OPEN STANDARDS IN SIMULATION

MODELICA AND FMI AS ENABLERS FOR VIRTUAL PRODUCT INNOVATION

Hubertus Tummescheit

Board member, Modelica Association & co-founder of Modelon

OVERVIEW

- Background and Motivation
- Introduction – why open standards matter
- Innovation in Model Based Design
- Modelica – the equation based modeling language
- The Functional-Mockup-Interface (FMI)
- Examples
- What's next: upcoming innovations
- Conclusions

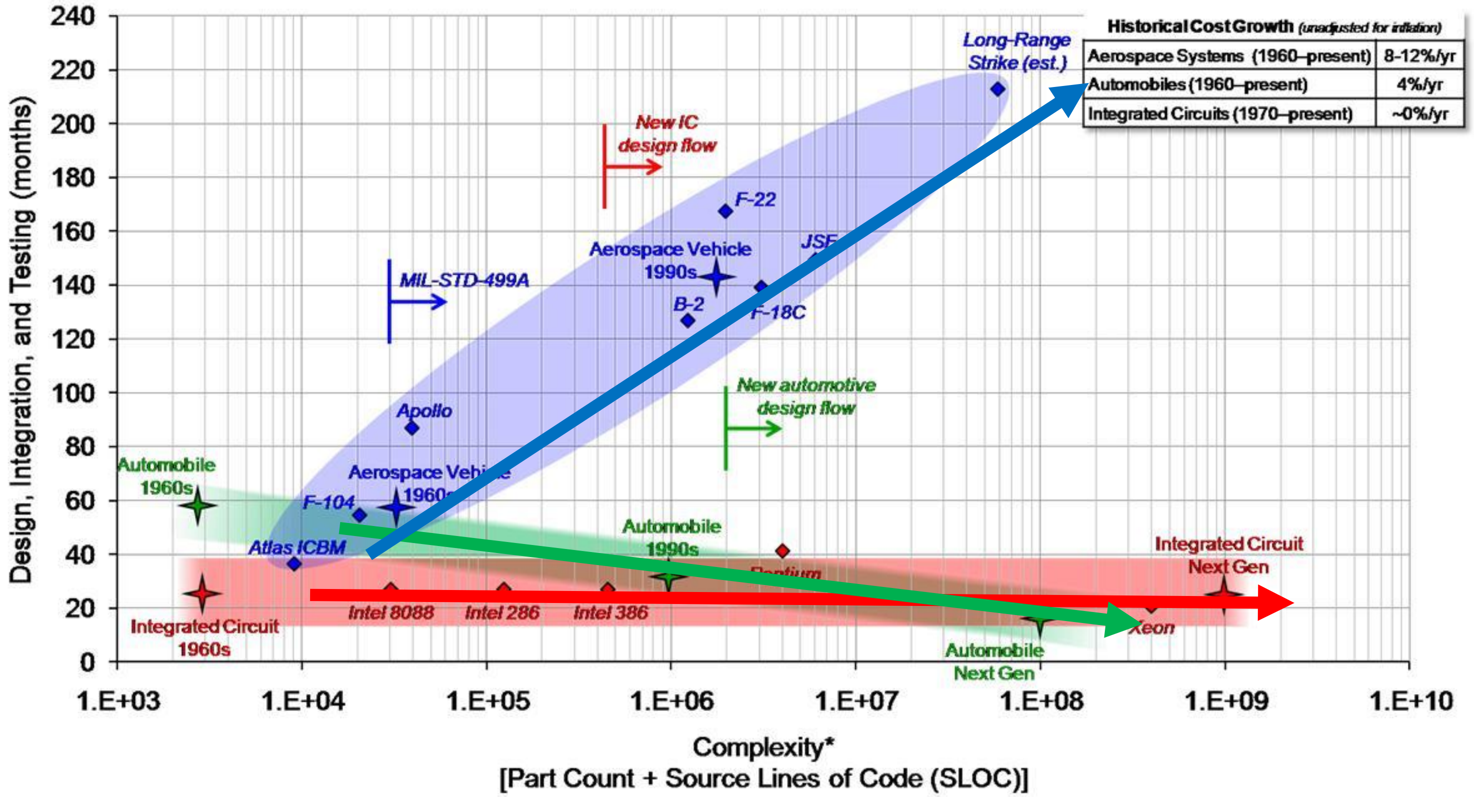
The Modelica Association

- An independent non-profit organization registered in Sweden. https://www.modelica.org
- Members:
  - Tool vendors
  - Government research organizations
  - Service providers
  - Power users
- Two standards and four core projects:
  - The Modelica Language
  - The Modelica Standard Library
  - The FMI Standard for model exchange and co-simulation
  - The SSP project for an upcoming standard on system structure and parameterization
- FMI web site: http://www.fmi-standard.org
- Next Modelica Conference: May 15-17 in Prague

MOTIVATION: THE COMPLEXITY ISSUE

- System complexity increases
- Required time to market decreases (most industries)
- Without disruptive changes, an impossible equation to solve.

Source: DARPA AVM project



Large part of complexity is in software!

WHY OPEN STANDARDS ARE NEEDED

- Computer Aided Engineering is a very fragmented industry
- Tools evolved domain by domain
- Interoperability has been an afterthought, at best
- Today's complex systems require interoperability!
- An everyday challenge for engineering design

- Open standards drastically reduce the cost of creating interoperability between tools
- There is an interplay with open source: open source can also increase the speed of software innovation

TIE YOURSELF TO STANDARDS, NOT TOOLS !

1. It will be cheaper
2. It will keep software vendors on their toes to compete on tool capability, not quality of lock-in
3. It returns ownership of the know-how in the models from the tool vendor to the end user
4. Process improvement speed moves from evolution to revolution

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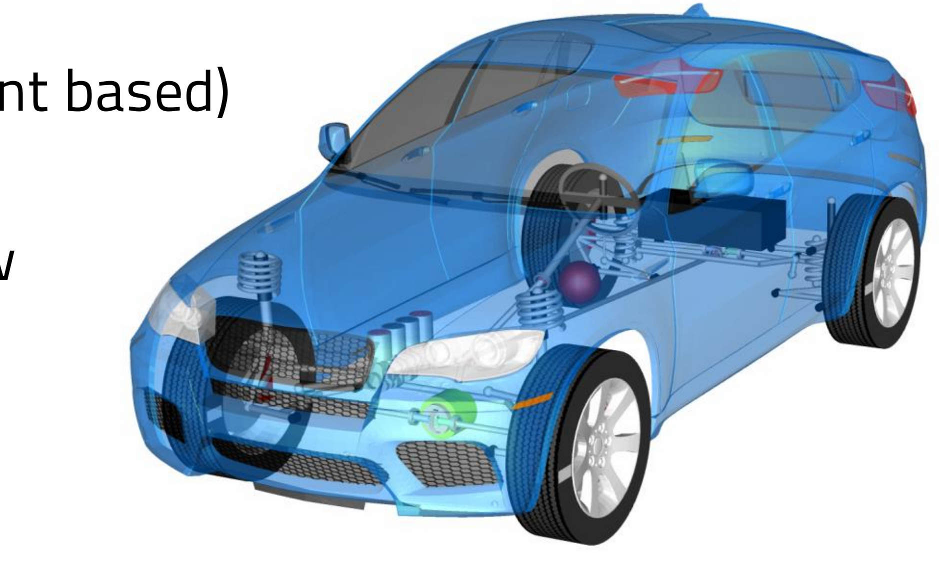
PRODUCT INNOVATION

Model Based Design: frontiers of virtual product design and what innovations are happening there

SYSTEM SIMULATION TECHNOLOGY WISH-LIST

- Multi-domain (electric, mechanic, thermal, fluid, etc.)
- Model fidelity adaptable to purpose (multi-fidelity)
- Scalable and robust simulation performance
- Re-usable models (model libraries, component based)
- Predictive (based on physics first principles)
- Extensible with proprietary IP and know-how
- Protect modeling investments over time
- Supported by community and open market
- Simple and robust connectivity



Modelica and FMI open standards meet all these!

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fmi FUNCTIONAL MOCK-UP INTERFACE

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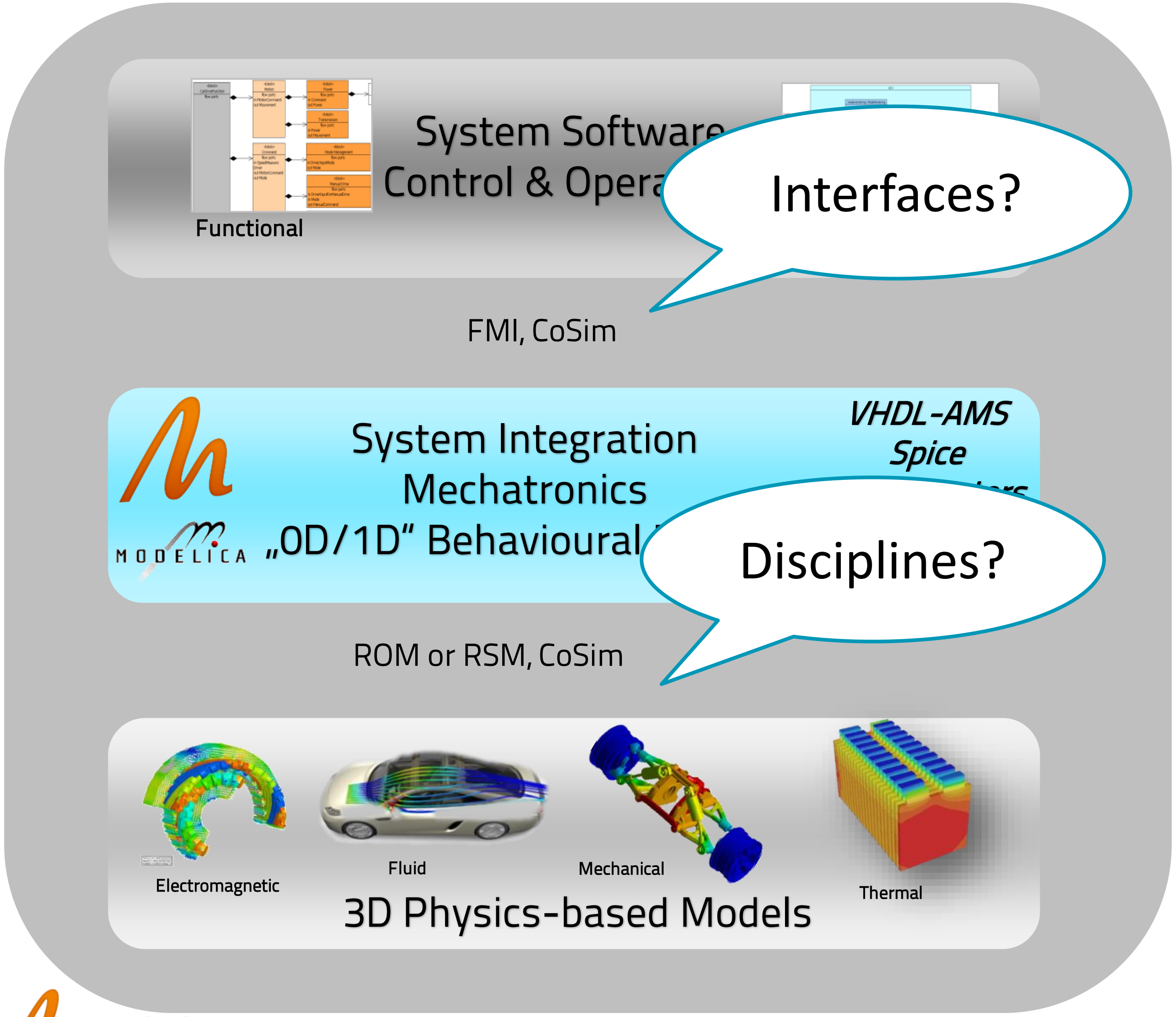
Systems Engineering Interoperability



ROM	= Reduced-Order Model
RSM	= Response Surface Model
FMI	= Functional mock-up interface
CoSim	= Co-Simulation

