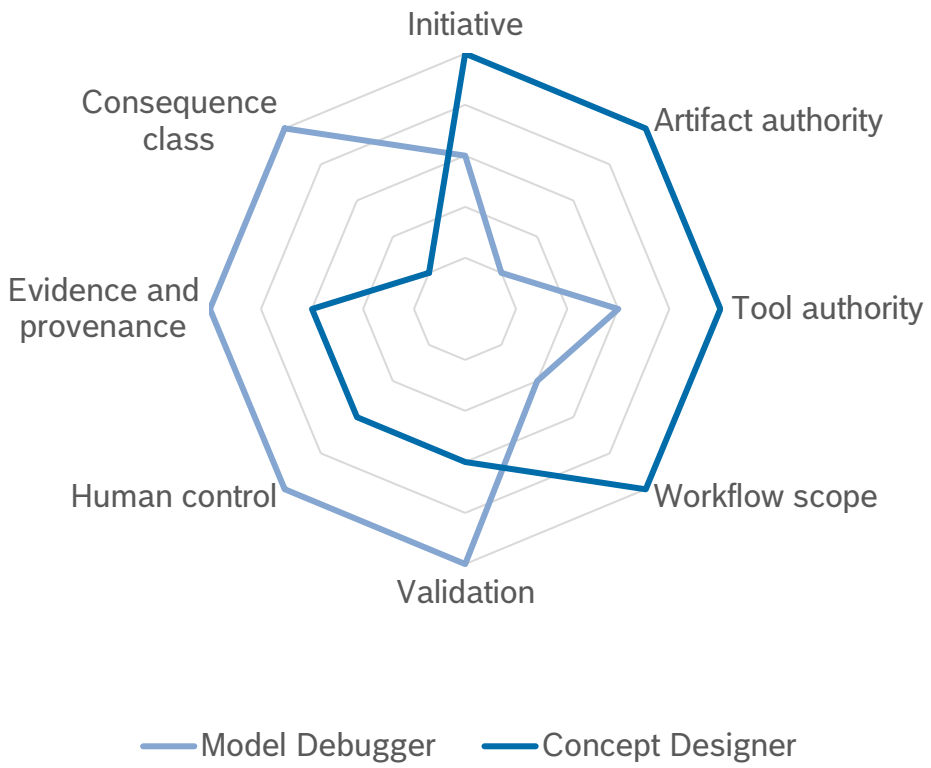
Guardrail and guidance

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Agentic Model-based Systems Engineering

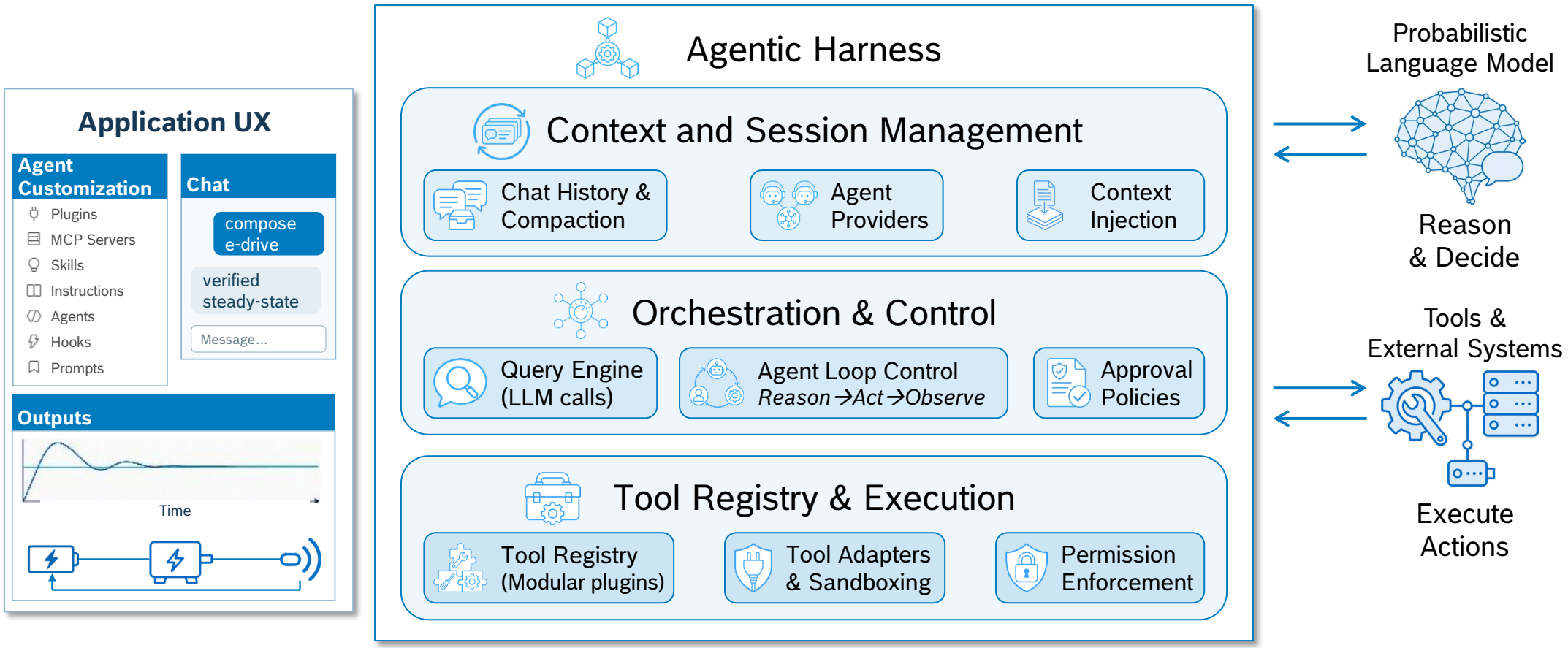
Classification Dimensions of Agentic Engineering Systems



1. **Initiative:** answer generation, recommendation, task execution, planning, or replanning.
2. **Artifact authority:** read-only, draft-only, reversible edits, persistent edits, or deployment authority.
3. **Tool authority:** documentation search, model APIs, compilers, simulators, optimization, or external systems.
4. **Workflow scope:** one interaction, one task, a multi-step workflow, a persistent project, or cross-system operation.
5. **Validation:** human review, syntax and type checks, compilation, regression tests, simulation KPIs, experimental validation, or independent assurance.
6. **Human control:** approve every action, approve mutations, approve validation gates, or intervene only by exception.
7. **Evidence and provenance:** prompts, tool traces, model and library versions, solver settings, assumptions, results, approvals, and rollback capability.
8. **Consequence class:** exploratory, design-supporting, decision-supporting, regulated, or safety-critical.

