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eFMI® Tutorial – Agenda

Part 1: eFMI® motivation and overview (40 min)

Part 2: Running use-case introduction (10 min)

Part 3: Hands-on demonstration in Dymola and CATIA ESP (25 min)

Coffee break (30 min)

Part 3: Hands-on demonstration in Dymola and CATIA ESP (35 min)

Part 4: Live demonstration in TargetLink (30 min)

Part 5: Short presentation of further tooling (5 min)

Part 6: Conclusion (5 min)

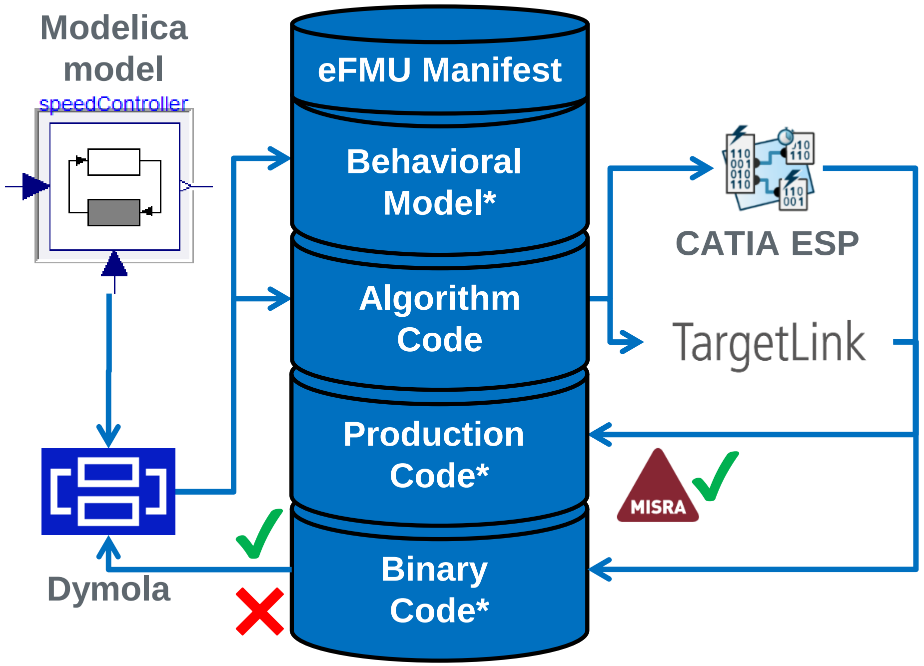
Tutorial leader:
Christoff Bürger

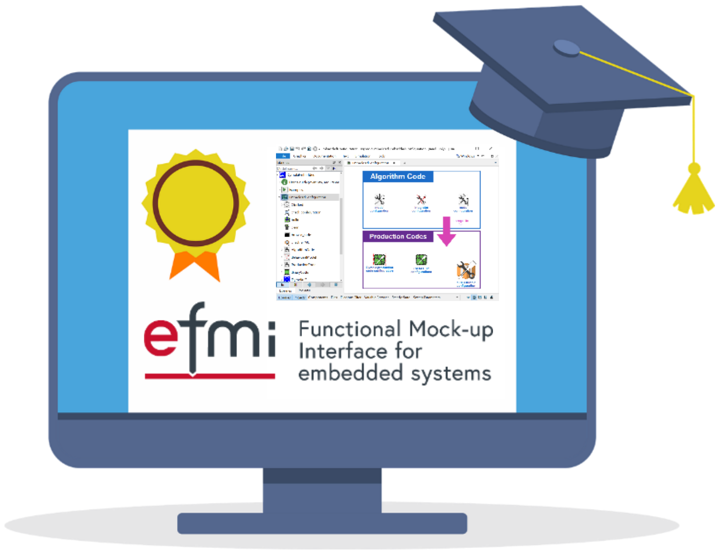
Presenter:
Oliver Lenord

Invented for life

Presenter:
Jörg Niere

Functional Mock-up Interface for embedded systems





Part 3: Hands-on demonstration in Dymola and CATIA ESP

eFMI® Tutorial – 15th International Modelica Conference – 9th of October 2023

Christoff Bürger
Dassault Systèmes
Christoff.Buerger@3ds.com

This handout provides a step-by-step guide how to generate and software-in-the-loop (SiL) test an eFMU in Dymola.

Tutorial requirements:

- Own computer with Windows 10 or 11, 64-Bit, x86

You – i.e., every tutorial participant – should have gotten a software bundle with:

- This documentation (`eFMI-Tutorial-Part-3.pdf` in root directory)
- Preinstalled Dymola 2024x Beta 4 (`/Dymola`)
- Preinstalled CATIA ESP prototype (included in Dymola)
- Workdirectory where eFMUs will be generated and simulation artefacts stored (`/work-directory`)
- Modelica models we actually want to develop; for your reference if something goes wrong (`/reference-models`)
- eFMUs we actually want to build; for your reference if something goes wrong (`/reference-eFMUs`)
- Portable Microsoft Visual C++ and Microsoft Windows SDK required by Dymola (`/portable-MSVC`)
- Portable Java required by CATIA ESP prototype (`/portable-Java`)
- Portable Cppcheck (`/portable-Cppcheck`) and Python (`/portable-Python`) required for MISRA C:2012 compliance checks of production code
- Licenses of provided software (`/licenses`)

Functional Mock-up Interface for embedded systems

DISCLAIMER

The *Microsoft Visual C++* and *Microsoft Windows SDK* provided in the `/portable-MSVC` directory are subject to licensing of *Microsoft*.

The *Java Development Kit* (*OpenJDK*) provided in the `/portable-Java` directory is subject to licensing of the *Free Software Foundation, Inc*.

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The *Cppcheck* provided in the `/portable-Cppcheck` directory is subject to licensing of *Cppcheck Solutions AB*.

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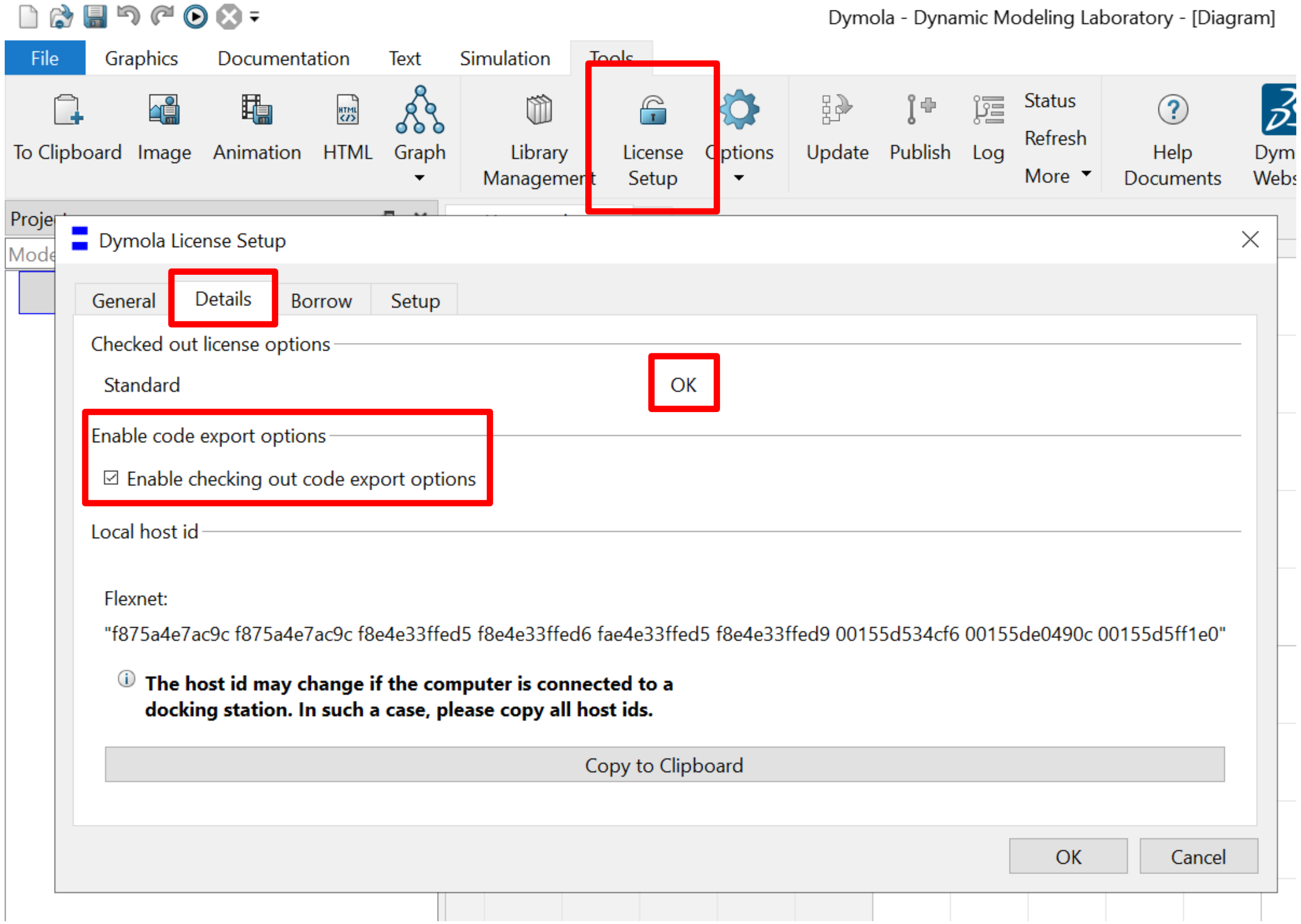
Functional Mock-up Interface for embedded systems

Before getting started, please make sure you can use the provided Dymola:

