Functional Mock-up Interface for embedded systems

eFMI® scope and delimitation

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Agenda

1. Scope of eFMI®: GALEC as example of satisfying non-functional quality requirements
2. Delimitation in embedded software domain: eFMI® vs. FMI®, AUTOSAR, ASAM, …

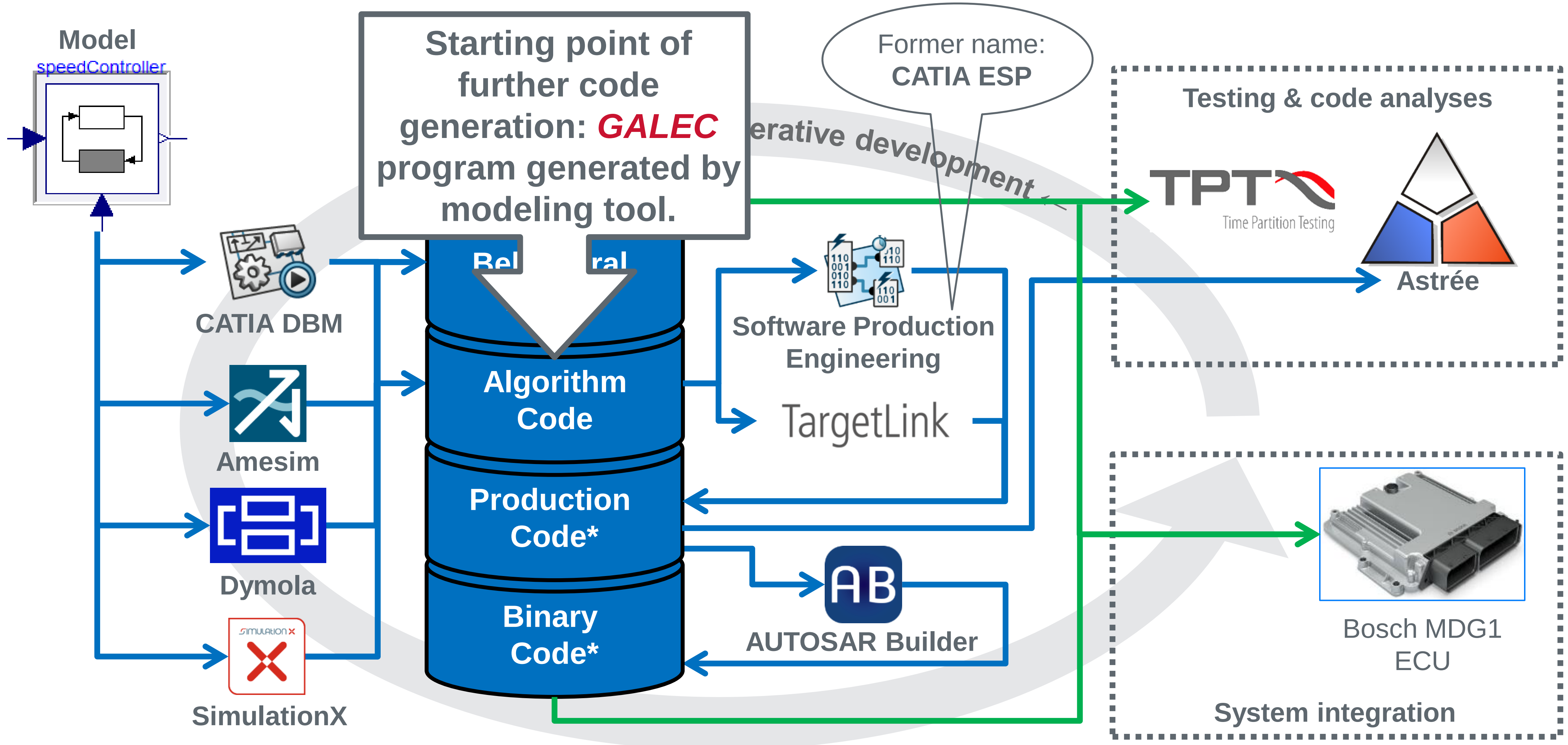
eFMI is all about:

How to *develop software satisfying non-functional requirements* besides just functional?

As an example, let us have a short look on eFMI GALEC.