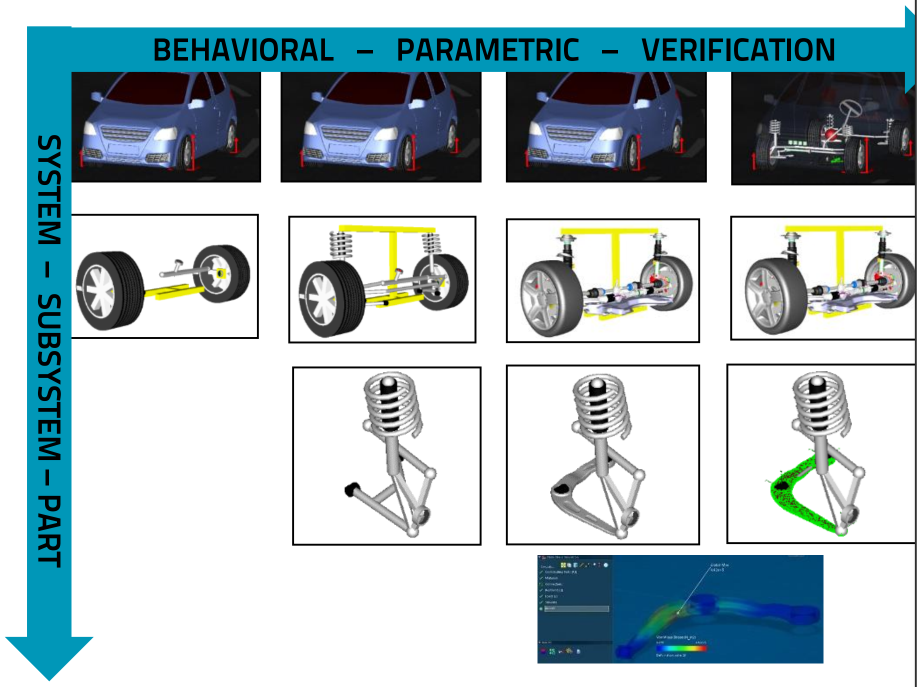
Tool Categories:
- 0/1-D ODE Simulators
- Multibody Simulators
- Communication Simulators
- HIL Simulators & SIL tool chains
- Scientific Computation tools
- Data analysis tools
- Co-simulation Backplanes
- Software development tools
- Systems engineering tools
- 3D Physics tools
  (CFD, FEM in many domains)
- Design & drawing, CAD
- Data management: PLM, ALM, PDM
- SDKs, legacy integration

KEYS TO SYSTEMS DESIGN AND ENGINERING

Fidelity just right for purpose

Inherent support for working with mixed fidelities

- Get the architecture right
- Keep the design connected and consistent
- Continuously evaluate design against requirements
- Executable specs <-> Detailed design



Design, simulation, analysis

Formal and open description

- Physics capture
- Constraint and cost definition
- Analysis and decision support
- Reduction/elemination of real tests

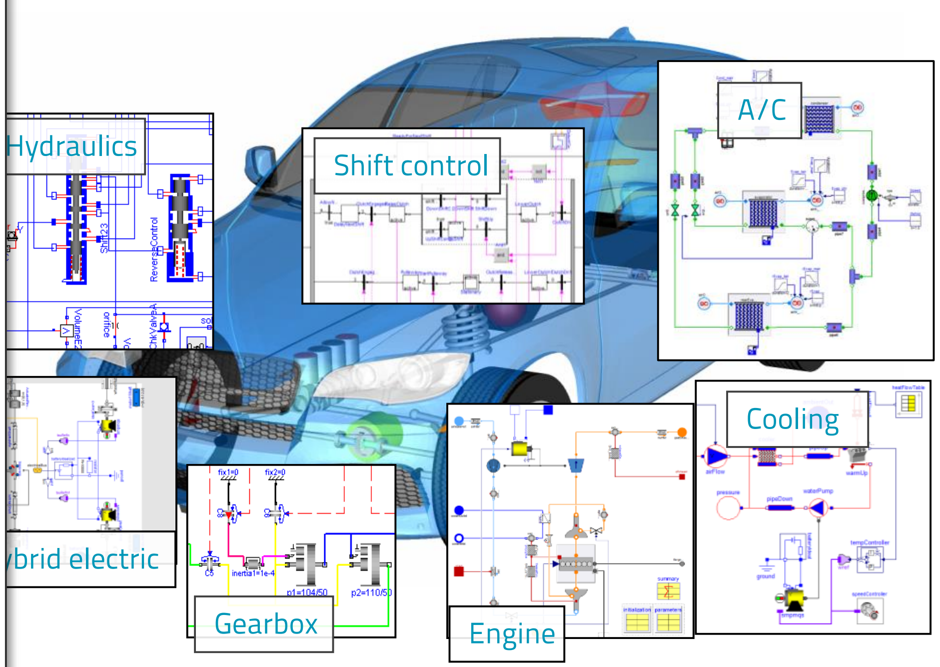
Examples:

- Dynamic simulation
- Steady-state
- Optimization
- Realtime/XIL
- Controls design
- Robust design
- Requirements definition
- Formal analysis

Multi-domain

Multi-domain by design

- Interaction and cross-dependencies between subsystems and physical domains captured
- Facilitates simultaneous engineering
- Allow for integrated design and optimization



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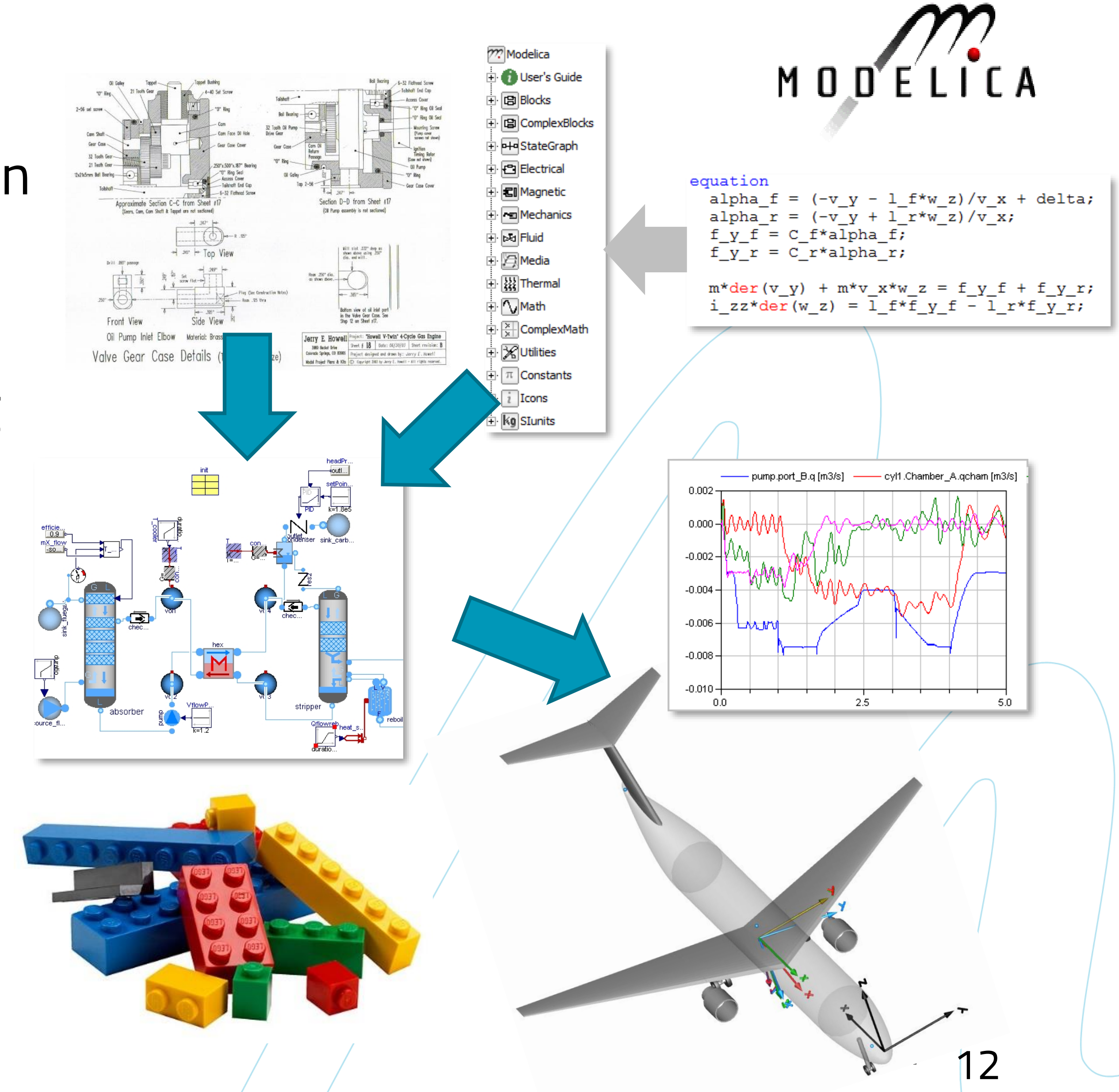
THE MODELICA LANGUAGE

A high-level language to develop physics based system models from architectural design to the component level

MODELICA: THE OPEN STANDARD FOR SYSTEMS MODELING

- Non-proprietary open standard, maintained by the Modelica Association (www.modelica.org)
- Object oriented modeling language
- Declarative: describes **what** something is, **not how** to solve it
- Non-causal and equation based
- First principles (mass, energy, momentum balances)
- Supports multi-domain modeling
- Large community and ecosystem of services, tools and model libraries



MODELICA SUPPORTING TOOLS

ALPHABETICAL

Commercial

- Dymola® by Dassault Systèmes
- IGNITE by Ricardo Software
- MapleSim® by MapleSoft®
- MWorks by Suzhou Tongyuan
- OPTIMICA® Toolkit by Modelon
- Simplorer by ANSYS
- SimulationX® by ESI-ITI GmbH
- SolidThinking Activate by Altair
- Wolfram SystemModeler by Wolfram

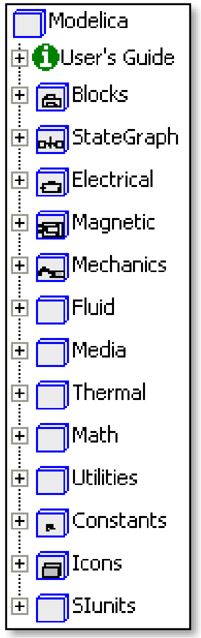
More tools coming (e.g. Amesim by Siemens LMS)