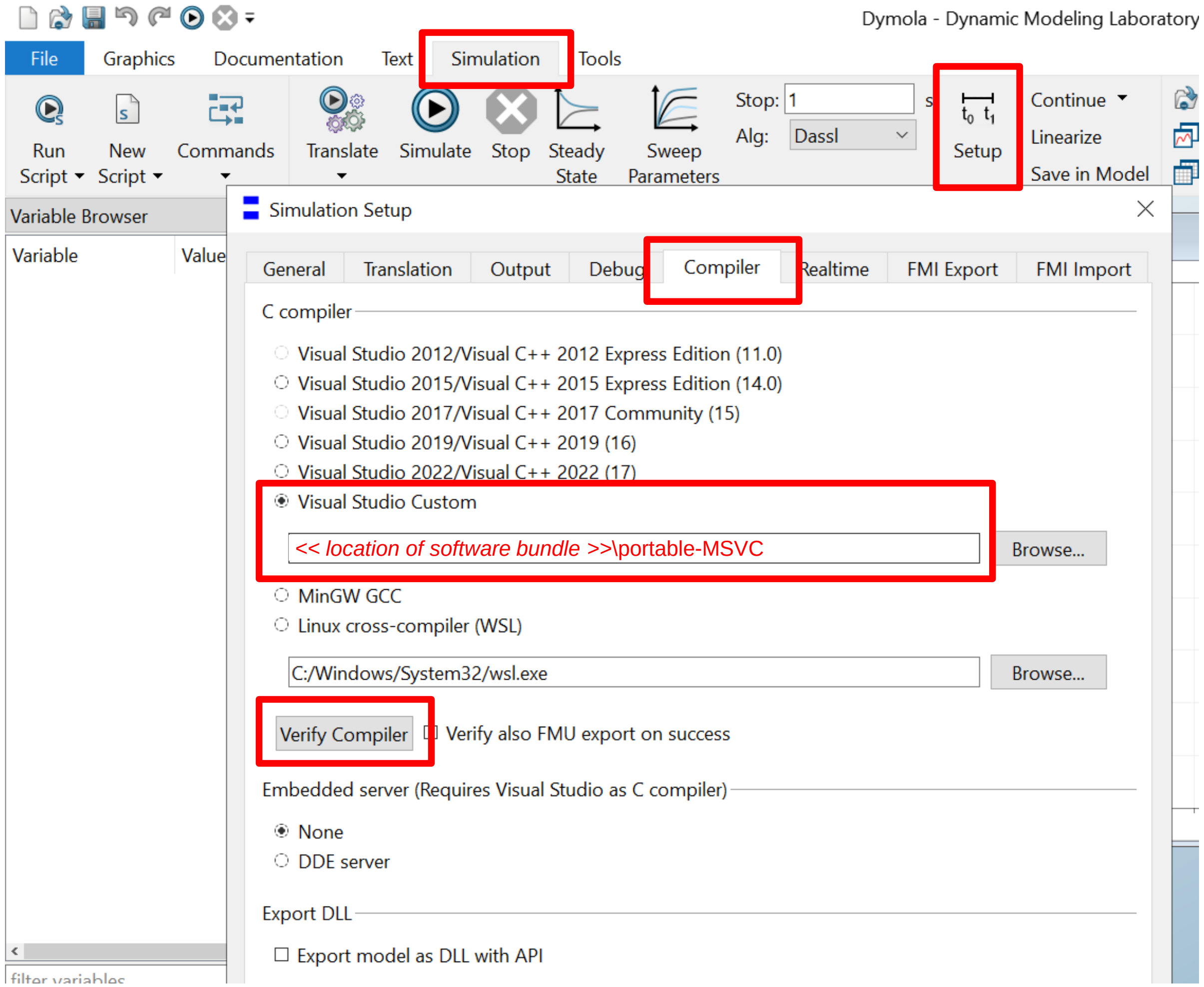


Execute `/Dymola/start-Dymola.bat` and check your license:

1. *Tools* ribbon
2. *License Setup*
3. *Details*
4. Code export is checked (*"Dymola Source Code Generation License"*)

Functional Mock-up Interface for embedded systems

Before getting started, please make sure you can use the provided Dymola:



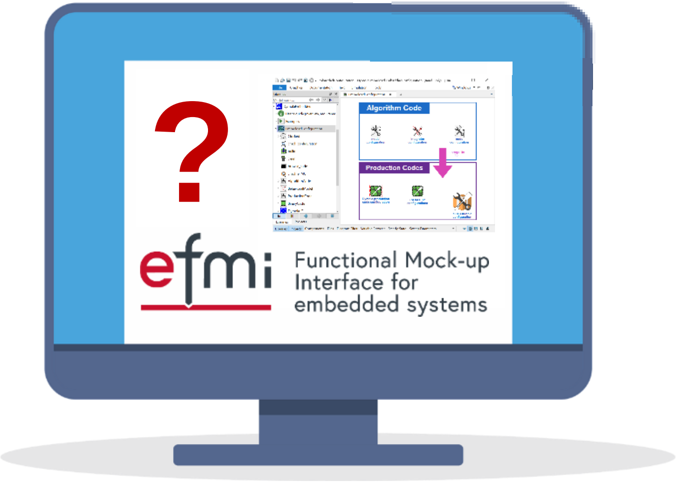
Check compilers are available for simulation:

1. *Simulation* ribbon
2. *Setup* button
3. *Compiler* tab
4. *Verify Compiler* button

You can also pick any of the default Microsoft Visual Studio versions if you have a local installation.

If not, please use the provided portable, on custom path `<< location of software bundle >> /portable-MSVC/`

Functional Mock-up Interface for embedded systems

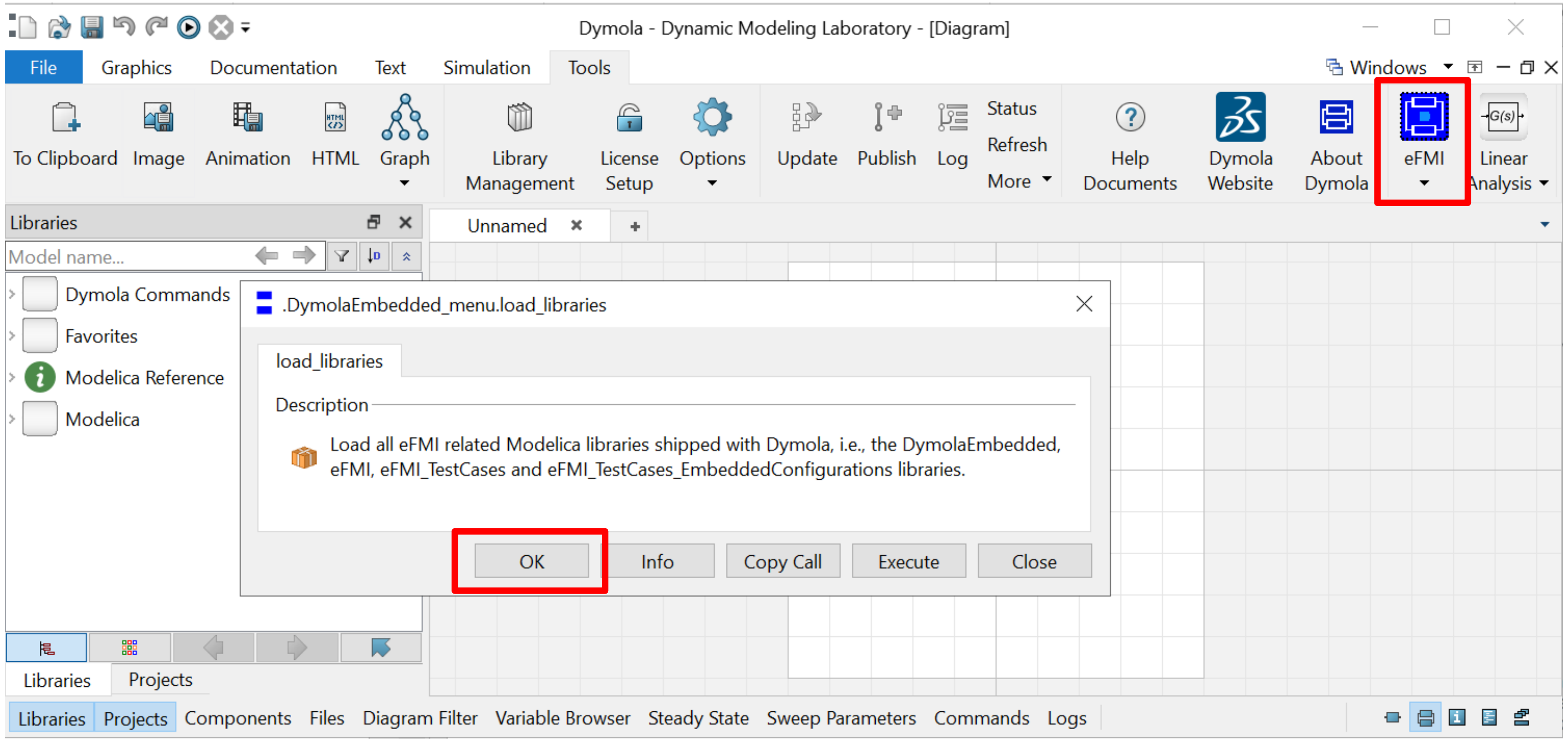


Ok, lets get started!

efmi Functional Mock-up Interface for embedded systems

The user interface for eFMI support in Dymola is provided by means of a Modelica library: `DymolaEmbedded`

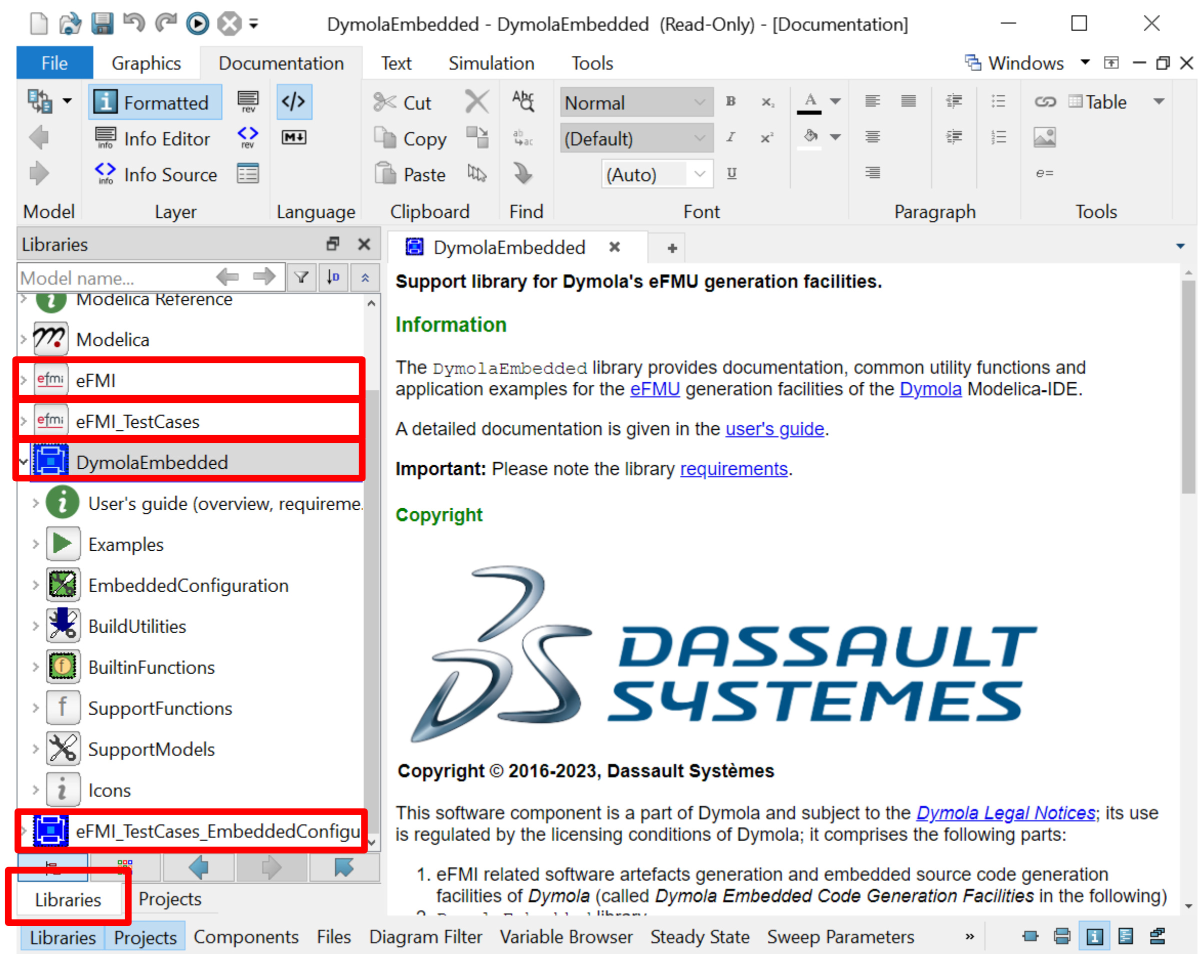
Load `DymolaEmbedded` via the *eFMI* button in the *Tools* ribbon → *Load Libraries…* → *OK*:



Other menu entries permit to build or delete eFMUs for whole package hierarchies and load their co-simulation stubs (this convenience use-cases will become clear throughout the tutorial).