(other examples would be eFMI Behavioral Models or inter-container linking for traceability)

eFMI Standard: Toolchain & workflow

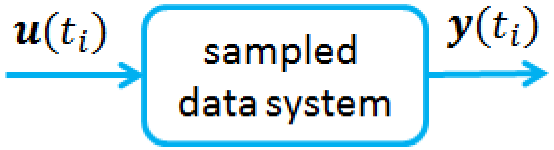


*several possible

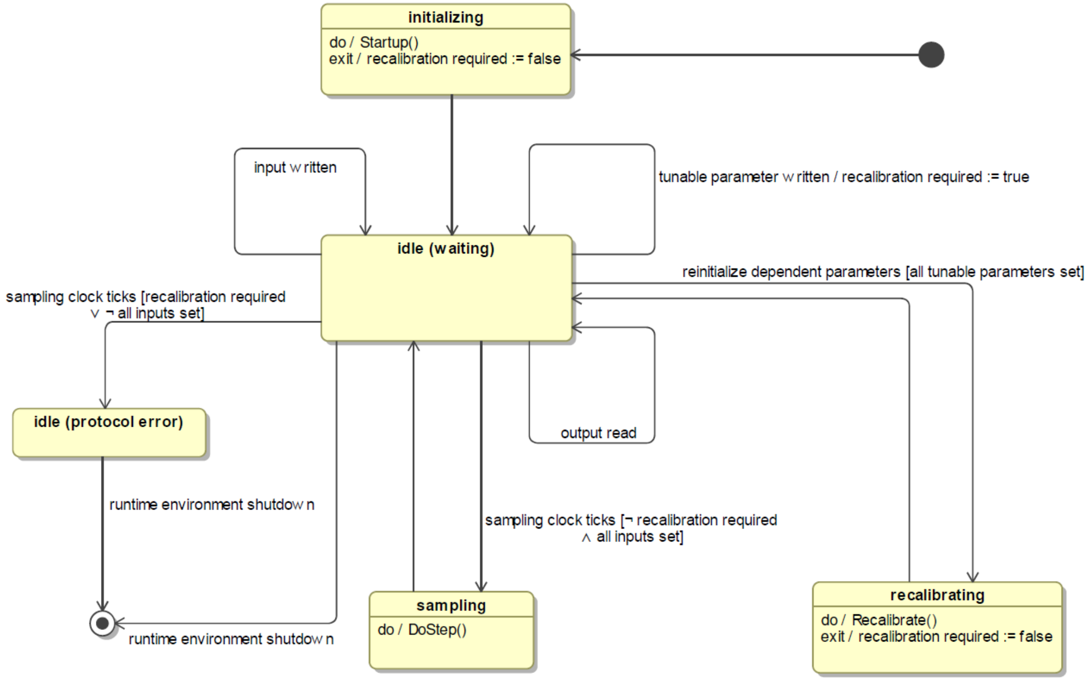
eFMI GALEC: Scope

GALEC (***G***uarded ***A***lgorithmic ***L***anguage for ***E***mbedded ***C***ontrol): Intermediate representation well-suited as code generation target for modelling tools & source for embedded-code generation

GALEC program: sampled algorithm with fixed sampling period.



$$x_{i+1} = f_x(x_i, u_i)$$
$$y_i = f_y(x_i, u_i)$$



Block life-cycle specifies usage via common interface:

- (default) initialization
- sampling
- recalibration
- reinitialization

⇒ Defines valid system integration scenarios.

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eFMI GALEC: Language characteristics

GALEC (***G***uarded ***A***lgorithmic ***L***anguage for ***E***mbedded ***C***ontrol): Intermediate representation well-suited as code generation target for modelling tools & source for embedded-code generation

- Imperative / causal language of high abstraction level (e.g., multi-dimensional real arithmetic, built-in mathematical functions like sinus, cosine, interpolation 1-3D, solve linear equation systems etc.)
- Safe – embedded & real-time suited – and well-defined semantics
  - Upper bound
  - Statically known sizes and safe indexing
  - Well-defined & never competing side effects
- Safe floating-point numerics
  - Guaranteed NaN propagation
  - Saturation of ranged variables
- Ordinary control-flow integrated, strict error handling concept
  - Guaranteed error signal propagation enables delayed error handling

⇒ Guards further eFMI tooling

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Imperative / causal language of high abstraction level:

- Target machine characteristics abstracted in:
  - Idealized types (Boolean, Integer & Real)
  - Builtin functions (e.g., construct & check NaN or ∞, convert Real ↔ Integer, extract fractional, rounding)

