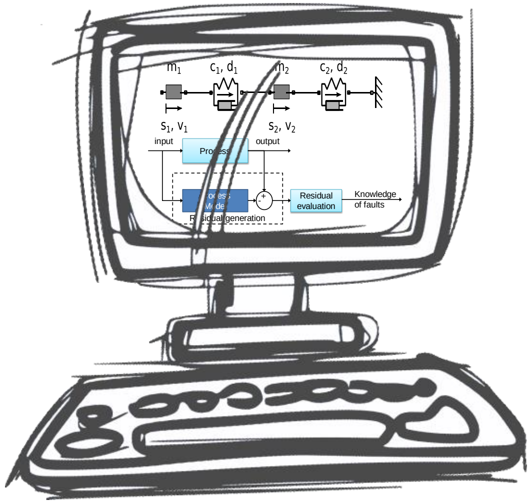
ITEA Review: EMPHYSIS #3

Introduction

Feb. 10, 2021 (13.00 – 17.00), Web-Meeting



EMPHYSIS Consortium

- **Germany**
  - Bosch[1,3]
  - DLR[2]
  - ETAS
  - ESI ITI
  - AbsInt
  - PikeTec
  - dSPACE
  - EFS
- **Sweden**
  - Dassault Systèmes AB[3]
  - Volvo Cars
  - Modelon
  - Linköping University
  - SICS East
- **France**
  - Siemens SAS[3]
  - Dassault Systèmes SE
  - Renault
  - CEA
  - University of Grenoble
  - FH Electronics
  - OSE
  - Soben
- **Belgium**
  - Siemens NV[3]
  - Dana
  - University of Antwerp
- **Canada***
  - Maplesoft[3]
- **OEM Advisory Board**
  - BMW
  - Daimler
  - Mazda
  - Volvo Trucks
  - JSAE

	Large	SME	Research
Germany	5	2	1
France	3	3	2
Sweden	2	1	2
Belgium	2		1
Canada*		1	

* w/o funding
1) Project Lead
2) Technical Coordination
3) National Coordination

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Project Overview

Project Overview
Bridge the gap

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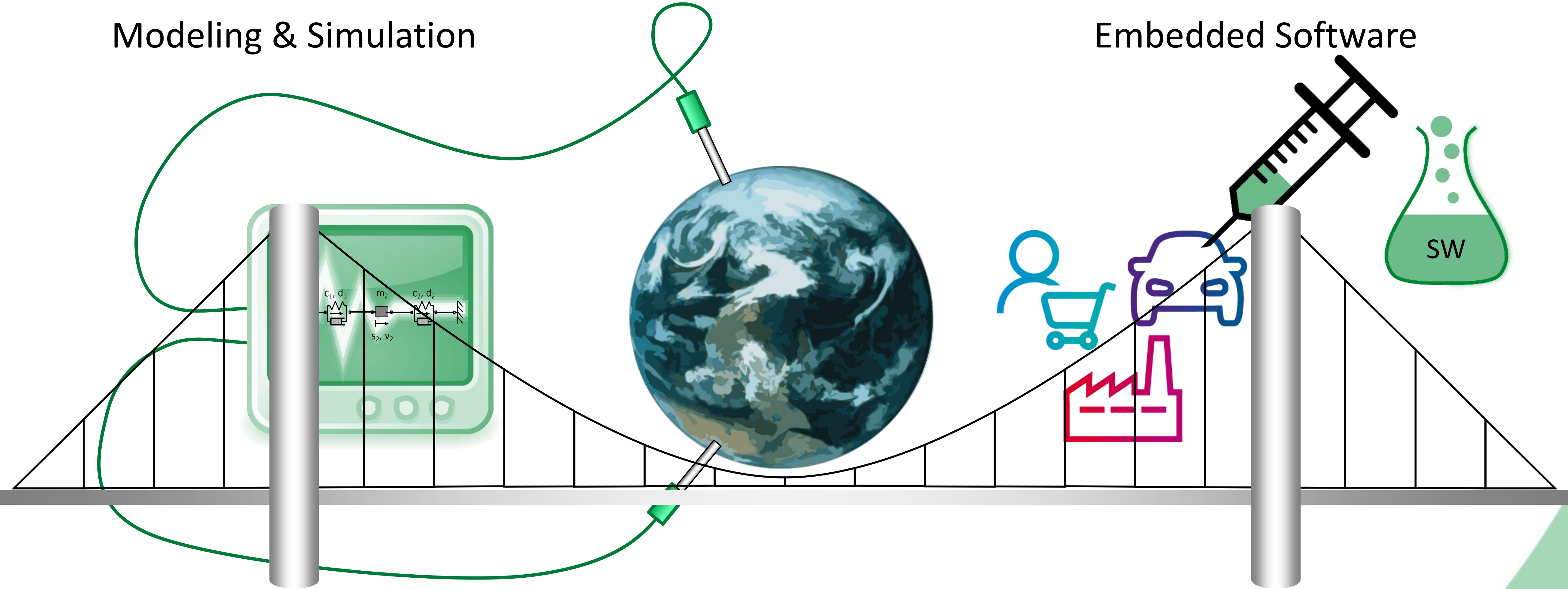
Project Overview
Bridge the gap



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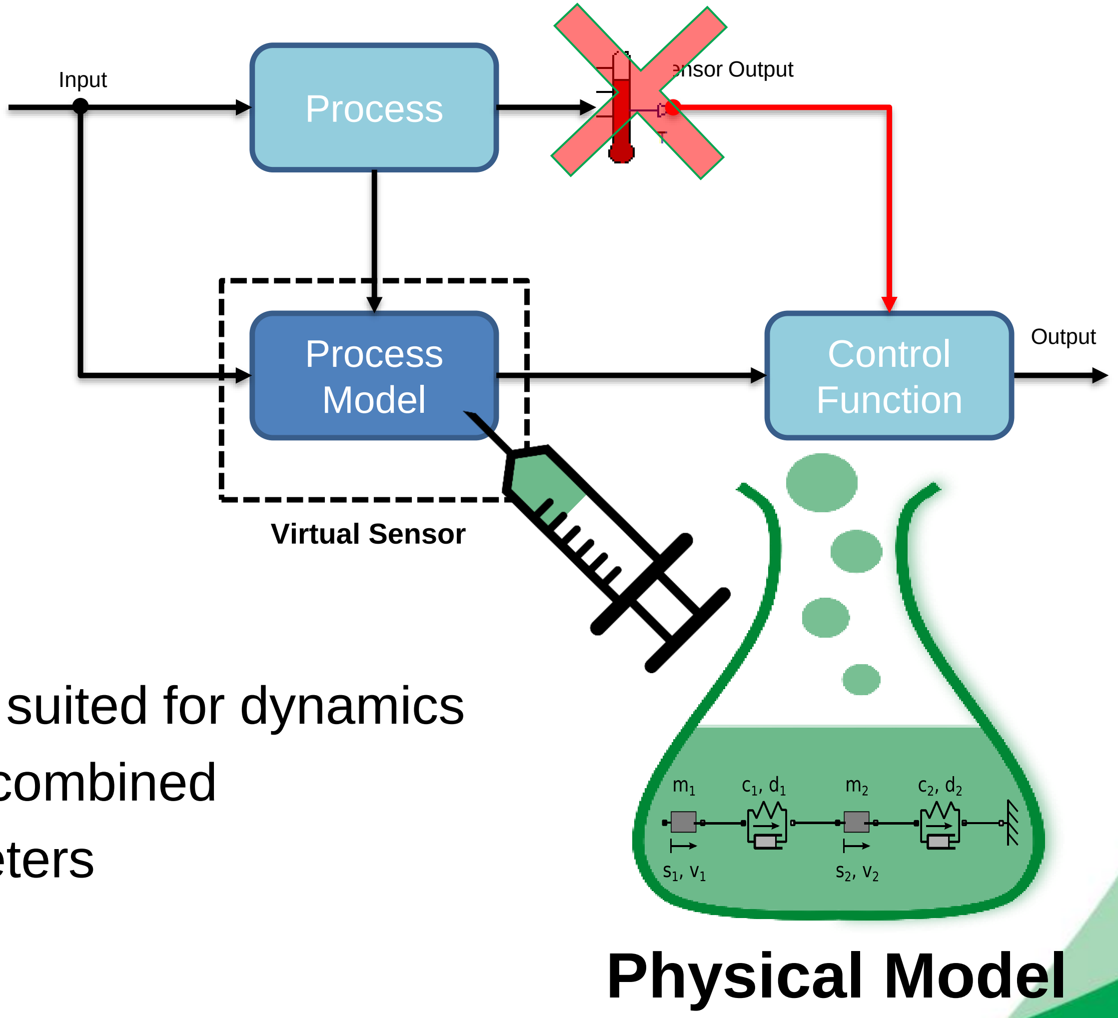
Project Overview
Physical models for embedded software

<u>Online physical models</u> key technology for advanced engine control software:

- virtual sensors, i.e., observers,
- model-based diagnosis,
- inverse physical models as feed forward part of control structures, and
- model predictive control.