Functional Mock-up Interface for embedded systems

The following libraries are loaded:



`eFMI`:

- Support library to ease adaptation of existing Modelica models for eFMI (mostly about MSL → eFMI table adapters)
- Public domain, © MA, MAP eFMI

`eFMI_TestCases`:

- eFMI application examples used for official cross-checks of eFMI tooling; Modelica tooling agnostic
- Public domain, © MA, MAP eFMI
- Contains our running use-case, M04

`DymolaEmbedded`:

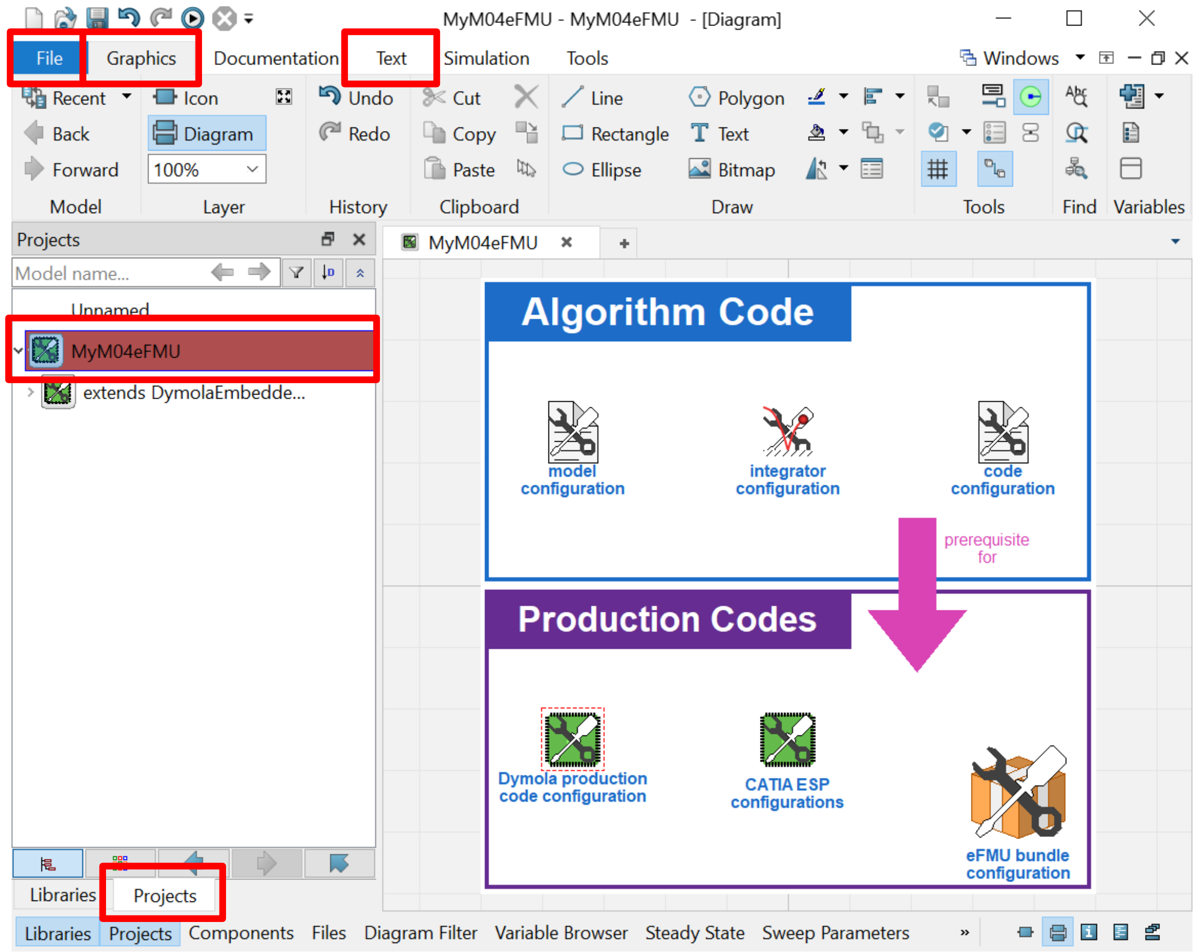
- Interface for Dymola's eFMI facilities
- Provides means to configure eFMU generation & generate various eFMI containers

`eFMI_TestCases_EmbeddedConfigurations`:

- eFMU generation configurations for `eFMI_TestCases`
- Already contains a configuration for M04 (we will develop from scratch in the following)

efmi Functional Mock-up Interface for embedded systems

Create a new eFMU generation configuration for the M04 controller:



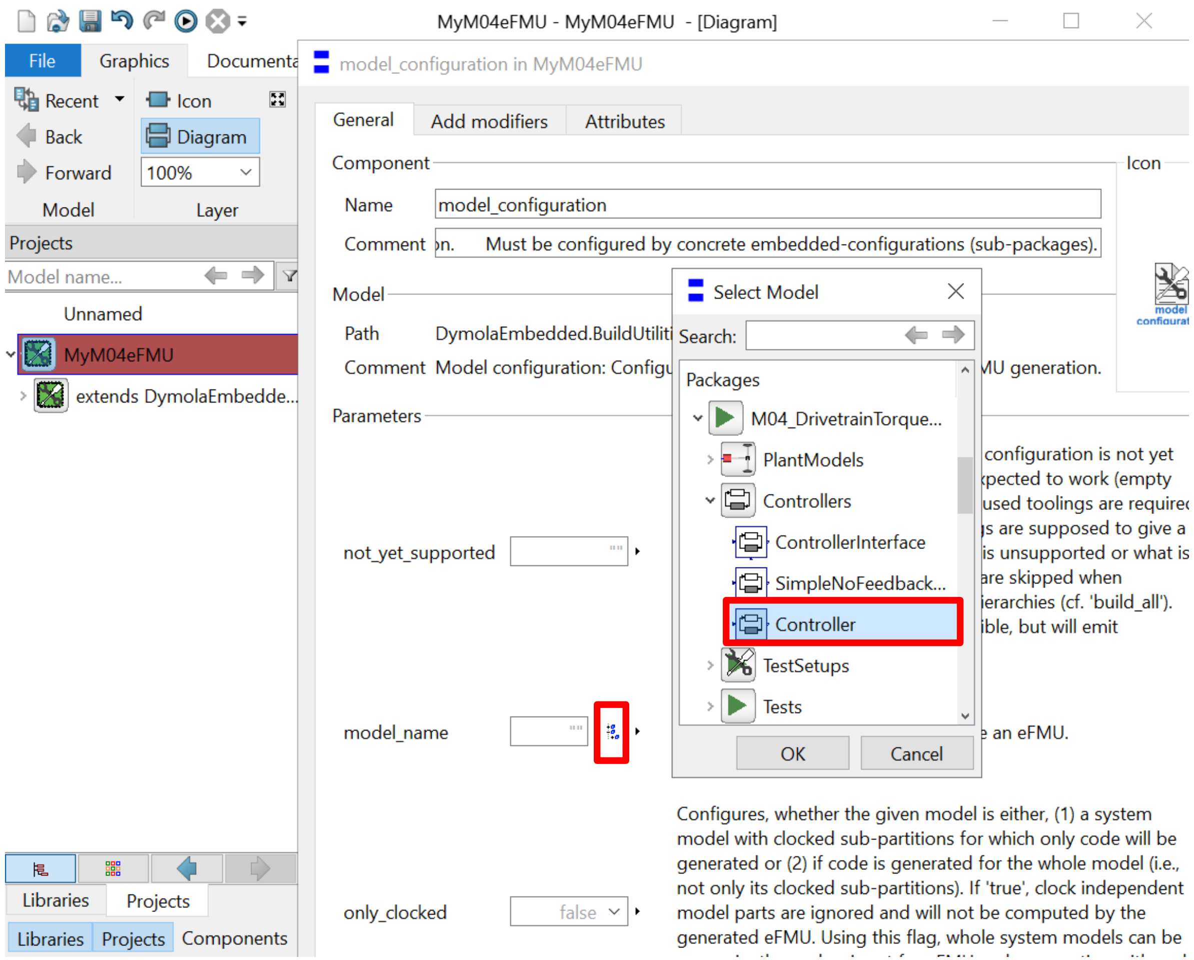
Create package extending `EmbeddedConfiguration`:

1. *File* → *New* → *Package*, Name: `MyM04eFMU`
2. New package visible in *Package Browser* & *Projects* (not *Libraries*)
3. Double click `MyM04eFMU`; switch to *Text* ribbon
4. Add **`extends`** `.DymolaEmbedded.EmbeddedConfiguration;`
5. Switch to *Graphics* ribbon

Dymola and CATIA ESP eFMU code generation can be configured from the diagram layer of `MyM04eFMU`.; it is an eFMU generation configuration.

Functional Mock-up Interface for embedded systems

Create a new eFMU generation configuration for the M04 controller:

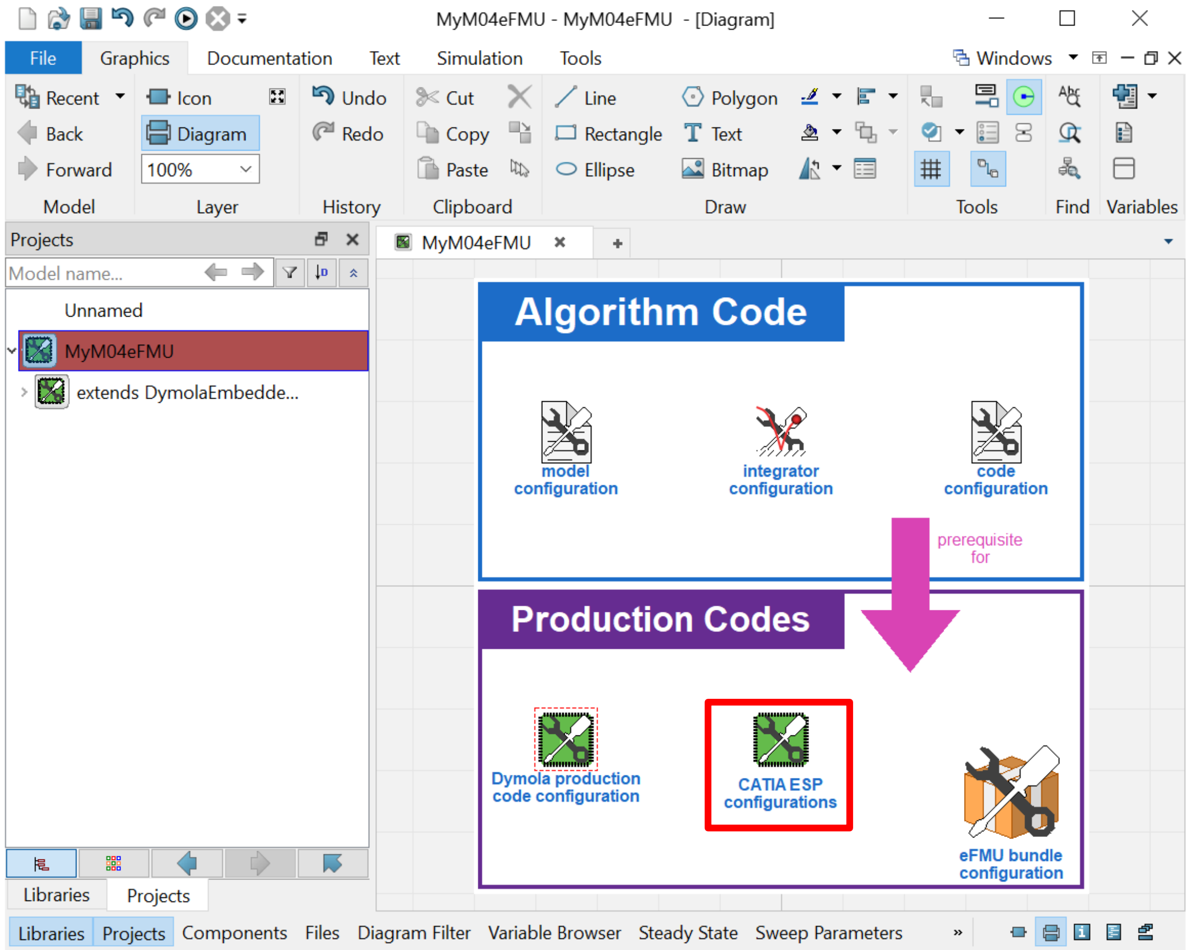


Configure Dymola's GALEC code generation:

1. Double click *model configuration*
   → *model_name*
   → *Edit* (package tree icon)
   → select `eFMI_TestCases .M04_DrivetrainTorqueControl .Controllers.Controller`
   → *OK*
   → *OK*
2. Double click *code configuration*
   → *obfuscate*: `None`
   → *OK*
3. Double click *integrator configuration*
   → *sample_period*: `5e-4`
   → *solver_method*: `Explicit Euler`
   → *OK*

efmi Functional Mock-up Interface for embedded systems

Create a new eFMU generation configuration for the M04 controller:



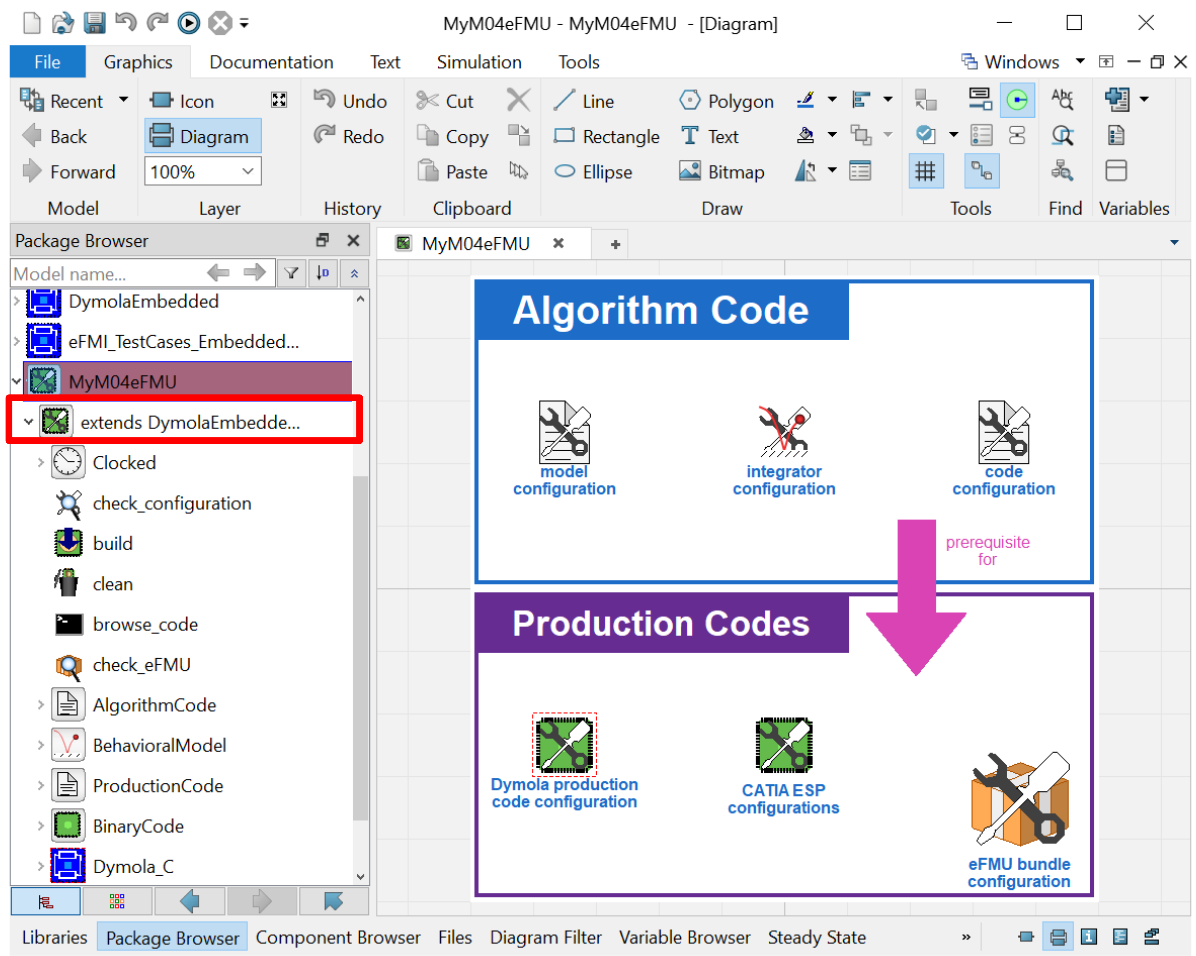
CATIA ESP is already default configured:

- 32-Bit and 64-Bit floating-point precision production codes
- 32-Bit and 64-Bit x86 ISA binary codes (self-contained static linked libraries)

⇒ 2 Production Code & 4 Binary Code containers

Functional Mock-up Interface for embedded systems

Investigate the eFMU generation configuration `MyM04eFMU` for the M04 controller:

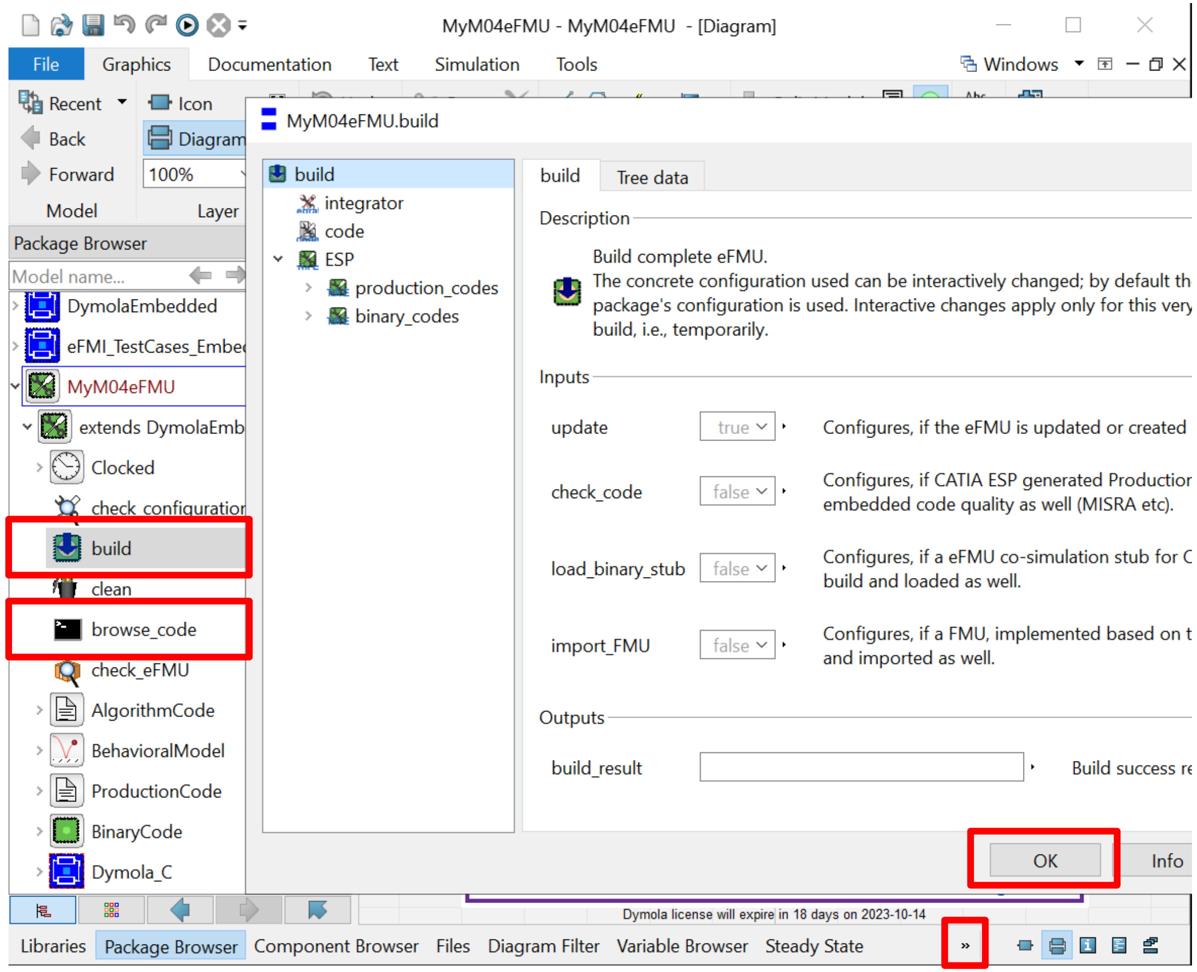


All eFMU build activities are inherited from `DymolaEmbedded.EmbeddedConfiguration`:

- Available via the *extends* entry in the *Package Browser* & *Libraries* / *Projects* view (depending if configuration is write protected or not)
- Preconfigured with eFMU generation configuration
- Activities grouped according to eFMI container type:
  - **Algorithm Code:** Generate GALEC code
  - **Behavioral Model:** Derive experiment packages to configure test scenarios & tolerances; use experiment packages to generate respective Behavioral Models
  - **Production Code:** Generate & MISRA C:2012 check CATIA ESP code
  - **Binary Code:** Generate CATIA ESP binaries & Modelica proxies for co-simulating such; export FMU

Functional Mock-up Interface for embedded systems

Generate the eFMU configured in `MyM04eFMU` for the M04 controller:



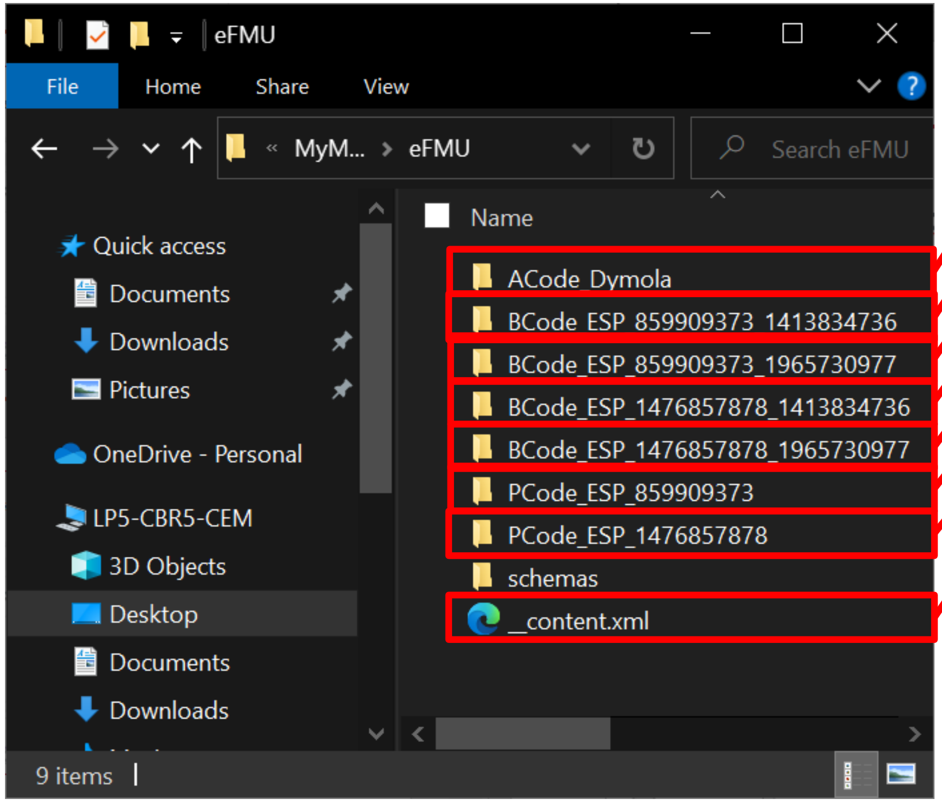
Build the eFMU with Algorithm Code, 2x Production Code and 4x Binary Code containers:

1. Right click `MyM04eFMU.build` in the *Package Browser / Projects* view
   → *Call Function…*
   → *OK*
2. You can check the build log in the *Commands* window

Browse the generated eFMU:

1. Right click `MyM04eFMU.browse_code` in the *Package Browser / Projects* view
   → *Call Function…*
   → *OK*

Investigate the generated eFMU (`MyM04eFMU/eFMU`):



Contained containers:

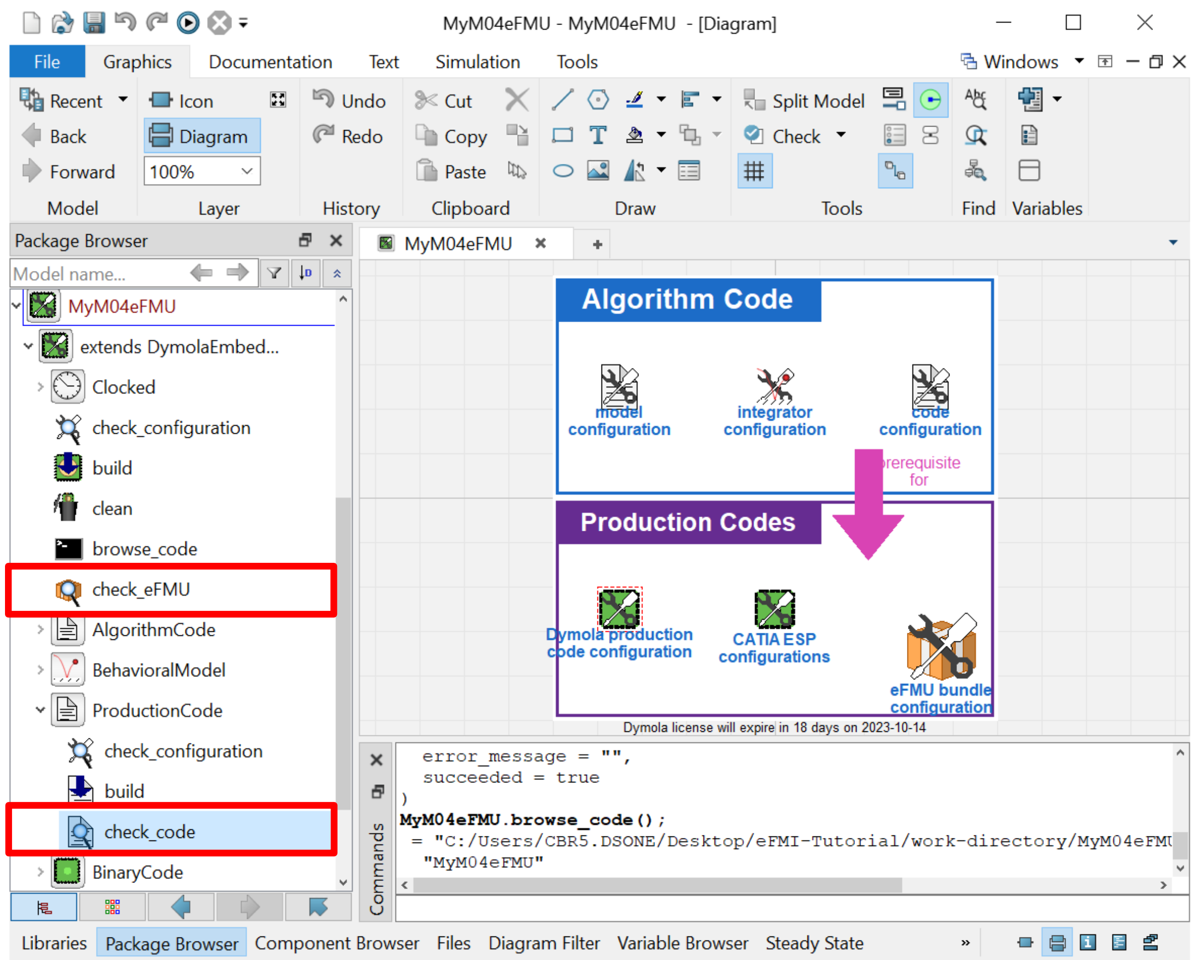
- **Algorithm Code** with GALEC code
- x64, 64-Bit floating-point precision **Binary Code**
- x86, 64-Bit floating-point precision **Binary Code**
- x64, 32-Bit floating-point precision **Binary Code**
- x86, 32-Bit floating-point precision **Binary Code**
- 64-Bit floating-point precision **Production Code**
- 32-Bit floating-point precision **Production Code**
- **Content manifest** listing all containers

Take some time to investigate the eFMU, e.g.:

- How cross references between manifests work
- Quality of generated GALEC code (self-contained / inlined, error handling of symbolic optimized linear equation systems, local vs. global variables etc)
- …

efmi Functional Mock-up Interface for embedded systems

Check the eFMU and its production codes:



Check MISRA C:2012 compliance of all production codes via Cppcheck:

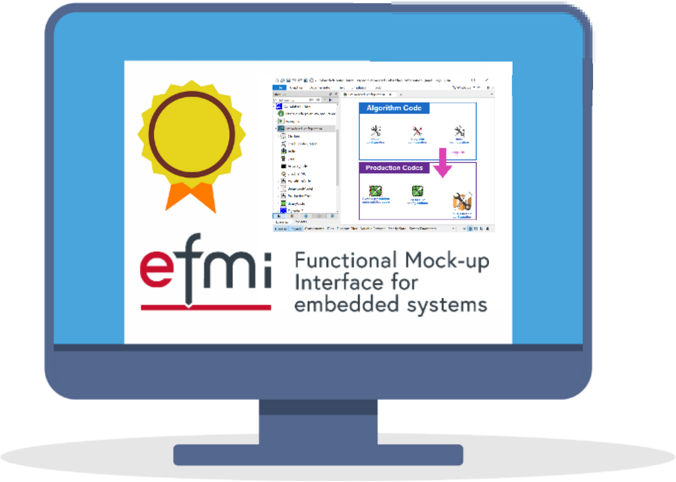
1. Right click `MyM04eFMU.ProductionCode.check_code` in *Package Browser / Projects* view
   → *Call Function…*
   → *OK*
2. Analyses reports for each production code are provided in your webbrowser (note, that `block.c`, the actual production code, satisfies MISRA)

Check eFMU with *eFMI Container Manager* and *eFMI Compliance Checker* (MAP eFMI released tools):

1. Right click `MyM04eFMU.check_eFMU` in the *Package Browser / Projects* view
   → *Call Function…*
   → *OK*

Functional Mock-up Interface for embedded systems

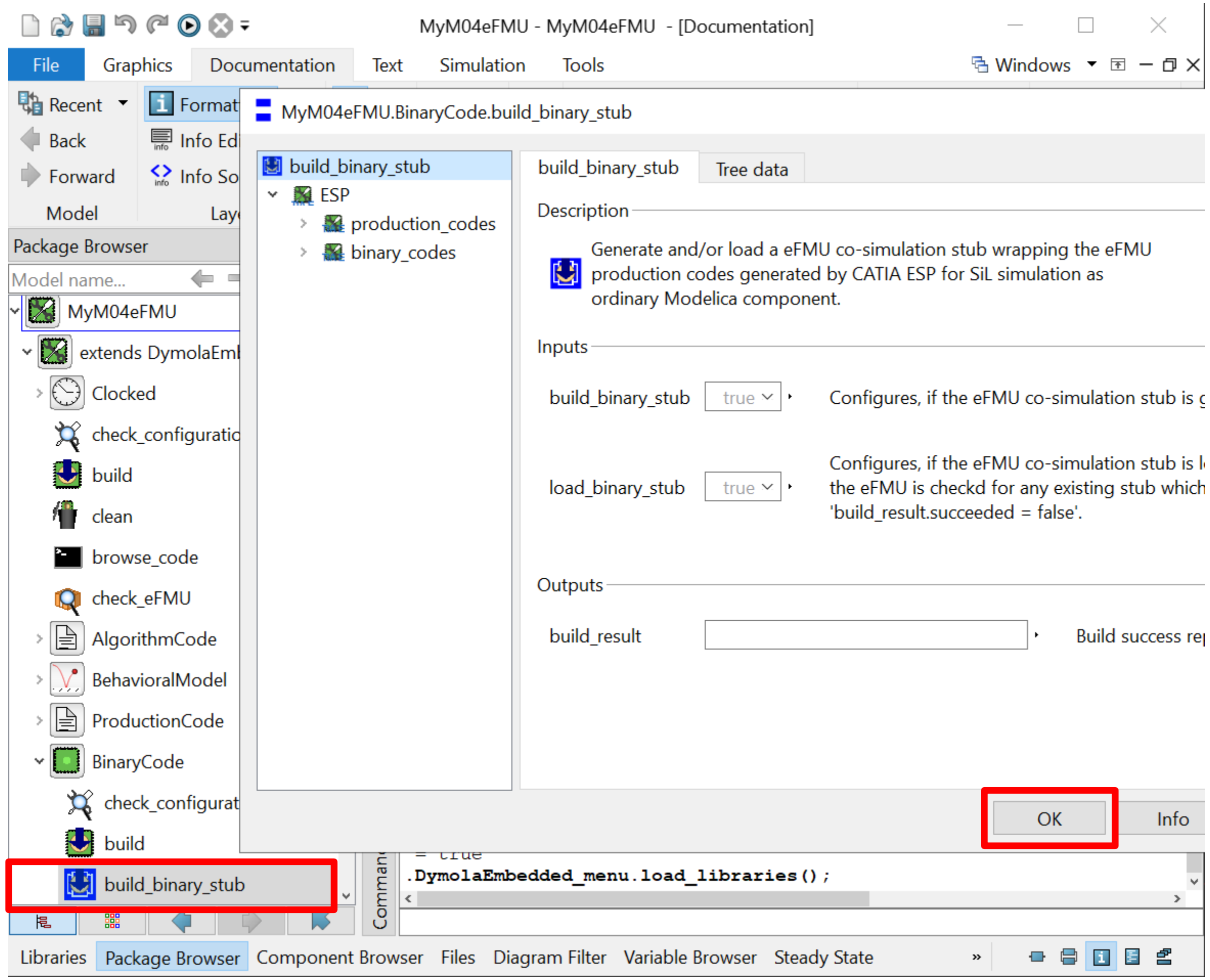
Congratulations, you are halfway through!



eFMU generation done.