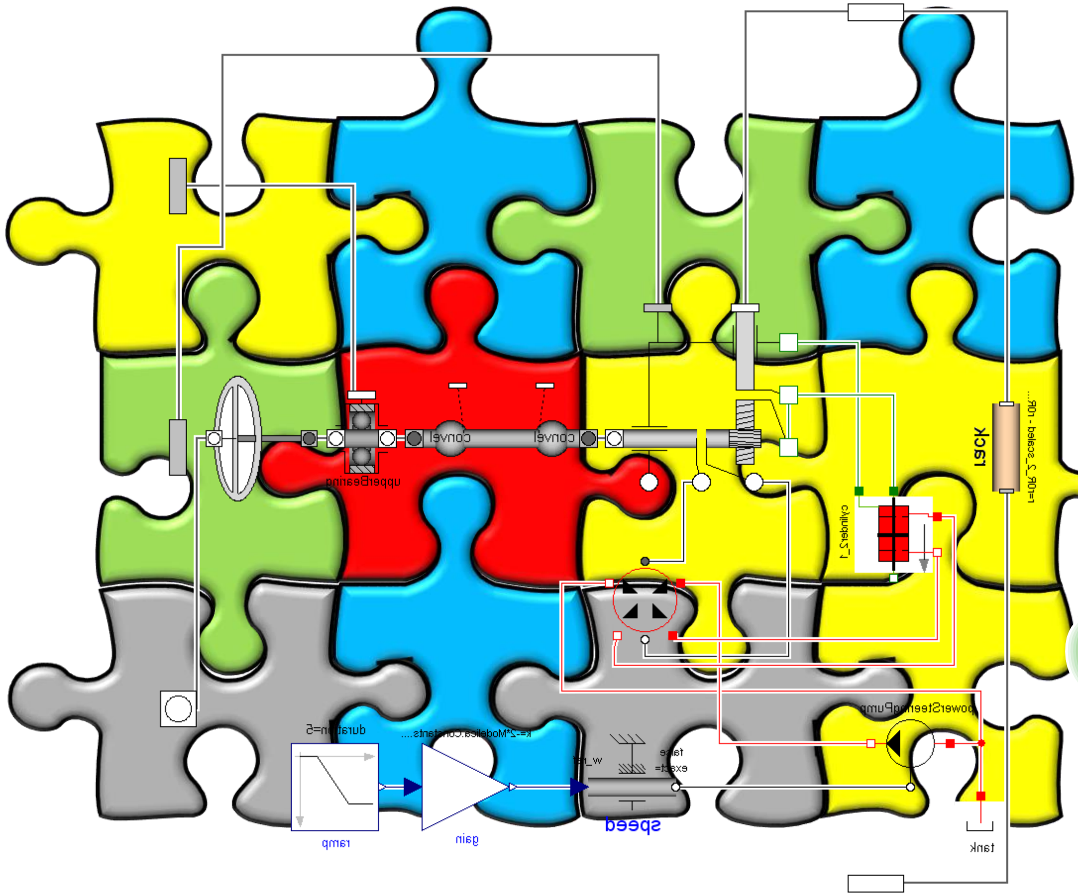
Open Source

- JModelica.org by Modelon
- OpenModelica by the OM Consortium

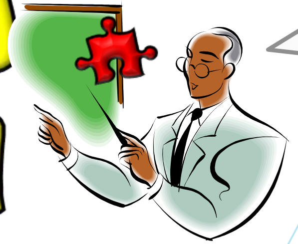
LEVERAGE EXISTING MODELS AND KNOW-HOW

- Off-the-shelf model libraries and components reduces maintenance
- Focus on core knowledge to grow the competitive edge
- Build innovative systems from standard component models

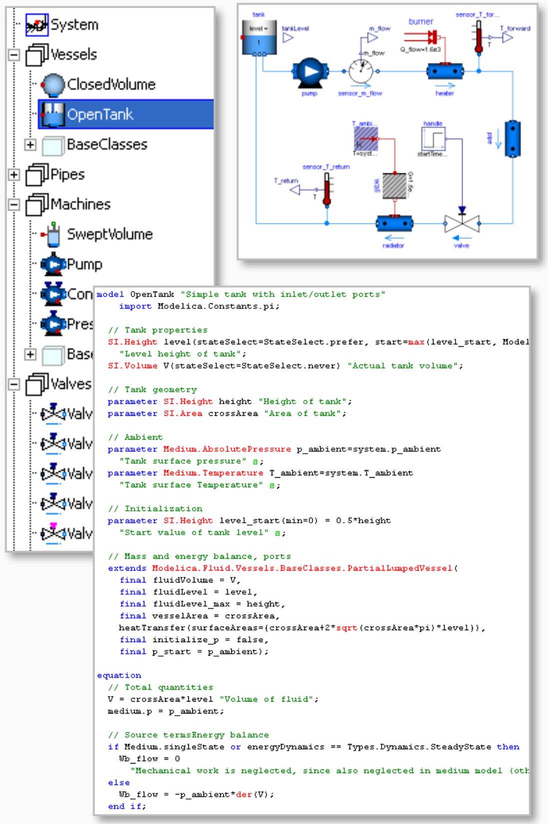




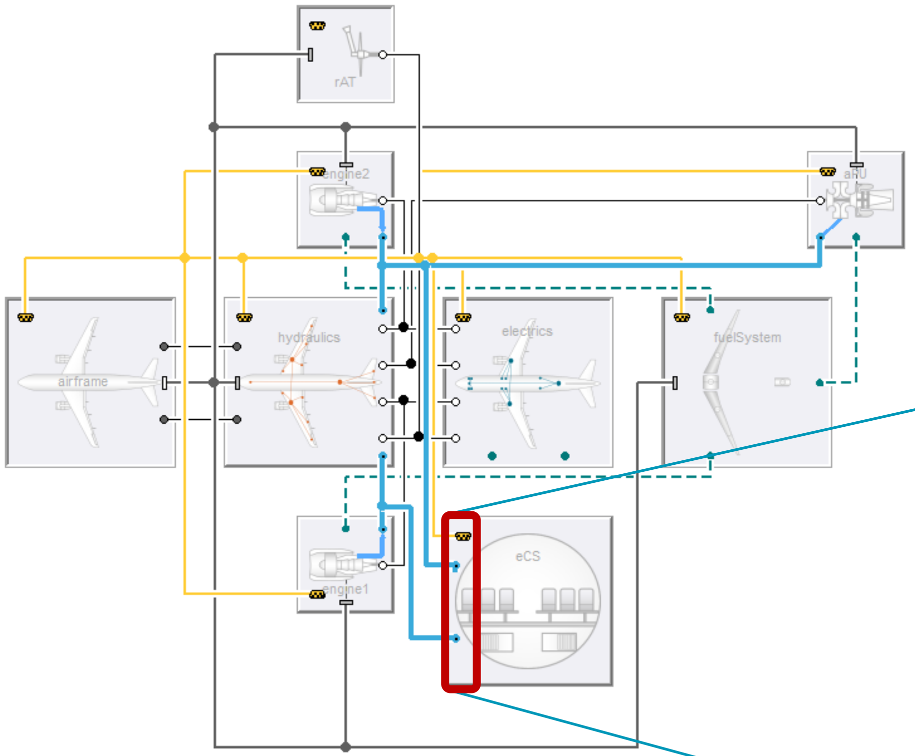
- Free open source
- Commercial off-the-shelf
- Consulting services
- Partners / suppliers / customers / academia
- In-house



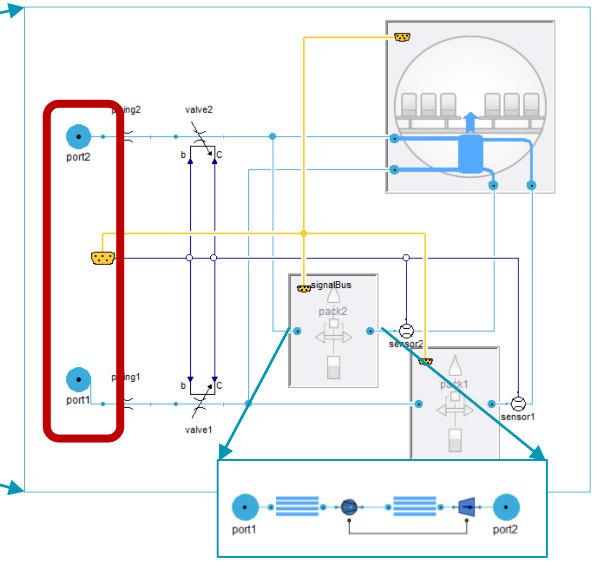
- Knowledge stored in Modelica model libraries
- Accessible, persistent, extensible in-house IP



ARCHITECTURES DESIGN & EXPLORATION



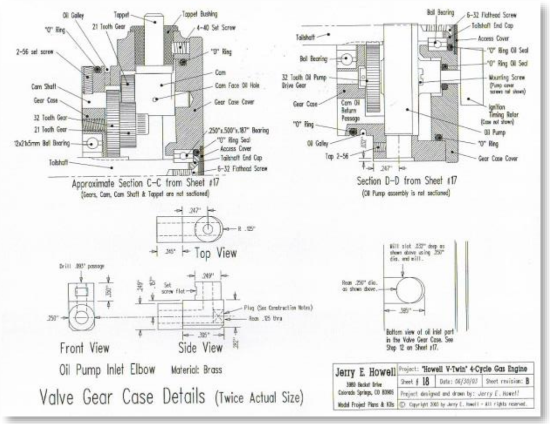
Organization of model into interfaces and templates promotes broader applicability and reusability reducing modeling effort in a product line context for re-validation.



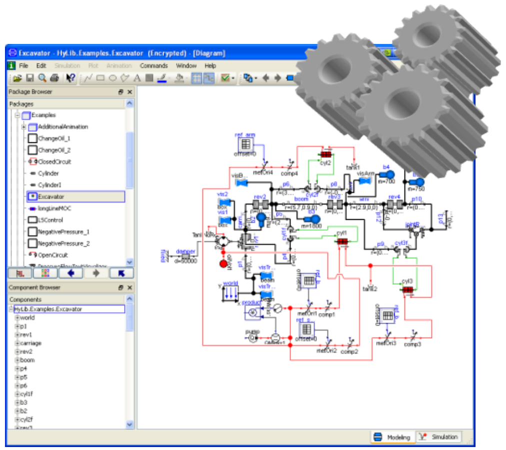
Modelica language support for abstract typing; strong typing (guarantees for plug-compatibility of models) enables rigorous checks for subsystem compatibility and interface consistency

UNIQUE BENEFITS WITH MODELICA

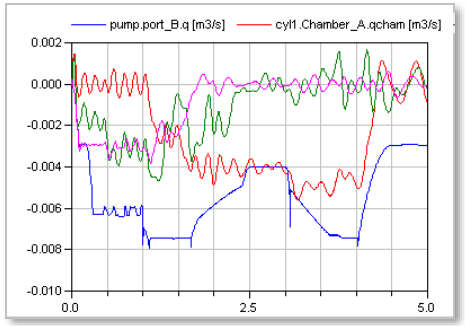
Focus on problem formulation and solution rather than encoding



System design



Modelica model



Behavior

Compile

...