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Agentic Model-based Systems Engineering
Agentic Harness Architecture



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Agentic Model-based Systems Engineering

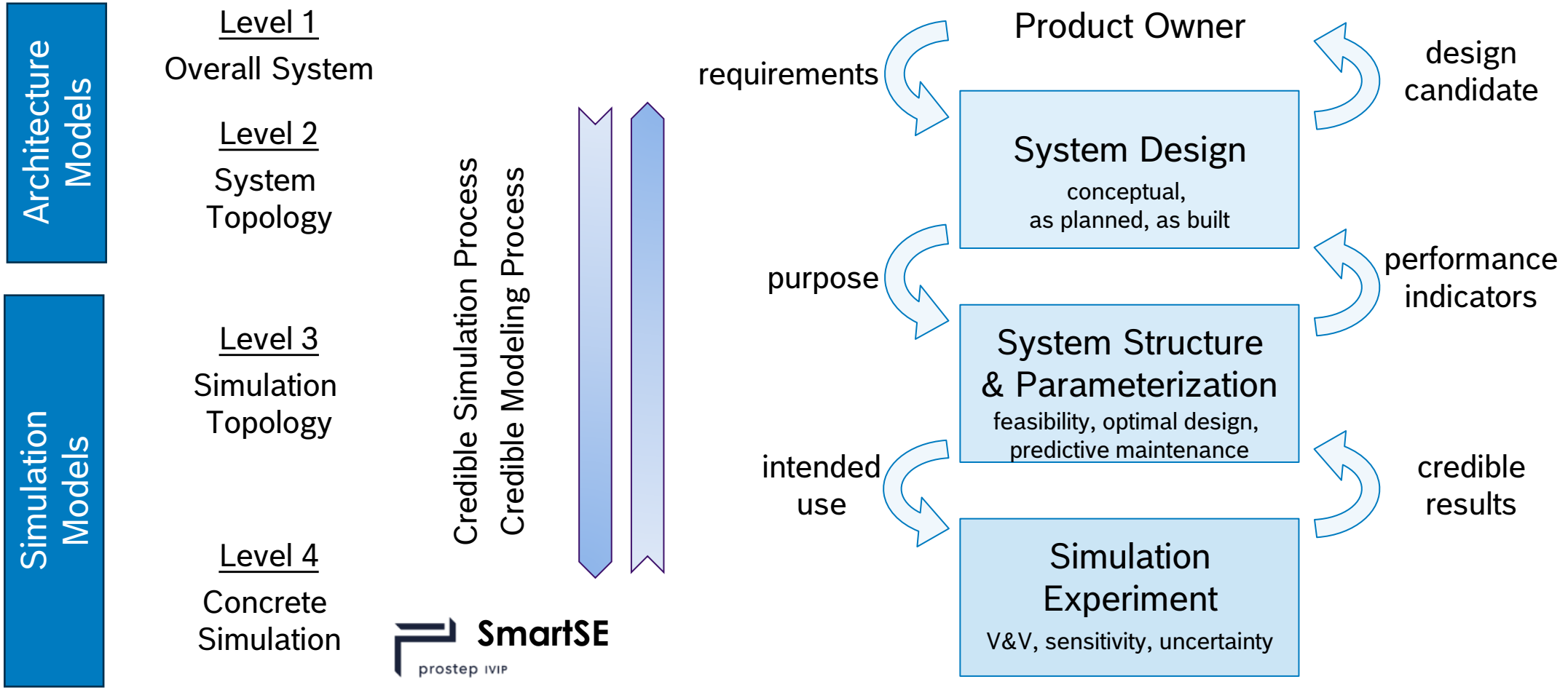
The Model is Commodity,

the **Context** is the Edge.

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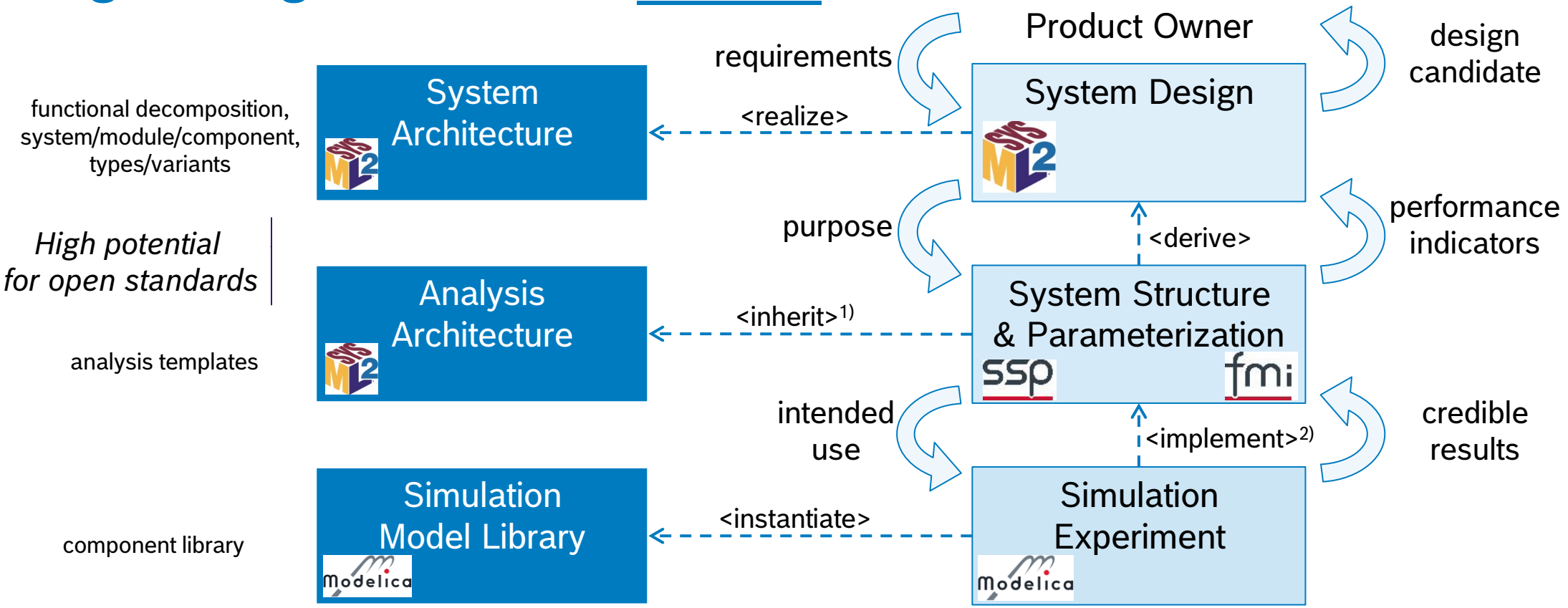
Agentic Model-based Systems Engineering

