INTO-CPS

Introduction to Modelling of Cyber-Physical Systems (CPSs)

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together with

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Claudio Gomes, Antwerp University

Horizon 2020 Programme

AARHUS UNIVERSITY

Newcastle University

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Who am I?

- Professor Peter Gorm Larsen; MSc, PhD
- Worked 17 years in industry (IFAD, Systematic); at IHA/AU since 2005
- Reviewer for EU and other countries on Research projects and applications
- Consultant for most large defence contractors on large complex projects
- Mostly proud of the firmware of NFC chip in 250+ million phones
- Served on 70+ program committees both as member and as chair
- Supervision: 9 post-docs, 11 PhD students, 60 MSc thesis students
- Has written books and 180+ articles (in particular about VDM and CPS)
- Member of the Danish Research Council for Independent Research (FTP)
- Coordinated INTO-CPS (8M€) + externally funded projects
- See http://pure.au.dk/portal/da/pgl@eng.au. dk for details

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MADE DIGITAL

INCOSE Denmark

What is a Cyber-Physical System?

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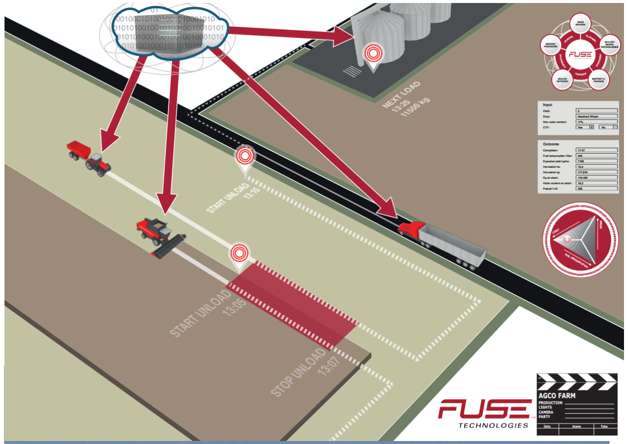
- Systems of interacting systems
  - Computing elements
  - Physical elements
  - Human interactions
- Complex, networked character
- Distributed control
- Error detection and recovery



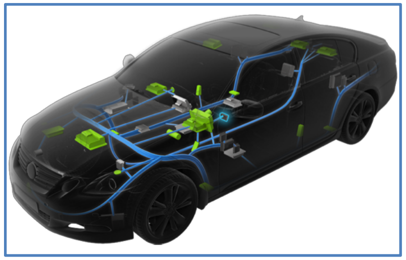
Our position in a nutshell

We advocate:

- Cyber-Physical Systems Engineering
  - The product is a system: software is not the end!
- Multidisciplinary collaborative modelling
- (Co-) simulation as well as verification
  - Promotes Design Space Exploration
  - Entails well-founded co-simulation orchestration

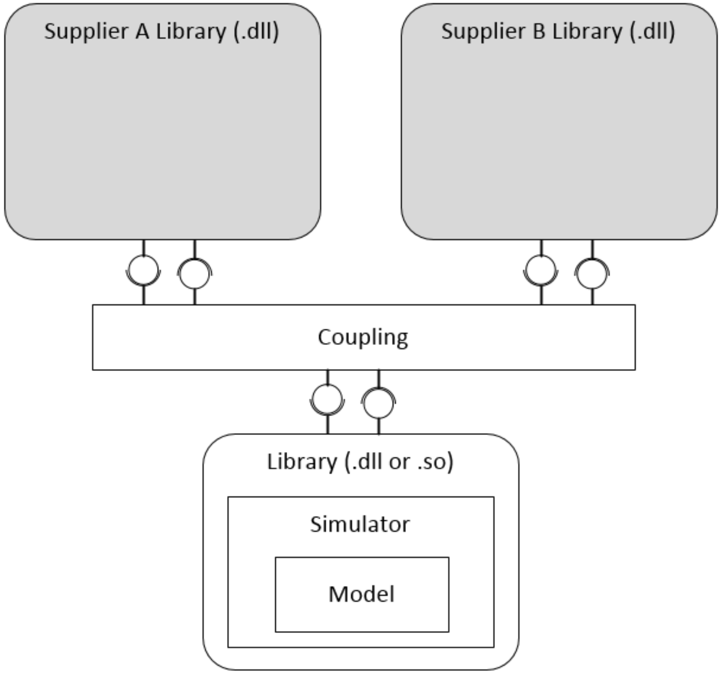
Our approach:

- Co-simulation of multiple Discrete Event and Continuous Time models
- A tool chain – not single tools
  - Requirements and Architectural models (in SysML)
  - Traceability support through development
- FMI interfaces constituent models
- Semantic foundations in Unifying Theories of Programming



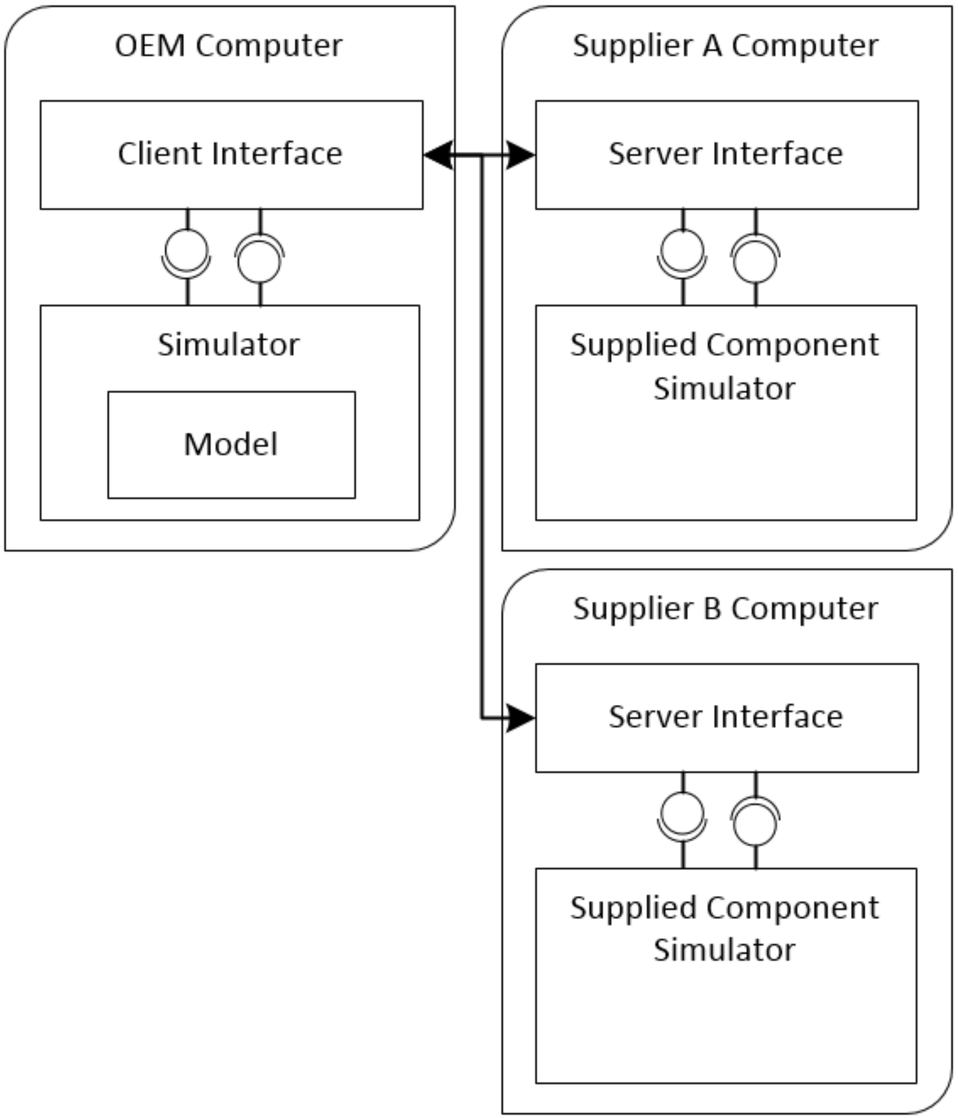
What is Co-simulation?

- Simulation of a system
- Coupling of multiple simulators
- Optionally as black-boxes
- Each simulating one or more models
- Built with different formalisms/tools.
- Co-simulation scenario
- Description of the system
- The simulators and their dependencies
- Data about the capabilities of each simulator.



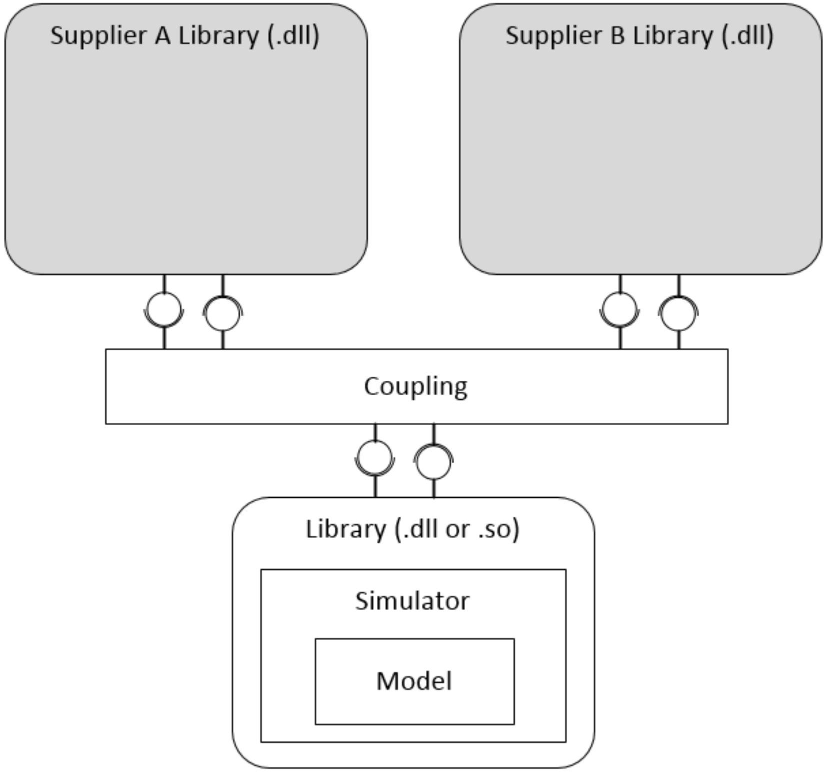
Remote Black-box Simulators

- Suppliers make a simulator available through an API
- Integrator takes care of programming an interface
- Good IP Protection
- Different suppliers require different interfaces