Generated code or executable

Algebraic equation system: steady-state design

DAE: transient simulation

NLP: optimal control

NLP: design optimization

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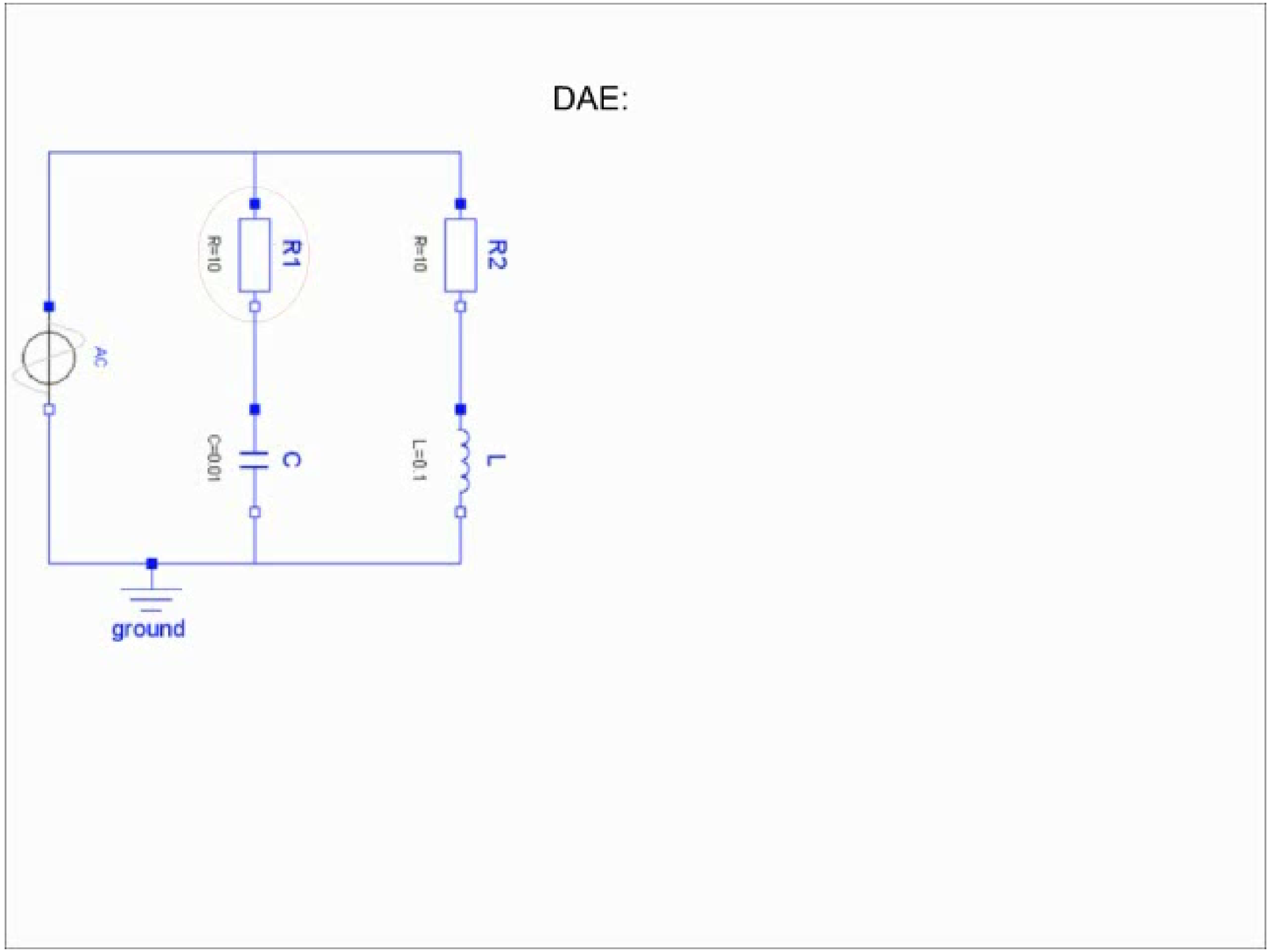
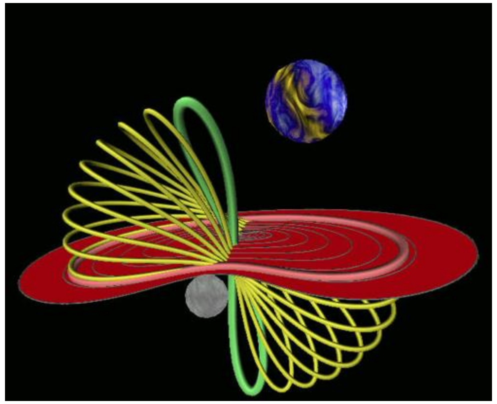
Efficient simulation: Differential Algebraic Equation Case

Modelica tools use symbolic manipulation to generate efficient simulation code

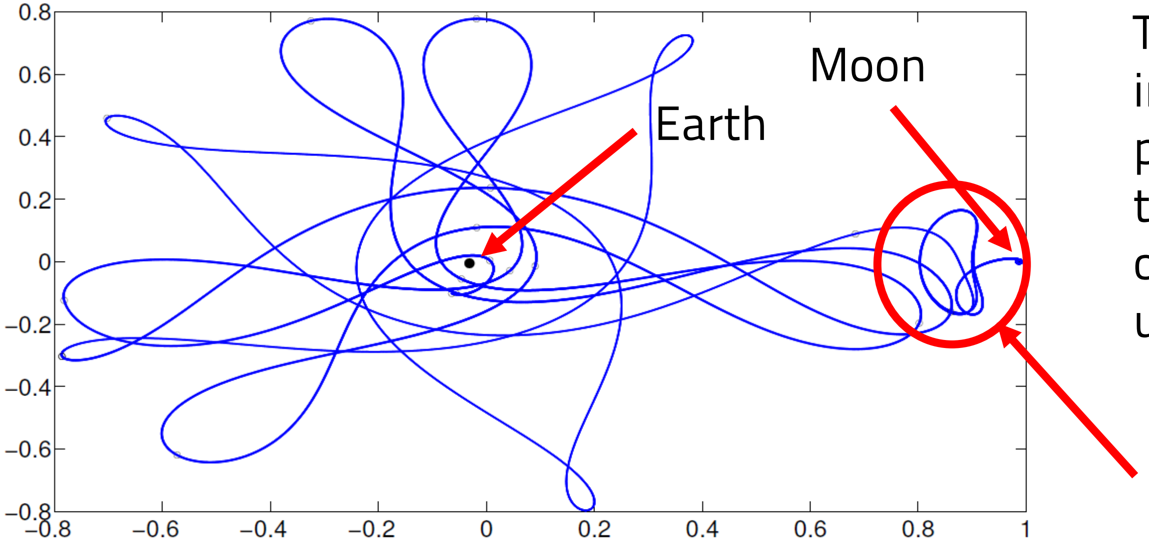


OPERATIONAL OPTIMIZATION & OPTIMAL CONTROL

Collocation of finite elements for trajectory optimization

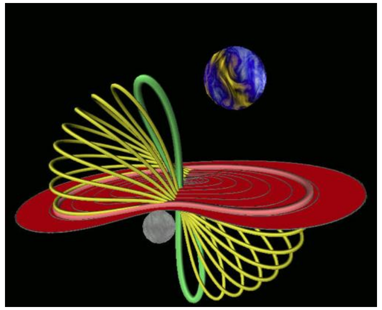


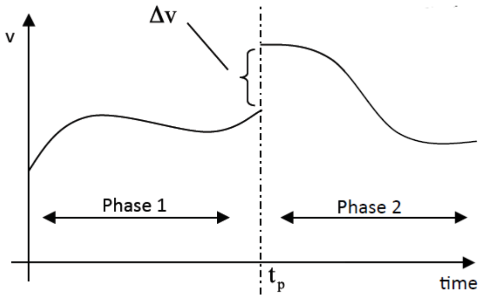
GOING TO THE MOON



The optimized trajectory in the rotating frame of PCR3BP involving the Earth, moon and the space probe. The space probe receives two consecutive gravity assists, and is then pushed onto the stable manifold of the L1 periodic orbit. Optimized delta-Vs then put on the low lunar orbit using the unstable dynamics near L1.

Given a Lyapunov orbit around L1, find the minimum fuel for a transfer into an orbit around the moon (m2). The controls are given as two discontinuous changes in velocity, corresponding to two rocket bursts.





Controls by Δv

Courtesy: Mitsubishi Electric Research Lab

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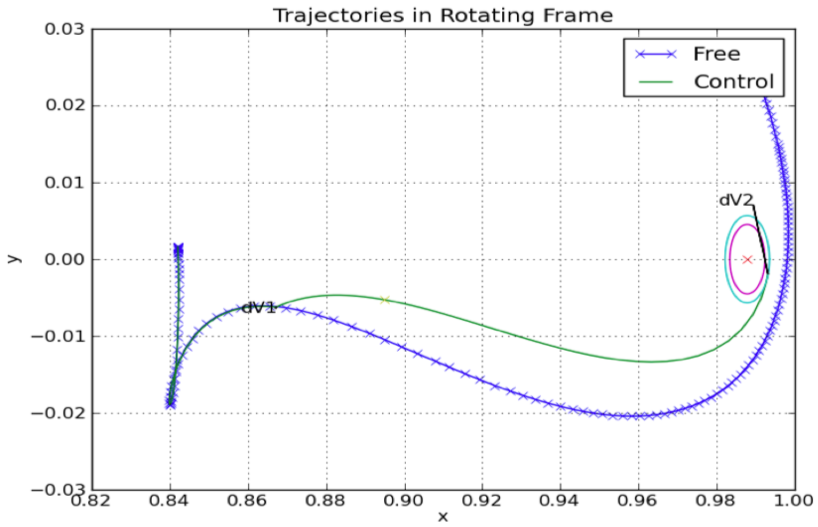
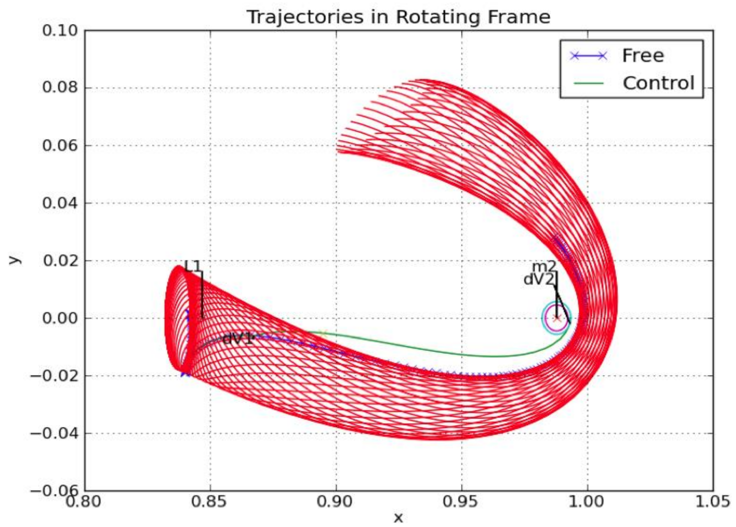
GOING TO THE MOON

Results for a fixed initial point with a small perturbation on the unstable manifold. Solved with a Gauss Pseudo-spectral Method in the open-source Modelica tool JModelica.org





The blue line represents the trajectory where no control is applied. The green line is the optimized trajectory with dV1 and dV2 as control.

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THE FUNCTIONAL MOCKUP-INTERFACE

An API for executable models for model exchange and co-simulation

FMI: THE OPEN STANDARD FOR MODEL DEPLOYMENT

FMI™ is:

- A tool independent standard for model exchange and co-simulation
- Currently supported by more than 95 tools
- Strong support from automotive industry

FMI™ enables:

- Model-sharing and IP protection
- Deployment in different applications
- Streamlined tool connectivity

WWW.FMI-STANDARD.ORG

What is FMI?

- FMI is a standard interface to enable the exchange of **compiled** models between tools, and for co-simulation
  - Has been adopted by over 95 CAE tools as a supported interface
  - Is propagated by several industrial consortia (ProSTEP iVIP, GAAG)

- The FMI licensing model revolutionizes the business model for enterprise model deployment
  - Model content and execution can be shared freely within the extended enterprise
  - Model authoring is done on typical CAE tools

- FMI is applicable to a much broader set of tools than Modelica: FEM, CFD, Controls & Software development, ...