Engineering Process and Context



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Engineering Process and Context



1) Rosenlund, Erik, Saab Aeronautics, Johan Cederbladh, Johan Naeser, and Robert Hällqvist. 2026. "Exemplifying SysML V2 as a Driver for Co-Simulation Using Open Standards."
2) Lenord, Oliver. n.d. "Towards a Credible System Simulation Architecture Applicable to Heat Pump Systems Using Modelica, FMI and SSP." Presented at the 16th International Modelica Conference - SSP User Meeting.

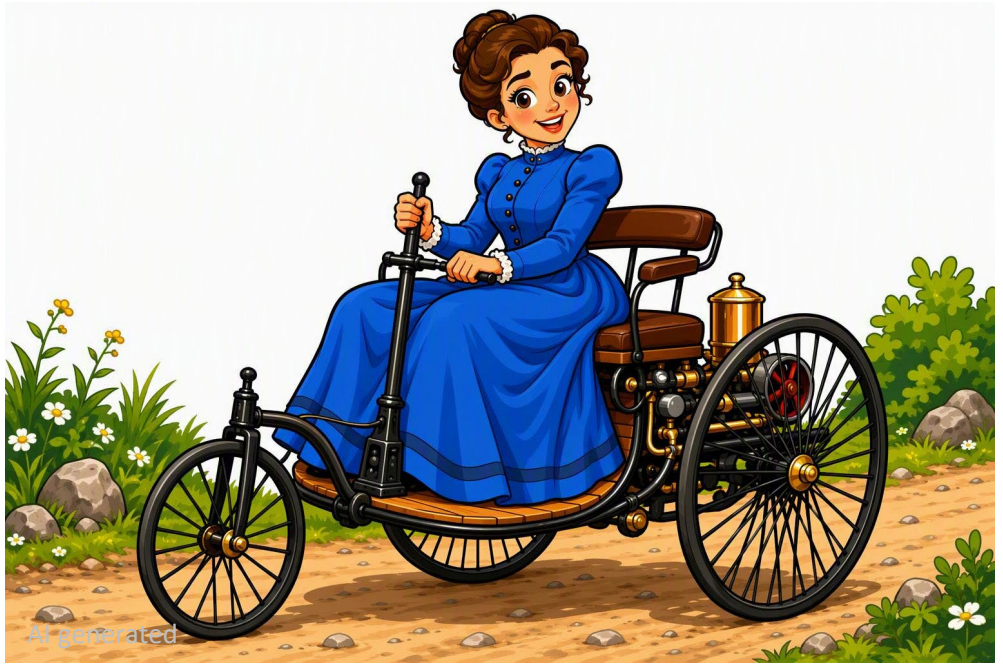
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Agentic Model-based Systems Engineering
Gold Rush or Sustainable Business Case

- America's 1st Gold Rush Dahlonega, Georgia starting 1820
  https://gastateparks.org/DahlonegaGoldMuseum

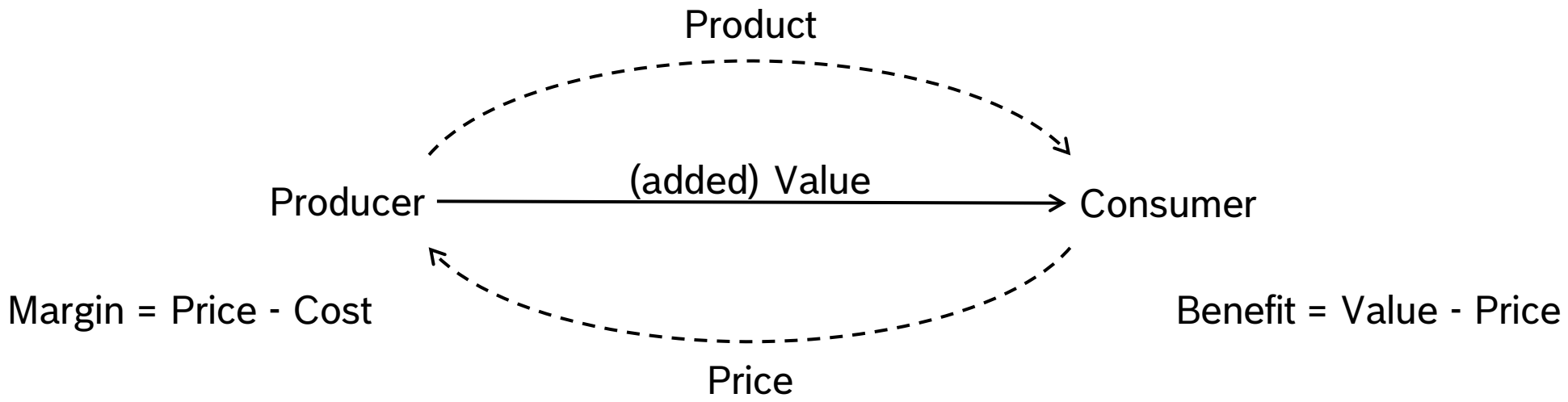


- First long-distance journey with an automobile by Bertha Benz 1888.
  https://group.mercedes-benz.com/company/tradition/founders-pioneers/bertha-benz.html



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Agentic Model-based Systems Engineering
Value Chain