Let’s go on to Behavioral Models & software-in-the-loop (SiL) simulation.

Generate eFMU co-simulation stub:

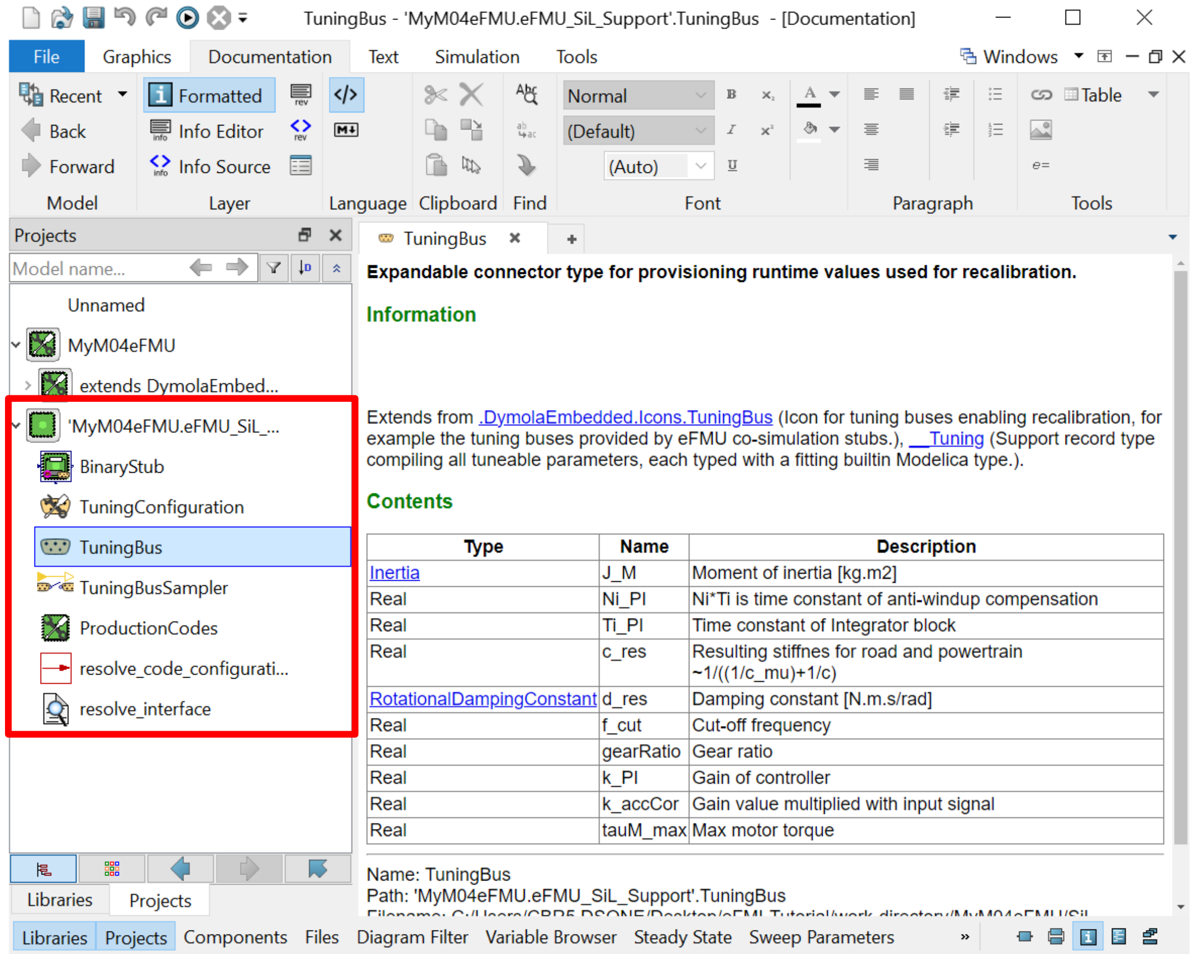


1. Right click `MyM04eFMU.BinaryCode.build_binary_stub` in *Package Browser / Projects* view → *Call Function…* → *OK*

A new package `'MyM04eFMU.eFMU_SiL_Support'` is generated. Its `BinaryStub` model is a Modelica proxy to the static linked libraries – and therefore production codes – generated by CATIA ESP.

Functional Mock-up Interface for embedded systems

Investigate generated eFMU co-simulation stub:

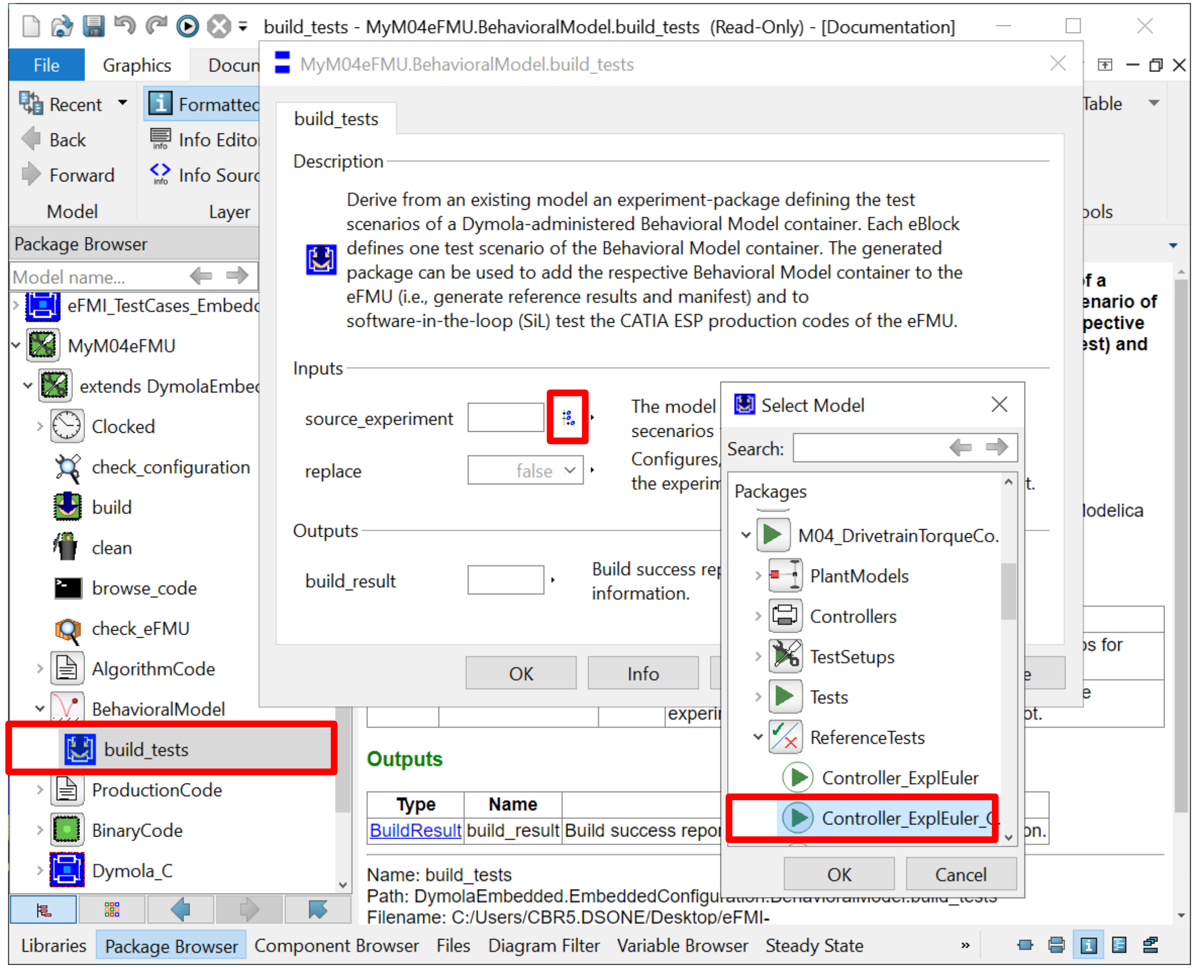


Main characteristics of eFMU co-simulation stubs:

- Support multiple instantiation (each is atomic)
- All production codes available (32-Bit & 64-Bit floating-point precision simulation)
- Support modification, input-dependent initialization, recalibration & reinitialization
- Provide & assert eFMI error signals
- Preserve original model interface (dimensionalities, diagramatic layout of in- & output connectors etc)
- Provide sampling with period of generated eFMU
- ”Just” a production code proxy (no additional equations; no solver required; ”simply” implement GALEC block live-cycle)

Functional Mock-up Interface for embedded systems

Derive experiment package to define test scenarios & generate Behavioral Model container:

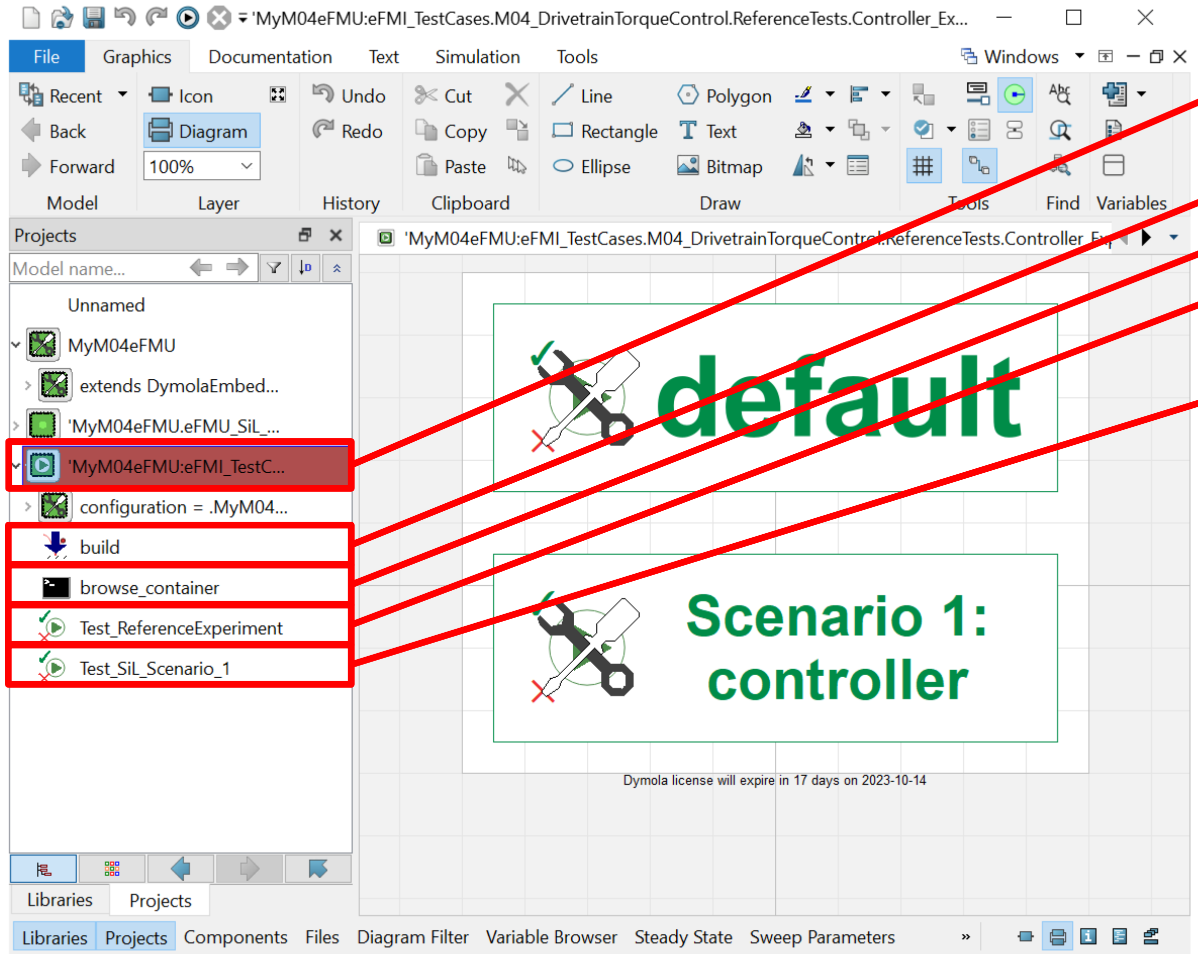


Derive experiment package from existing closed loop experiment:

1. Right click `MyM04eFMU.BehavioralModel.build_tests` in *Package Browser / Projects* view
   → *Call Function…*
   → *source_experiment*
   → *Edit* (package tree icon)
   → select `eFMI_TestCases.M04_DrivetrainTorqueControl.ReferenceTests.Controller_ExplEuler_ClosedLoop`
   → *OK*
   → *OK*

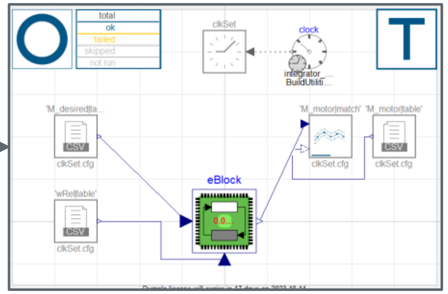
Functional Mock-up Interface for embedded systems

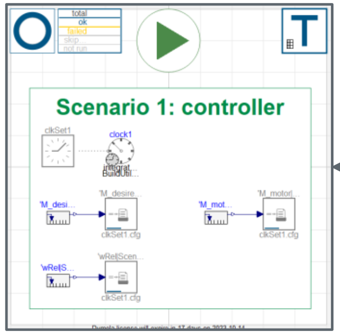
Investigate the derived experiment package:



The generated experiment package contains:

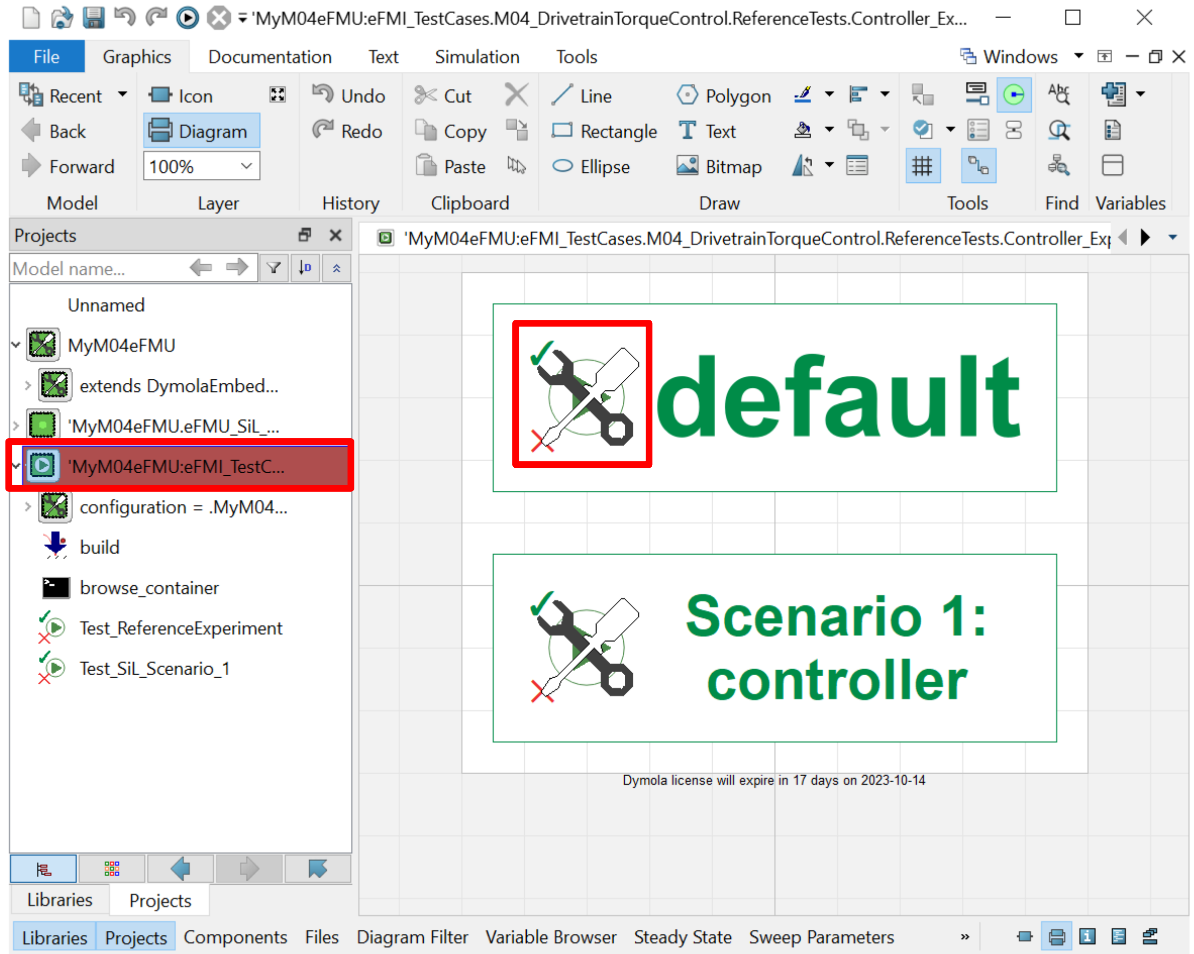
- Records to define absolute & relative tolerances for test scenarios
- Function to generate the Behavioral Model container
- Function to browse the Behavioral Model container
- A single reference experiment to regression test the source experiment and generate reference results
- A SiL test for each ”controller” instance (i.e., test scenario) in the source experiment





Functional Mock-up Interface for embedded systems

Define tolerances for the test scenarios of the experiment package:

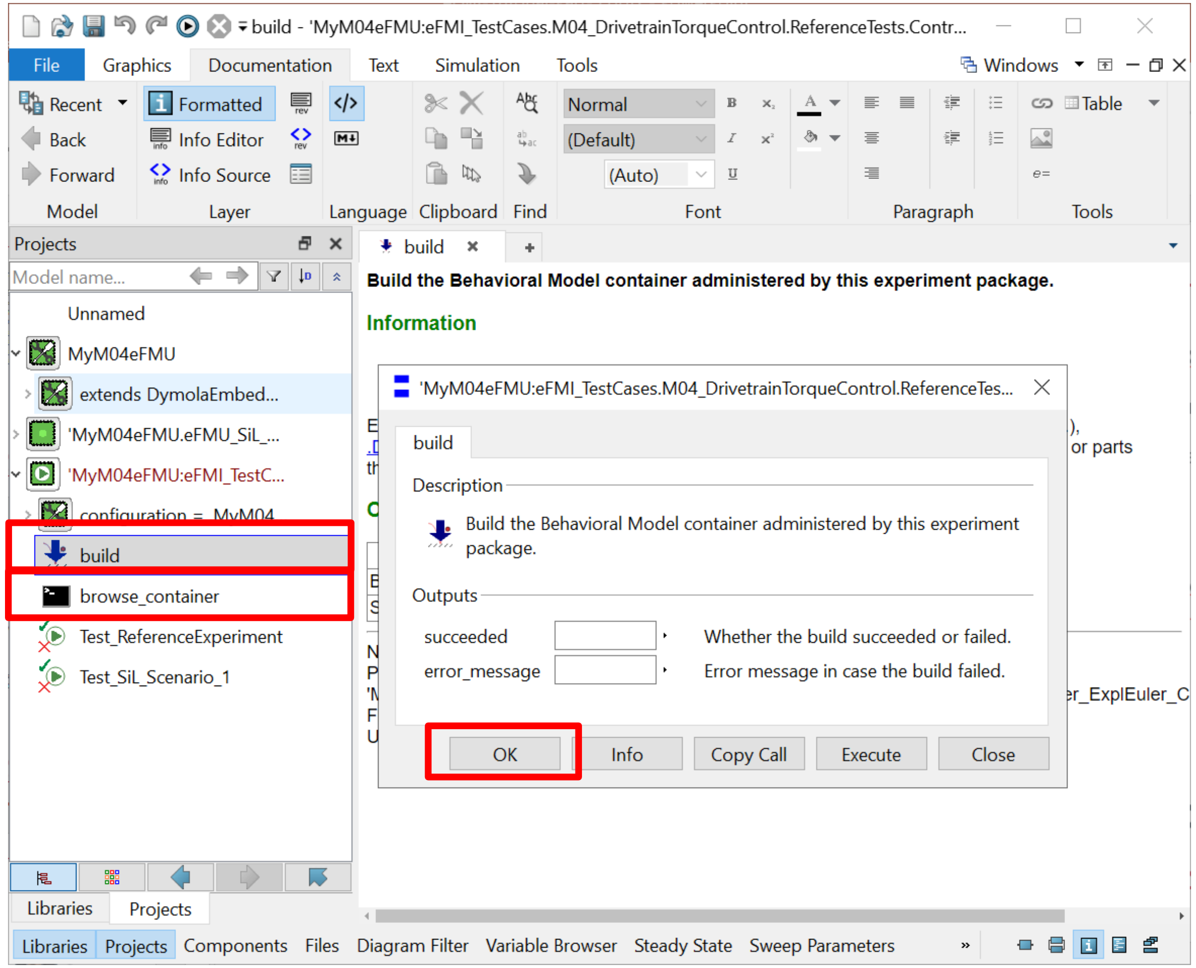


Define absolute and relative tolerances for all floating-point precisions and test scenarios (i.e., SiL tests). We can use a default for all scenarios (here only a single):

1. Double click `tolerances_default` (labeld **default**) in *Diagram* view of the experiment package
   → set tolerances for `M_motor` output a follows
   `absolute_x32(M_motor=1e-3)`
   `relative_x32(M_motor=1e-4)`
   `absolute_x64(M_motor=1e-6)`
   `relative_x64(M_motor=1e-8)`
   → *OK*