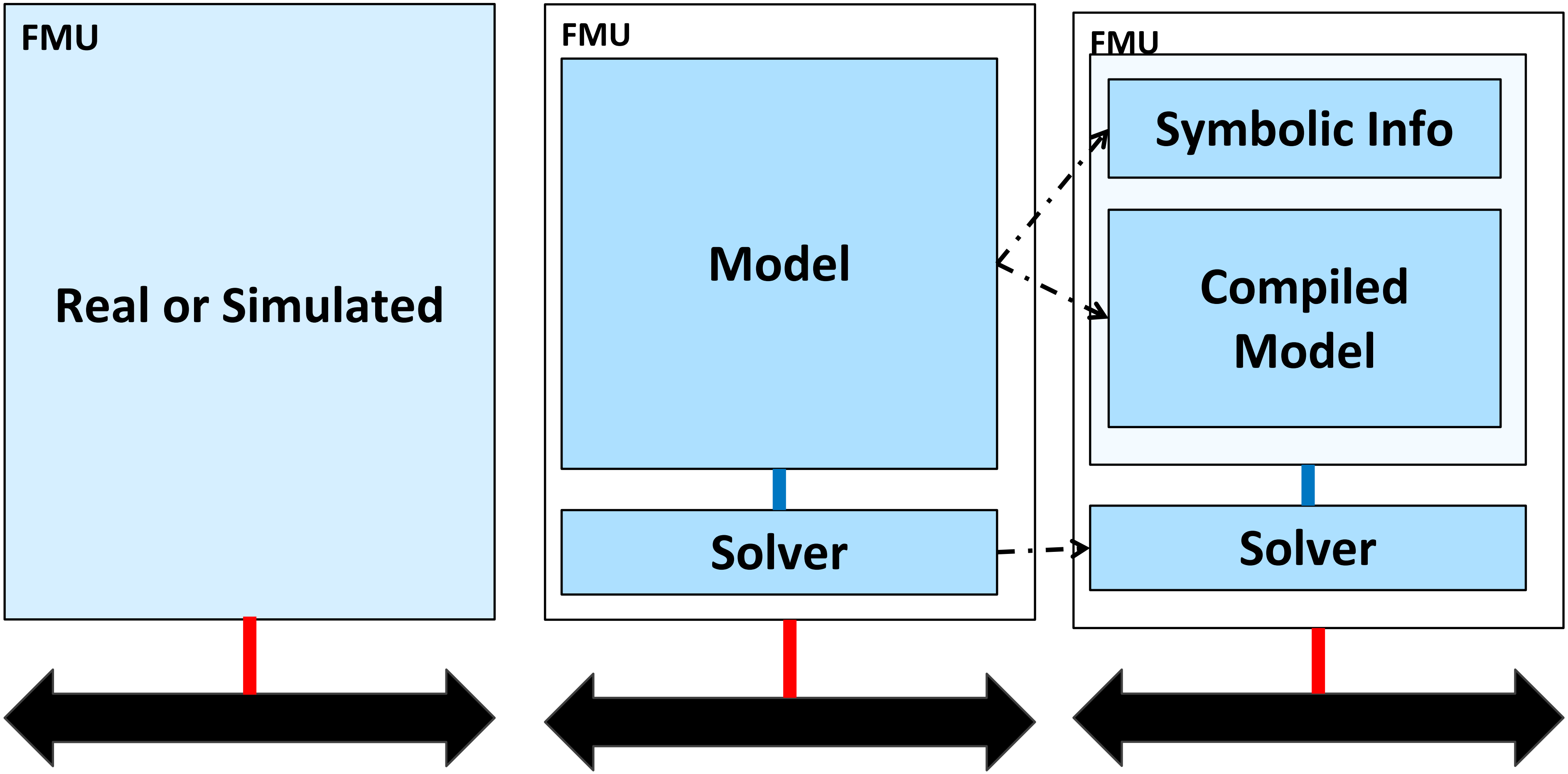


Functional Mock-up Interface Standard

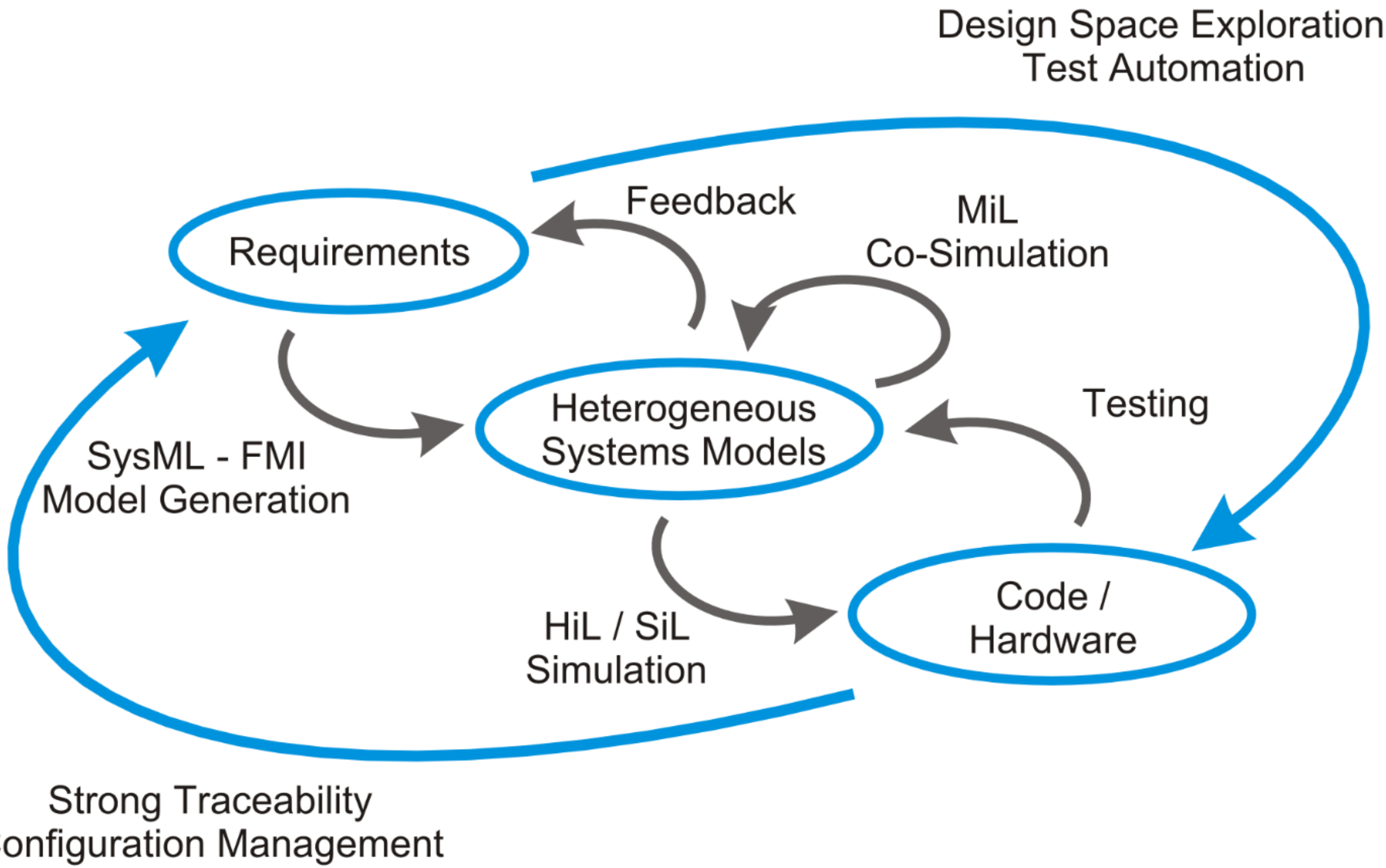
- Simulator and model exported as a standardized C library
- Standard interaction with any simulator
- Every simulator can be a black box.
- Executed locally but can communicate with a remote server



Inside an FMU



A New Toolchain for CPS Design



INTO-CPS Unique Selling Points

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1. Faster route to market for engineering CPSs
2. Avoiding vendor lock-in by open tool chain
3. Exploring large design spaces efficiently
4. Limiting expensive physical tests
5. Enabling traceability for all project artefacts

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CPS Engineering Needs

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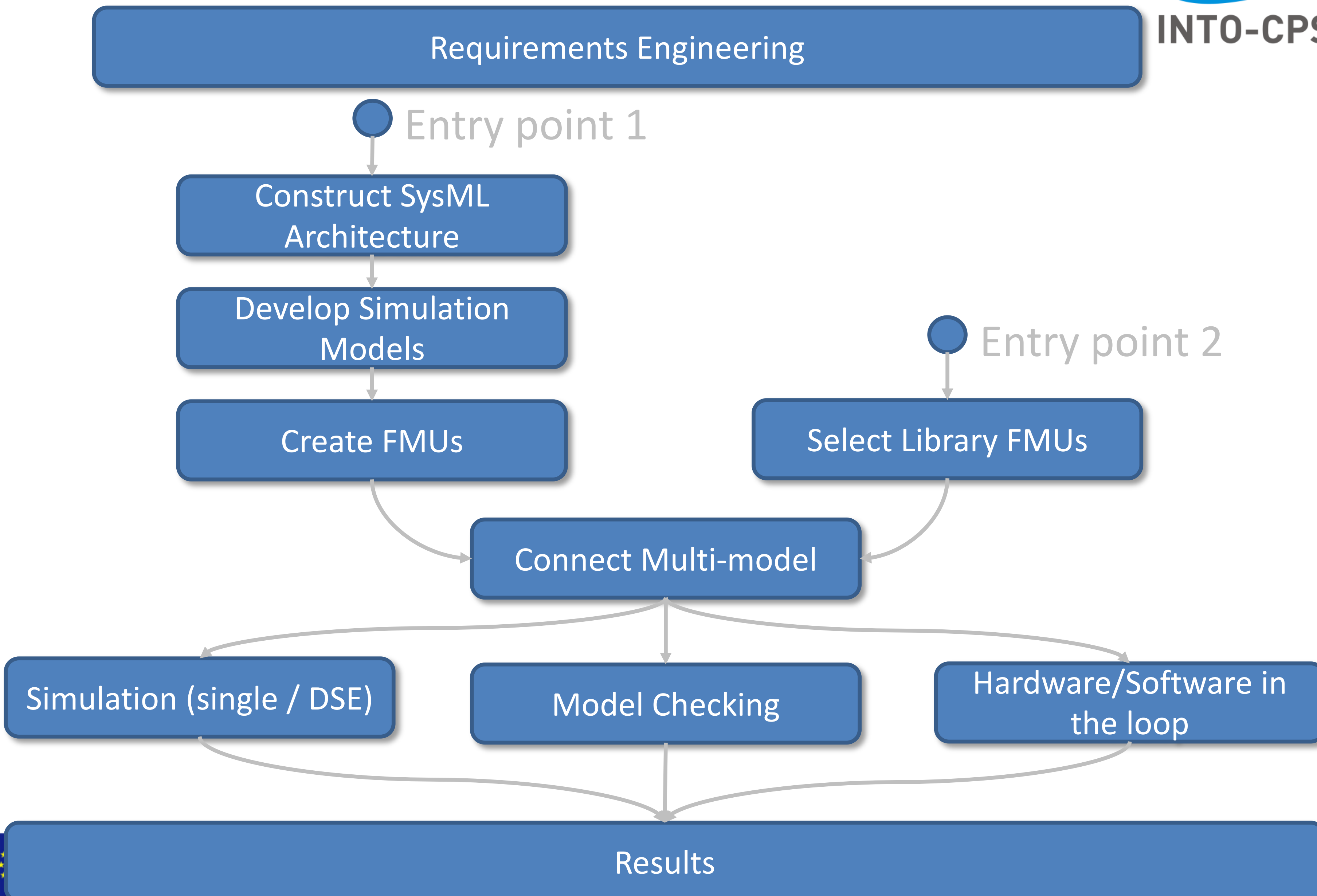
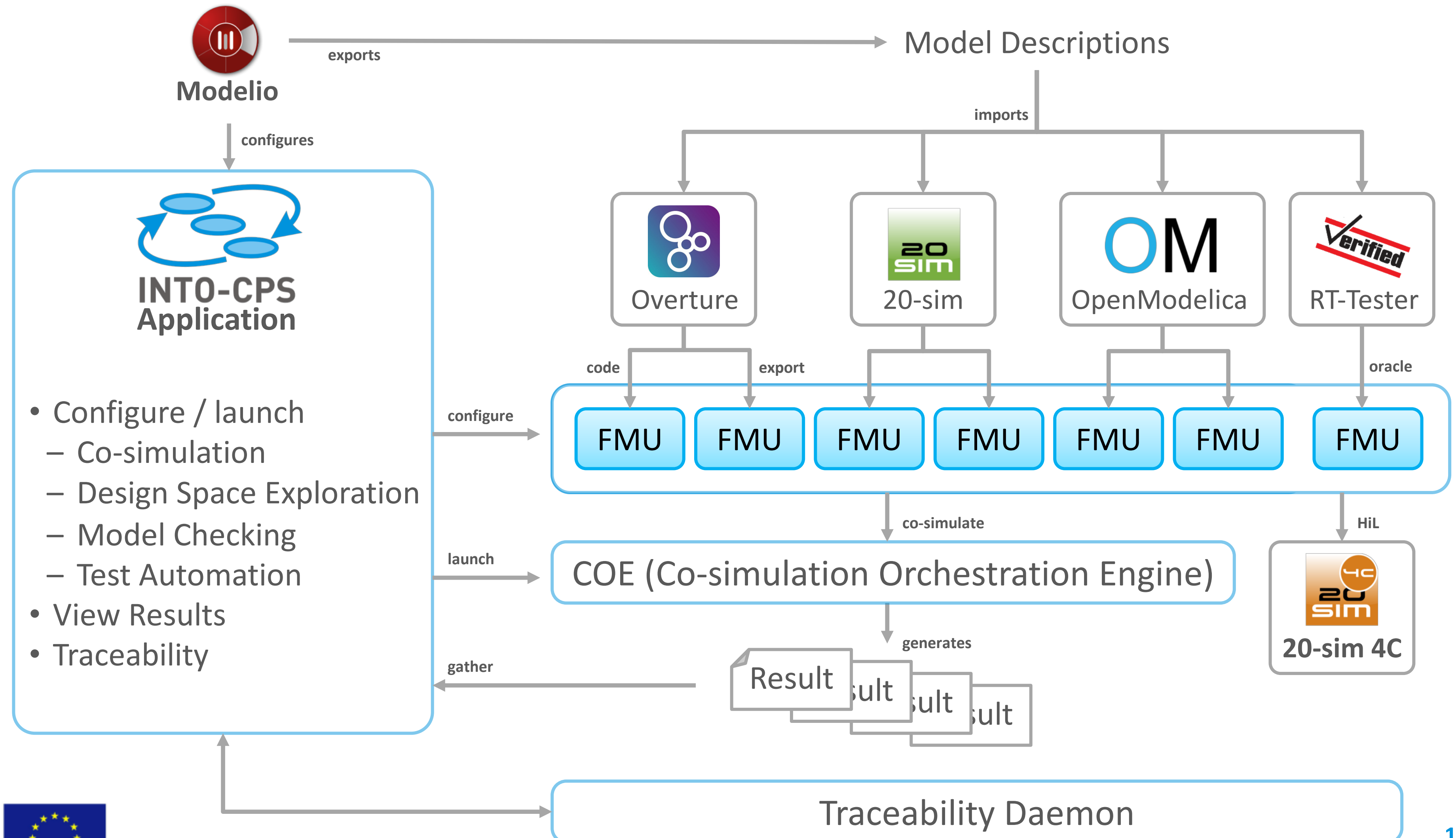
- Enable collaboration across disciplines
- Keep development costs low
- Keep time-to-market short
- Explore the complex design space efficiently
- Ensure tolerance against “nasty” faults
- Build up documentation for the working solution
- Provide confidence to external stakeholders