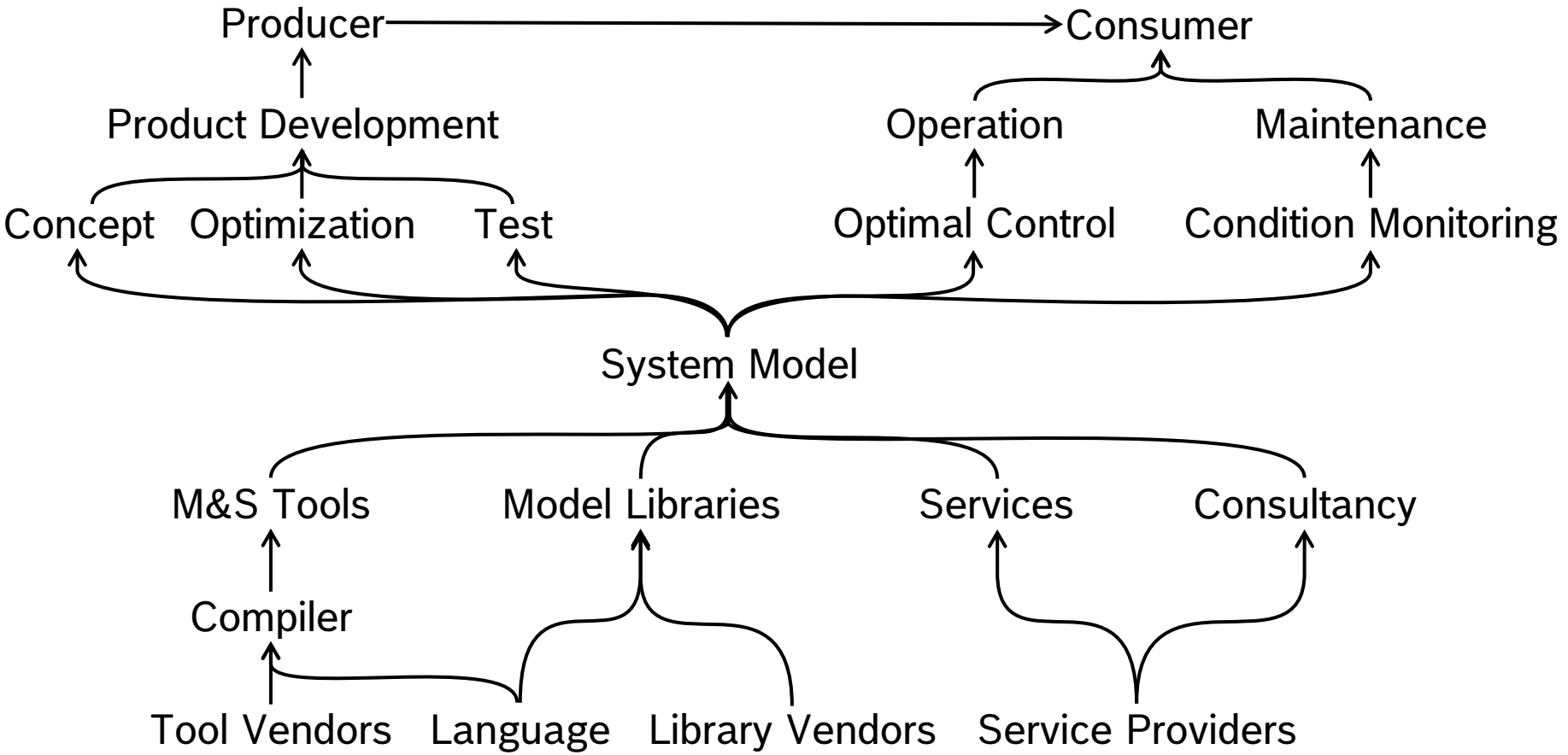


Higher Value → Higher Benefit

Lower Cost → Higher Margin

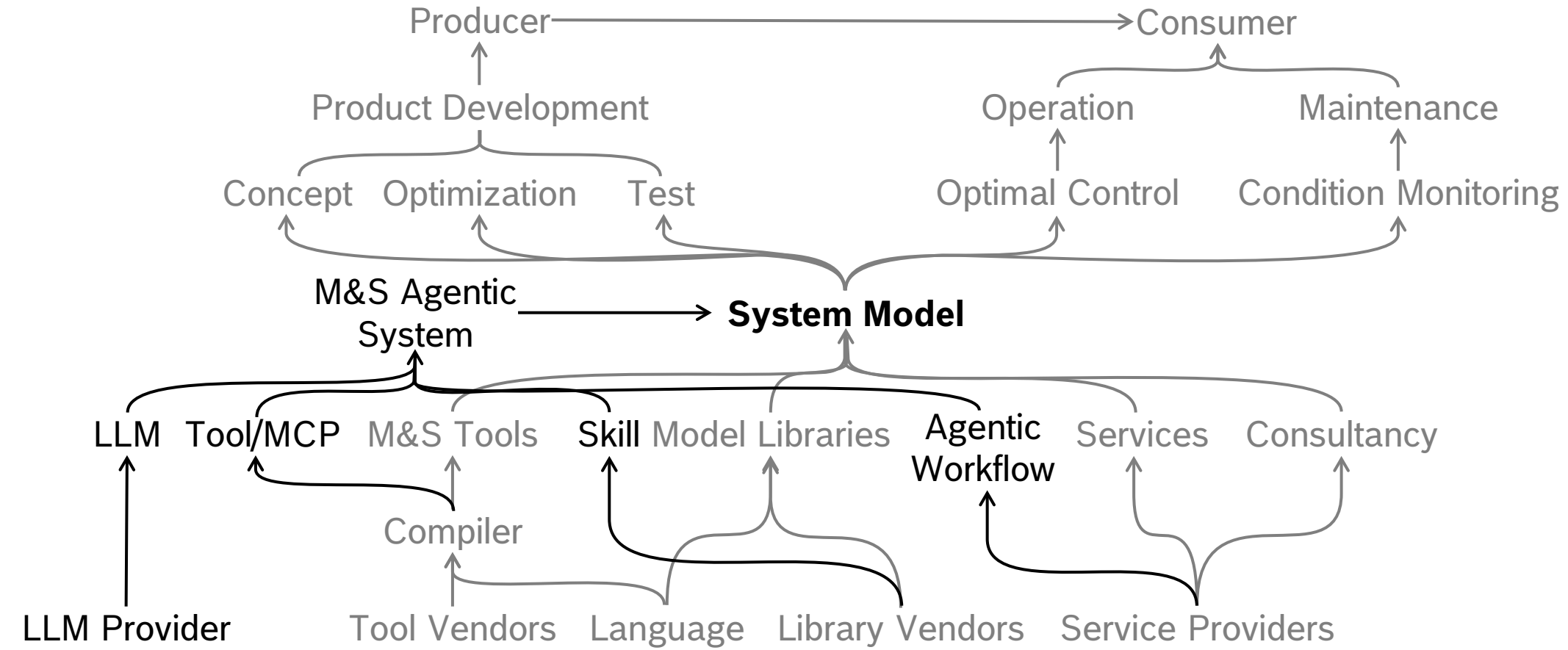
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Agentic Model-based Systems Engineering
Value Chain – Traditional