EXCERPT OF FMI-COMPATIBLE TOOLS

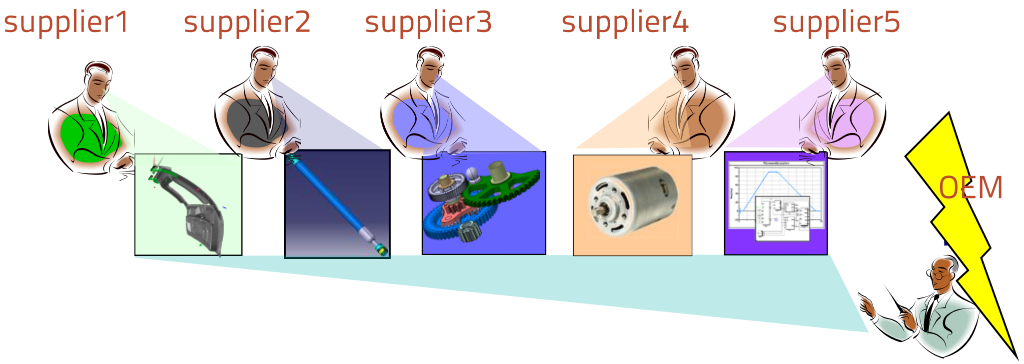
Total numbers	Filter	⇄ ModelExchange		% CoSimulation		
Tools supporting FMI	**FMI Version**	**Export**	**Import**	**Slave**	**Master**	**Notes**
Adams	FMI_1.0		Available 35	Available	Available 42	High end multibody dynamics simulation software from MSC Software
	FMI_2.0		Available 34	Available	Available 40	
Algoryx Dynamics	FMI_1.0			Available		Algoryx Dynamics is a professional multi-purpose physics engine for simulators, engineering, large scale granular simulators and more.
	FMI_2.0			Available		
Amesim	FMI_1.0	Available 29	Available 27	Available 36	Available 62	Integrated simulation platform for the analysis of multi-domain mechatronics systems by Siemens PLM Software
	FMI_2.0	Planned	Planned	Available 15	Available 109	
ANSYS SCADE Display	FMI_1.0	Available		Available		SCADE Display facilitates embedded graphics, display and HMI development and certified code generation for safety-critical displays from ANSYS.
ANSYS SCADE Suite	FMI_1.0	Available		Available		SCADE Suite is a model-based development environment with certified code generation for safety critical embedded applications from ANSYS.
ANSYS Simplorer	FMI_1.0	Available	Available 60		Planned	ANSYS Simplorer is a multi-domain, multi-technology simulation program from ANSYS.
	FMI_2.0	Planned	Available 15		Planned	
ANSYS DesignXplorer	FMI_1.0	Available				DesignXplorer is able to export a computed response surface as an FMU.
	FMI_2.0					
ASim - AUTOSAR Simulation	FMI_1.0	Available 3		Available 3		AUTOSAR product from Dassault Systèmes
	FMI_2.0	Planned		Available 3		
@Source	FMI_1.0	Available				Simulink via @Source
Automation Studio	FMI_1.0					B&Rs Automation Studio is a software engineering platform for industrial automation targetting PLCs, industrial PCs, HMI and embedded controllers from B&R.
	FMI_2.0		Planned	Available		
AVL CRUISE	FMI_1.0	Planned	Available 21	Available 8	Available 30	Vehicle system analysis tool for the optimization of fuel efficiency, emission, performance and driveability, from office to HiL to testbed.
AVL CRUISE M	FMI_1.0		Available 70		Available 111	AVL CRUISE™ M is a realtime, multi-disciplinary, vehicle system simulation software used in office environments for the design of powertrains and thermal management systems, in HiL environments for control function development and calibration, and in testbed environments to provide simulation models for component testing.
	FMI_2.0		Available 73	Available	Available 92	
AVL Model.CONNECT	FMI_1.0		Available 153		Available 164	Model.CONNECT™ is a neutral model integration and co-simulation platform to connect virtual and real components

95+ tools

Supported by different tool classes:

- 0/1-D ODE Simulators
- Multibody Simulators
- HIL Simulators /SIL tool chains
- Scientific Computation tools
- Data analysis tools
- Co-simulation Backplanes
- Software development tools
- Systems engineering tools
- SDKs, legacy integration

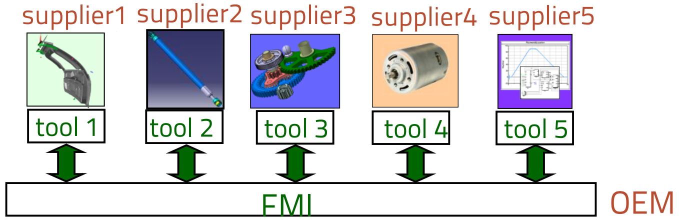
FMI USE CASE I: COMBINE MULTIPLE DOMAINS



Combined simulation for system integration

Solution

- As a universal solution to this problem the **Functional Mockup Interface (FMI)** was developed by the EU-project MODELISAR, and is now maintained by the Modelica® Association



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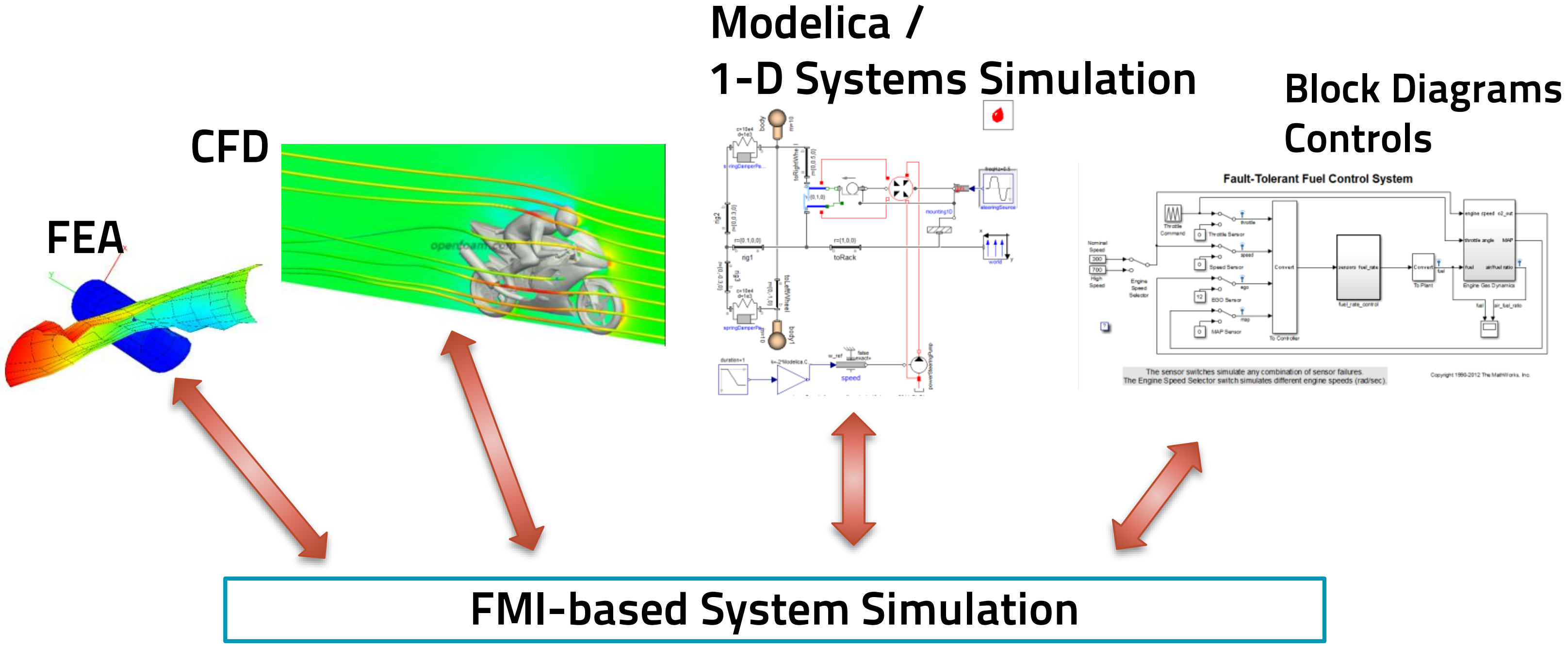
FMI USE CASE II: CONNECT SYSTEM LEVEL WITH 3D

- Combine different modeling domains into coherent co-simulation (cyber-physical systems)
  - Physical models, 0D/1D to 3D (but not 3D to 3D!)
  - Models of controls & software



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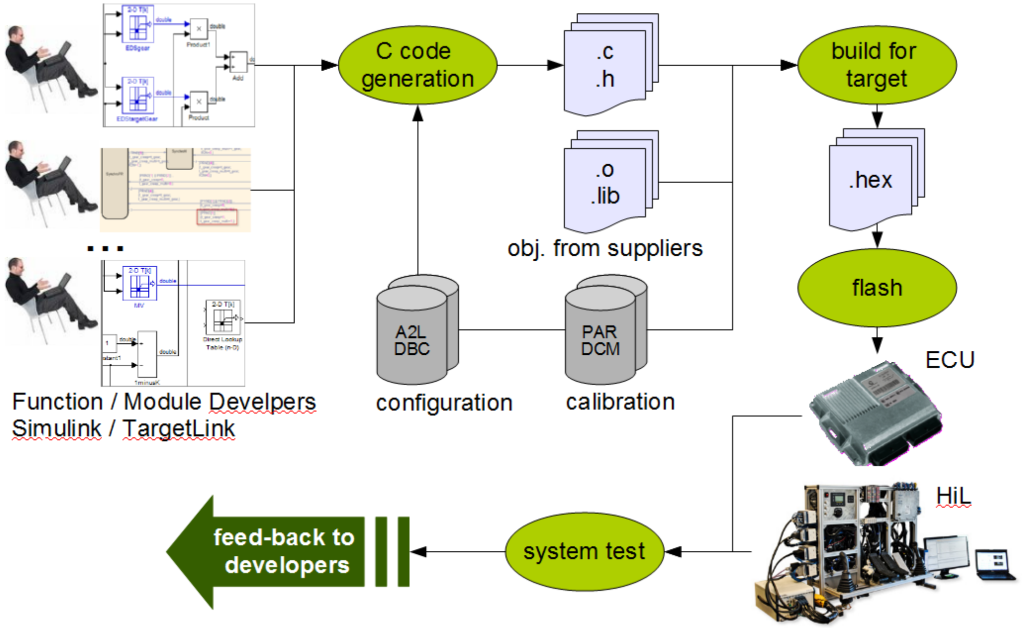
FMI USE CASE III: COMBINE SOFTWARE & PHYSICS

- FMI export support from Controls Tools:
  - Matlab/Simulink through FMIT Coder (Modelon)
  - SCADE Suite (safety critical applications)
  - IBM Rational Rhapsody
  - Easy to integrate manually written control code through FMI-wrappers
- FMI supported by most major HIL Vendors
  - DSPACE
  - National Instruments
  - Concurrent
  - IPG
  - Speedgoat
- FMI for ECU virtualization
  - Silver by Qtronic
  - ETAS tools (Bosch)



MIL, SIL and HIL

FMI: A BUSINESS MODEL INNOVATION

- FMI-compliant tools often allow liberally licensed export of models for distribution in the organization
- Exported FMU's most often don't require a license from the model authoring tool
- Deployment from few simulation specialists to designers, domain specialists, control engineers
  - One FMU used by many engineers (control design)
  - One FMU run on many cores (robust design)

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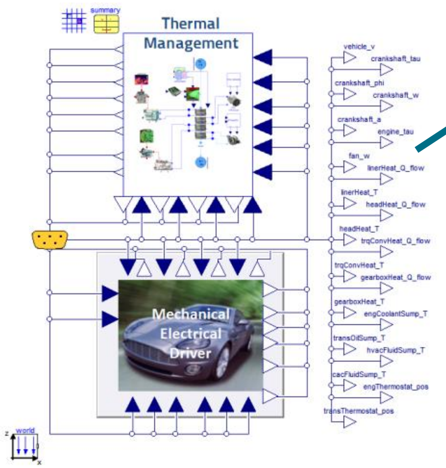
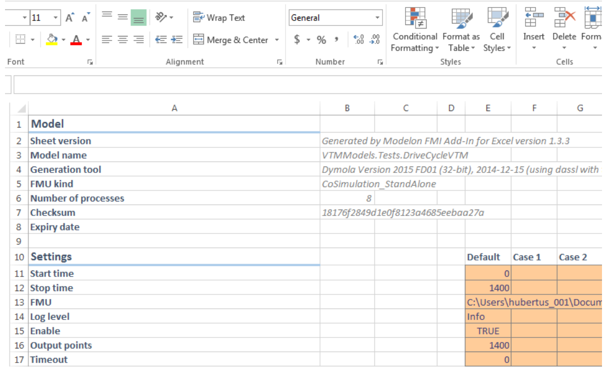
TYPICAL FMI-BASED WORKFLOWS



Model Authoring Tool(s)

Export model as freely licensed FMU



	A	B	C	D	E	F	G
1	Model						
2	Sheet version	Generated by Modelon FMI Add-In for Excel version 1.3.3					
3	Model name	VTMModels.Tests.DriveCycleVTM					
4	Generation tool	Dymola Version 2015 FD01 (32-bit), 2014-12-15 (using dassl with					
5	FMU kind	CoSimulation_StandAlone					
6	Number of processes	8					
7	Checksum	18176f2849d1e0f8123a4685eebaa27a					
8	Expiry date						
9							
10	Settings				Default	Case 1	Case 2
11	Start time				0		
12	Stop time				1400		
13	FMU				C:\Users\hubertus_001\Docum		
14	Log level				Info		
15	Enable				TRUE		
16	Output points				1400		
17	Timeout				0		

Low-cost Model Execution Platform
May combine FMUs from several tools

- Additional work flow automation for
  - pre-processing,
  - model calibration,
  - post-processing,
  - analysis,
  - automated reporting
  - automated requirements verification