Physical models:

- Typically described by differential equations, best suited for dynamics
- Complementary to data-based modeling, can be combined
- Reduced calibration effort due to physical parameters

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What is new?
State-of-the-art

Control Engineering

(System Theory, Stability, Robustness, …)

Numerics

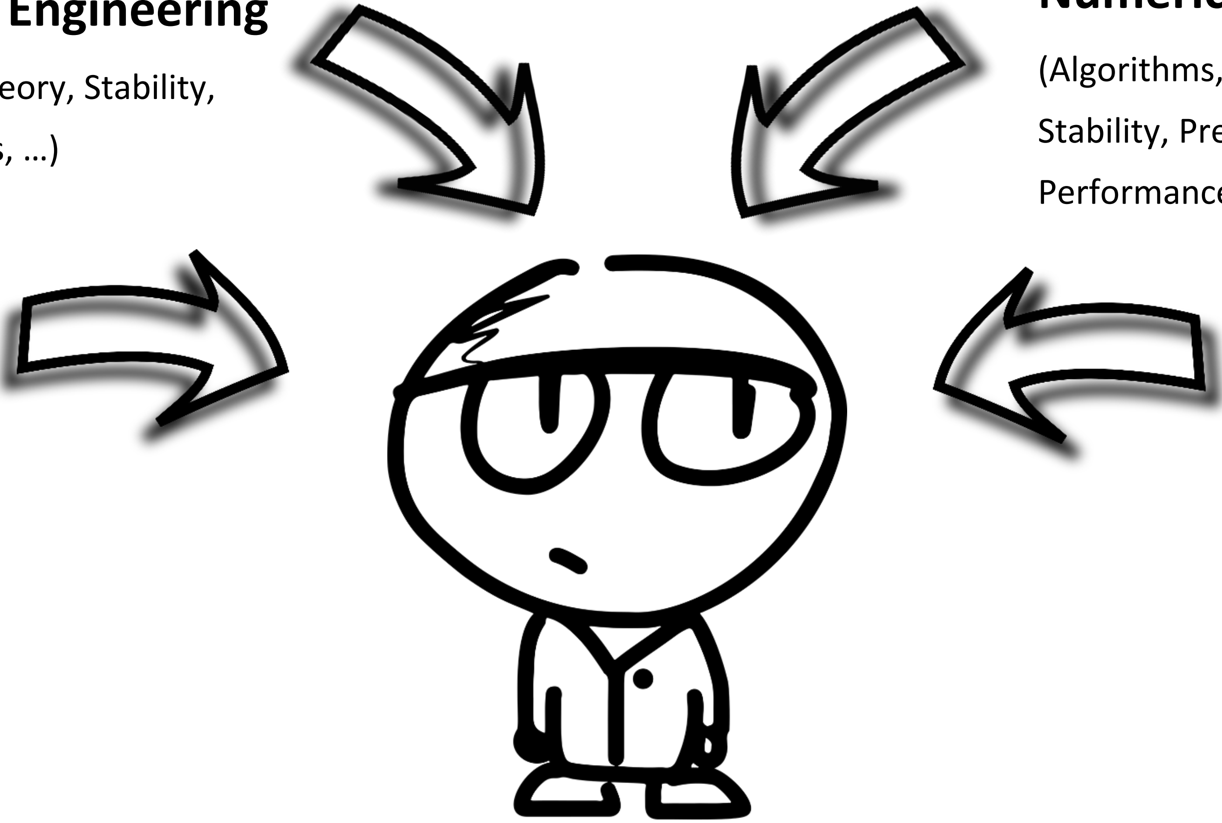
(Algorithms, Complexity, Stability, Precision, Realtime Performance…)

Physical Modeling

(Domain Knowledge, Physical Principles & Phenomena, System Dynamics, Model Validation, …)

ECU Software

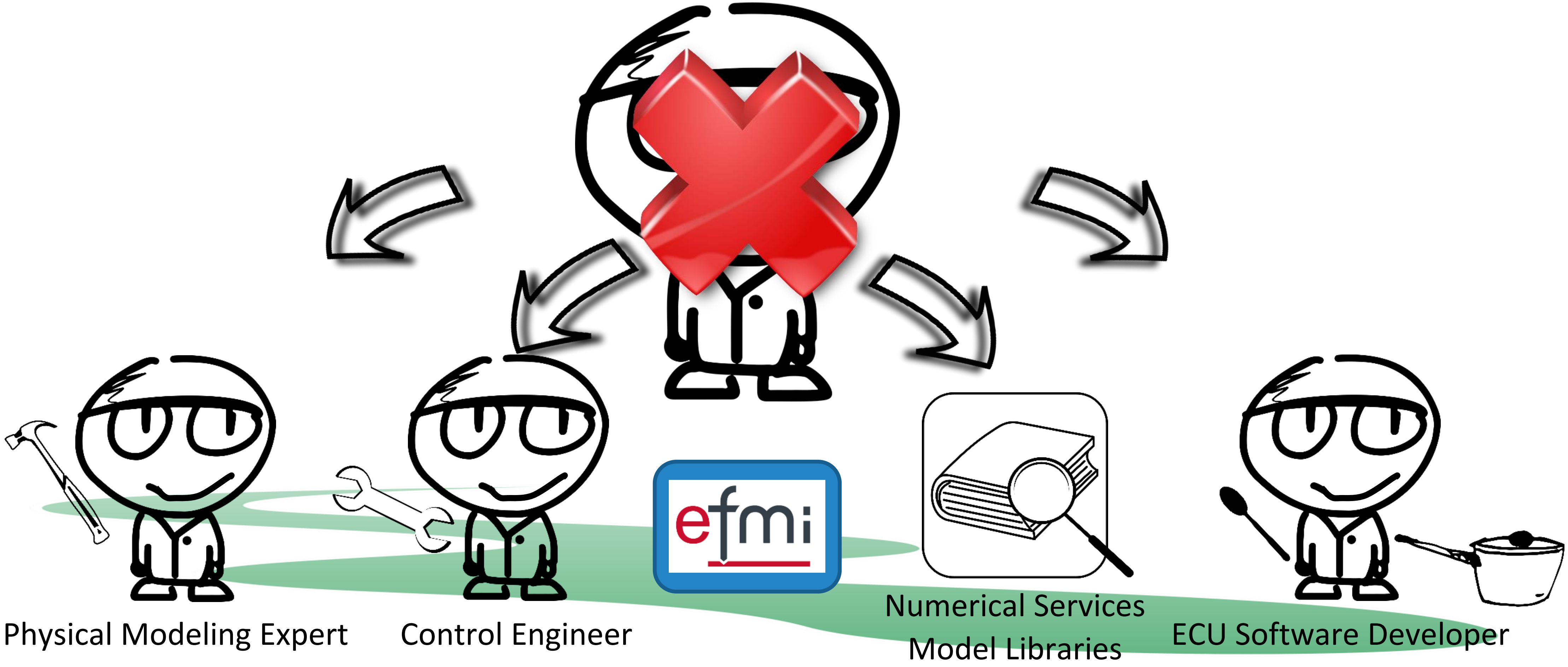
(MISRA, ASIL, MSR, AUTOSAR, …)



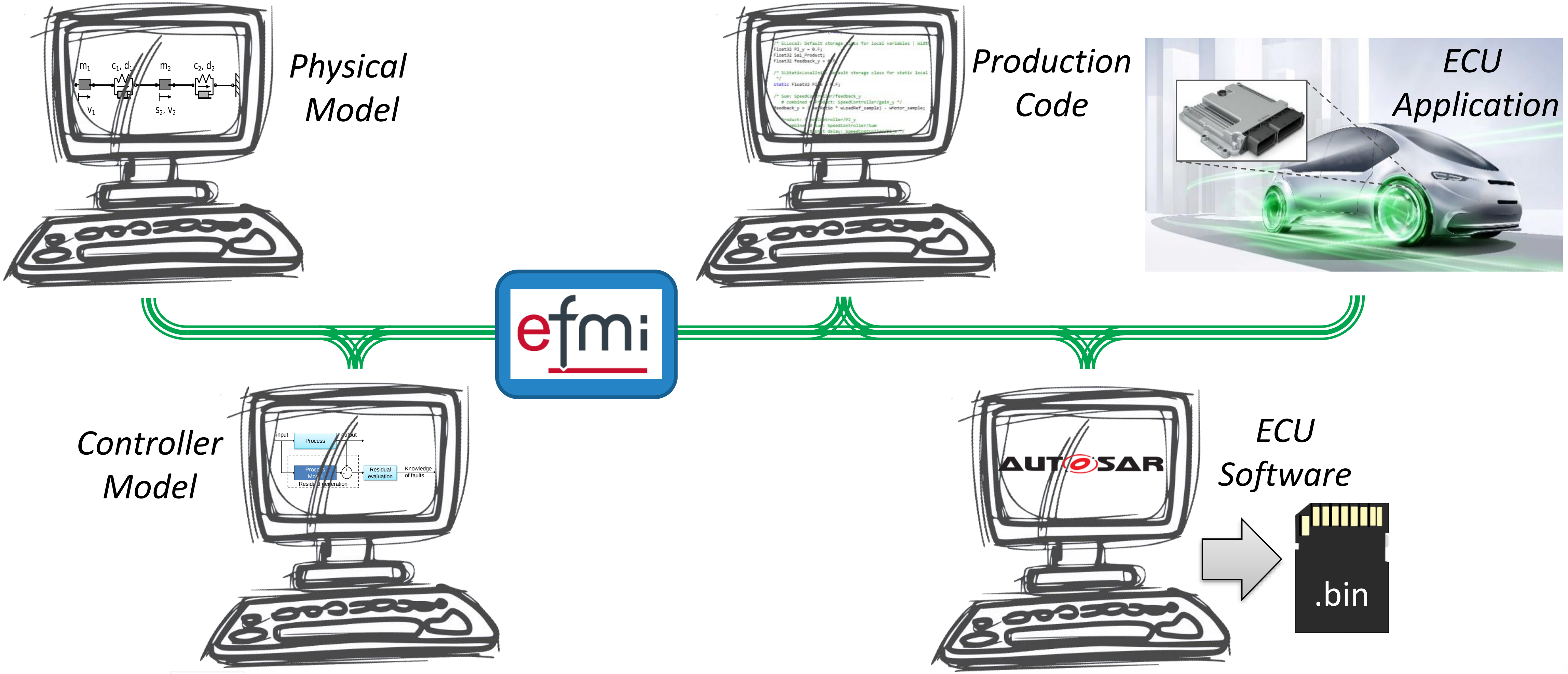
Super Hero Function Developer

What is new?

New standard, new tool chains, new ways of collaboration



Project Overview
The eFMI workflow



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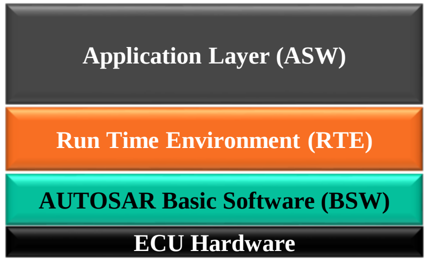
Project Overview
Special requirements of automotive embedded systems

- Specialized hardware: µController
  - Limited data memory and code memory, static memory allocation.
  - Single precision due to restricted data types (fixed-point, float).
- High safety requirements on the software:
  - Special coding guidelines, e.g., MISRA rules,
  - No exception handling (NaN, Division-by-zero,...),
  - Inbound guarantees.
- Hard realtime requirements on cyclic tasks:
  - Guaranteed execution time.
  - Limited smallest possible sampling rate (typically 1ms).
- Special realtime operating systems (AUTOSAR-OS)
- Specialized tools and tool chains (compilers etc.)