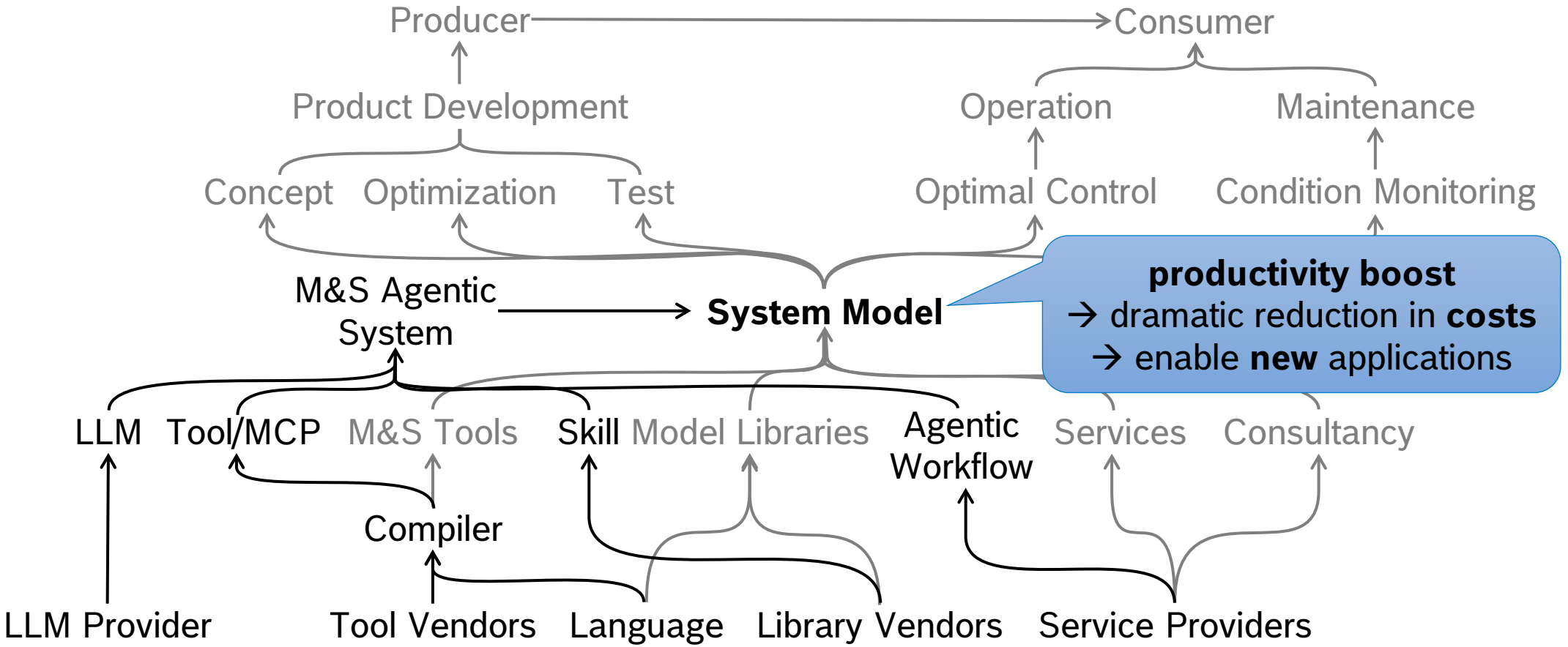
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Agentic Model-based Systems Engineering
Value Chain – Agentic



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Agentic Model-based Systems Engineering
Value Chain – Agentic



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Agentic Model-based Systems Engineering