  ⇒ Idealized, but executable algorithms (math algorithms on computers)
- Builtin operators for multi-dimensional real arithmetic & builtin functions encapsulating common mathematical algorithms (e.g., interpolation 1-3D, solve linear equations)

  ⇒ Optimization for target environment at production code generation

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Imperative / causal language of high abstraction level:

- Well-defined onion-layered initialization:
  - Dependencies: constants ← tuneable parameters ← dependent parameters ← inputs ← states & outputs
  - Each has separate *algorithmic* initialization function

  ⇒ Safe, complex and optimizable initialization
- Simple block life cycle with support for input-dependent initialization, reinitialization & recalibration

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eFMI GALEC: Language characteristics

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Imperative / causal language of high abstraction level:

- Safety & simplicity first:
  - Only for-loops and if-elseif-else control-flow
  - Only Integer, no, int, short, unsigned, long long etc
  - No implicit type conversions
  - Unique way to write Real literals: X.X[e(+|-)X] (not 1e10, 1E+10, 1.0e10, .0)
  - Only LF line endings, only UTF-8 encoding (code ASCII, comments UTF-8)
  - …

eFMI GALEC: Language characteristics

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Safe – embedded & real-time suited – and well-defined semantics:

- Statically known sizes and safe indexing:
  - No pointer arithmetic
  - No memory-layout implications for multi-dimensionals (like vector elements must be consecutive memory)
    ⇒ Production code generators can rearrange (e.g., scalarize & decompose) multi-dimensionals
  - Clear separation of statically-evaluable and run-time expressions; same syntax, but different evaluation times
    ⇒ Complex indexing expressions including, e.g., function calls, supported
  - Dependent dimensionalities (e.g., input must be square matrix, vector twice length of 1st dimension of matrix)
- Upper bound:
  - No recursion, only statically known looping (over size-fixed multi-dimensionals)
    ⇒ GALEC programs can be unrolled to sequence of conditional assignments.

eFMI GALEC: Language characteristics

GALEC (***G****uarded* ***A****lgorithmic* ***L****anguage for* ***E****mbedded* ***C****ontrol*): Intermediate representation well-suited as code generation target for modelling tools & source for embedded-code generation.

Safe – embedded & real-time suited – and well-defined semantics:

- Well-defined & never competing side effects
  - Unique access to global state (`self.name`)
  - Clear separation of functions (no access to global state) vs. methods (access to global state)
  - Fixed evaluation order of function/method arguments (left-to-right)
  - No method calls in argument-expressions
  - No aliases, only call by value, inputs cannot be assigned

⇒ For every two GALEC statements, it is decidable if they can be switched (automatic parallelization).

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eFMI GALEC: Language characteristics

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Safe floating-point numerics & ordinary control-flow integrated, strict error handling concept :

- Errors must be either handled in ordinary if-statements or propagated
  - Operations that can cause NaN signal errors (e.g., relational operators like <, <=, >, >=)
  - Signaled errors can be checked at later if-statements
    ⇒ delayed error handling (not C style spaghetti code on machine flags after each and every operation)
- Builtin functions signal errors:
  - Every builtin function when undefined either, propagates NaN as result or signals NaN error
  - Predefined signals for singular or non-unique linear equation systems, size issues (convert Real ↔ Integer) etc

⇒ Errors are always recognized (nothing slips through).

⇒ Enables handling of *unforeseen* runtime errors, for example, using a backup controller, reset to previous state etc.

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eFMI GALEC: Summary

GALEC (***G****uarded* ***A****lgorithmic* ***L****anguage for* ***E****mbedded* ***C****ontrol*): Intermediate representation well-suited as code generation target for modelling tools & source for embedded-code generation

⇒ GALEC is by language design safe and guards further eFMI tooling.

- Not an (operating) system level programming language
  (that needs to be tamed by plethora of further anlyses tooling; pun on C & Co. intended)
- Production code tooling can optimize code – thanks to GALEC guarantees – by lowering abstraction
  (which need no artificial taming, but can be if required, e.g., MISRA C:2012 compliance)

⇒ Simple language with well-defined semantic, well-suited for expressing and long term archiving algorithmic solutions of physics models.

⇒ A language for safety-critical and real-time suited (control-)algorithms.