Bosch MDG1 ECU: current multi-core ECU

Motor Industry Software Reliability Association

AUTOSAR



AUTOSAR architecture

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Project Overview
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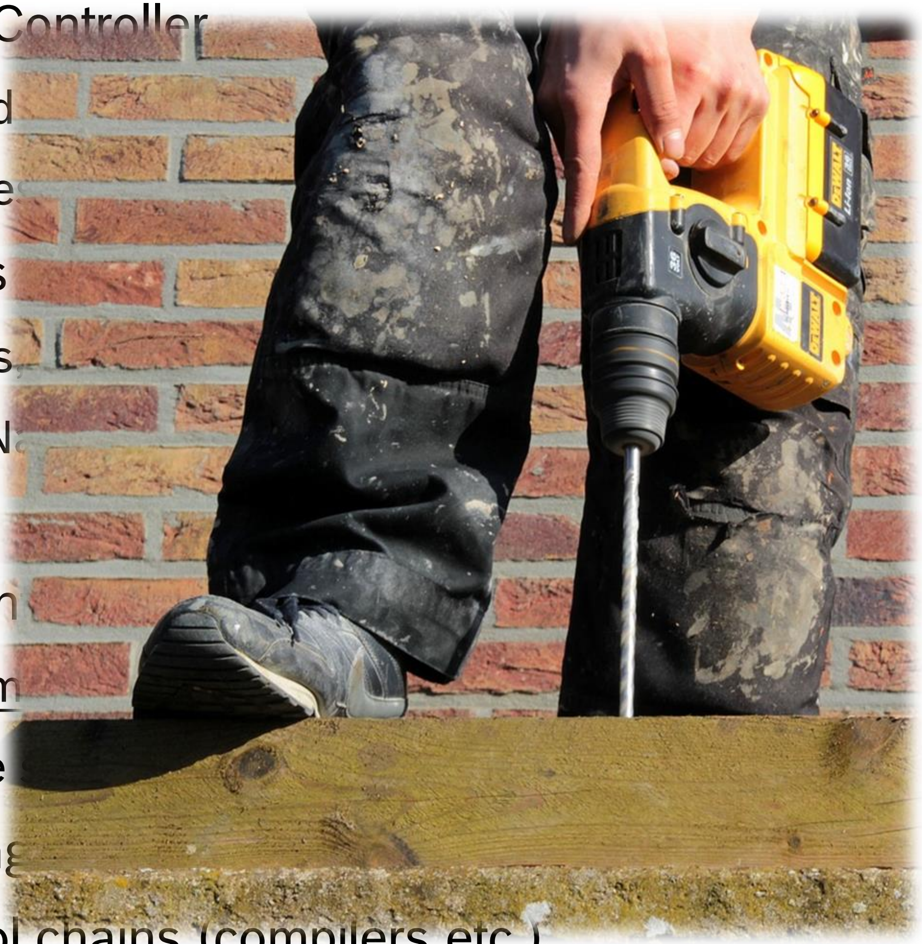
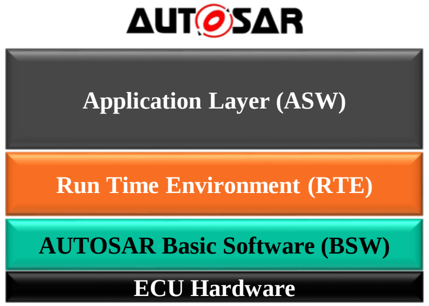


Bosch MDG1 ECU:
current multi-core ECU

Motor Industry Software Reliability Association



AUTOSAR architecture

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Project Overview
Business impact

Increase Productivity

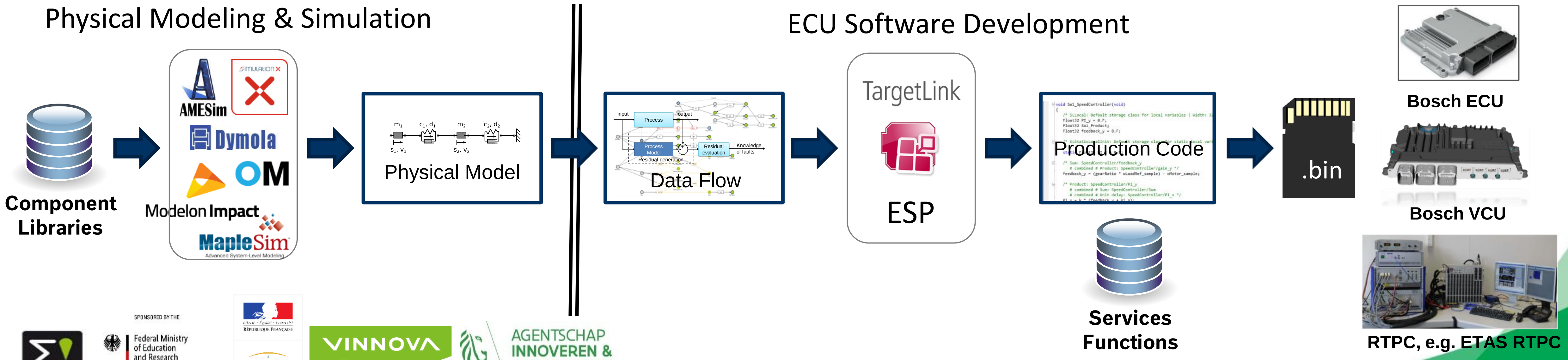
- Reuse
  - Model Libraries
  - Numerical Service Functions
- Automation
  - Model Transformations
  - Code Generation
- Seamless Tool Chain

Master Complexity

- Software Design
  - Abstraction
  - Encapsulation
- Separation of Concerns
  - Physical Behavior
  - Data Flow
  - Embedded Code

Software Innovations

- Tool Vendors
  - Added Value
  - Expand Market in MBD Domain
- Supplier/OEM
  - New Advanced Functions
  - Replace HW with SW
  - New Modes of Collaboration



Project Overview
Main Goals

- eFMI Standard
  - ✓ Exchange format from physical models to embedded software.
- eFMI Workflow → Tool Chain
  - ✓ eFMI supporting tools through all stages
- eFMI Demonstrators
  - ✓ Mature prototypes close to product release.
  - ✓ Better than state of the art performance.
  - ✓ Proven benefits for model-based control applications.
  - ✓ New innovative solutions enabled by eFMI.
  - ✓ New products, services, collaborations after project end.

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Key Achievements

Key Achievements - Specification

eFMI Specification
Introduction

eFMI Specification 1.0.0-alpha.3 available for **public review**:

https://emphysis.github.io/

Provided to FMI group in 2020 and incorporated their feedback.

Formal standardization process via the Modelica Association **started**.

Expected to be released as a Modelica Association standard in 2-3 months.

Contents

Functional Mock-up Interface for Embedded Systems (eFMI)

Version 1.0.0-alpha.3 (Draft), January 27, 2021

Preamble

.1. CopyRight and License

.2. Release Notes

.2.1. Version 1.0.0-alpha.2

Disclaimer

This alpha release is a draft version of the eFMI standard (= Functional Mockup Interface for Embedded Systems). It is planned to standardize a potentially improved version by the Modelica Association.

.3. Abstract

The eFMI (FMI for embedded systems) standard specified in this document aims to extend the scope of FMI (https://fmi-standard.org) from simulation towards software development. The eFMI standard is intended as exchange format for workflows and tool chains from *physical models to embedded software*. It is defined as a layered approach built upon the FMI for Co-Simulation standard (any version). The effect is that an eFMU (Functional Mockup Unit for embedded systems) can be simulated with an FMI compliant tool (https://fmi-standard.org/tools) to perform Software-in-the-loop (SiL) testing. Code generation for an embedded device requires however dedicated tool support for eFMI.

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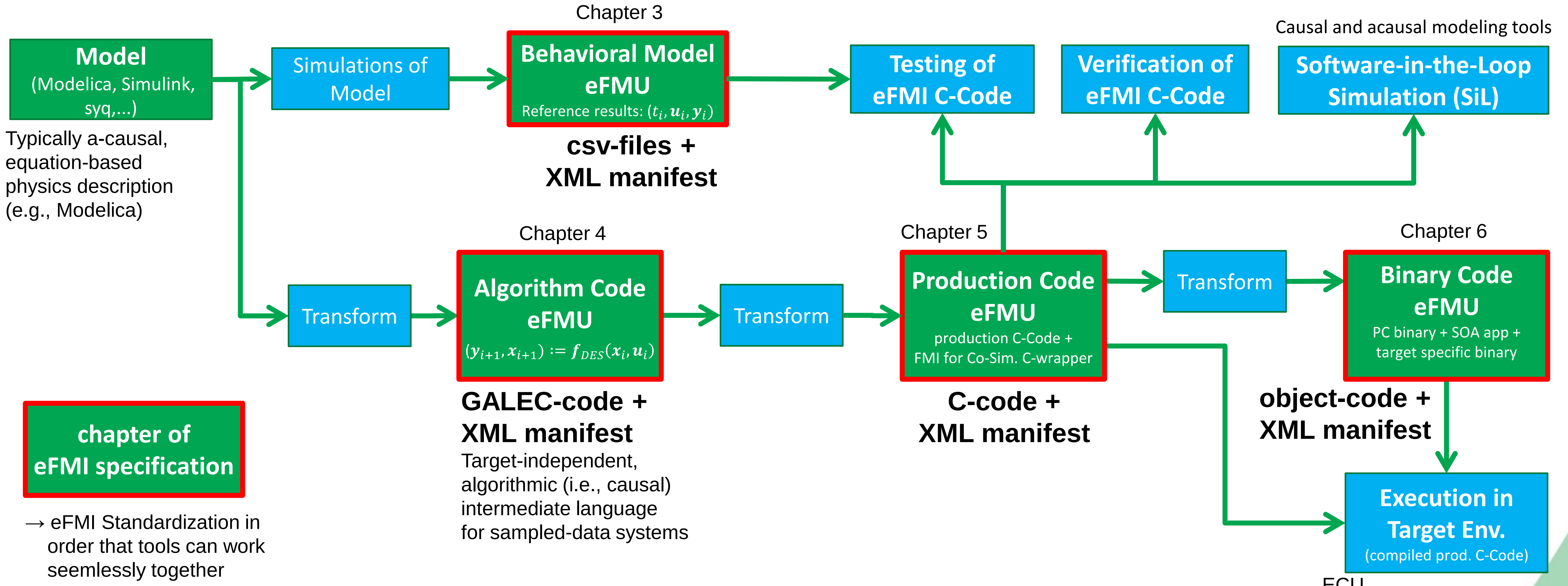
eFMI Specification
Overview (chapter 3-6)



ECU
Realtime-PC
Rapid Prototyping Systems
AUTOSAR
AUTOSAR Adaptive
...