Outline Work Flow



The INTO-CPS Tool Chain



- Configure / launch
  - Co-simulation
  - Design Space Exploration
  - Model Checking
  - Test Automation
- View Results
- Traceability

Co-simulation engine

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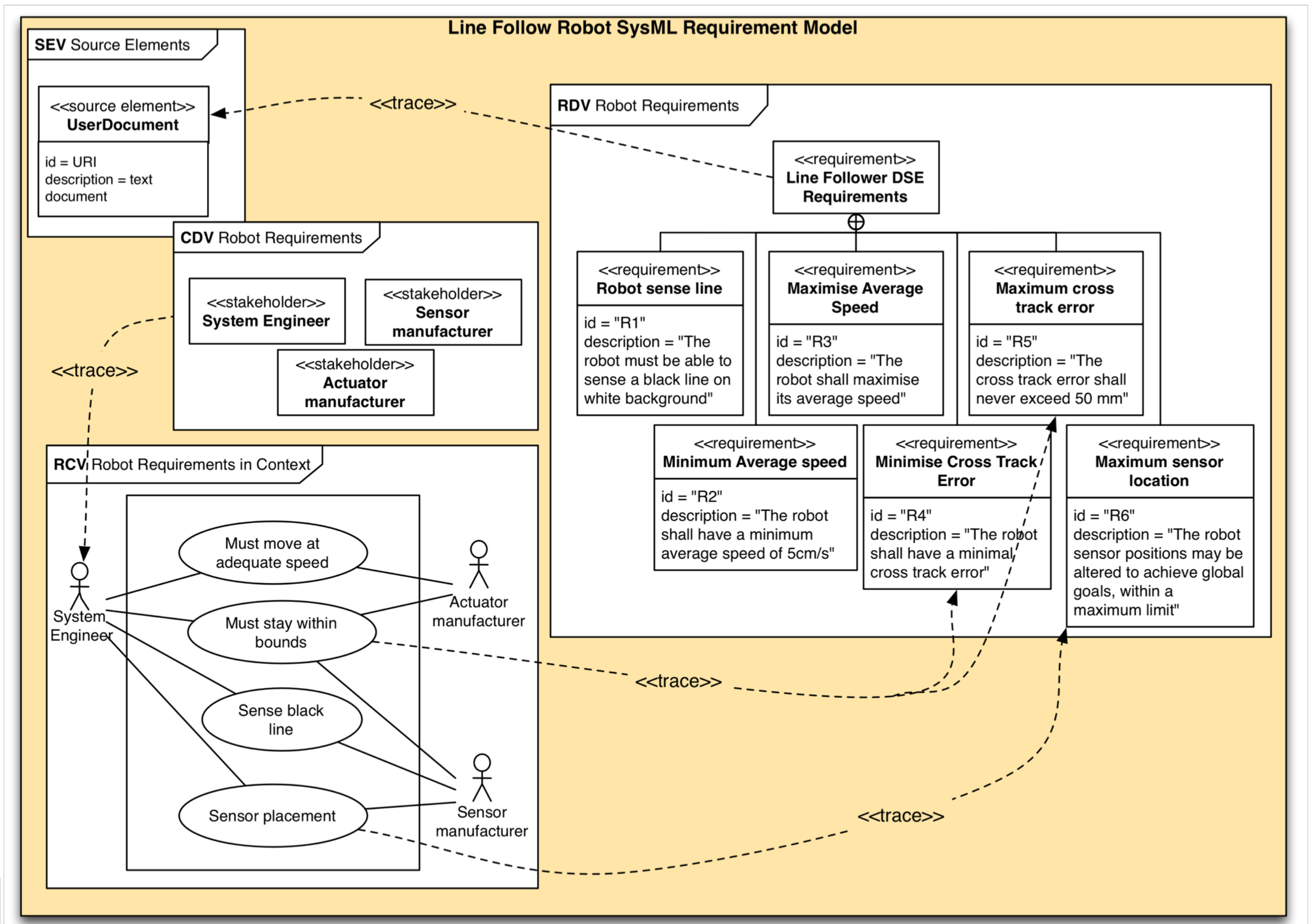
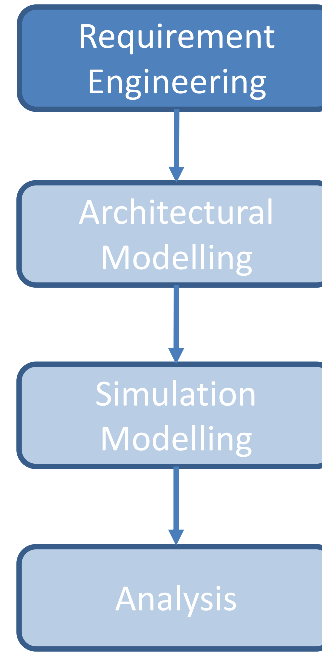
- Fully FMI 2.0 compliant Master Algorithm
- Support for discrete event (DE) and continuous time (CT) models, using proposed FMI extensions
- Multi-platform, 32/64 bit (Java-based)
- Application based on Electron (web-technology)
- Fixed and variable step size algorithms
- FMI 2.0 Import/Export created for Overture, OpenModelica, 20-sim
- Has also been tested with:
  - Dymola
  - Modelon FMI Toolbox for MATLAB/Simulink
  - 4DIAC
  - SimulationX
  - Unity

INTO-CPS Methodology





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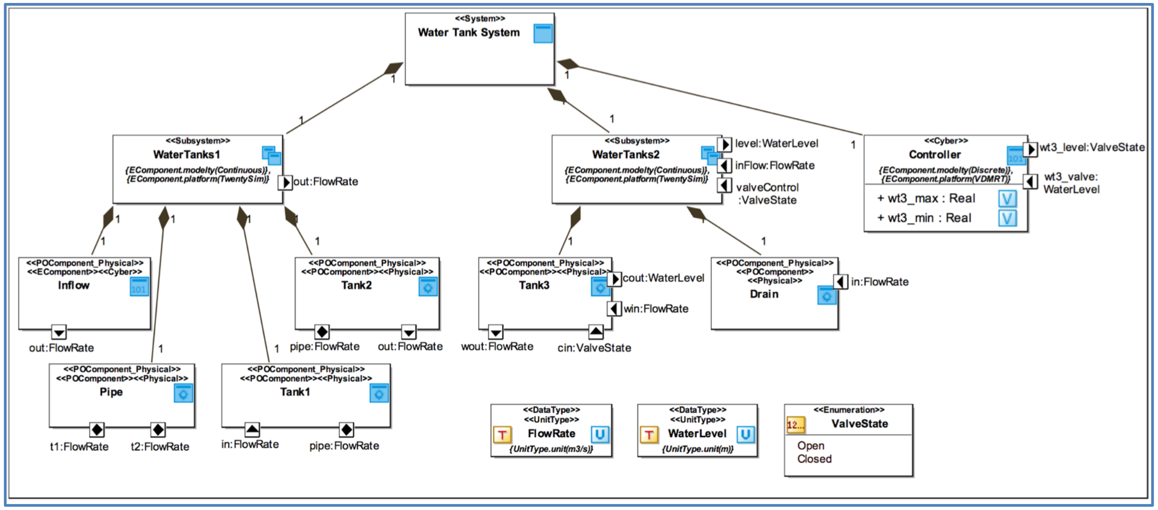
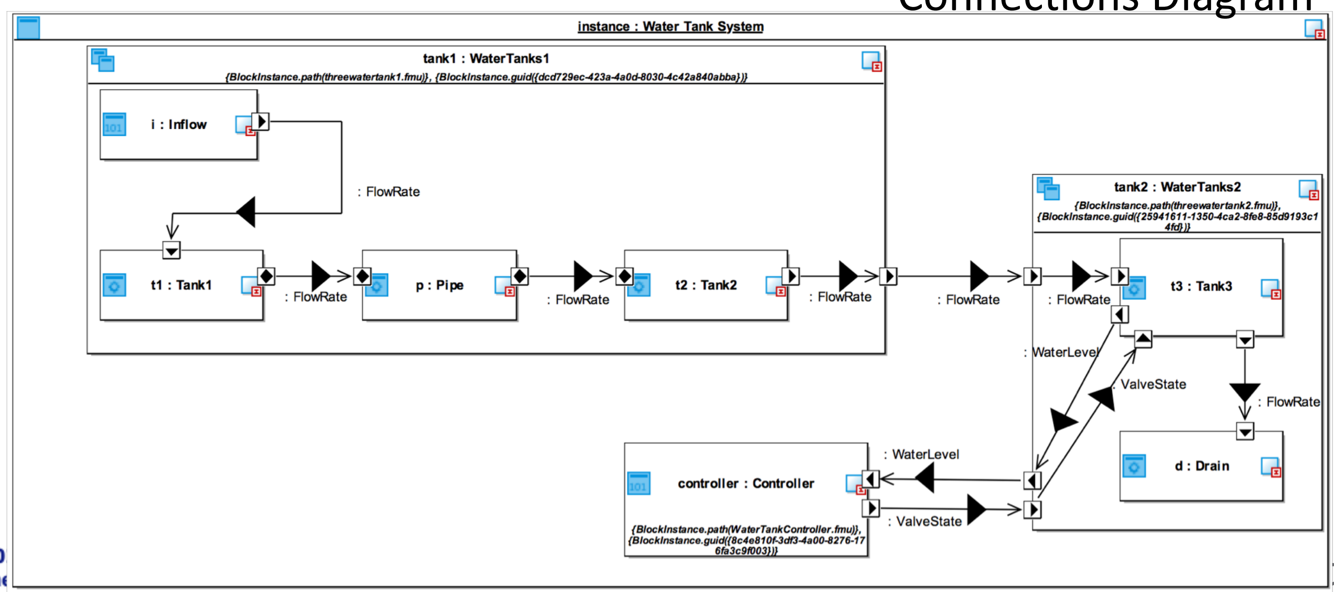
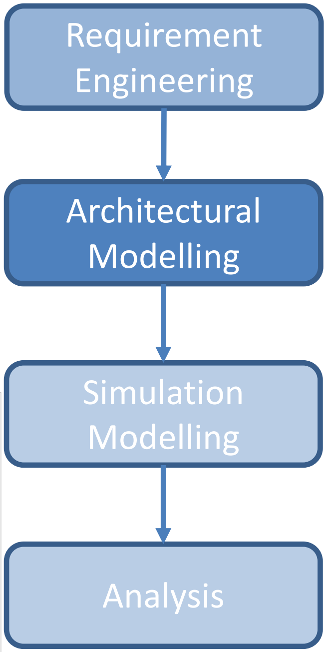
Architectural Modelling

Architecture Structure Diagram



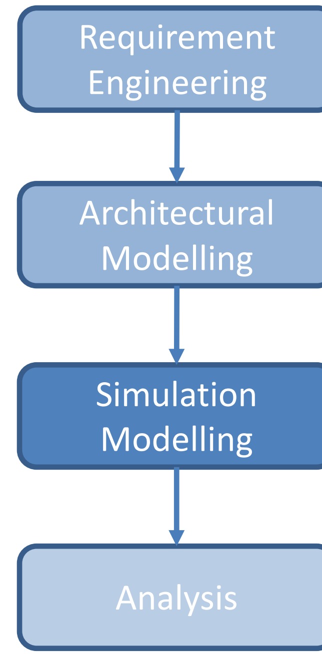
Connections Diagram



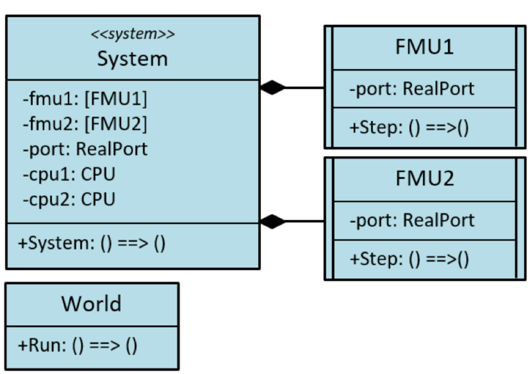


Simulation Modelling

- "DE-first" approach, used in IPP4CPPS
  1. Model and test entire system in DE
     - One class per EComponent, both DE and (abstract) CT
     - Use Ether pattern to connect classes if necessary
  2. Move to multi-model
     - One project per EComponent (link class definition)
     - Export FMUs



1.