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Scope of eFMI in embedded software domain

An eFMU is about the *development* of *one* software component (controller, virtual sensor etc) of a complex cyber-physical system:

- Not about system integration of components
  - Many other standards in different industries available (e.g., AUTOSAR, ASAM etc)

  ⇒ Use established standards for eFMU system-integration
- Not about system level programming (embedded OS, drivers, software frameworks etc)

  ⇒ Production Code generators tailor code for given target environment
- Not about distributing, interconnecting and parameterizing system simulations
  - That is what FMI, DCP & SSP are for

  ⇒ Use FMI & co. ecosystem to distribute and setup (desktop environment) system simulations…
  …by exporting your production code as FMU

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eFMI vs. FMI: Two complementary standards

FMI: Standardized C interface to enable exchange and interoperability of simulations

- About how to distribute and integrate simulations
- Single abstraction level, 1 ↔ 1 (producer to consumer)
- Focus on interface of black-box implemented functionality

eFMI: Standardized development workspace to implement models in embedded environments

- About how to step-wise develop simulations from high-level model to low-level code
- Chain of abstraction levels, N ↔ M ↔ … ↔ L
  (many development stakeholders with different tools and viewpoints)
- Focus to guarantee non-functional requirements (safety-critical & real-time) besides functional

⇒ We can develop functionality with eFMI and distribute it with FMI

⇒ Two complementary standards

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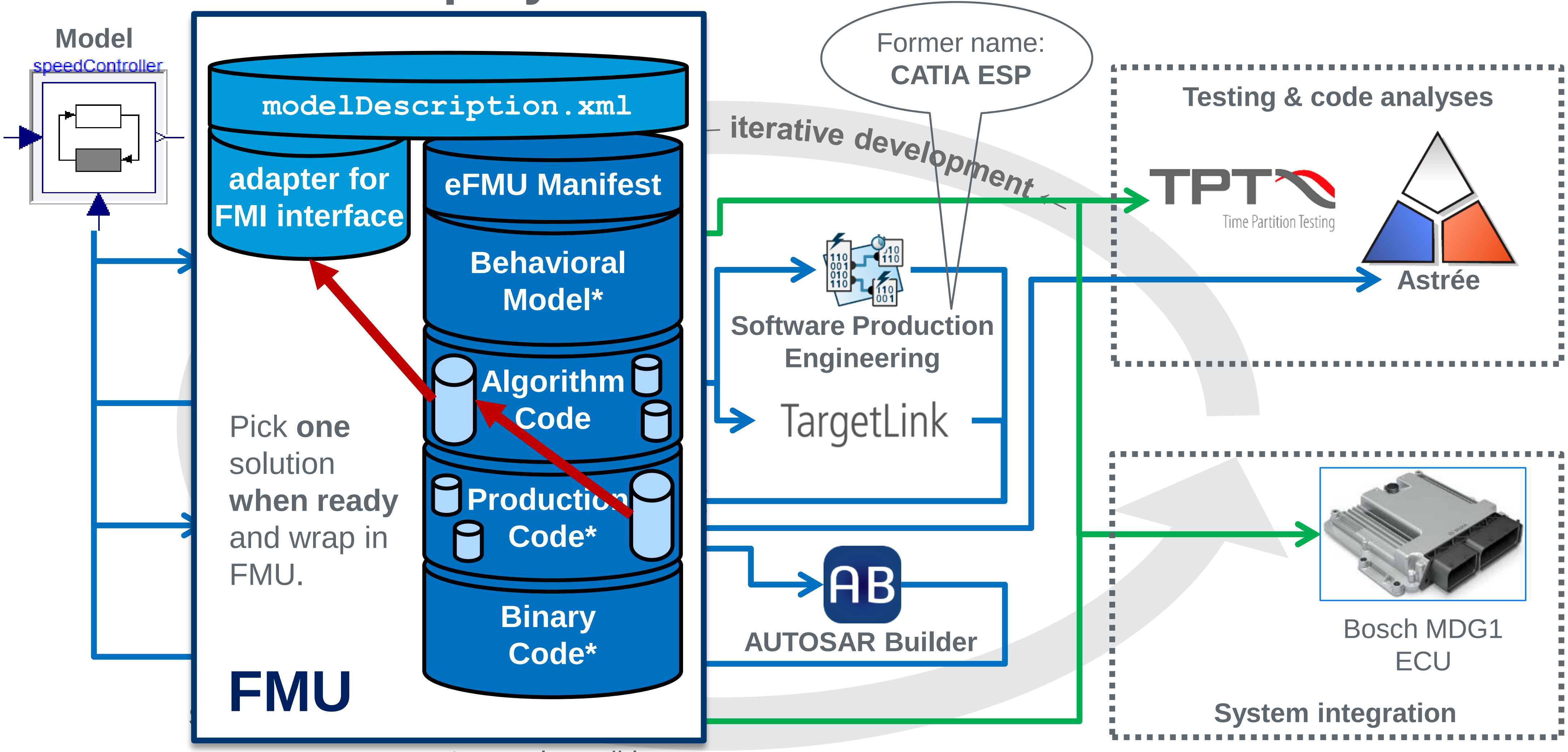
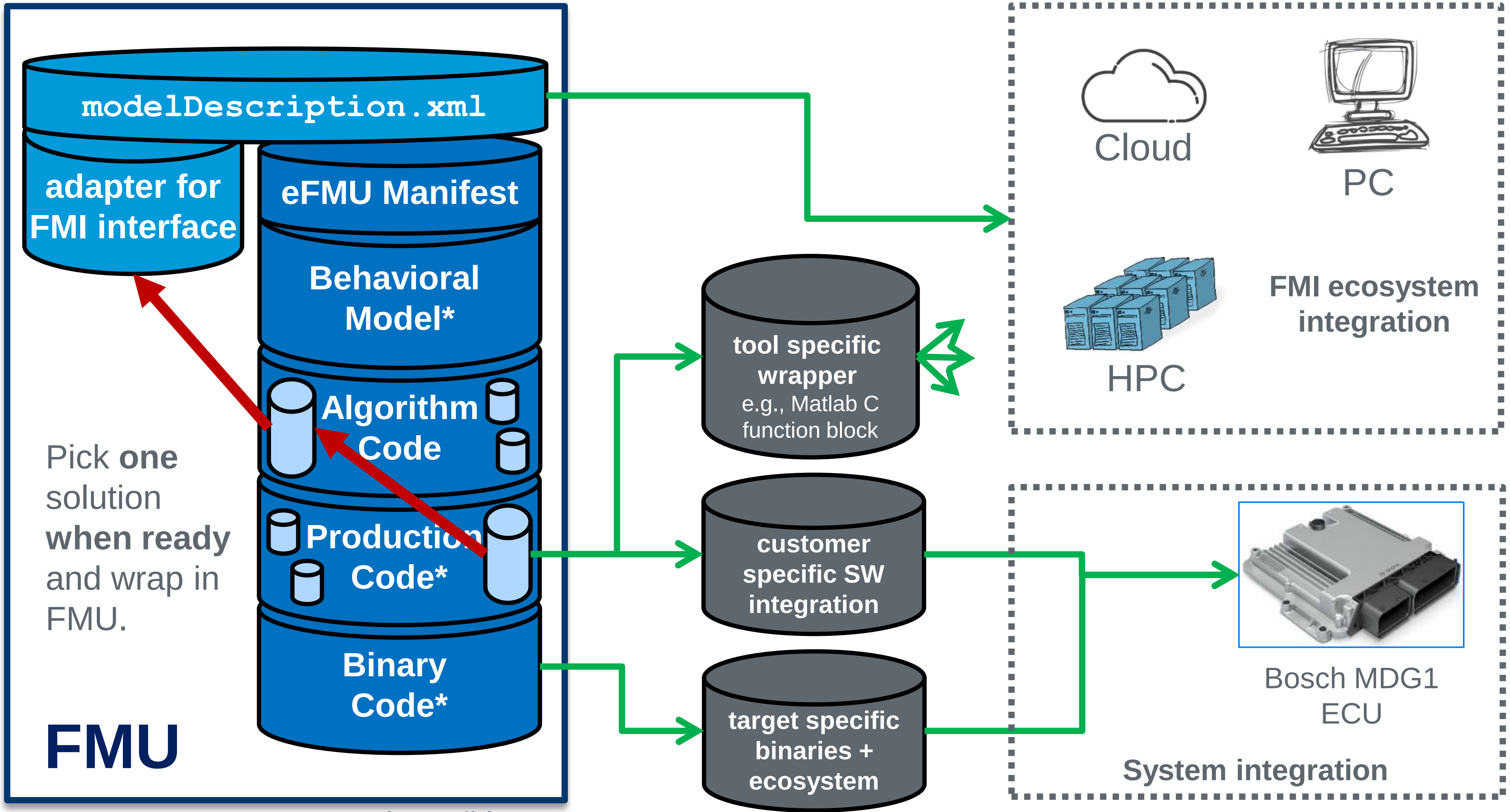
eFMI Standard: Deployment scenarios



*several possible

eFMI Standard: Deployment scenarios

Use existing standards / ecosystems for system integration (**not defined by eFMI**).