Abbreviations
eFMI: Functional Mockup Interface for Embedded systems
eFMU: Functional Mockup Unit for Embedded systems
GALEC: Guarded Algorithmic Language for Embedded Control

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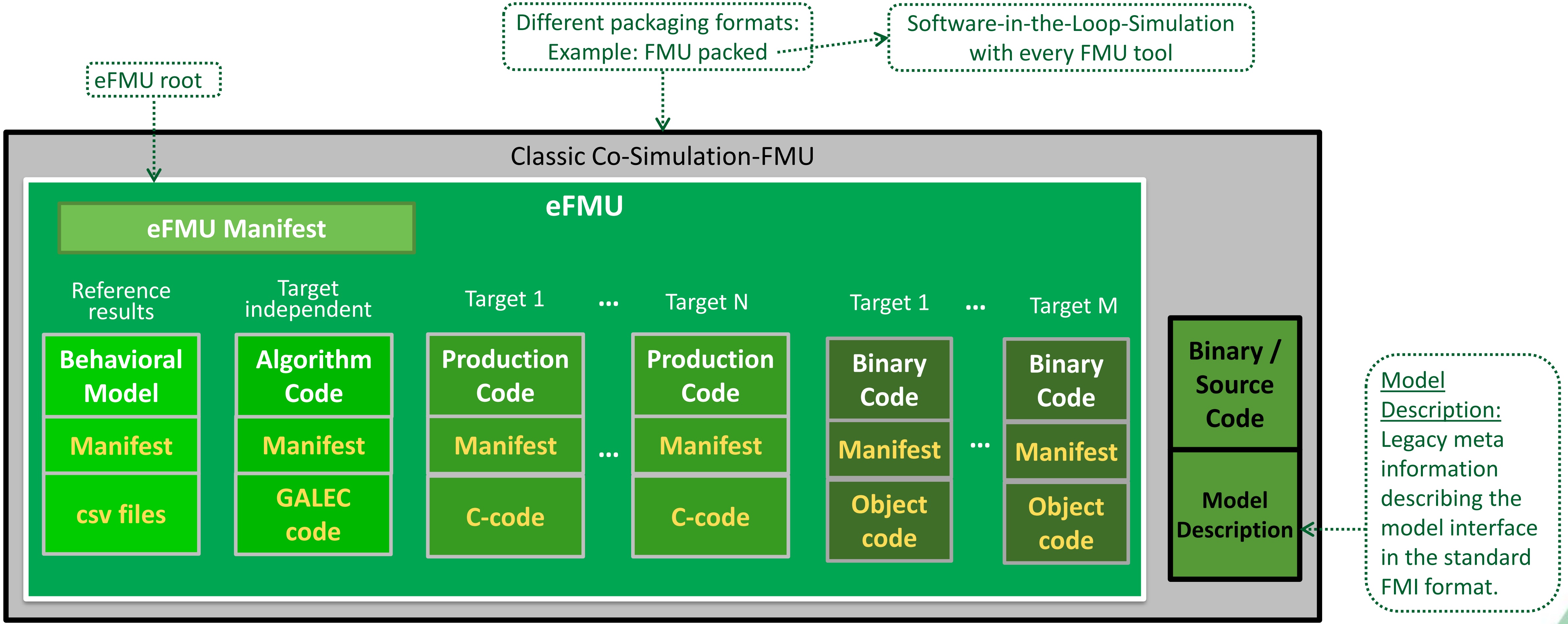
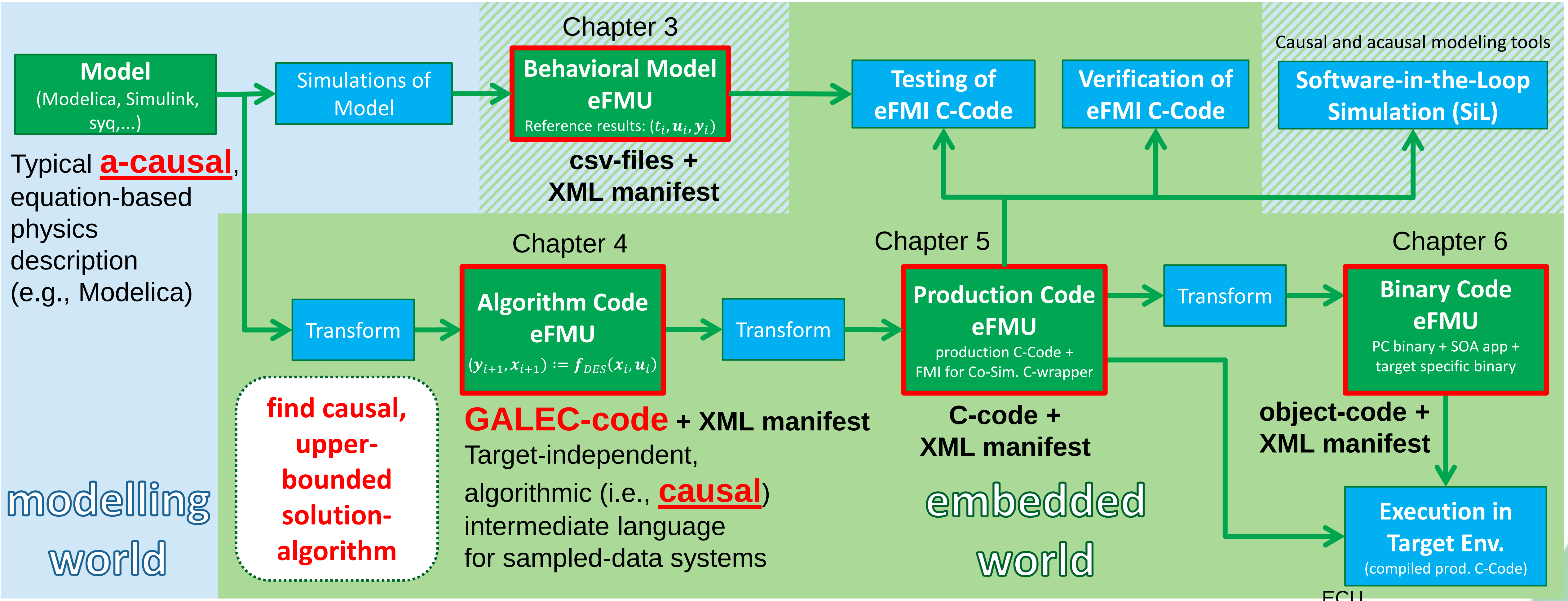
eFMI Specification

Container Architecture (chapter 2)



Manifest:
Description of the interface of the associated code and additional meta information on how to access and utilize the code.

eFMI Specification
Overview (chapter 3-6)



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eFMI Specification

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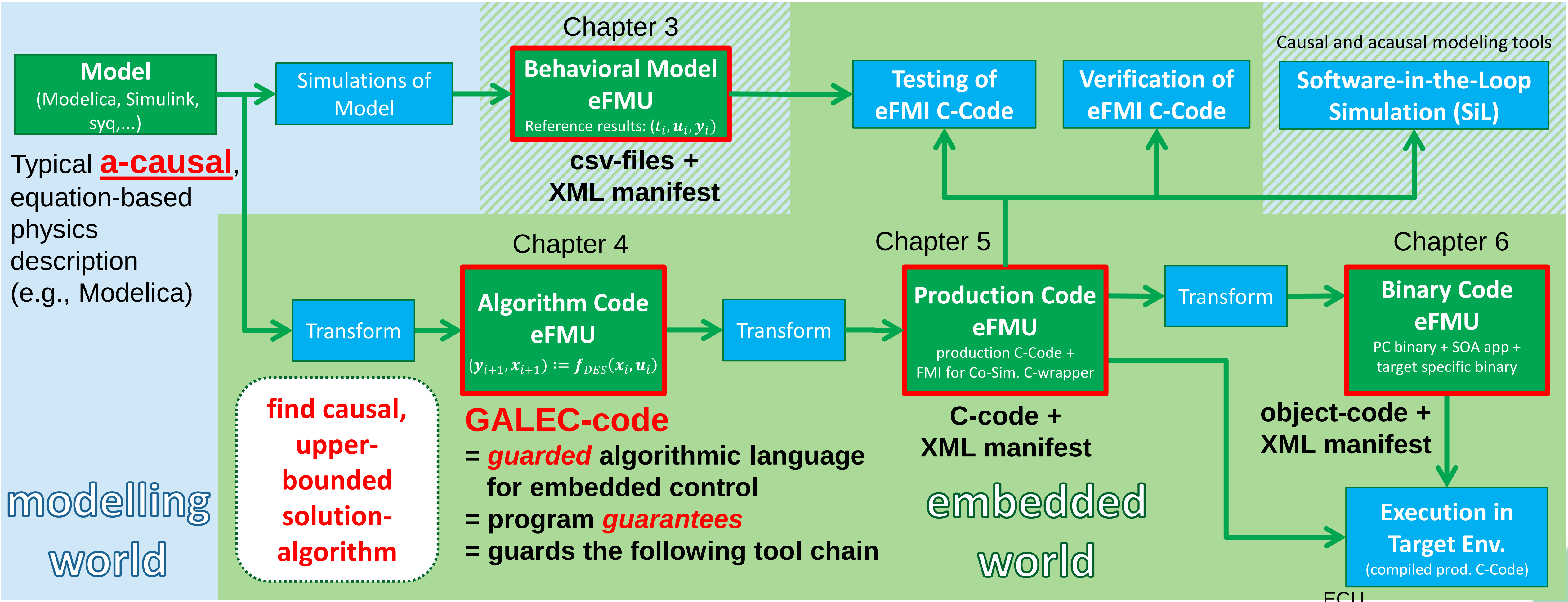