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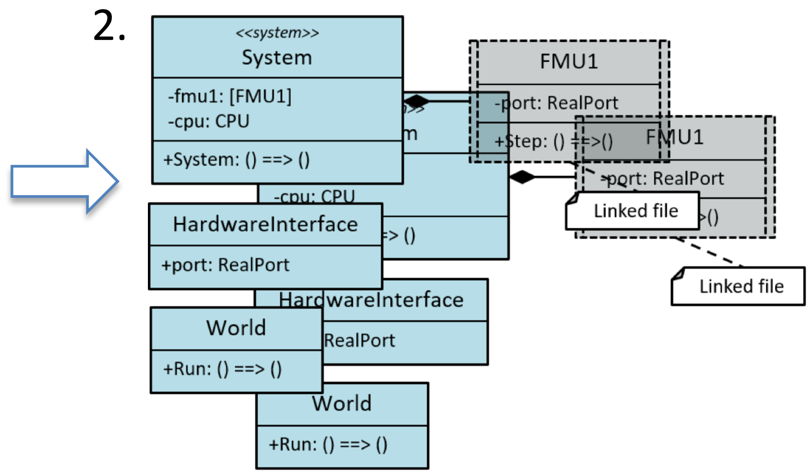

Design Space Exploration

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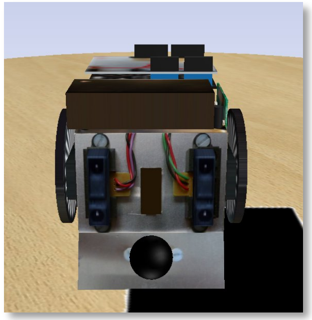
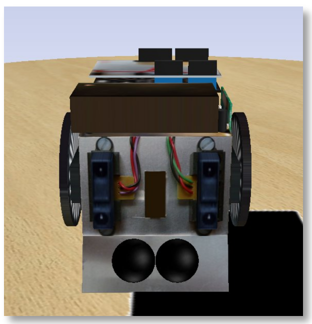
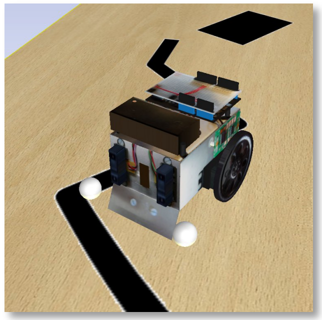
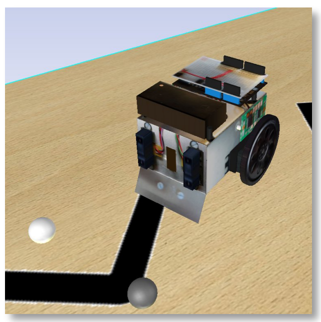




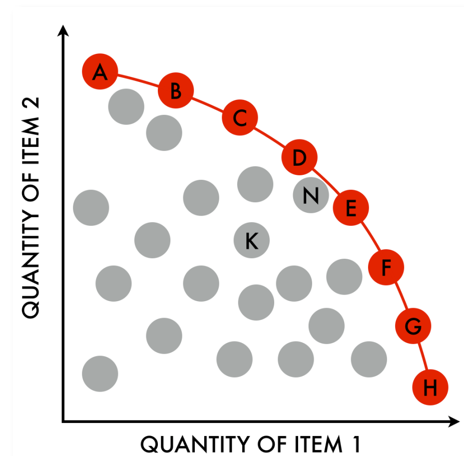




How to Explore?

- Exhaustive
- Taguchi Methods
- Space Culling
- Genetic Methods

How to Assess?



$$V_a = w_1^a v_1^a(x_1^a) + w_2^a v_2^a(x_2^a) + \ldots. + w_n^a v_n^a(x_n^a)$$

DSE Driver	Objective Evaluator	Ranking	Presentation
Simulation parameters, control of process	Objective measures and constraint satisfaction from raw simulation results	Ranking designs according to objective values	Display of results and search progress to the user

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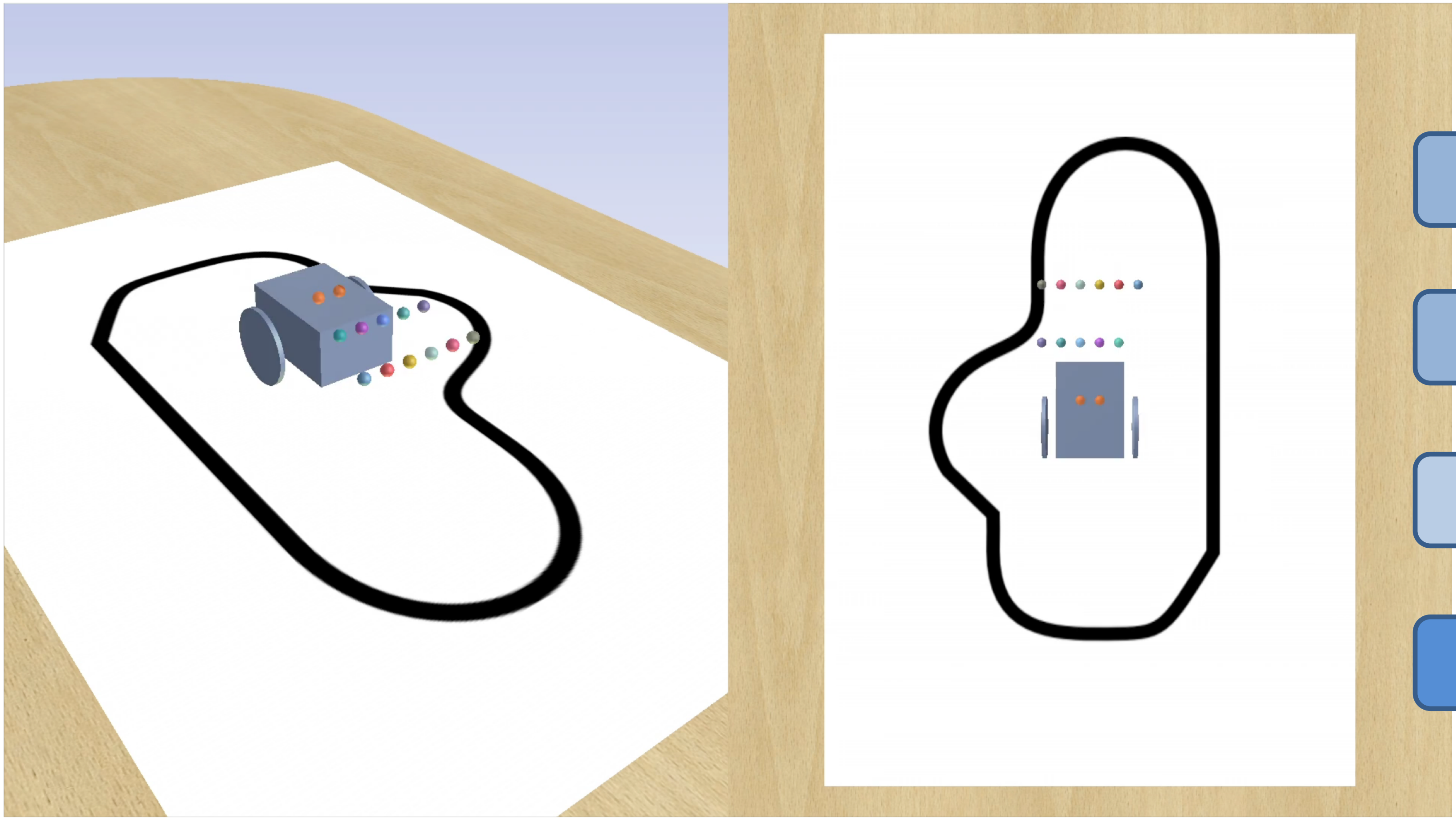
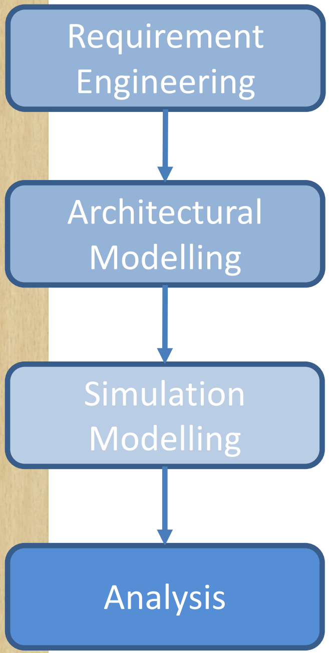
Example DSE Analysis





Co-Simulation Foundations

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- Initial foundations developed for
  - SysML
  - VDM-RT
  - Modelica
  - FMI
- SysML CPS profile defined
  - Architecture Structure Diagram
  - Connections Diagram
  - Design Space Exploration Diagram
  - Support for units in the exported model descriptions