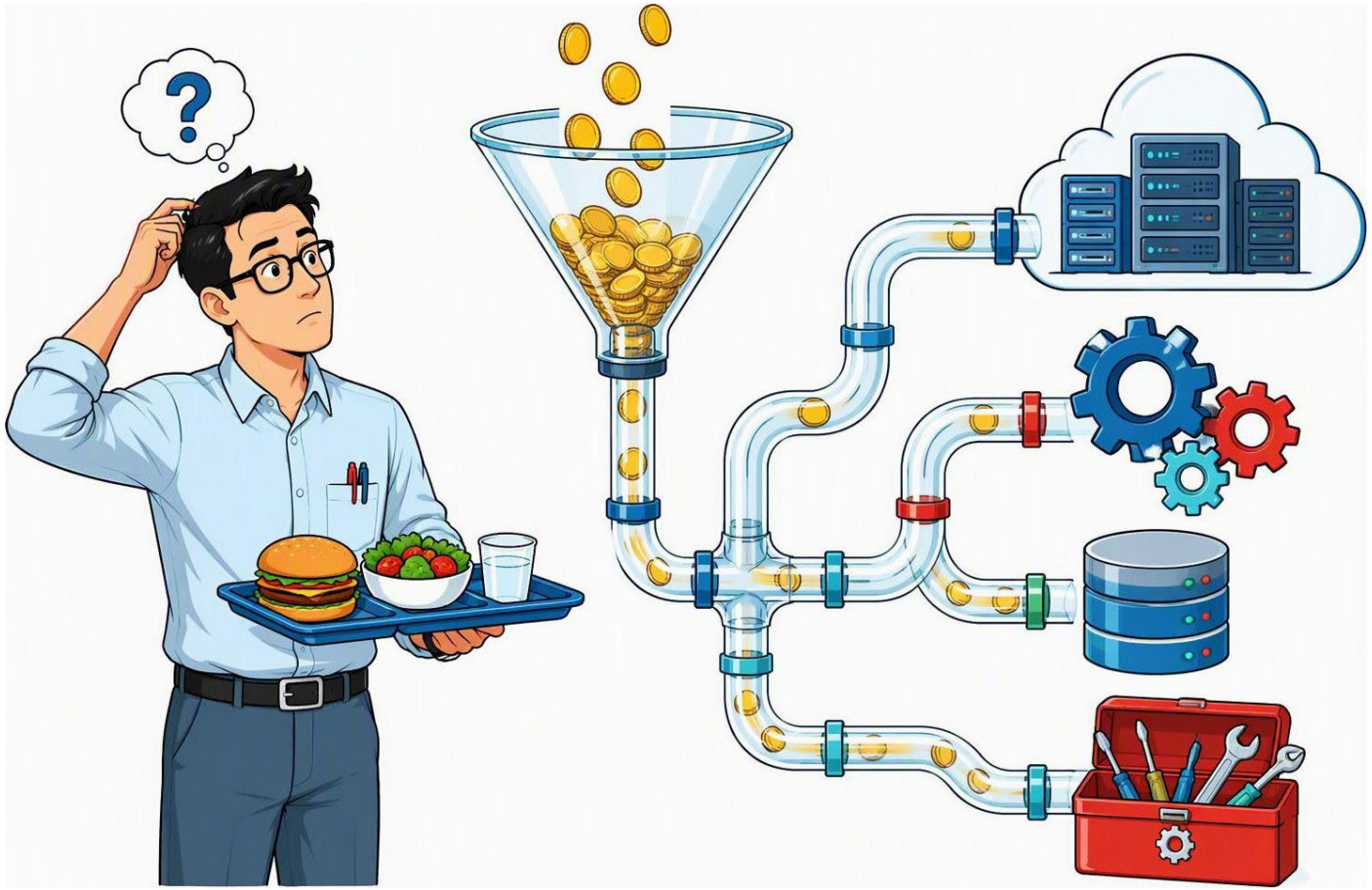
The new era of:

Simulate Everything

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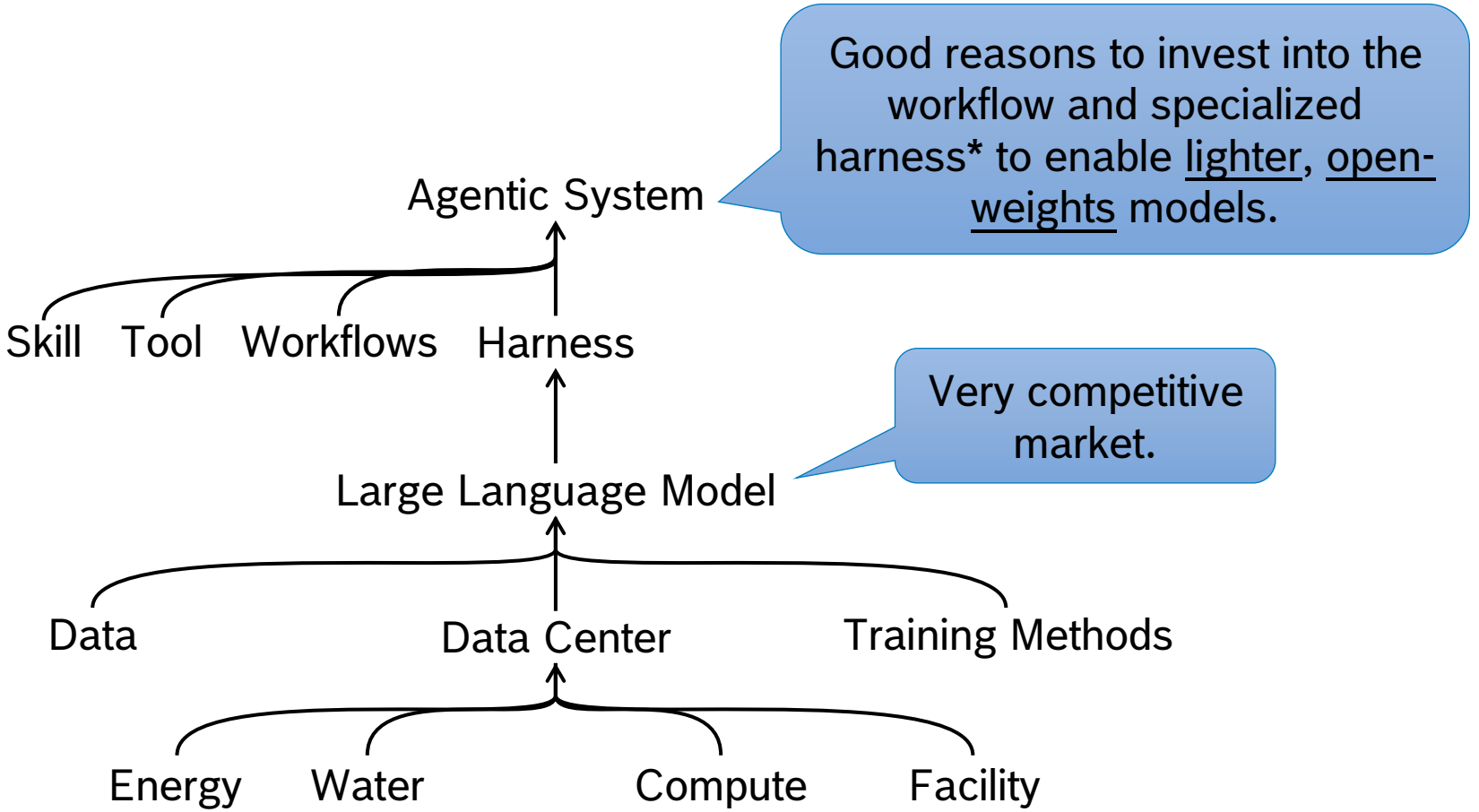
Agentic Model-based Systems Engineering

No Free Lunch — Where Does the Money Go?