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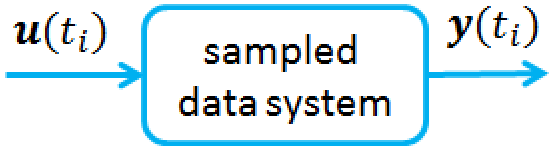
eFMI Specification
GALEC (chapter 3)

GALEC: *G*uarded *A*lgorithmic *L*anguage for *E*mbedded *C*ontrol

- Target-independent, intermediate representation for bounded algorithms with multi-dimensional real arithmetics
- Imperative / causal language
- Safe – embedded & real-time suited – semantics
- Safe floating-point numerics
- Built-in mathematical functions
  (e.g. sin, cos, interpolation 1D & 2D, solve linear equation systems)



$$\boldsymbol{x}_{i+1} = \boldsymbol{f}_x(\boldsymbol{x}_i, \boldsymbol{u}_i)$$
$$\boldsymbol{y}_i = \boldsymbol{f}_y(\boldsymbol{x}_i, \boldsymbol{u}_i)$$

```
'gain.y'     := self.gearRatio * self.wLoadRef;
'feedback.y' := 'gain.y' - self.wMotor;

'PID.D.y' := self.kd * ('feedback.y' - self.'PID.D.x') / self.Td;
'PID.y'   := self.k * ('PID.D.y' + self.'PID.I.x' + 'feedback.y');
```

eFMI Specification
GALEC (chapter 3)

Safe – embedded & real-time suited – semantics

- Upper bound on number of operations
- Statically known sizes (vectors, matrices etc.)
  - ⇒ **statically know resource requirements**
  - ⇒ **exception free runtime semantic**
- Well-bounded indexing
  - ⇒ **never out-of-bounds / illegal memory accesses**
- By value semantics with only well-defined & never competing side-effects
  - ⇒ **Huge potential for parallel execution (e.g., SIMD on multi-dimensions)**

Language guarantees
⇒ satisfied by every GALEC program
⇒ following eFMI tool chain can leverage on

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eFMI Specification
GALEC (chapter 3)

Safe floating-point numerics

- Ranged variables & implicit limitation at start/end of sample period
- Guaranteed qNaN (quiet-Not-a-Number) & error signal propagation
  + control-flow integrated error signal handling

⇒ **No undetected errors**

⇒ **Enables back-up strategy at end of algorithm in case of *any unexpected* errors**

Language guarantees
⇒ satisfied by every GALEC program
⇒ following eFMI tool chain can leverage on

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Key Achievements - Tooling

Tool Prototypes
Introduction

- The eFMI workflow is supported by these categories of tools
  - Modeling & simulation tools (WP4)
  - Embedded software tools (WP5)
  - Verification & validation tools (WP6)

- Tool prototyping running in parallel with the eFMI specification work from the start

- Cross-testing of tools in close collaboration between WP4/5/6
  - Test cases developed in WP7.1 were used to verify tool coverage
  - Several eFMI plug fests were organized for efficient interactions between tool vendors

- eFMI Compliance Checker developed to support tool implementations

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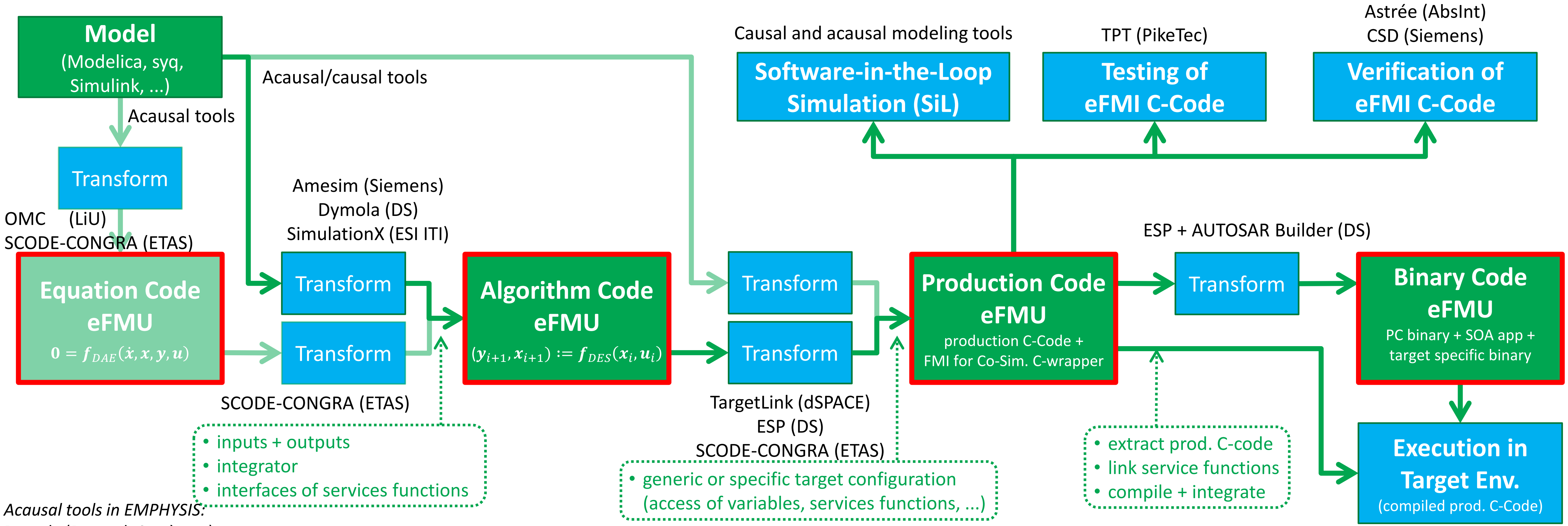
Tool Prototypes

EMPHYSIS Workflow – Tool Positioning



Acausal tools in EMPHYSIS:
Dymola (Dassault Systèmes)
OpenModelica Compiler (LiU)
SCODE-CONGRA (ETAS)
SimulationX (ESI ITI)
OPTIMICA (Modelon) – under dev.

Causal tools in EMPHYSIS:
Amesim (Siemens SAS)
Simulink (Mathworks)

Model in EMPYHSIS:
- Physical model (e.g. vehicle model)
- Controller, estimator, ...
- Diagnosis system, neural network, ...
- Any combination from above

Further tool chains (not shown above):
- *Physical model is transformed to eFMI Algorithm-Code which is used in a (controller/...) model from which eFMI Algorithm-Code is generated.*
- *Production C-Code may be directly generated from eFMI Algorithm Code.*
- *Embedded software architecture - design space exploration*

AUTOSAR Adaptive
MDG1 ECU (Bosch)
Pre-devel. ECU (EFS)
ECU (KW-automotive)
Realtime-PC

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Tool Prototypes

Support for eFMI Import and Export

Tool Name	Vendor	EquCode	AlgCode	ProdCode	BinaryCode
Amesim	Siemens				
Dymola	Dassault Systèmes				
OPTIMICA Compiler Toolkit	Modelon				
OpenModelica	Linköping University				
SimulationX	ESI-ITI				
SCODE-CONGRA	ETAS				
AUTOSAR Builder	Dassault Systèmes				
TargetLink	dSPACE				
Astrée	AbsInt				
CSD	Siemens				
TPT	PikeTec				
CATIA ESP	Dassault Systèmes				
QuaRTOS-DSE	CEA				

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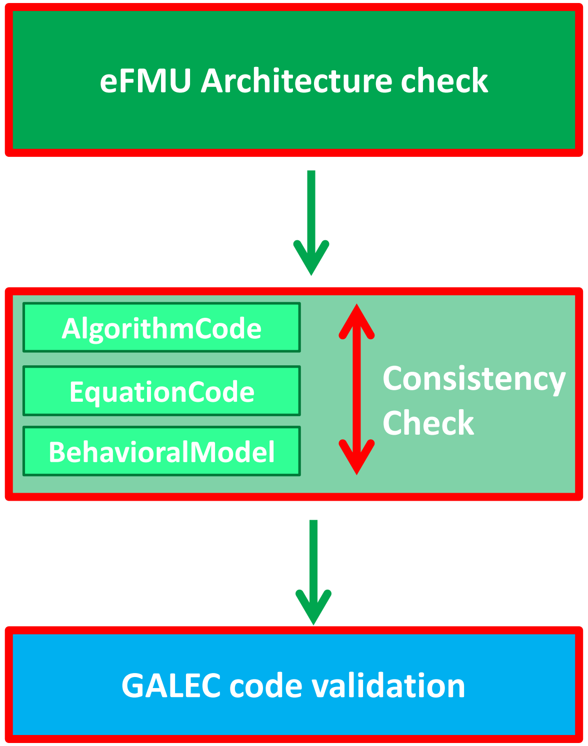
Import Prototype Under dev.

Export Prototype Under dev.