Common Semantics using UTP

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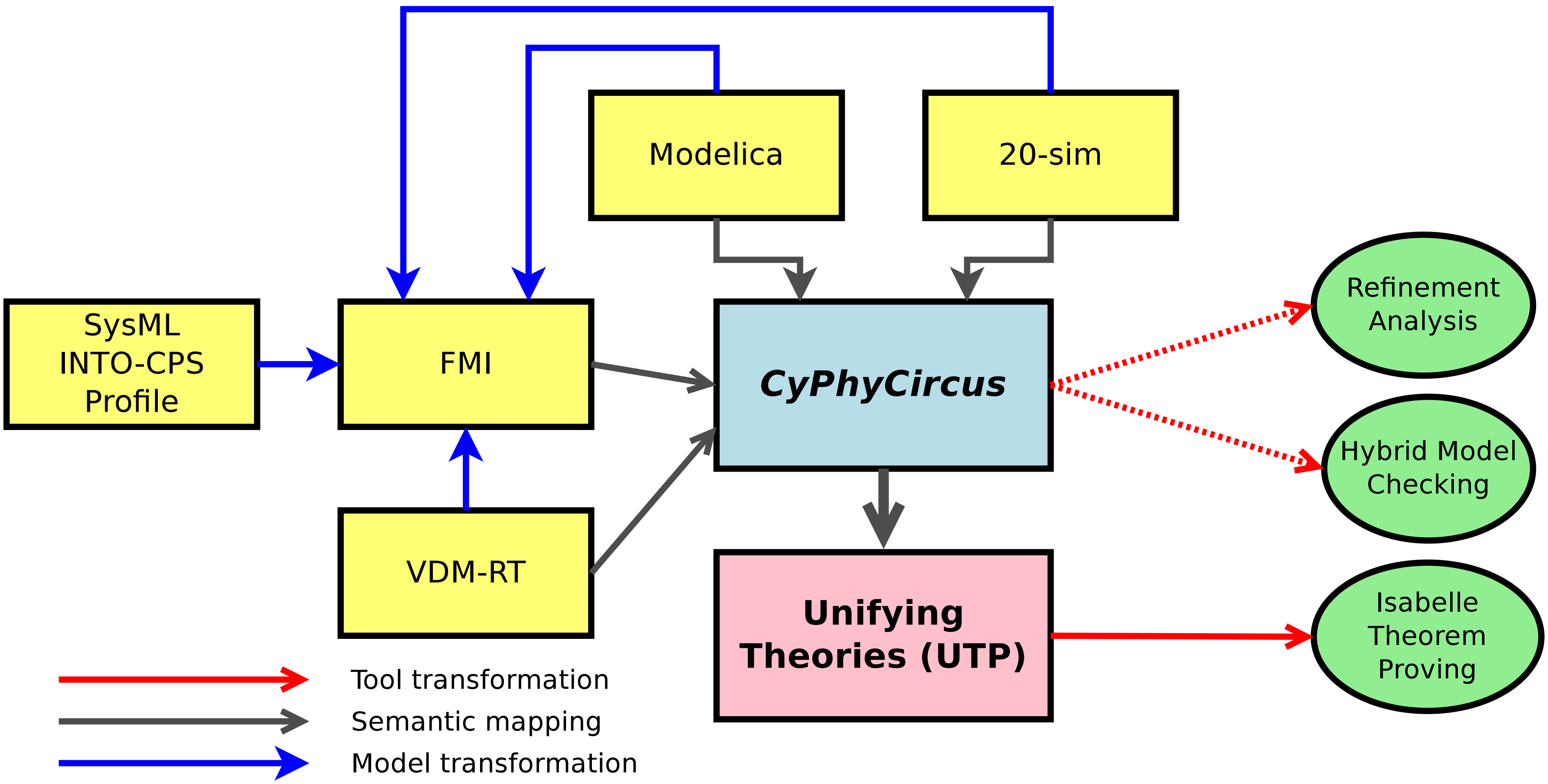
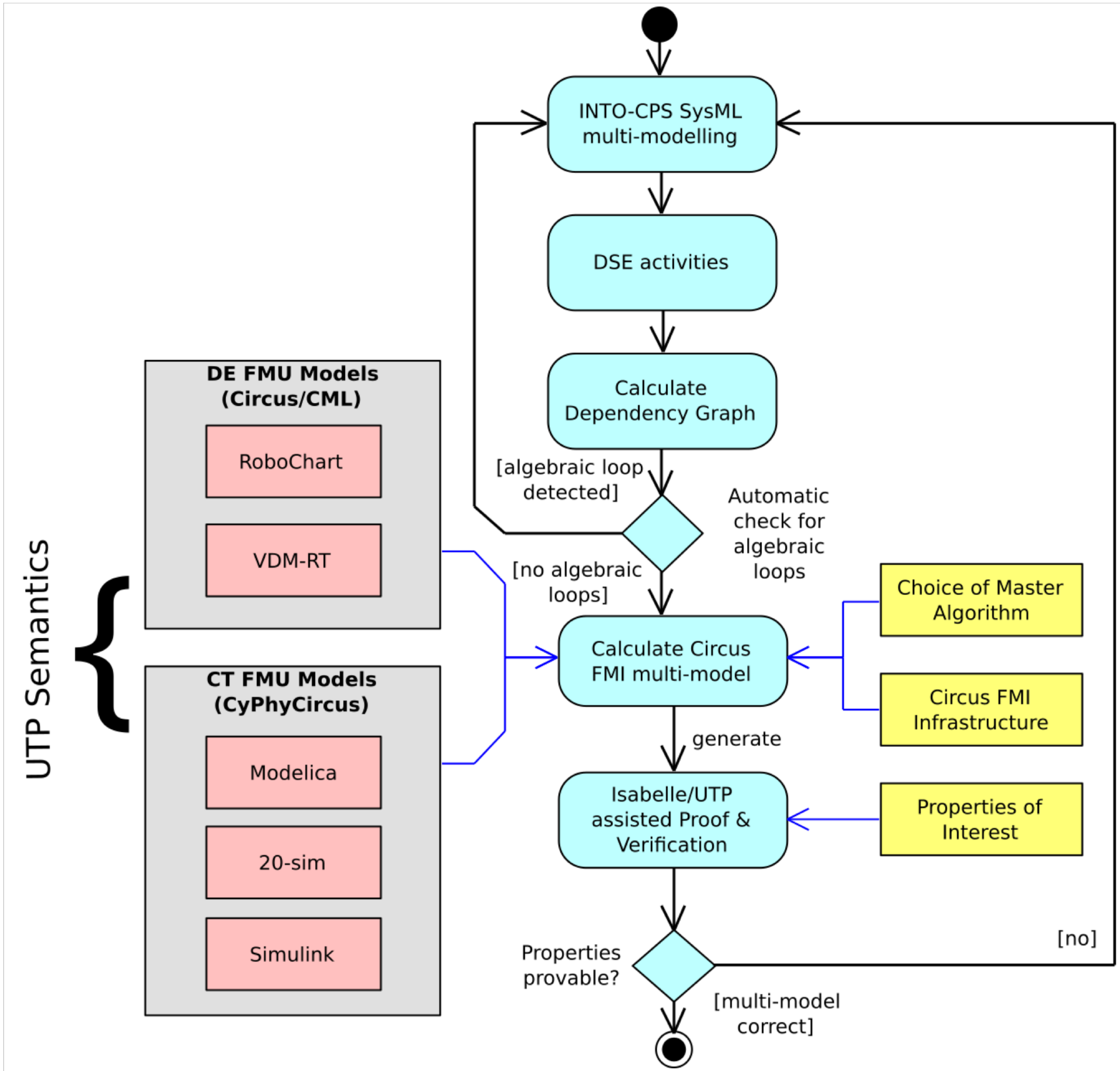
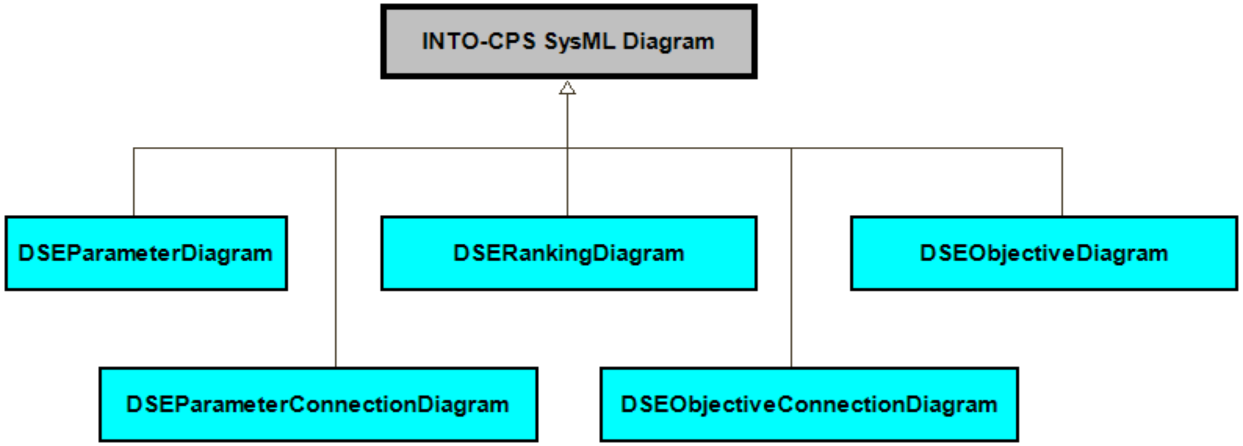
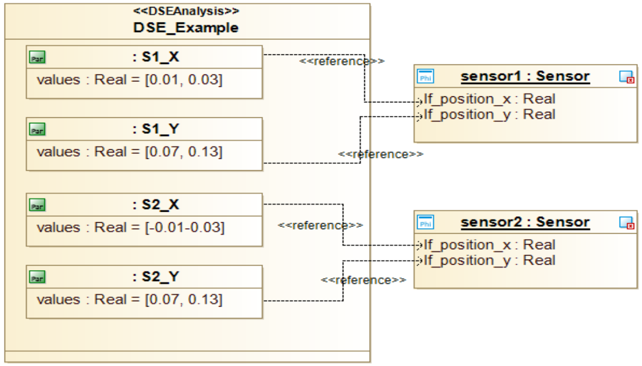