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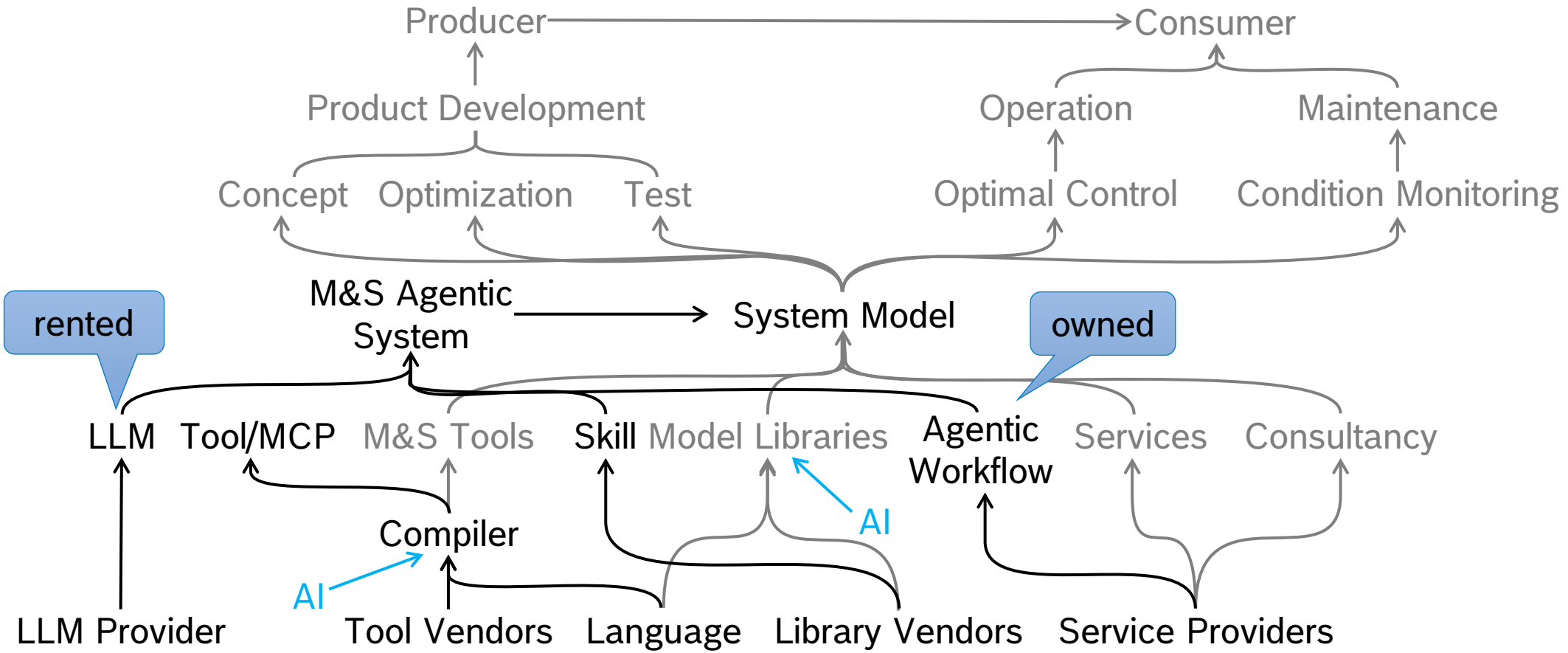
Agentic Model-based Systems Engineering
Value Chain



* https://juliahub.com/blog/open-weight-models-physical-ai-specialized-harnesses

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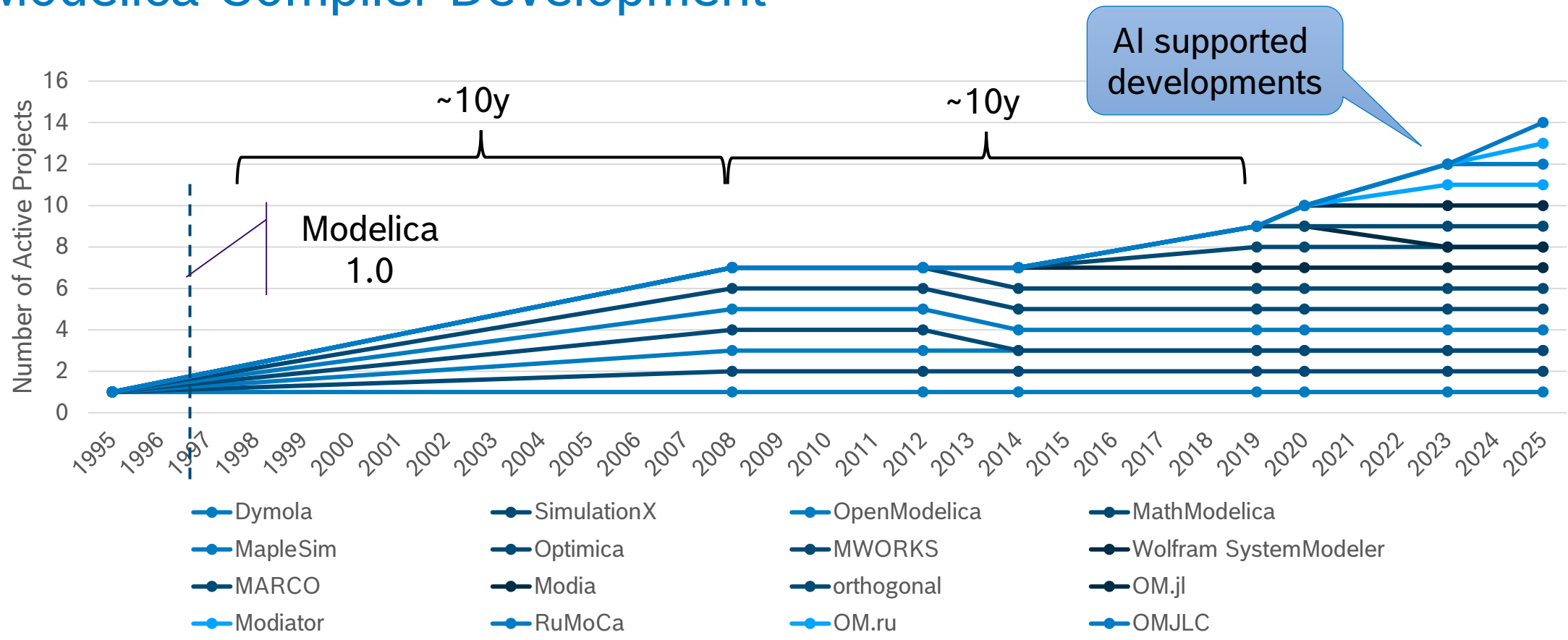
Agentic Model-based Systems Engineering
Value Chain – Agentic



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Agentic Model-based Systems Engineering

Modelica Compiler Development



Disclaimer: Some data based on assumptions, not confirmed by the tool vendors or developers.