- **True democratization of simulation**
- **Greatly improved utilization of models**

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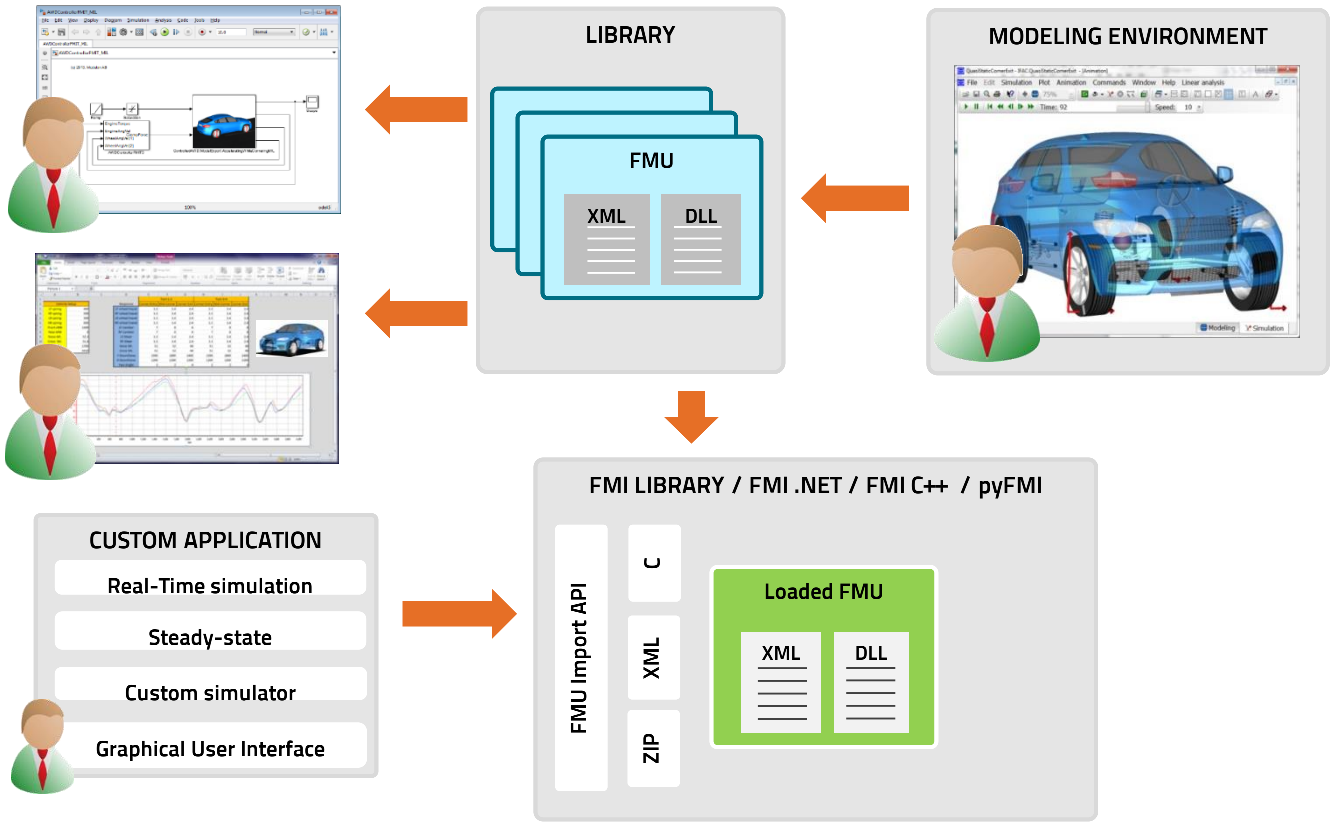
FMI TOOLCHAIN SOLUTIONS



One Model, many uses !

" FMI reduces the integration efforts and therefore allows BMW to concentrate on the core competences of the development. Several projects at BMW have confirmed that FMI is our best chance yet to establish cross-domain simulations throughout the vehicle development process.

Stefan-Alexander Schneider, BMW

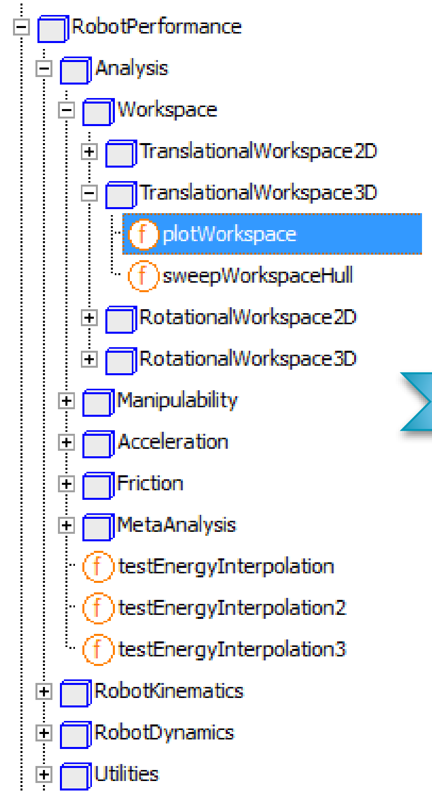
FLEXIBILITY OF MODELICA KEY TO VIRTUAL DESIGN OF INNOVATIVE PRODUCTS

Examples from many industries where Modelica and FMI helped design innovative products

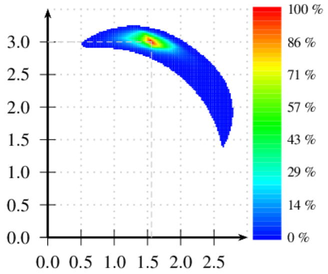
The DLR Robotic Motion Simulator - Utilizing Modelica for the development

The DLR Robot Motion Simulator:

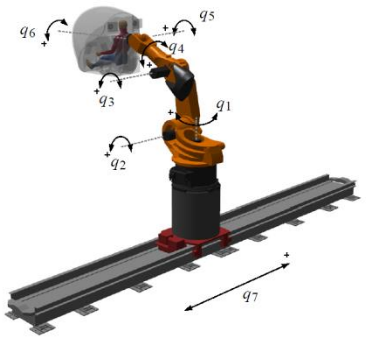
- Industrial robot based motion simulator
- Linear axis + 6 axis robot
- 500 kg payload
- Additionally a version with a DA42 cockpit has been developed



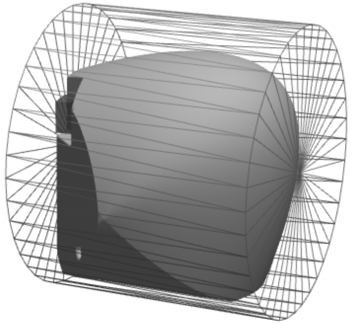
Workspace optimization



Working point definition



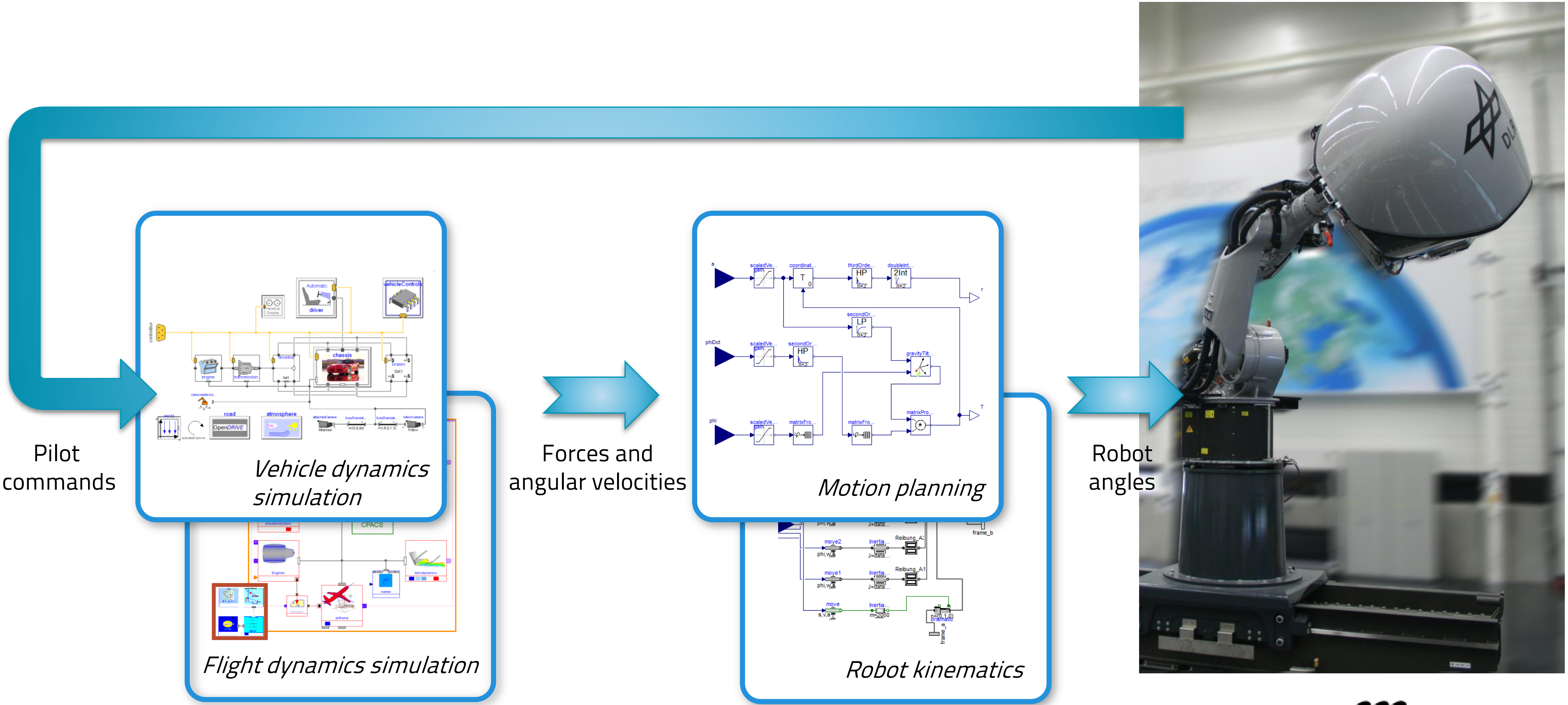
System simulation



Cell dimensions

courtesy: DLR - Institute of System Dynamics and Control (www.dlr.de/sr)

Optimization based Pathplanning with Modelica



courtesy: DLR - Institute of System Dynamics and Control (www.dlr.de/sr)