Tool Prototypes
eFMI Compliance Checker

- An open-source library for:
  - Verifying the eFMU architecture
  - Consistency checking of all model representation manifests
  - Validating the GALEC code against the specification
- Implemented in Python:
  - Fully documented
  - Easy to update and extend
  - Will be hosted on the Modelica Association Github repositories
  - Will be provided to the PyPI repository



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Tool Prototypes
eFMI Compliance Checker

ITEA 3 EMPHYSIS

Test results and number of eFMUs that passed the compliance check:

eFMUs vendor	Total	Consistency Check	GALEC code validation
Amesim	**3**	**3**	**3**
Dymola	**29**	**29**	**29**
SimulationX	**27**	**27**	**27**

➔ **100%**

KPI5: The eFMI compliance checker prototype (D6.1) does not report errors to <u>at least 90%</u> of the eFMI test components exported by <u>all</u> tool prototypes of WP4.

```
Running the consistency check for all model representations in the __content.xml file
   - The EquationCode model representation
         The representation id matches the id in the manifest
         The representation checksum matches the calculated checksum of the manifest
         The manifest.xml manifest file was correctly validated against the relevant schema file
         The manifest.xml manifest file does not contain any manifest references

   - The AlgorithmCode model representation
         The representation id matches the id in the manifest
         The representation checksum matches the calculated checksum of the manifest
         The manifest.xml manifest file was correctly validated against the relevant schema file
         All manifest references in the manifest.xml manifest file are valid

   - The BehavioralModel model representation
         The representation id matches the id in the manifest
         The representation checksum matches the calculated checksum of the manifest
         The manifest.xml manifest file was correctly validated against the relevant schema file
         All manifest references in the manifest.xml manifest file are valid

Other consistency checks
         All variables in the AlgorithmCode manifest are consistent with the variables in the EquationCode manifest

Validating the __content.xml file against the efmiContainerManifest.xsd schema file
         The __content.xml file was validated correctly against the efmiContainerManifest.xsd schema file

Reading all 'alg' files from the manifest.xml file and checking if these files exist in the AlgorithmCode folder
         The block.alg file is listed in the manifest.xml file
         block.alg exists in the D:\projects\Emphysis\eFMUs\eFMU\AlgorithmCodeContainer_Dymola directory
```

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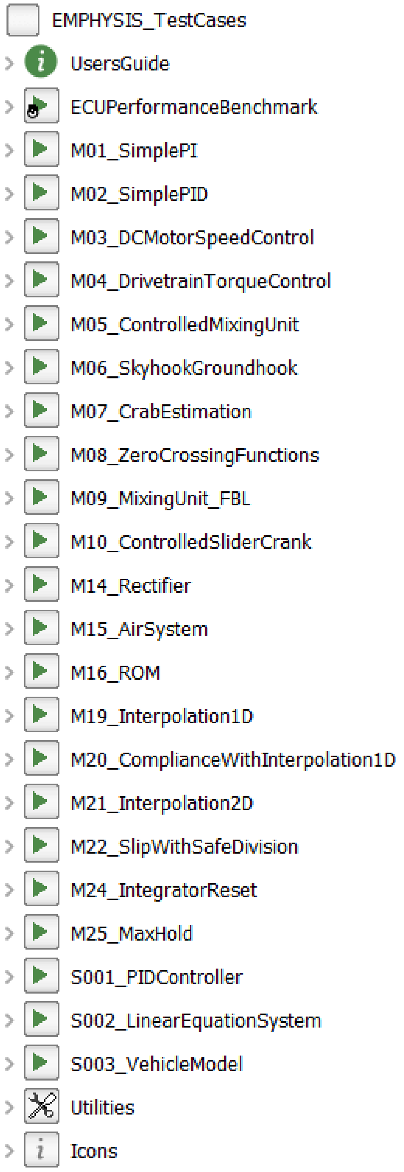
Key Achievements - Test cases

Tool Prototypes
Test Cases and Test Coverage – Demonstrator D7.1

Test cases:
- Modelica library with 22 test cases containing 43 variants
- 3 Amesim models
- 2 manual GALEC codes

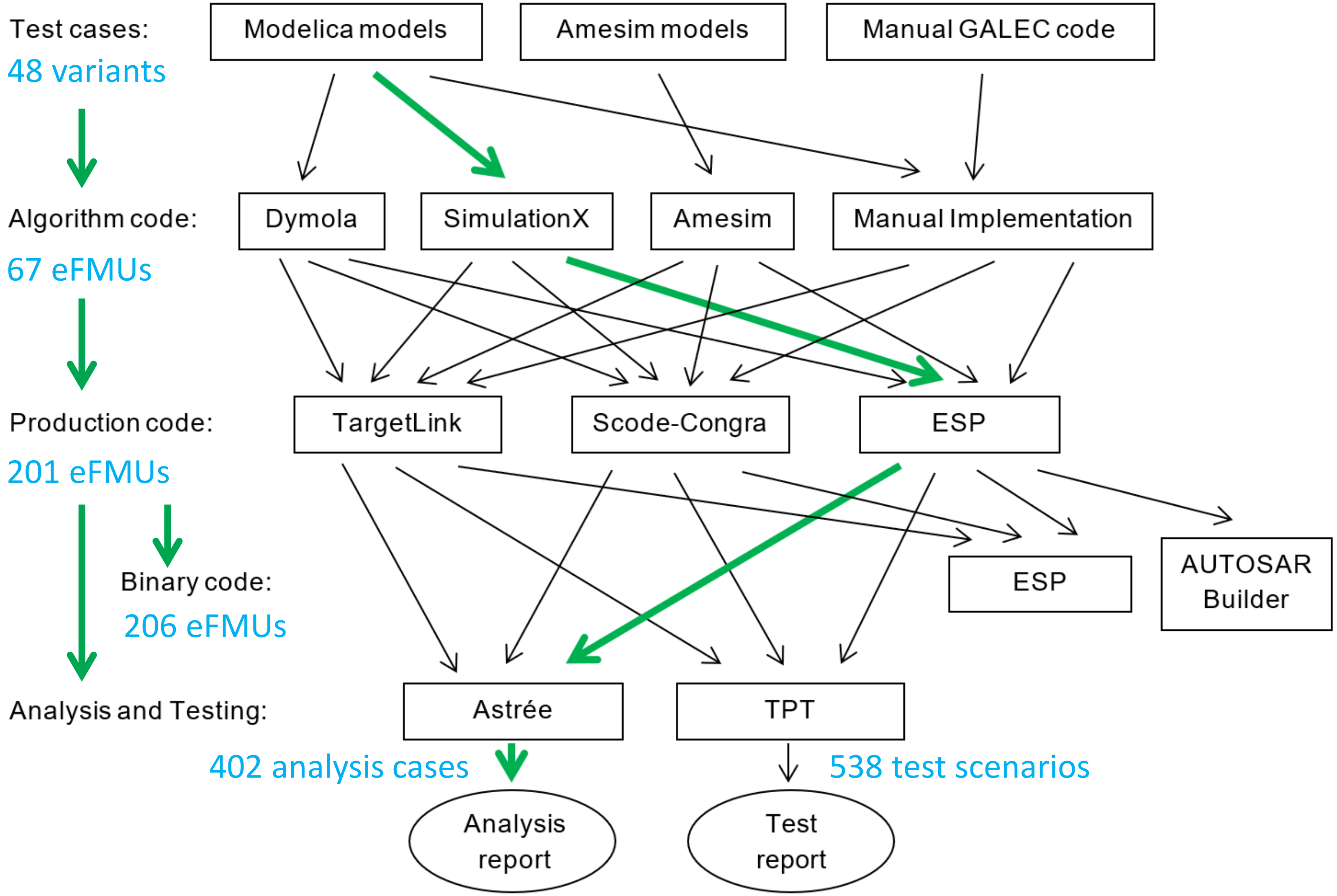
Features and Challenges:
- Inverse model or feedback linearization based controllers
- Explicit and implicit integration schemes
- Event-based re-initialization of continuous states
- Neural networks
- Important built-in functions:
  - Solving linear equation systems
  - 1-D and 2-D interpolation of tables
- Error handling
- Implicit saturation



Tool Prototypes
Test Cases and Test Coverage – Demonstrator D7.1

eFMI toolchain for test cases:

- 9 commercial tools
- 50 toolchain paths
- Common GIT repository for eFMU-exchange and reports (~ 7 GB)
- 11 two-day plug fests
  - to test tool compatibility
  - to enhance eFMI specification



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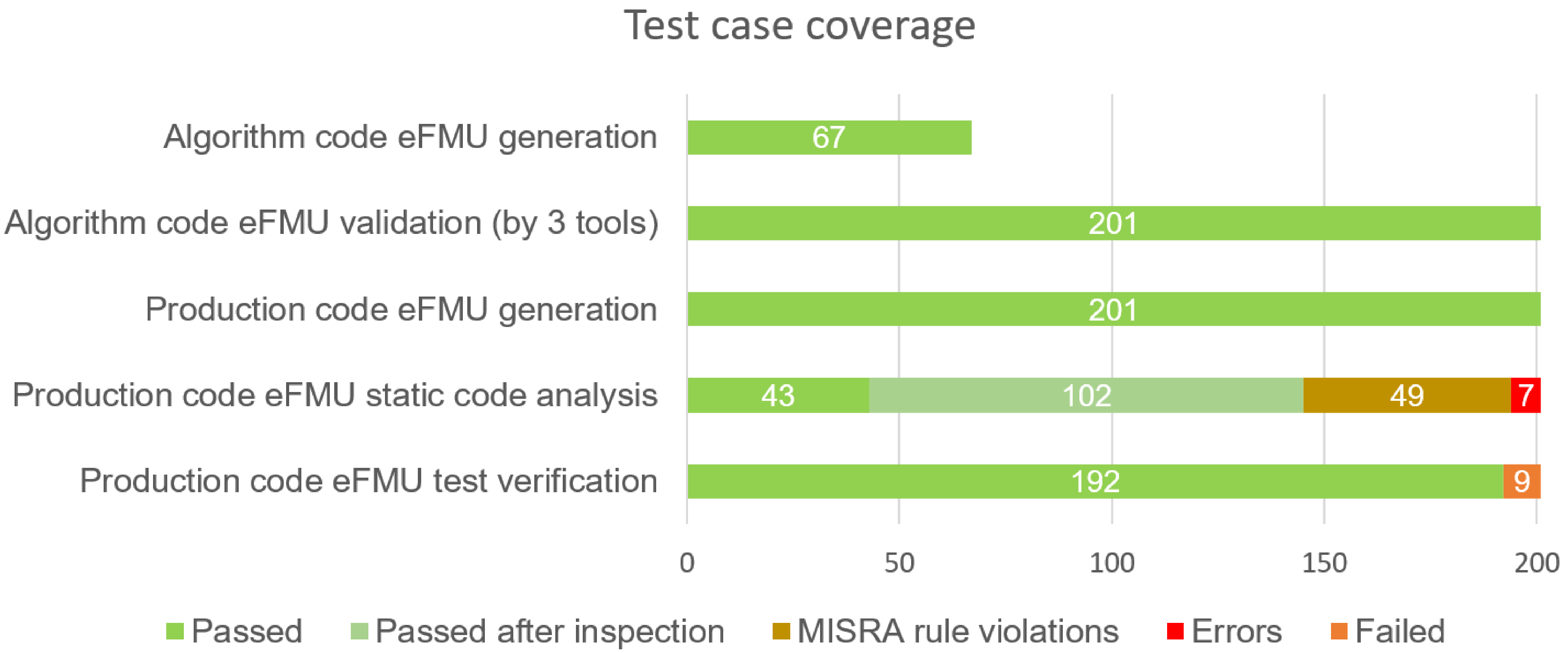
Tool Prototypes

Test Cases and Test Coverage – Demonstrator D7.1



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EMPHYSIS Demonstrators
D7.2 eFMI Performance Assessment (Bosch)

Problem Statement:

- Embedded performance is crucial for user acceptance.