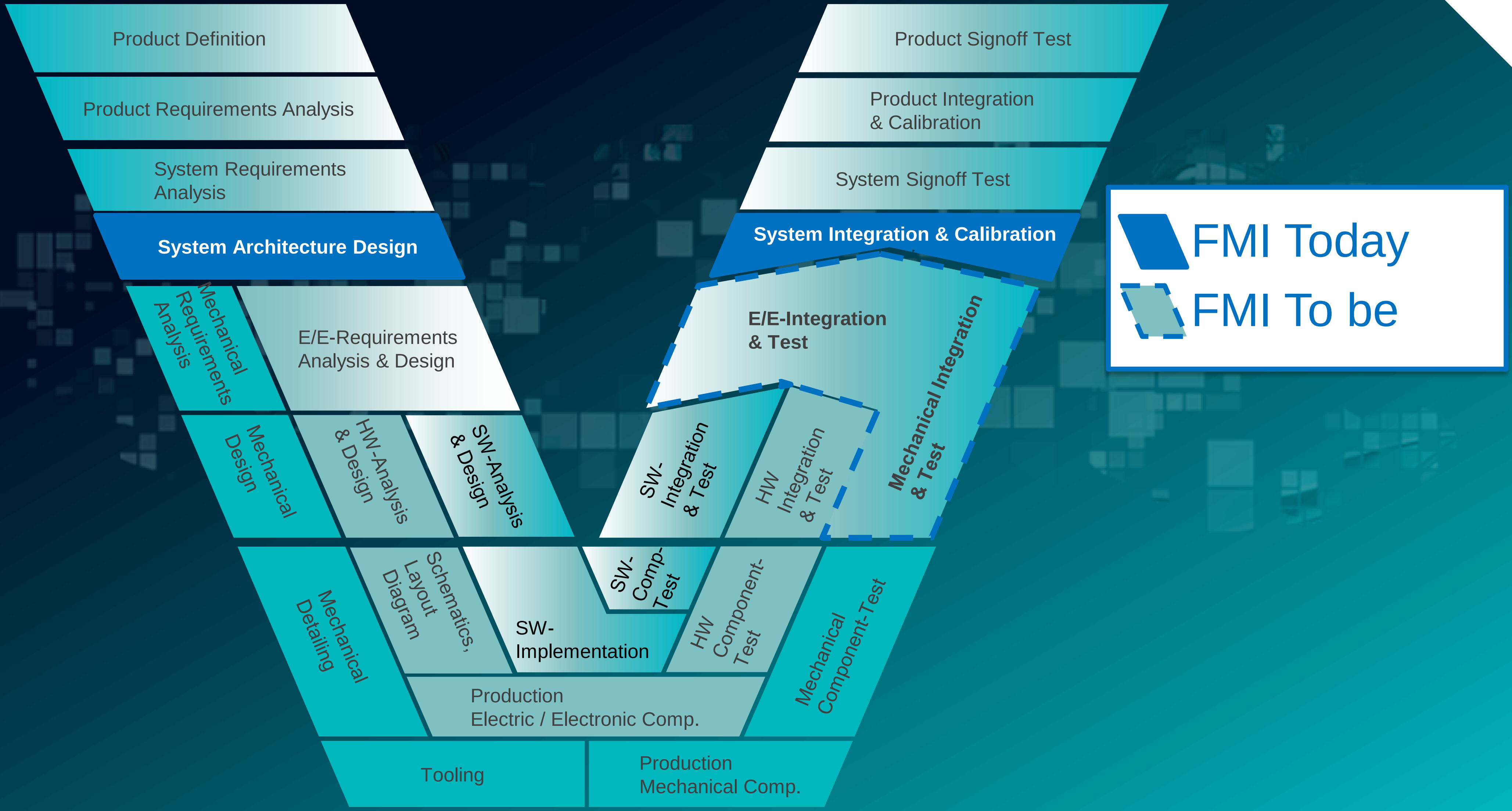
*several possible

Classification of eFMI w.r.t. ProSTEP V-Model & V-ECUs

ProSTEP provides two interesting ”towards embedded software” recommendations:

- ProSTEP V-Model
  - Software development process model
  - Suited to position to which development processes eFMI contributes and helps with
- ProSTEP Smart Systems Engineering (SSE) group envisioned V-ECU levels
  - Grades of ECU support (from high-level controller-model to deployment on ECU)
  - Suited to position eFMUs and their supported containers

eFMI w.r.t. ProSTEP V-Model

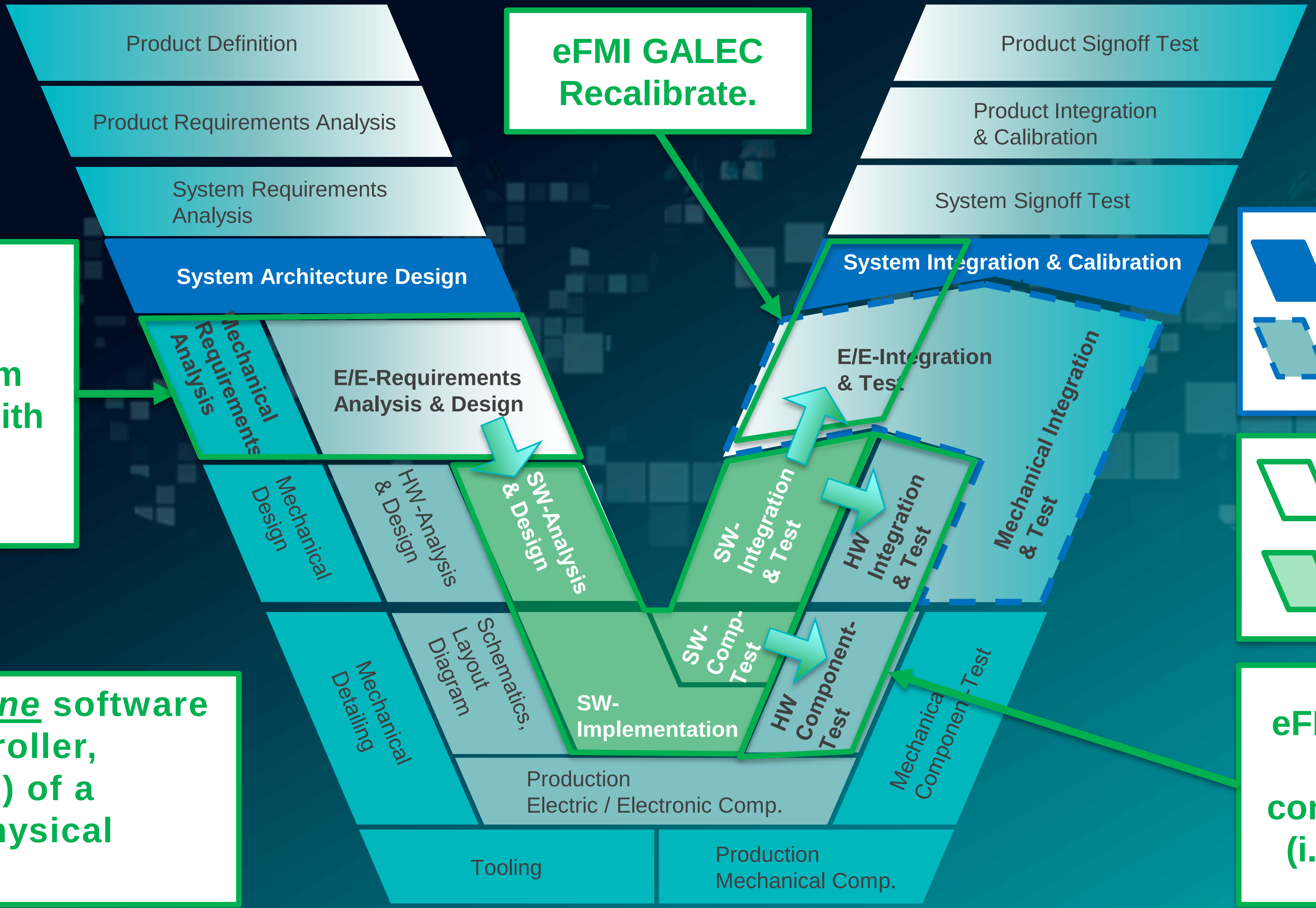


prostep IVIP

eFMI w.r.t. ProSTEP V-Model

eFMI GALEC Recalibrate.

In simulation environment (eg. whole system Modelica model with controller(s) & plant(s)).