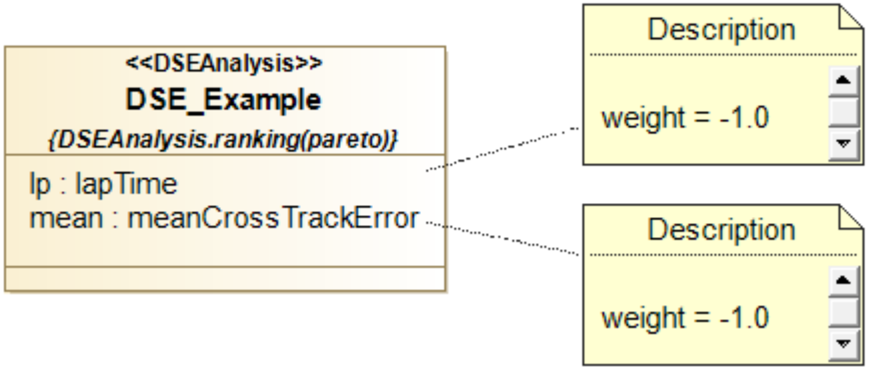
Underlying Unified Semantics

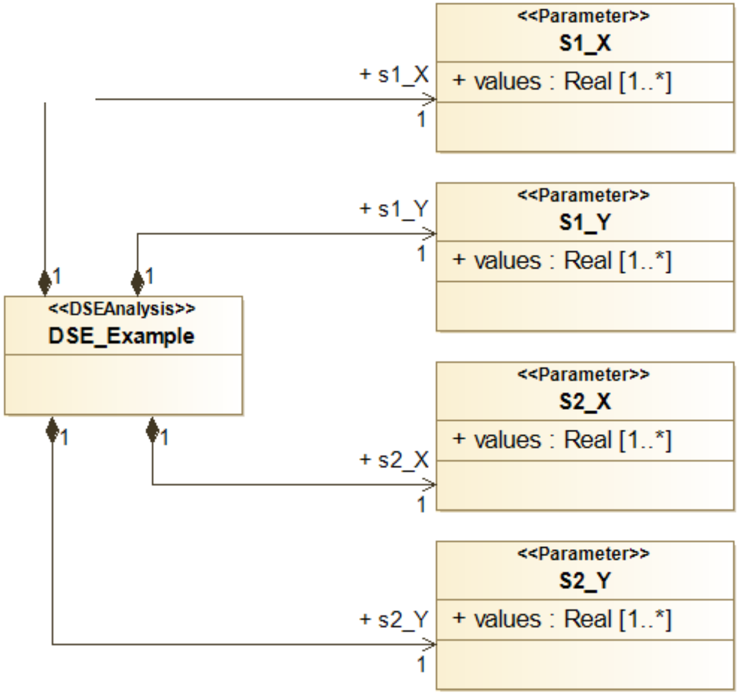


DSE Views in the SysML Profile









Cloud: Condor Exhaustive Search

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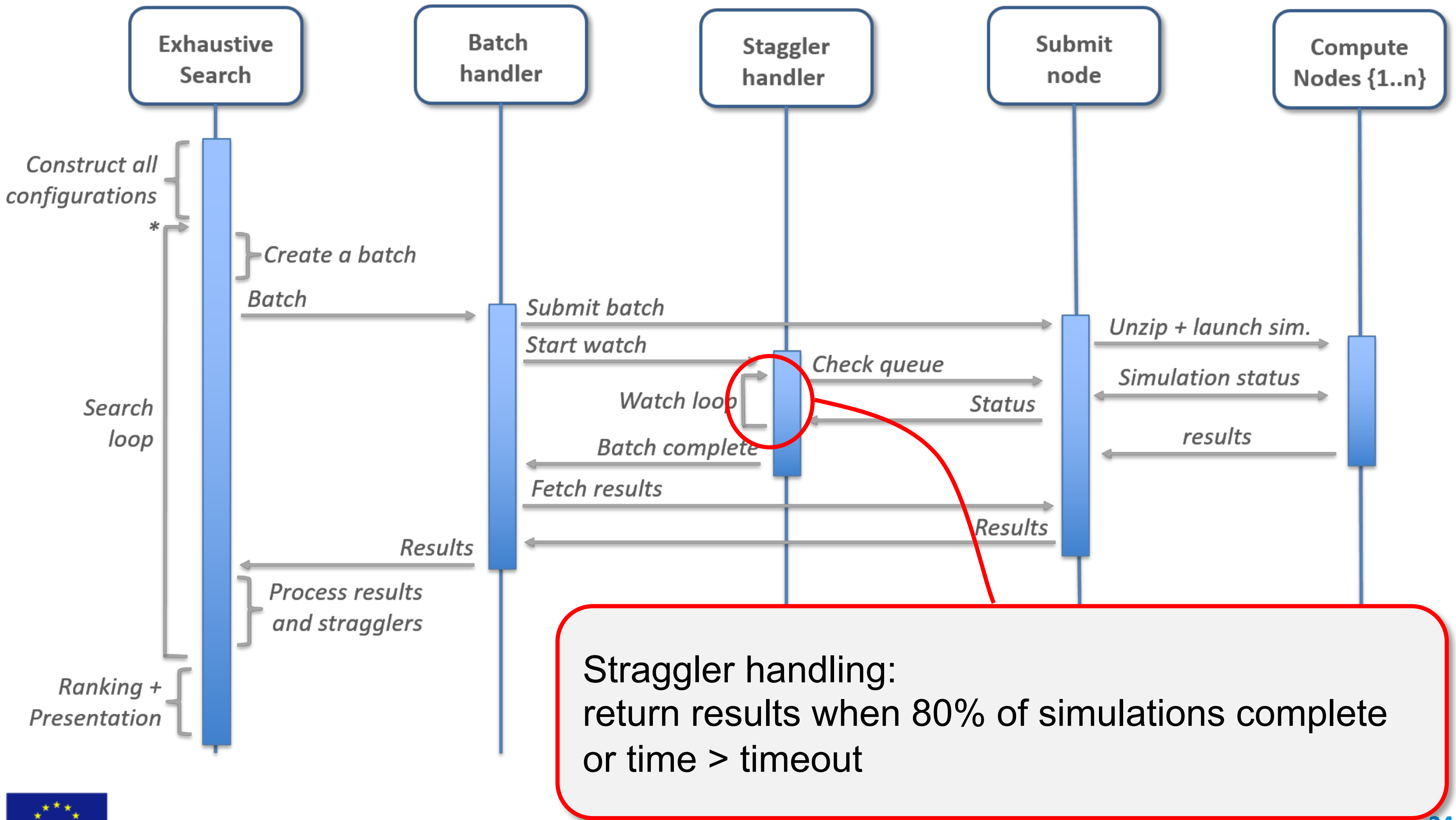
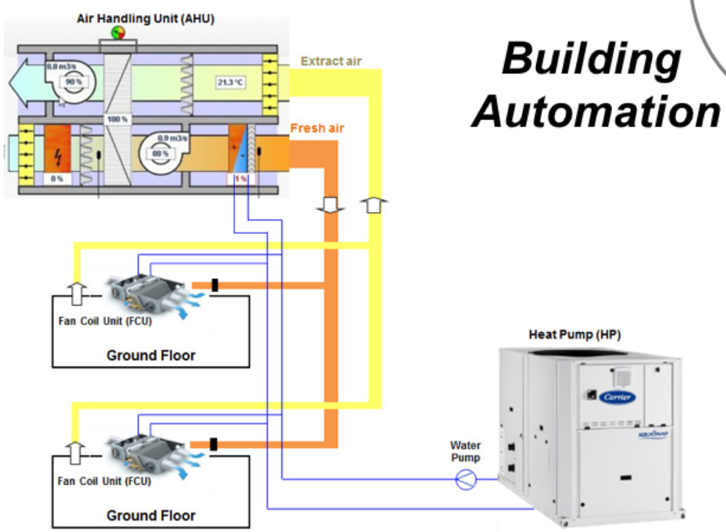
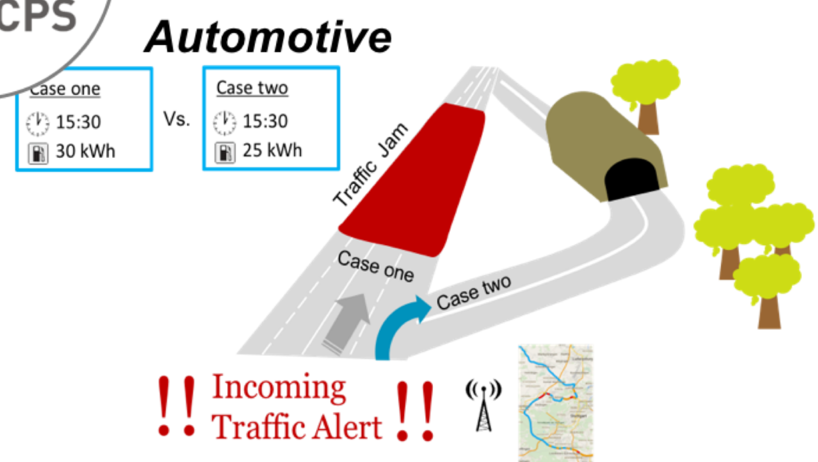
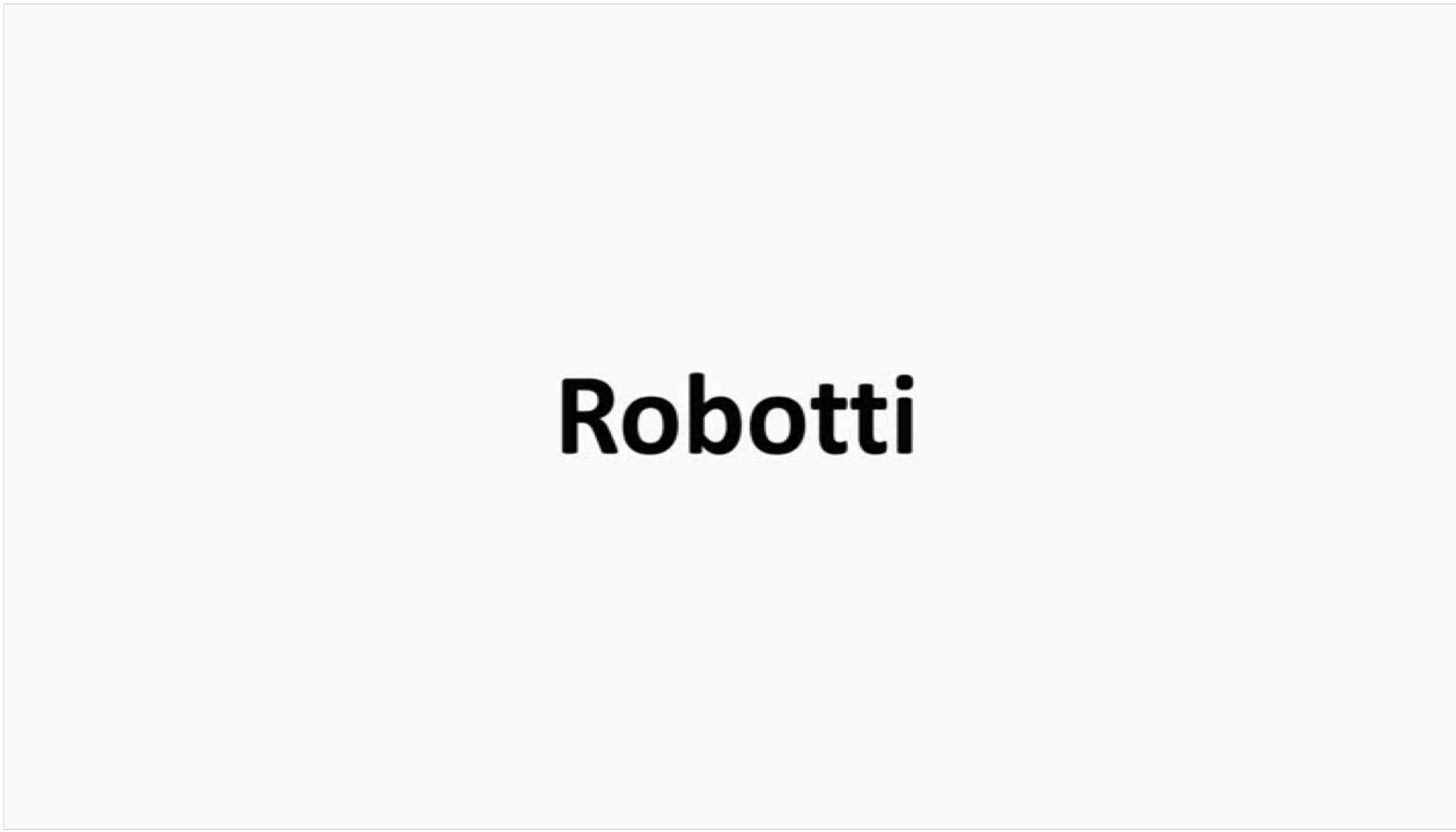