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Agentic Model-based Systems Engineering
Conclusions

- **Strengthen the Ecosystem**
  - **Modelica Standard Skills**
    Open source set of skills enhancing the value of Modelica and Modelica Library
  - **Agent-friendly** compiler interaction:
    - API
    - model statistics
    - error message format
  - **Ontology** of physical principles supported by Modelica libraries
- **Bill the agent**
  - Modelica-as-a-Service:
    AI credits paid to the compiler behind the Tool/MCP

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Agentic Model-based Systems Engineering
Conclusions



- **Stay in front of the wave**
  - Cash in productivity gains for your own business
  - Preserve the head start advantage for tool/service excellence

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Agentic Model-based Systems Engineering
Summary

- OpenSCALING outcomes
  - Larger models
  - Faster compilation
  - Fre-compilation / avoid re-compilation
  - Modelica and NN integration
    - PeN-ODE modeling
    - PeN-ODE training
  - Credible M&S processes
    - enhanced exchange format: ls-vvuq
    - enhanced tool support
  - List of all 34+ Publications: https://openscaling.org/publications/

➔ Foundation stronger than ever!

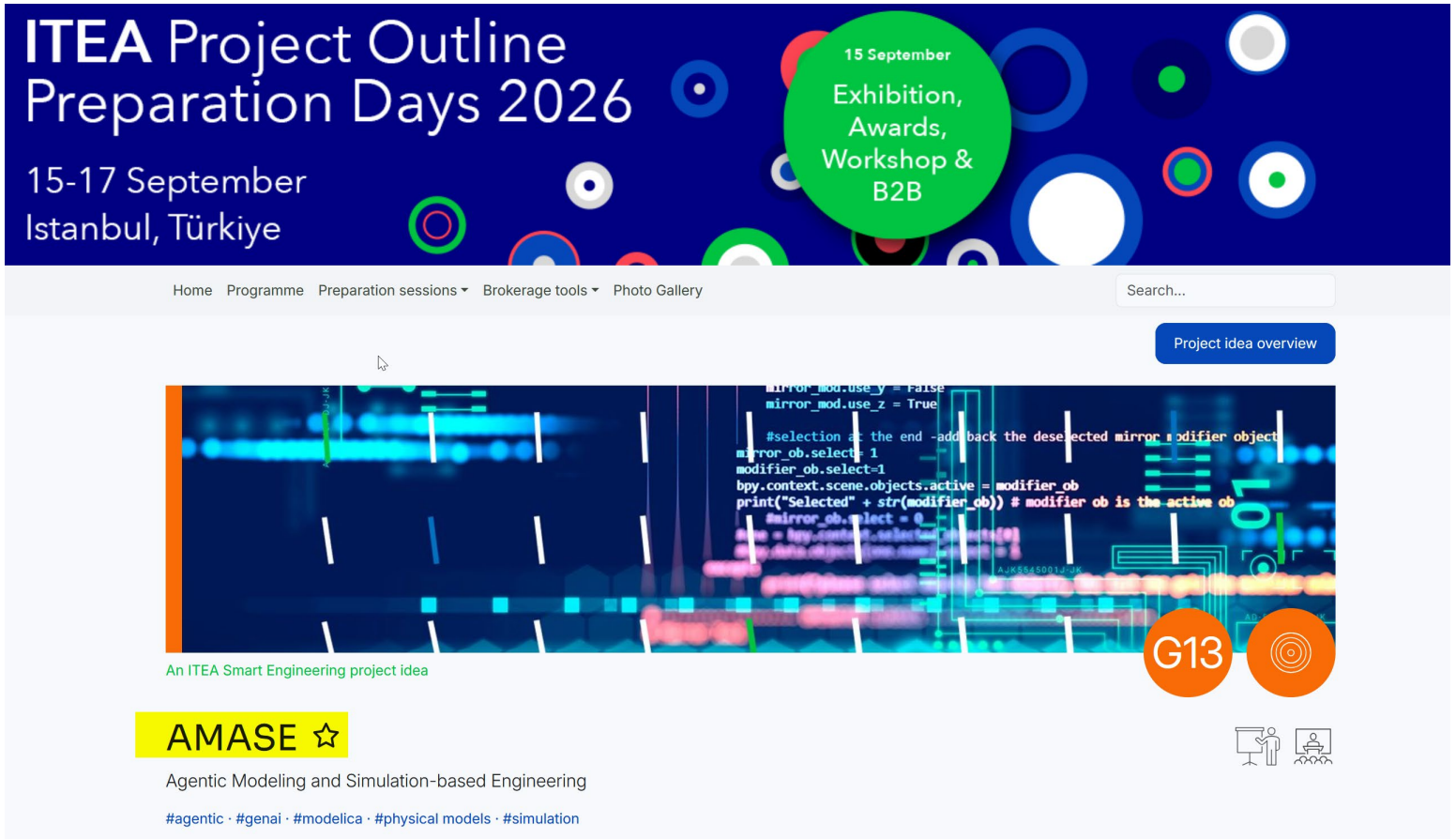
- Agentic Model-based Systems Engineering
  - Boost in productivity → Boost of future business
  - Modeling expertise will remain a key asset
  - Strengthen and foster the Modelica eco system
  - Leverage open standards

➔ Modelica: Now or Never!

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Agentic Model-based Systems Engineering
Outlook

- AMASE
  Agentic Modeling and Simulation-based Engineering
  - New European publicly funded project in preparation
  - 20-30 Partners
  - 3-6 Countries:
    Germany, Sweden, Portugal, Turkey, Belgium, Netherlands
  - Expected start Oct 2027
- Goal
  - Leverage Modelica in Agentic Engineering Loops



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