FMI Today

FMI To be

eFMI helps

eFMU

eFMI Behavioral Model & Binary Code containers can be used (i.e, functional tests).

Scale of eFMU: *One* software component (controller, virtual sensor etc) of a complex cyber-physical system.

eFMI w.r.t. ProSTEP V-ECUs

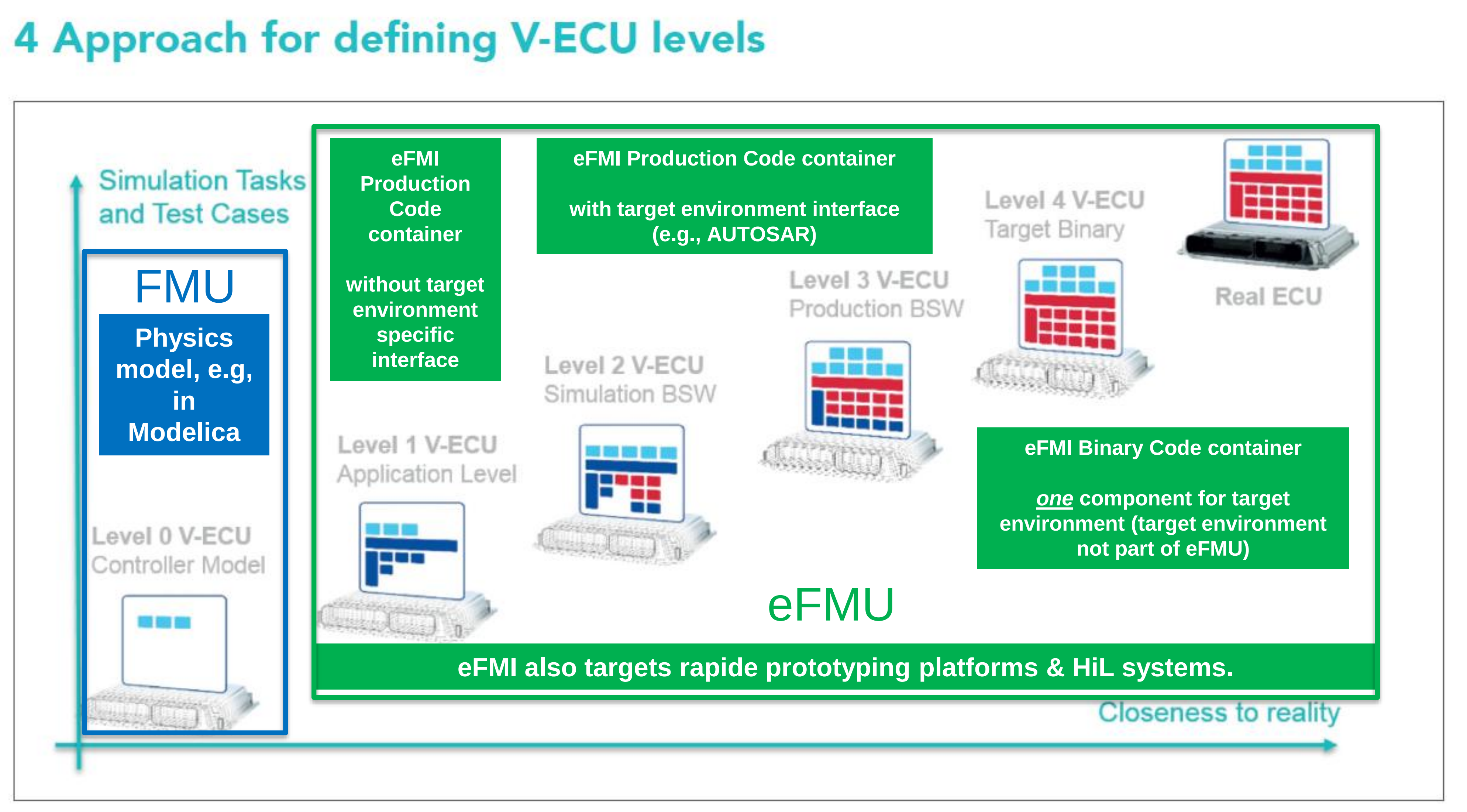


Figure 8 Proposed V-ECU levels

Source: ProSTEP - White Paper - SmartSE - Virtual Electronic Control Units (released 3/2020)

Modelica Association Project eFMI (MAP eFMI)

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Modelon

https://efmi-standard.org/