Industrial Case Studies

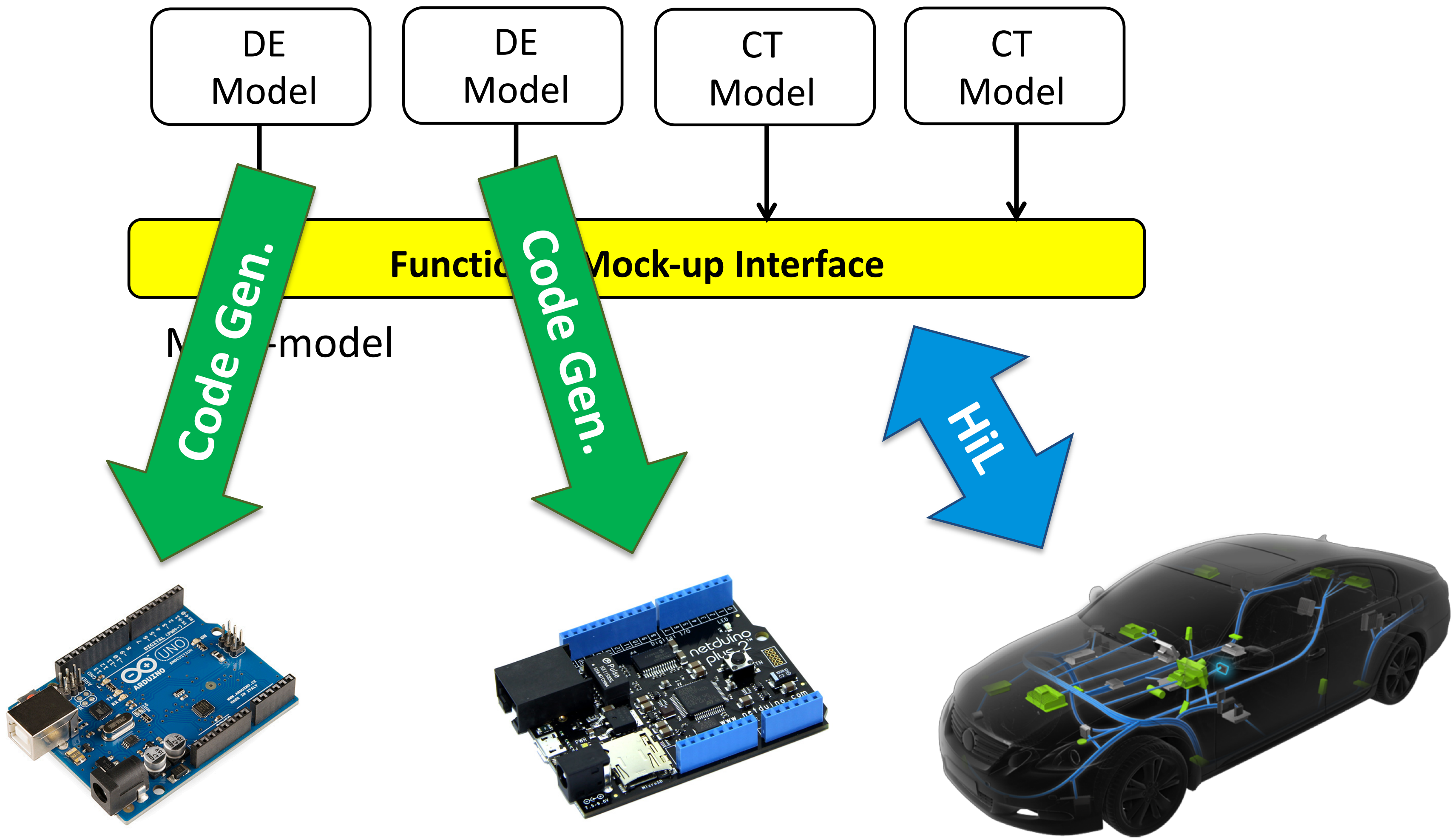




Robotti : Implement Operation



Hardware-in-the-Loop (HiL) and Code Generation



Oculus Rift and Simulation

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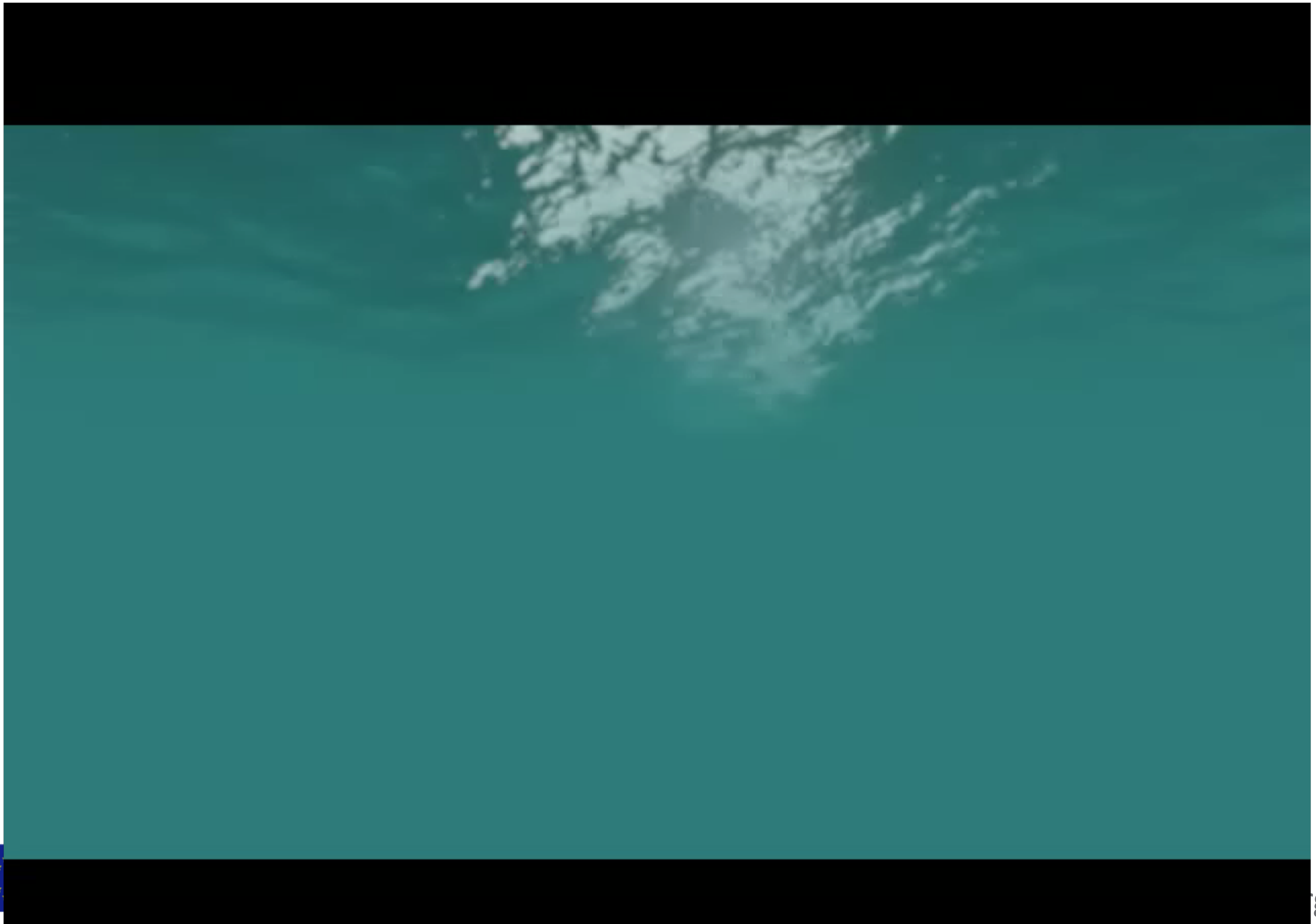
Seeing a Product before it exists



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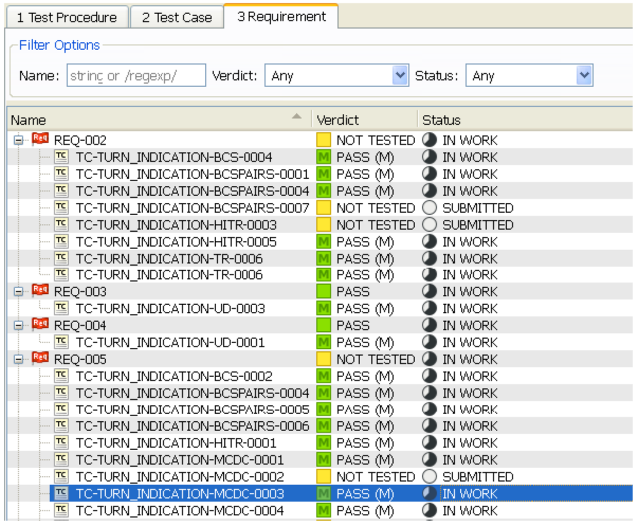
Test Automation

- Based on RT Tester tool suite
- Status:
  - Test sets generated from XMI import (from Modelio)
  - Test procedures are generated as FMUs, connected to Co-simulation
- Outlook:
  - Identify SuT in SysML profile, connect to Test Automation
  - Connect SysML requirements with LTL formulas



Name	Verdict	Status
REQ-002	NOT TESTED	IN WORK
TC-TURN_INDICATION-BCS-0004	PASS (M)	IN WORK
TC-TURN_INDICATION-BCSPAIRS-0001	PASS (M)	IN WORK
TC-TURN_INDICATION-BCSPAIRS-0004	PASS (M)	IN WORK
TC-TURN_INDICATION-BCSPAIRS-0007	NOT TESTED	SUBMITTED
TC-TURN_INDICATION-HITR-0003	NOT TESTED	SUBMITTED
TC-TURN_INDICATION-HITR-0005	PASS (M)	IN WORK
TC-TURN_INDICATION-TR-0006	PASS (M)	IN WORK
TC-TURN_INDICATION-TR-0006	PASS (M)	IN WORK
REQ-003	PASS	IN WORK
TC-TURN_INDICATION-UD-0003	PASS (M)	IN WORK
REQ-004	PASS	IN WORK
TC-TURN_INDICATION-UD-0001	PASS (M)	IN WORK
REQ-005	NOT TESTED	IN WORK
TC-TURN_INDICATION-BCS-0002	PASS (M)	IN WORK
TC-TURN_INDICATION-BCSPAIRS-0004	PASS (M)	IN WORK
TC-TURN_INDICATION-BCSPAIRS-0005	PASS (M)	IN WORK
TC-TURN_INDICATION-BCSPAIRS-0006	PASS (M)	IN WORK
TC-TURN_INDICATION-HITR-0001	PASS (M)	IN WORK
TC-TURN_INDICATION-MCDC-0001	PASS (M)	IN WORK
TC-TURN_INDICATION-MCDC-0002	NOT TESTED	SUBMITTED
TC-TURN_INDICATION-MCDC-0003	PASS (M)	IN WORK
TC-TURN_INDICATION-MCDC-0004	PASS (M)	IN WORK

Model Checking Capabilities

- Now finding shorter counter examples.
- Integration of traceability.
- Provides abstractions for CT signals:
  - Interval-based abstraction
  - Simulation-based abstraction (new)
  - Gradient-based abstraction (new)

Simulation-based abstraction

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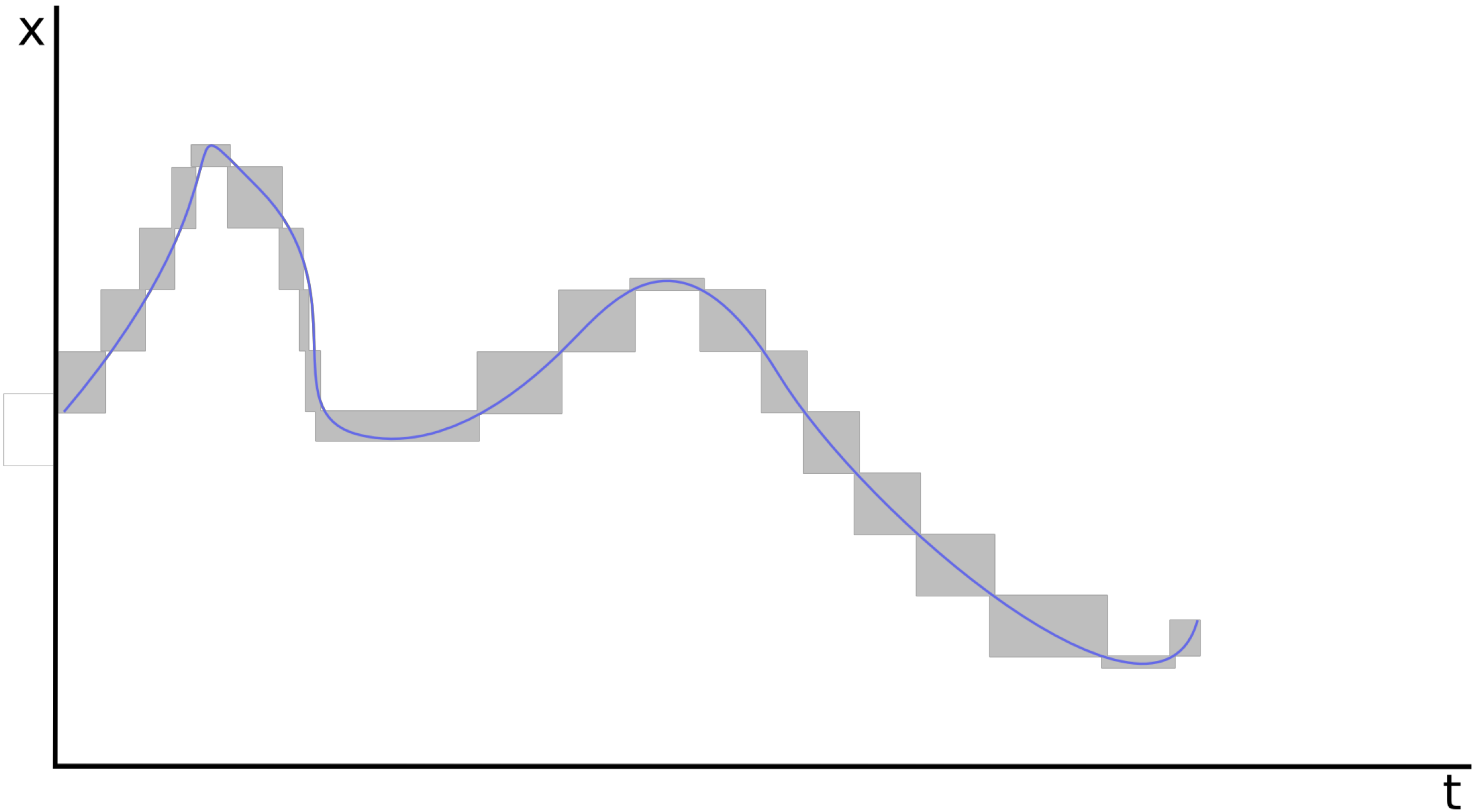
- During model checking a CT variable should behave similar to a previous concrete execution of the entire system.
- Extract signal flow from a test-run.
- Signal flow is abstracted by a succession of interval abstractions.
- Specify max allowed size of intervals to adjust granularity.

Abstraction by Interval Boxes



Gradient-based Abstraction

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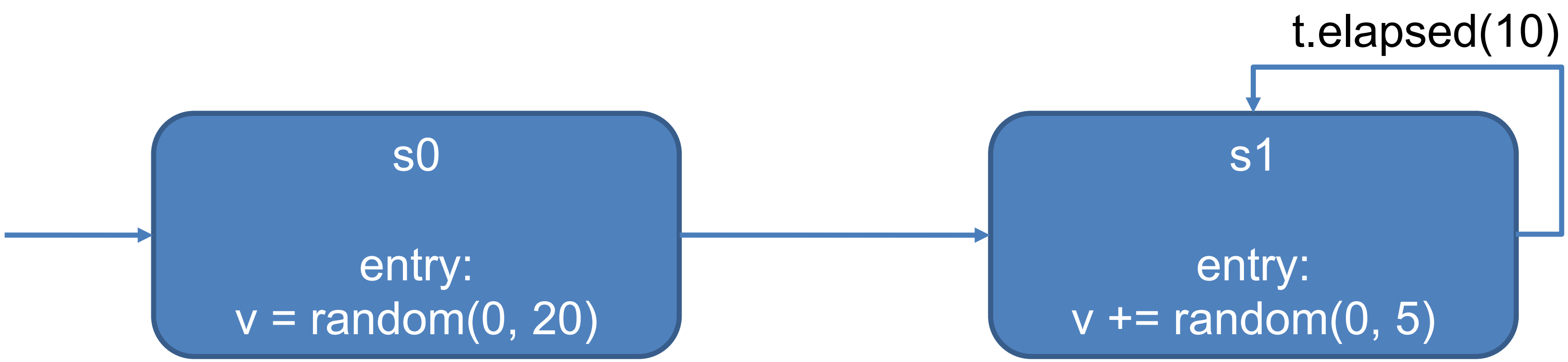
- Allow CT variable to increase/decrease only up to a certain amount per time.
- Implemented by a simple DE state machine.