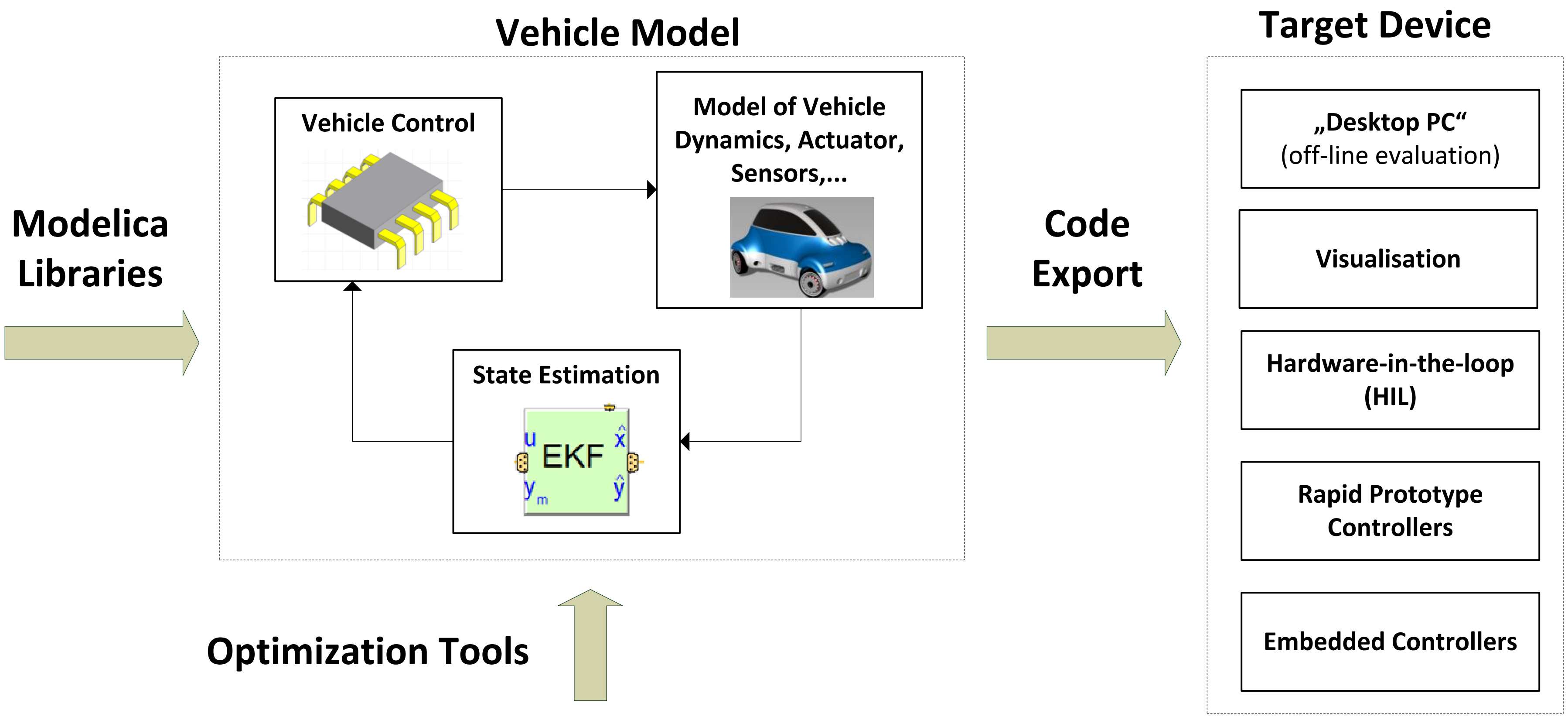

Wissen für Morgen
DLR
DLR Robotic Motion Simulator
Utilizing the DLR Flight Dynamics Library

DLR ROboMObil - Robotic Electric Vehicle for future mobility research

- Four **"wheel robots"**:
  - Wheel hub drives (each 160Nm)
  - Independently actuated steering (steering angle: -25c…95c)
- Autonomous driving through camera system and image recognition
- Various by-wire input devices combined with force feedback and driver assistance as well as remote control

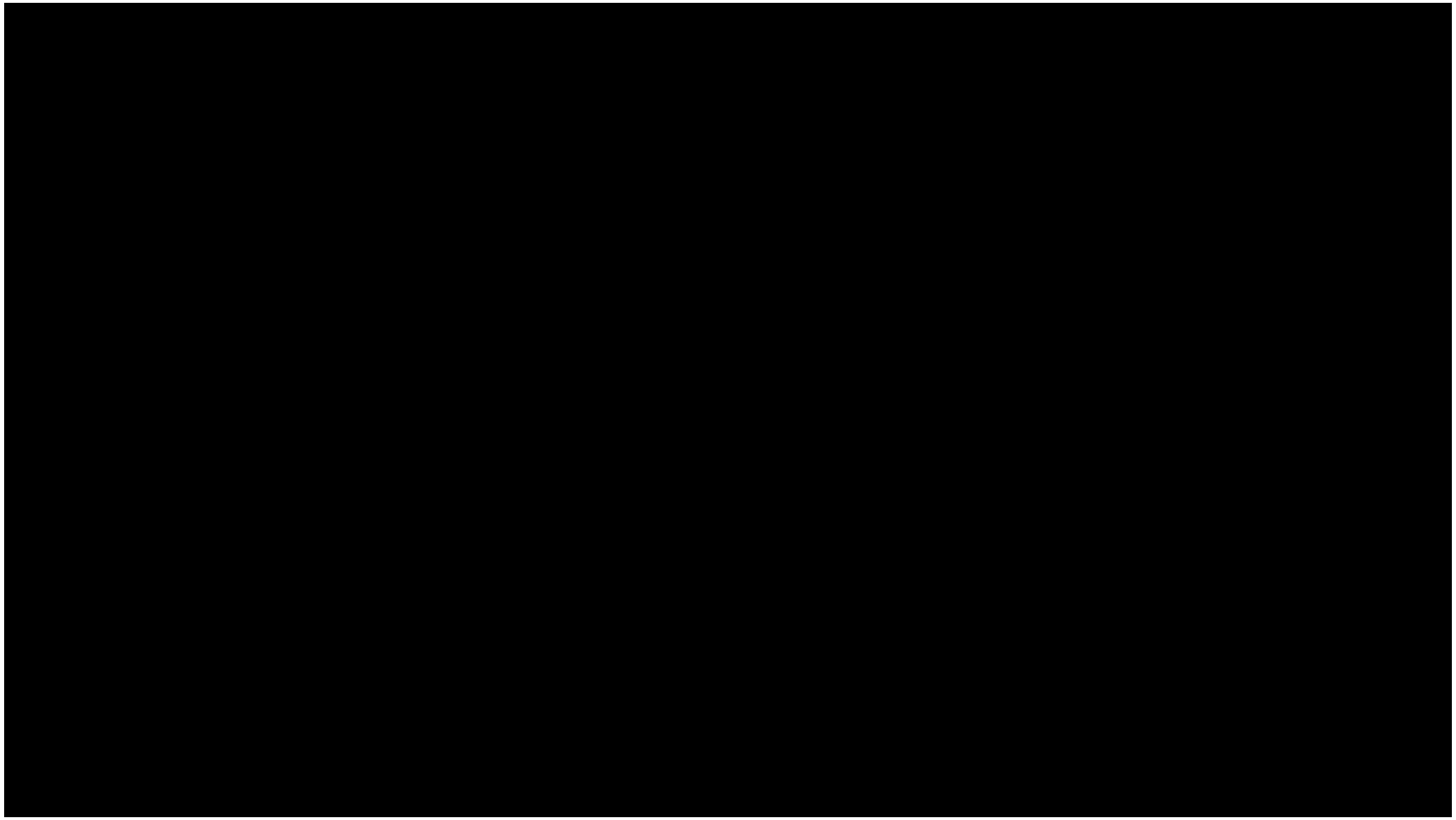
courtesy: DLR - Institute of System Dynamics and Control (www.dlr.de/sr)

DLR RObоMObil – Designed and Operated with Modelica



courtesy: DLR - Institute of System Dynamics and Control (www.dlr.de/sr)

DLR RObоMObil - Robotic Electric Vehicle for future mobility research

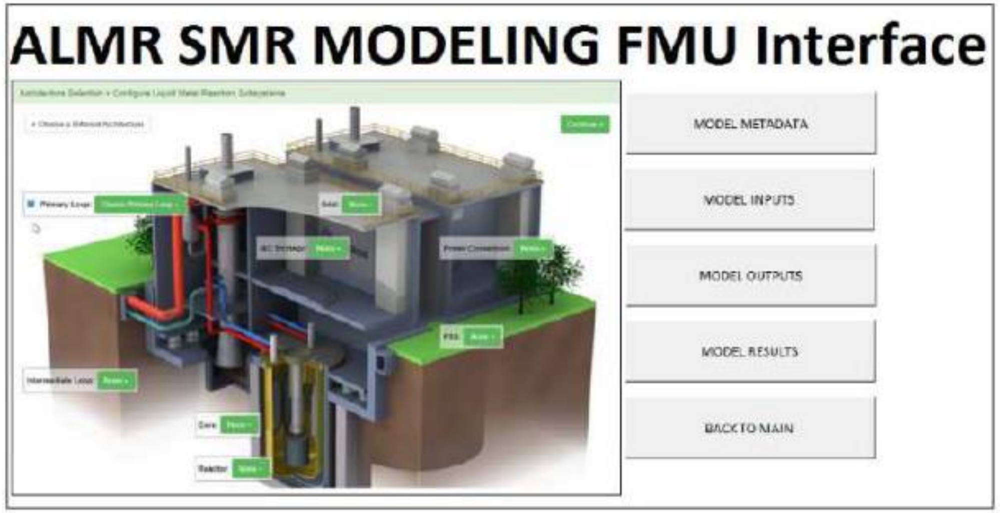


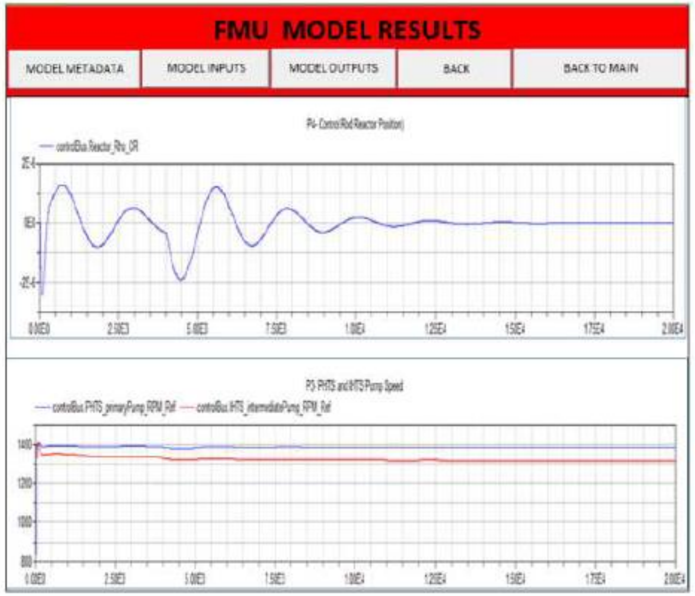
courtesy: DLR - Institute of System Dynamics and Control (www.dlr.de/sr)

MODEL DEPLOYMENT FOR NEW REACTOR TYPES

Model Deployment from Simulation Experts to Reactor Design Experts, by Oak Ridge National Labs

Custom-built, pre-packaged work flow based on FMI Excel interface by Modelon

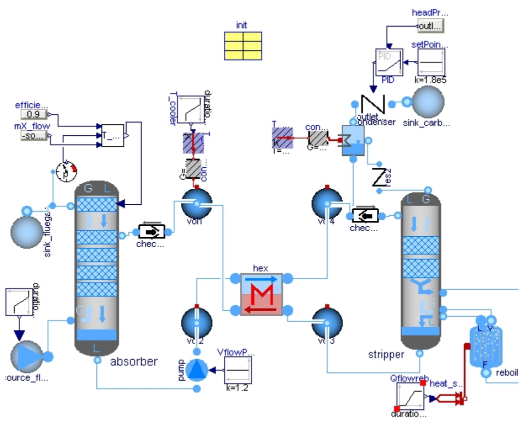




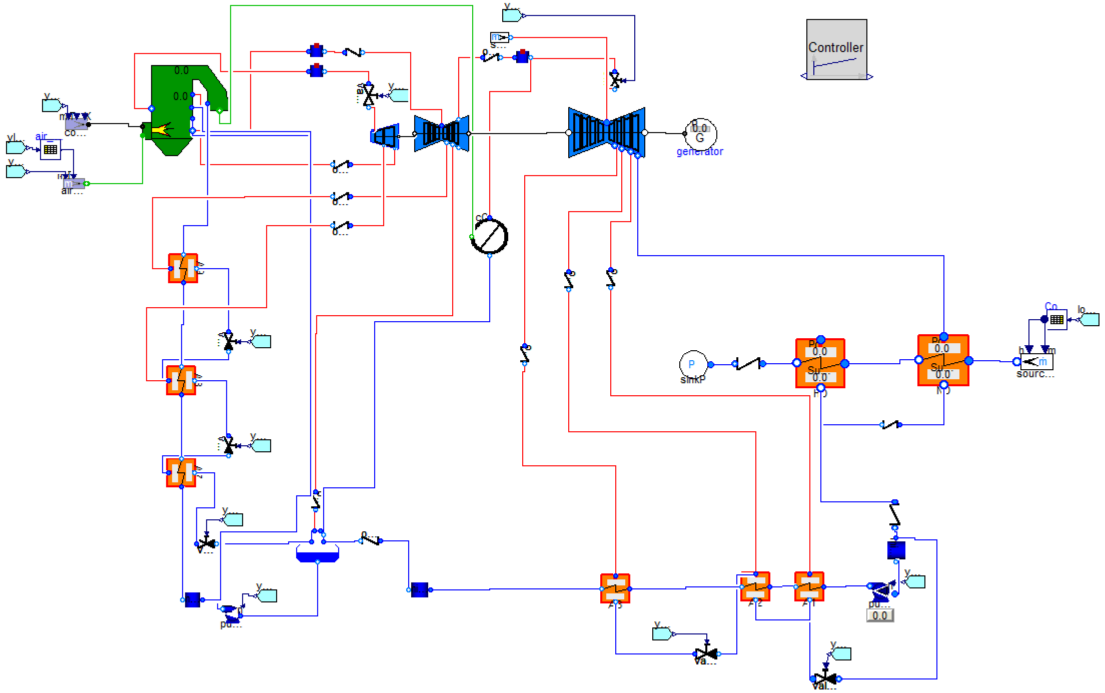
FMU exporter: Dymola
FMU Importer: Microsoft Excel