Objective

- Evaluation of the eFMI tool chain results against state-of-the-art embedded SW development.

Targeted Results

- KPI 8: Performance against state of the art (manual) implementation
  - At least 5 times less time to deliver model/controller function.
  - At most 25% less efficient code.
  - At most 25% more memory consumption.
    (25 % increased overhead is acceptable due to the large increase in development efficiency and the expected increase in computing power and available memory in the next years.)
- KPI 11: Gain in productivity [ΔPY/PY %]
  - Acceleration by >20%.

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Key Achievements - Performance Assessment

EMPHYSIS Demonstrators

D7.2 eFMI Performance Assessment (Bosch)

Model
(Modelica Library)

6 Benchmark Test Cases
(out of 22 EMPHYSIS Test Cases)

#	Name	Difficulty*	Challenge
M03	PID	low	Minimal footprint incl. saturated IOs
M04	Drivetrain	medium	Inverse linear physical model
M15	Air System	medium	Stiff ODE with delay operator
M10	Inverse Slider Crank	high	Inverse non-linear physical model (DAE Index-1)
M16	ROM	high	High dimensional maps, solve a large linear eq system
M14	Rectifier	high	Advanced symbolic transformation to compact ODE form

Transform

Dymola (DS)
SimulationX (ESI-ITI)

Algorithm Code eFMU
$(y_{i+1}, x_{i+1}) := f_{DES}(x_i, u_i)$

Transform

ESP (DS)
SCODE-CONGRA (ETAS)
TargetLink (dSPACE)

Production Code eFMU
production C-Code +
FMI for Co-Sim. C-wrapper

Automated Performance Test Environment (Bosch)

Transform

Execution on Target
(compiled prod. C-Code)

Performance Benchmark

Bosch ECU MDG1

*Difficulty for an automated procedure to achieve same quality as manual implementation.

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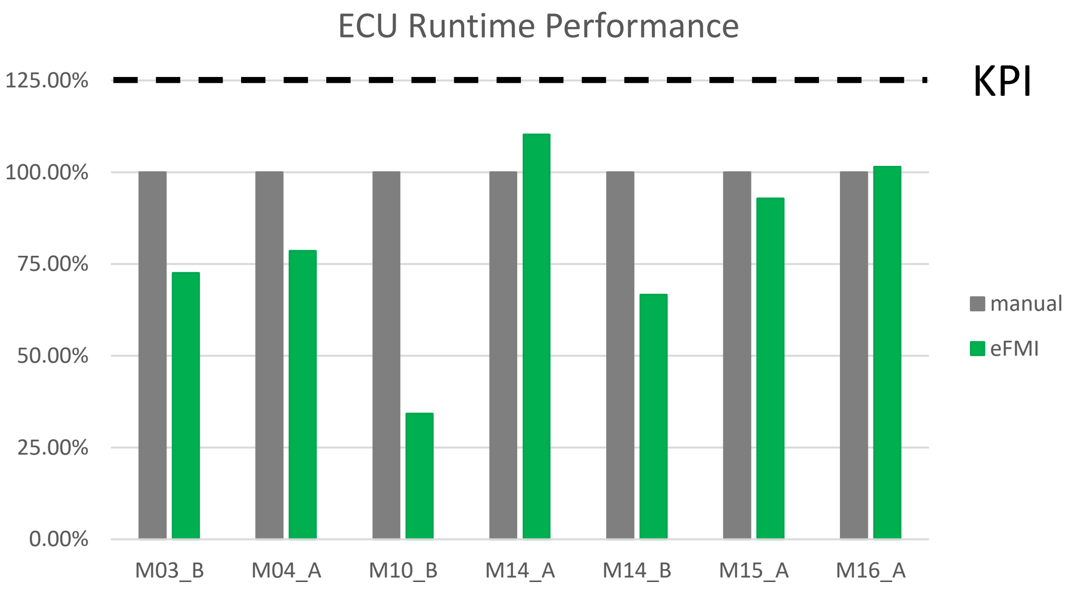
EMPHYSIS Demonstrators
D7.2 eFMI Performance Assessment (Bosch)

ECU Runtime Performance:

- In all cases the eFMI generated code is below the +25% KPI margin.
- In 5 of 6 examples an eFMI exists that <u>outperforms</u> the hand code.
- In average the best performing eFMUs are **26% faster than the hand code**.

#	Name	Difficulty*	Relative ECU Runtime Average	Min.	Max.
M03	PID	low	-7%	**-27%**	+29%
M04	Drivetrain	medium	+9%	**-21%**	+44%
M15	Air System	medium	+38%	**-7%**	+132%
M10	Inverse Slider Crank	high	-65%	**-66%**	-64%
M16	ROM	high	+4%	**+1%**	+6%
M14	Rectifier	high	+3%	**-33%**	+44%
	Average		**-3%**	**-26%**	32%

*Difficulty for an automated procedure to achieve same quality as manual implementation.



Graphical modeling:
- high level of reuse
- component-oriented

Textual modeling
- compact formulation

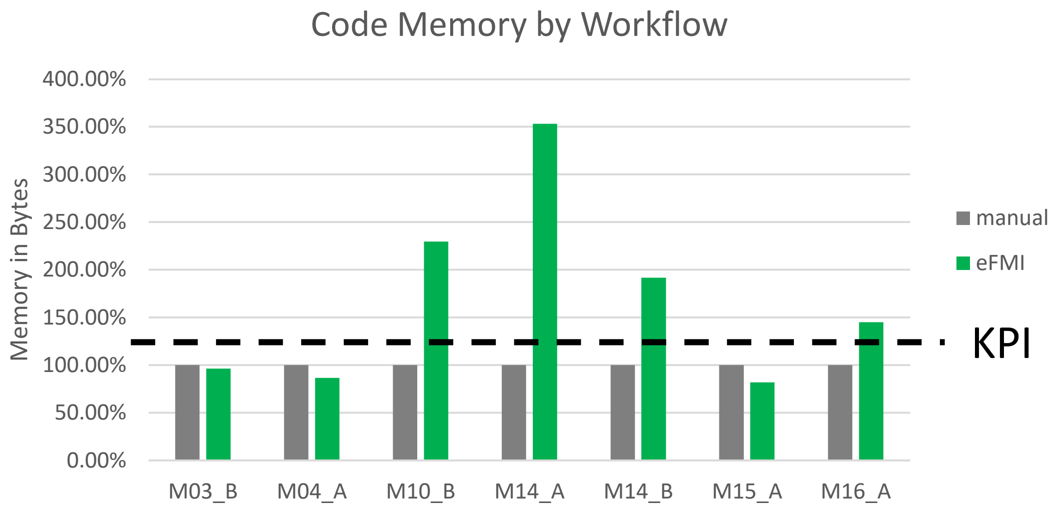
M14 in both variants

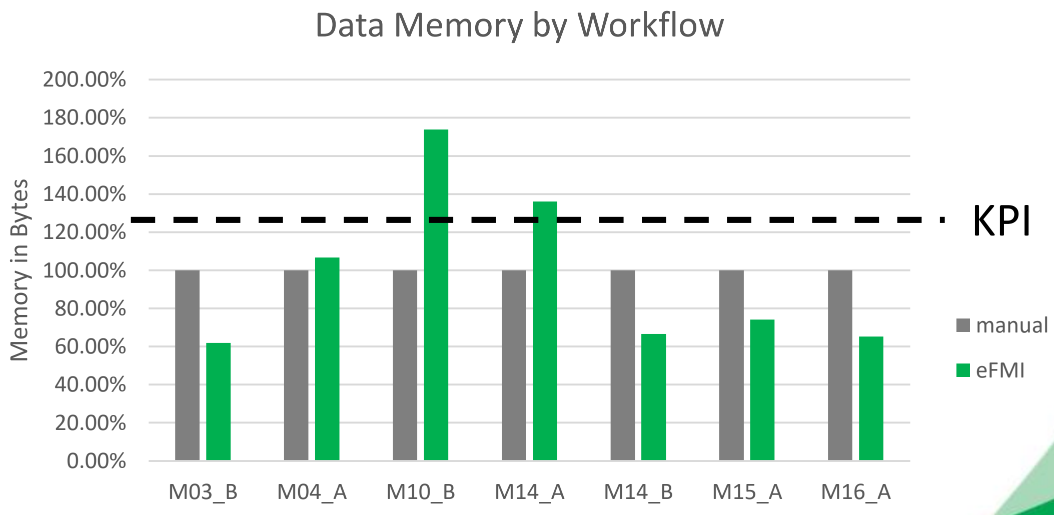
EMPHYSIS Demonstrators
D7.2 eFMI Performance Assessment (Bosch)

ECU Memory Consumption:

- In 3 of 6 cases an eFMU is below the +25% KPI w.r.t. code memory.
- In 4 of 6 cases an eFMU is below the +25% KPI w.r.t. data memory.
- In **4 of 6** cases an eFMU **outperforms** the hand code.
- In average the best performing eFMU requires
  - 39% more code memory
  - **9% less data memory**

  than the hand code.