Traceability & Provenance

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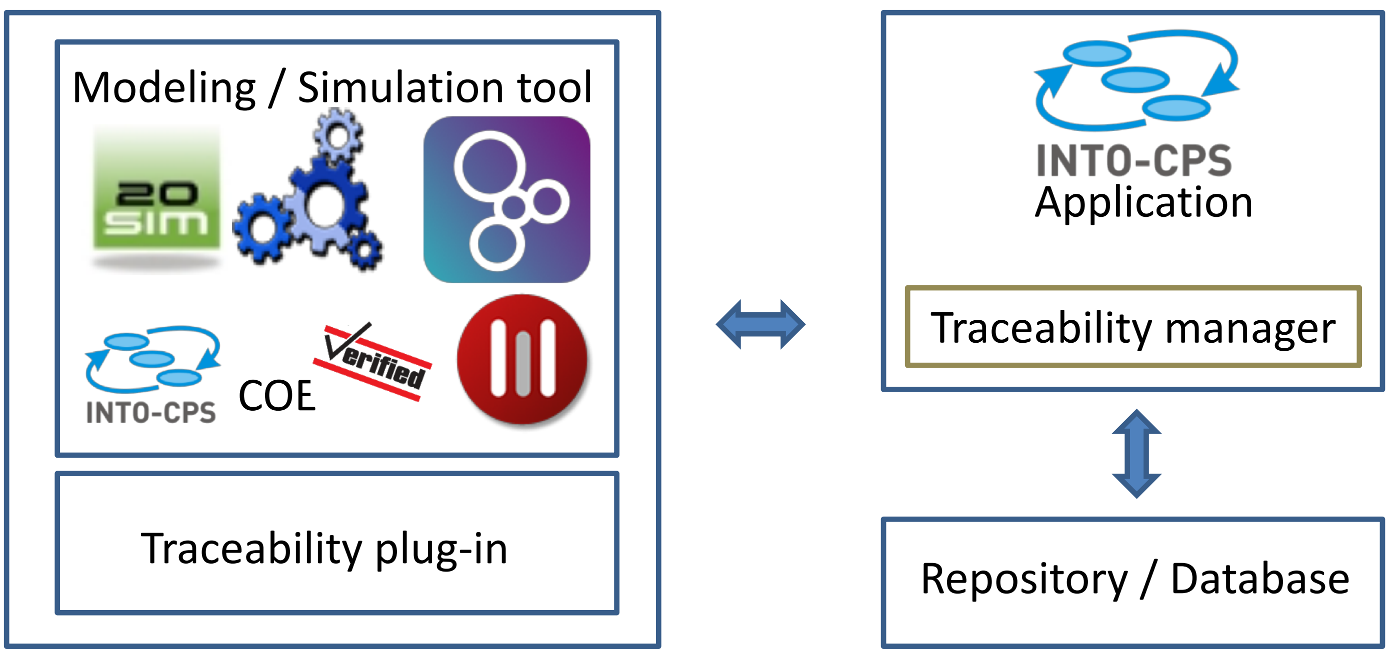
- Goal: Ensure tracing between requirements, models, results, code
- Keep track of changes
- Use OSLC / Prov-N standards



Traceabilty – tool support

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- Modelio
- OpenModelica
- Overture
- 20sim
- RT Tester
- INTO-CPS App

Requirements creation / linking with SysML blocks
Architecture modelling
ModelDescription.xml export
Configuration export

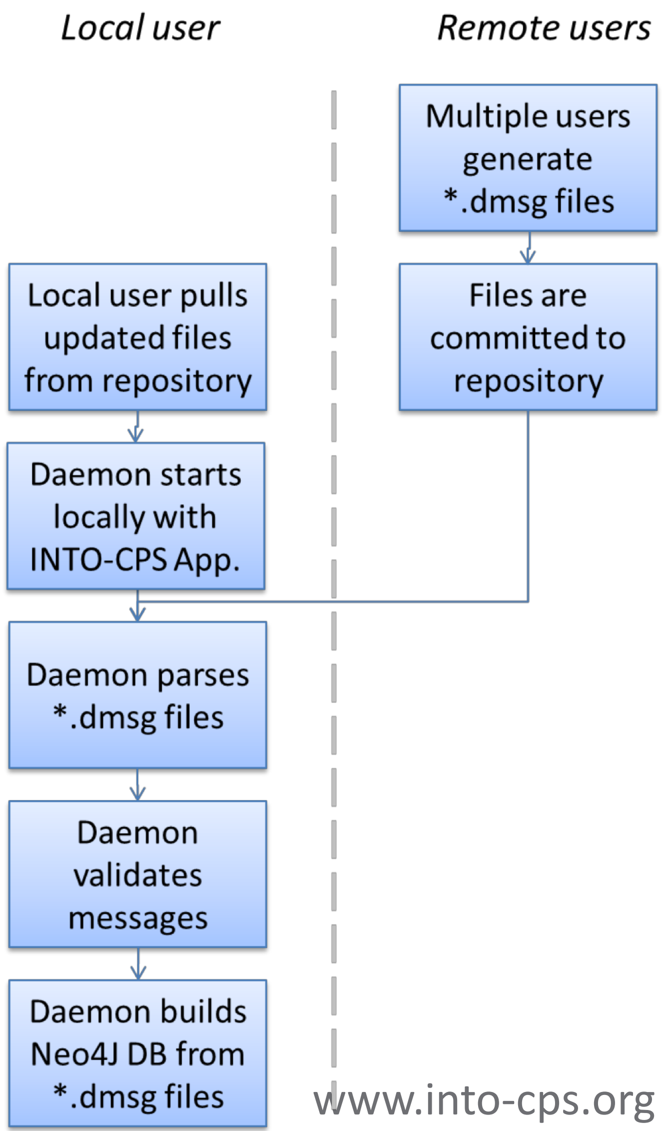
ModelDescription.xml import
Model creation / modification
FMU export

Define test model
Define test objectives
Run test
Define MC model
Define CT abstraction
Run MC query

Configuration to Multi-Model
Multi-model to COE configuration
Simulation

Traceability – multi-user support

- Each message is a single plain text file (*.dmsg)
- Messages are committed to common repository
- Each user can generate messages



Industrial Follower Group

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AGCO, Denmark
Airbus, UK
Alcatel Lucent, Ireland
Almende, Netherlands
Alten, Sweden
Altran, UK
Andritz Hydro, Austria
Bachmann Electronic, Netherlands
Bakker-Sliedrecht, Netherlands
Bang&Olufsen, Denmark
Beia Consult, Romania
Beumer, Denmark
Bombardier, Germany
Bosch, Germany
Carrier, France
CCFE, UK
CeTIM, Netherlands
Chemring Technology, UK
Conpleks Innovation, Denmark
Continental, Romania
Critical Software, Portugal
Daimler, Germany
Danish Aviation, Denmark
Dassault Aviation, France
Delphi, Poland
Denso Corporation, Japan
Dredging International, Belgium
DSTL, UK
EDF, France
Enginsoft, Italy
European Space Agency, Netherlands
Fortiss, Germany
Goodrich, UK
Grundfos, Denmark
GN Resound, Denmark
HADATAP, Poland
Holonix, Italy
HMF, Denmark
Huisman Equipment, Netherlands
IBM, Israel
IBM, Finland
Ikergune, Spain
Inestec, Portugal
Irmato, Netherlands
ISMB, Italy
Jaguar, UK
John Deere, Germany
JNE Systech, Korea
MAN Diesel & Turbo, Denmark
MFAtech, UK
NII, Japan
Nupark Accelerace, Denmark
Odego, Germany
OFFIS, Germany
Omflow, UK
ONERA, France
Oticon, Denmark
Phillips MRI, Netherlands
PLM Consult, Denmark
Polar Electro, Switzerland
Postech, South Korea
Prime Solutions Group, USA
Projectglobe.com, UK
Rockwell-Collins, France
Rolls-Royce, UK
Saab, Sweden
Santer Reply, Italy
Seluxit, Denmark
Siemens, Sweden
Synelixis Solutions,Greece
Syntell, Sweden
TailSiT, Austria
Tecnalia, Spain
Terma, Denmark
Thalès R&T, Germany
TTTech, Austria
thyssenkrupp Marine Systems, Germany
UTC Aerospace, UK
Vesta System, France
West Consulting, Netherlands

In total: 80

The INTO-CPS Association Created

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Purposes

- Maintain and develop further software that was created in the project
- Enable the widespread use of the software through open source licenses
- Promote its usage in academic and industrial settings
- Allow members to steer direction of development and incorporate software into products

Solutions for CPS Engineering Needs

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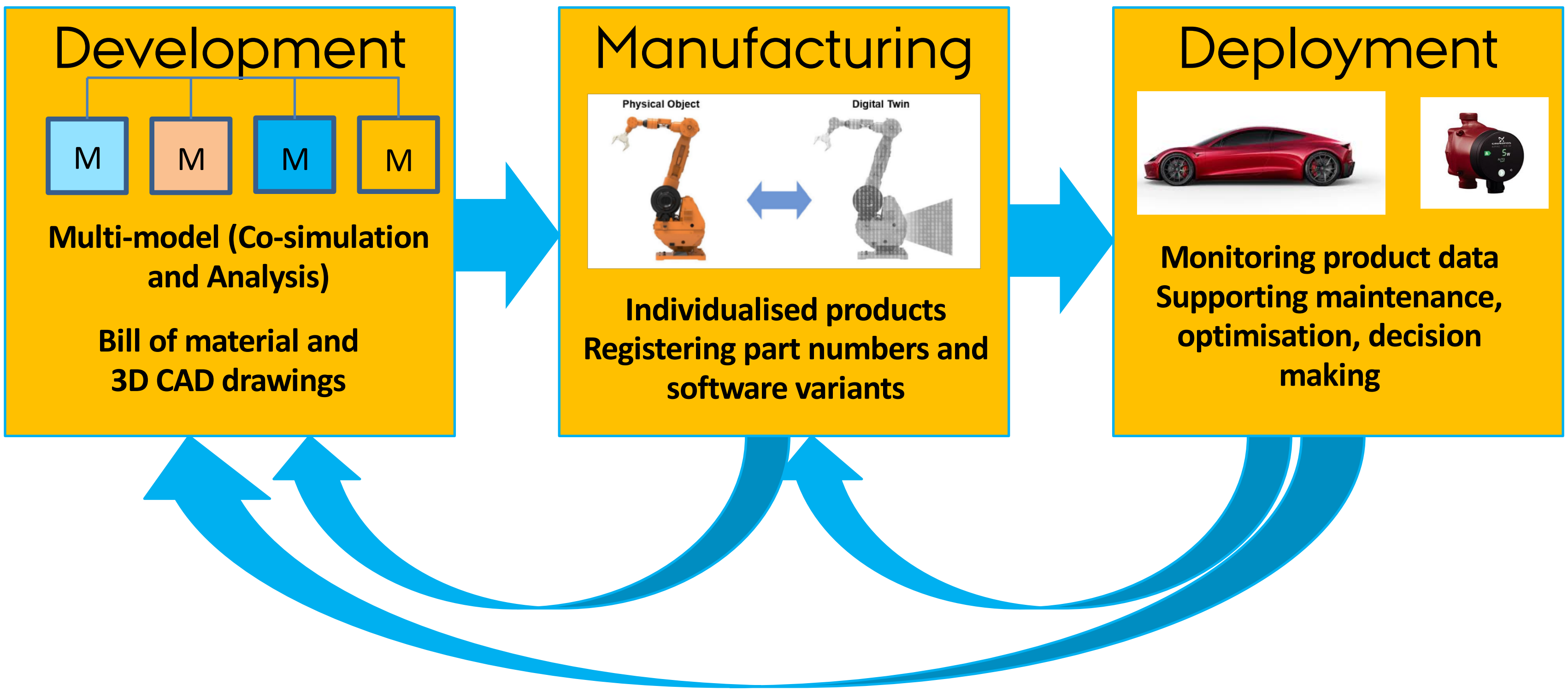
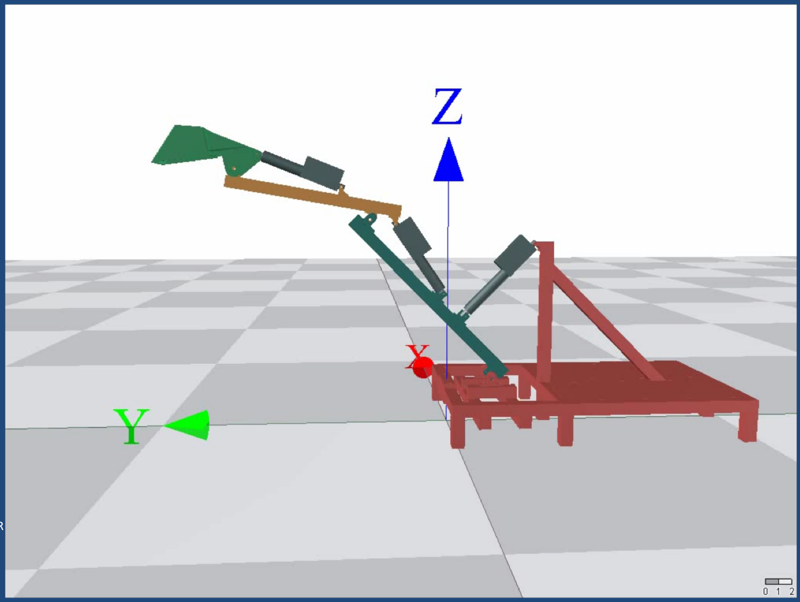
- Enable collaboration across disciplines
  - Collaborative well-founded tool chain
- Keep development costs low
  - Lower need for physical tests by virtual co-simulation examination
- Keep time-to-market short
  - Enable concurrent engineering and gradual integration
- Explore the complex design space efficiently
  - Using Design Space Exploration
- Ensure tolerance against “nasty” faults
  - Experiment with what-if scenarios in a virtual setting
- Build up documentation for the working solution
  - Using combination of ad-hoc and automated tests
- Provide confidence to external stakeholders
  - Traceability between all project artefacts

Digital twins:
Smart product ecosystem



DIGIT CENTRE FOR DIGITALISATION
BIG DATA AND DATA ANALYTICS



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