COAL-FIRED POWER PLANT WITH CARBON CAPTURE

- Coal-fired power plant with CO_2 separation
  - Integration with a carbon capture library
  - Use case based on mix of off-the shelf libraries & specialized solution



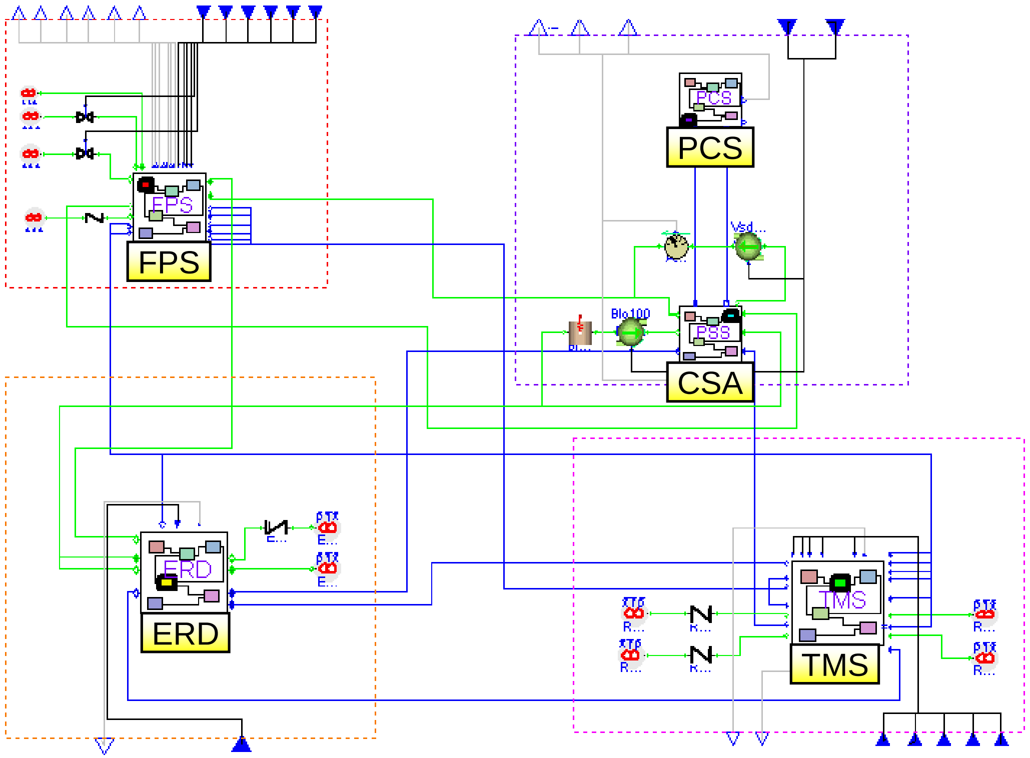
Capture Plant Model built with Modelon Post-Combustion Carbon Capture Solution



Fuel Cell SLDM for controls

UTC Fuel Cells
A United Technologies Company
The Research Center
UNITED TECHNOLOGIES RESEARCH CENTER

Eborn, *et. al*: System Level Dynamic Modeling of Fuel Cell Power Plants, *In* Proc. of American Controls Conference, Denver, CO, 2003.

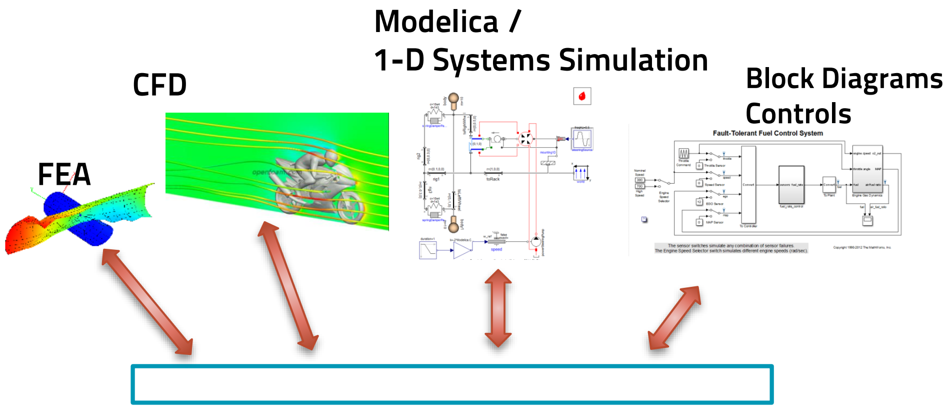


- System model includes; fuel processing, stack, power section and thermal management
- Detailed model with >20000 equations, >500 dynamic states
- System model the enabler for innovative integrated solutions

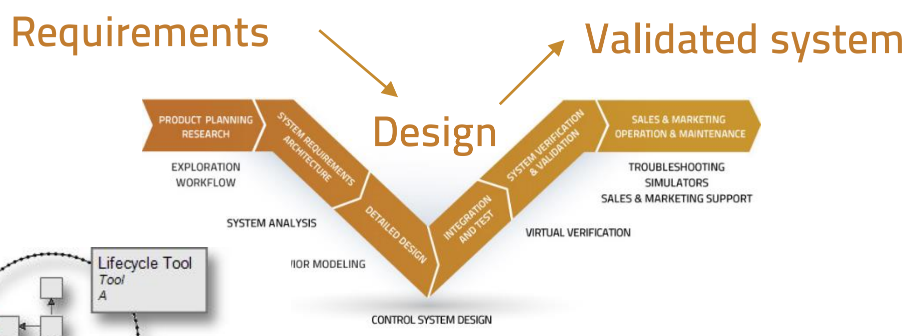
Modelon
MODELICA

UPCOMING INNOVATIONS

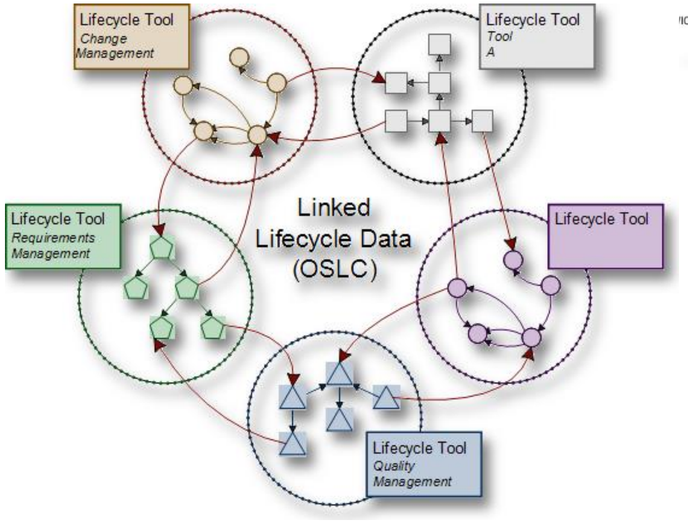
More connectivity between
3-D tools and system simulation tools



Connection between Systems engineering and system simulation

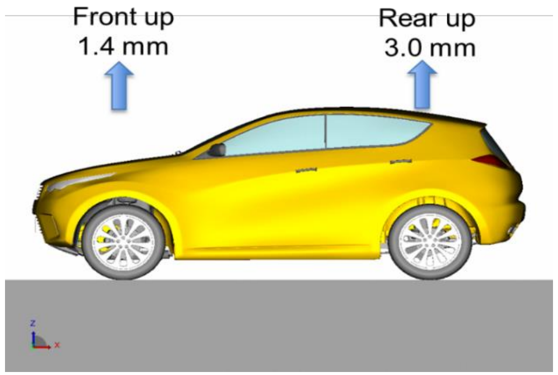


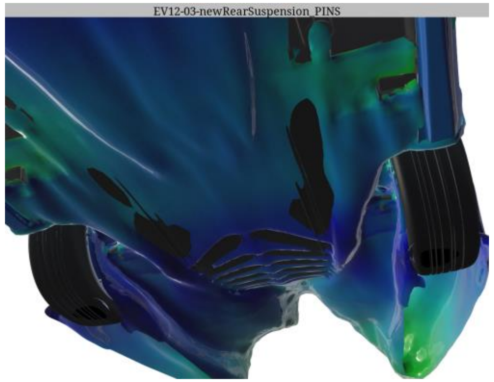
Connection to PLM & PDM systems, possibly via OSLC

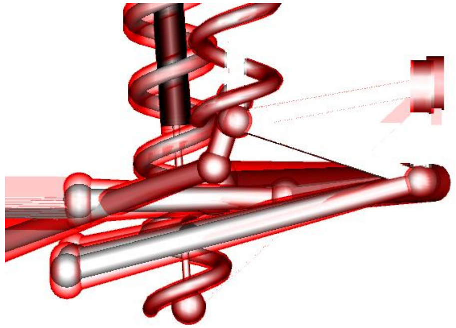


COUPLING CFD TO MULTIBODY: ENABLED BY FMI

- CFD: aerodynamic drag very important for fuel economy or range
- Multi-body tools: important for handling, NVH, safety
- Past: Posture & drag/lift have always been treated uncoupled
  - Significant error has gone unnoticed due to difficulties in wind tunnel validation
- Problem: lift and drag determine the posture, posture determines lift and drag
  - ➢ The correct solution requires coupling!







Superimposed frames of suspension under aerodynamic load and no load

Solution: FMI enabled coupling between Optimica compiler (generates FMU) and CFD tool (imports FMU)

- Little effort & cost involved for software integration
- Out-of-the-box benefit: it works with many tools
- Process & data exchange between departments that did not collaborate before has been main challenge
- Without basing this on FMI, time & cost of realization would have been significantly higher

Modelon MODELICA

SYSTEMS ENGINEERING & SIMULATION

- Today: connectivity between simulation and system engineering tools is ad-hoc, pretty much non-existent.
- Linking requirements to Model Based Design has a big potential to improve productivity
- Connectivity built on Modelica, FMI and OSLC: 3 open standards !

- Closing the Design Cycle Loop with Executable Requirements and OSLC (Incose IW 2017 workshop presentation jointly by Modelon, Procter & Gamble and The Reuse Company)

SUMMARY: HOW MODELICA AND FMI PROMOTE INNOVATION

- Modelica enables innovation because,
  - It is a high-level description of the model
  - It is open to be connected and optimized for many solvers and algorithms, without a need to change the high-level description
  - Can describe architectures and variants efficiently
- FMI enables innovation because
  - It makes all the low-level interaction easy and standardized
  - It is at the same time so simple that it is easy to adopt, and powerful enough to solve tough problems
  - Applies to a much broader class of tools than Modelica
- Modelica and FMI jointly enable process innovation because the cost of interoperability is lowered significantly