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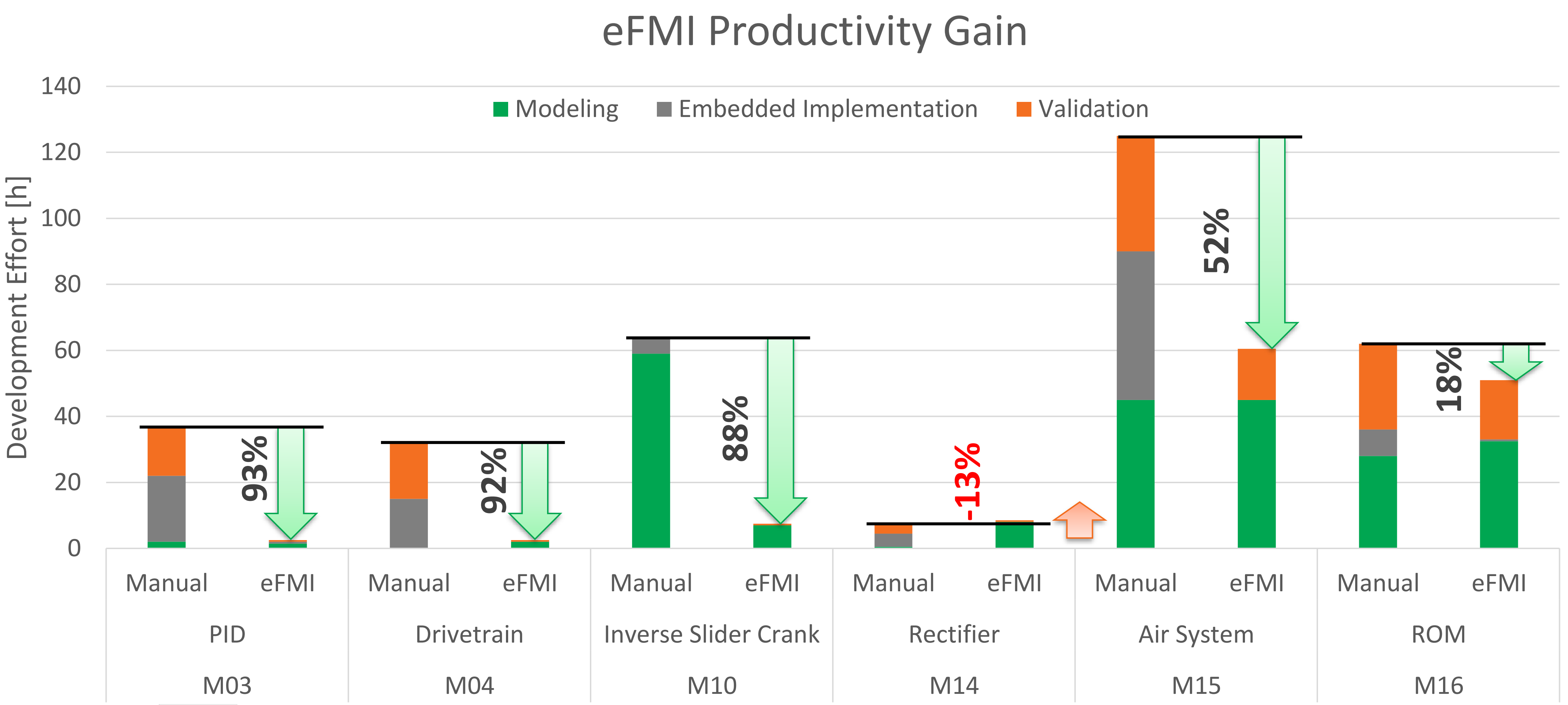
EMPHYSIS Demonstrators

D7.2 eFMI Performance Assessment (Bosch)



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EMPHYSIS Demonstrators
D7.2 eFMI Performance Assessment (Bosch)

Conclusion

- Applications with component-oriented models (M03, M04, M10) show
  - an eFMI development **productivity gain of ~90%**
  - with a **speed-up in runtime of ~40%**
  - and better or reasonable memory consumption.
- Textually implemented Modelica models (M14, M15, M16) show
  - an eFMI development **productivity gain of ~20%**
  - and allow to provide solutions that outperform the hand coded solutions also for difficult systems.
- The configuration of the code generators allows to chose the best trade-off between runtime performance and memory consumption for the application.

Better code, less effort!

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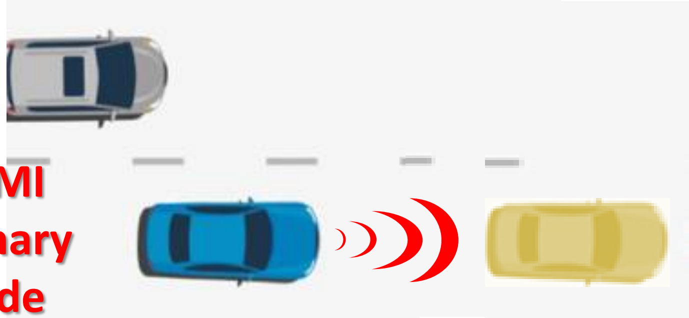
Key Achievements –
Comprehensive Industrial Demonstrators

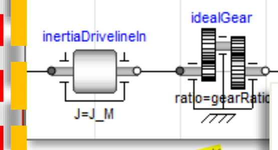
D7.14 Dassault Systèmes Demonstrator

Advanced Emergency Braking System controller



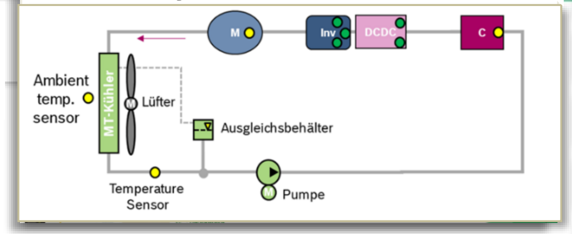
eFMI Binary Code

D7.3 Powertrain Vibration Reduction



eFMI DAE Eq. Code

D7.4 Model-based Diagnosis of Thermo System

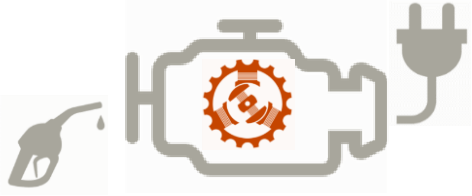


D7.2 eFMI Performance Assessment

#	Name	Difficulty*	Challenge
M03	PID	low	Minimal footprint incl. saturated IOs
M04	Drivetrain	medium	Inverse linear physical model
M15	Air System	medium	Stiff ODE with delay operator
M10	Inverse Slider Crank	high	Inverse non-linear physical model (DAE Index-1)
M16	ROM	high	High dimensional maps, solve a large linear eq system
M14	Rectifier	high	Advanced symbolic transformation to compact ODE form

D7.10 Siemens Dana Demonstrator

Hybrid engine torque prediction using scale model Neural Network



D7.12 DLR Demonstrator

Semic-active damping controller with nonlinear inverse model and nonlinear Kalman filter

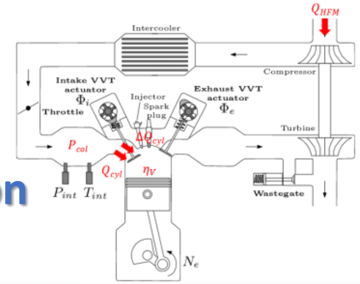
D7.07 GipsaLab

Vehicle dynamics control by Parameterized Nonlinear Model Predictive Control for semi-active control with Neural Network prediction model

D7.06 Renault Demonstrator

Step 1 : Identify AMESim model

Kalman Filter air filling estimation using scale model Neural Network predictor

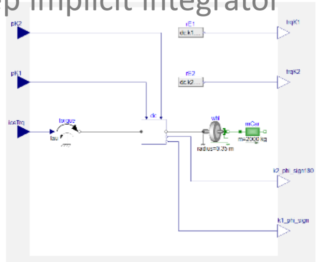


eFMI Prediction Model

D7.08 Daimler Demonstrator

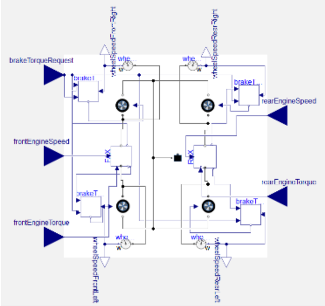
Dual-Clutch Transmission Diagnosis

Seamless production code build process with multiple step implicit integrator



D7.13 Volvo Demonstrator

Transmission model as virtual sensor



Demonstrators Presentations

D7.14 Dassault Systèmes
Advanced Emergency Braking System controller

D7.3 Powertrain Vibration Reduction
Powertrain Vibration Reduction

D7.4 Model-based Diagnosis of Thermo System
Model-based Diagnosis of Thermo System

D7.2 eFMI Performance Assessment
Six different use cases from simple PID control to complex physical ODE model

D7.10 Siemens Dana Demonstrator
Hybrid engine torque prediction using scale Neural Network model

D7.12 DLR
Semic-active damping controller with nonlinear inverse model and nonlinear Kalman filter

D7.07 GipsaLab
Vehicle dynamics pNMPC for semi-active control with Neural Network prediction model

D7.05 Renault
Kalman Filter TDC air filling estimation using scale Neural Network predictor model

D7.06 Renault
Throttle high frequency position estimation using scale NN predictor model

D7.08 Daimler
Dual-Clutch Transmission Diagnosis using multiple step implicit integrator

D7.13 Volvo
Transmission model as virtual sensor

EMPHYSIS Key Achievements
Summary

- eFMI Specification – Alpha version published
- Formal standardization process started via the Modelica Association
  - Expected to be released as a Modelica Association standard within 2-3 months
- Open-source Modelica library EMPHYSIS_TestCases to be released by end of Feb.
  - Facilitating qualified cross-checking of the toolchain
- 13 tools are currently supporting different parts of the eFMI standard
- eFMI Compliance Checker available to support further adoption of the standard
- Extensive test library with 22 test cases containing 43 variants
- Excellent performance results
- Comprehensive industrial demonstrators of varying eFMI application scenarios

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Synopsis

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Synopsis
Main Goals

- eFMI Standard
  - Exchange format from physical models to embedded software.

- eFMI Workflow → Tool Chain
  - eFMI supporting tools through all stages

The journey has just begun!

- eFMI Demonstrators
  - Mature prototypes close to product release.
  - Better than state of the art performance.
  - Proven benefits for model-based control applications.
  - New innovative solutions enabled by eFMI.
  - New products, services, collaborations after project end.

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