Functional Mock-up Interface for embedded systems

Generate Behavioral Model container form the experiment package:



Build the Behavioral Model container with reference results taken from simulation of the reference experiment `Test_ReferenceExperiment`:

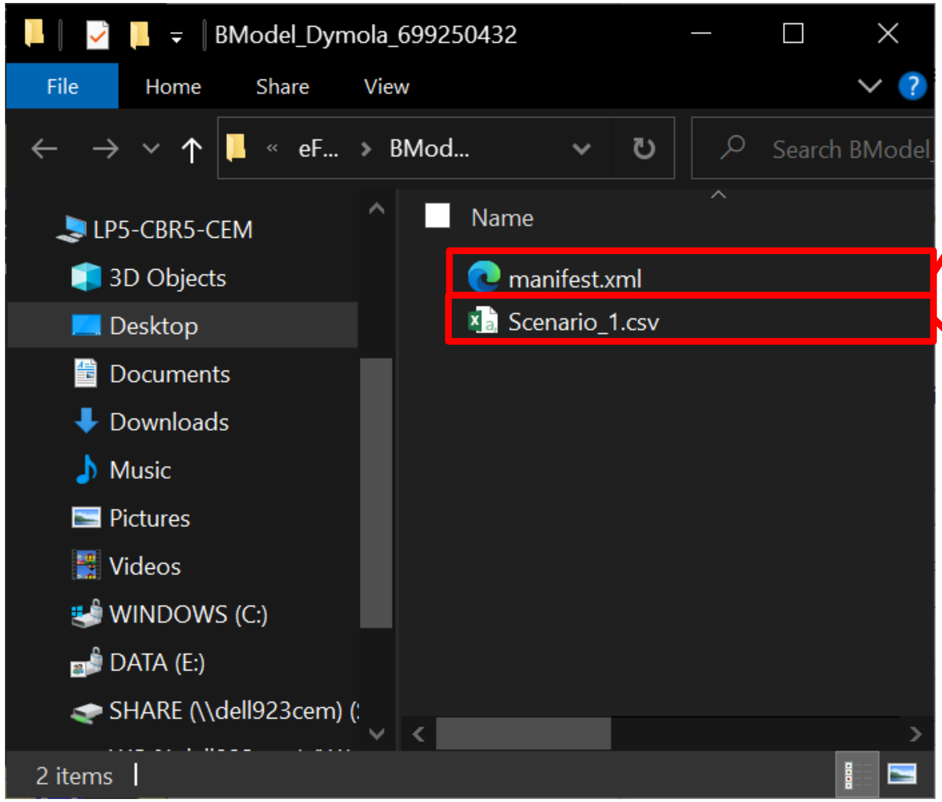
1. Right click `build` of experiment package in *Package Browser / Projects* view
   → *Call Function…*
   → *OK*

Browse the generated Behavioral Model container:

1. Right click `browse_container` of experiment package in the *Package Browser / Projects* view
   → *Call Function…*
   → *OK*

Functional Mock-up Interface for embedded systems

Investigate the generated Behavioral Model container (`BModel_Dymola_699250432`):



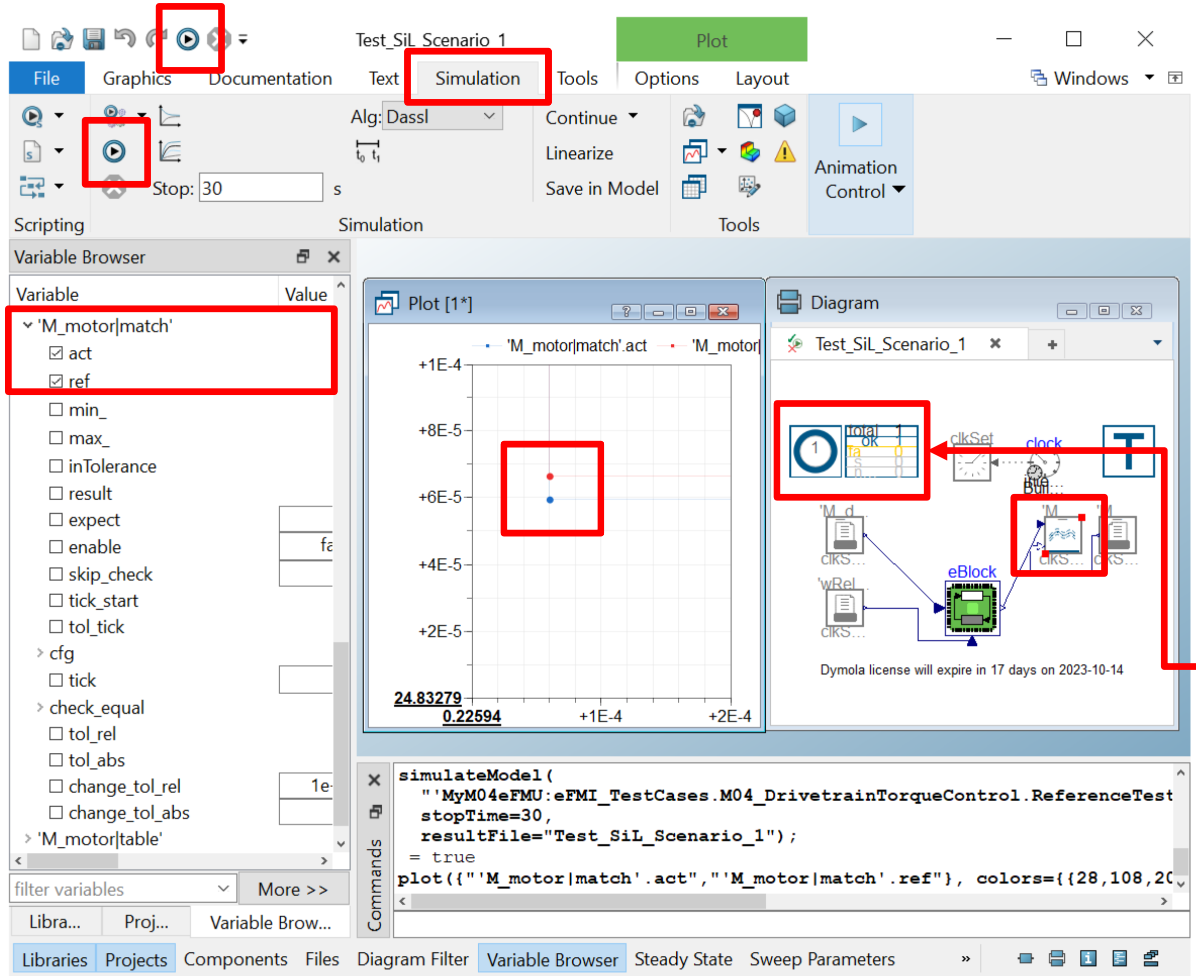
Container content:

- **XML manifest** with
  - Test scenarios
  - Links to Algorithm Code manifest for variable names and types (in-, output, tuneable parameter) & sample period
  - Variables → CSV column name links (multi-dimensions are flattened to individual columns)
  - Tolerances for various floating-point precisions
- **Reference trajectories** in comma separated values (CSV) files (one file per test scenario)

Take some time to investigate the manifest and CSV file.

Functional Mock-up Interface for embedded systems

Conduct SiL test of CATIA ESP generated production codes:

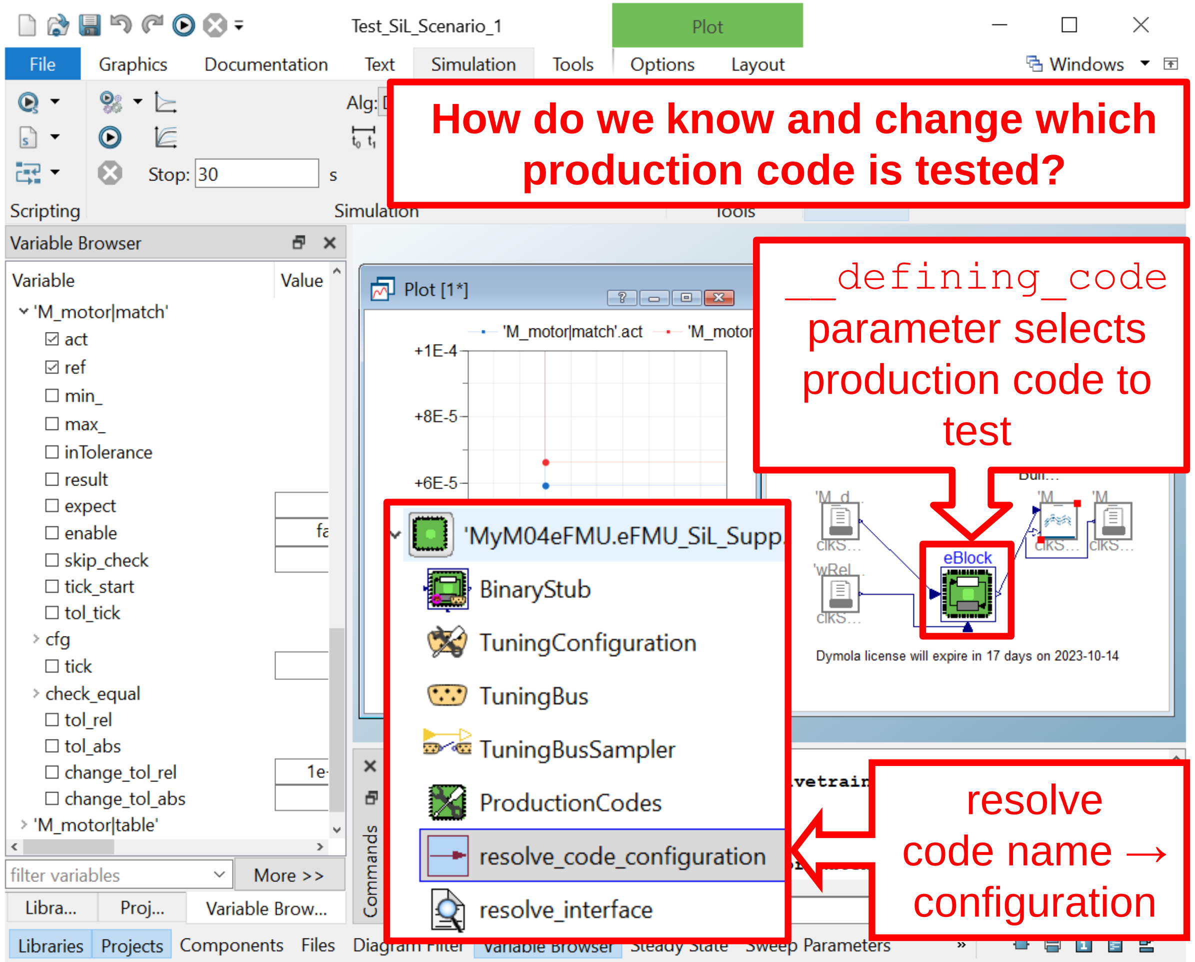


1. Double click `Test_SiL_Scenario_1` of the experiment package in *Package Browser / Projects* view
2. Switch to *Simulation* ribbon
   → Click *Simulate* button
3. Right click `'M_motor|match'` in diagram plot
   → *Plot Variable*
   → select *act* (actual SiL simulation trajectory)
   → select *ref* (expected reference trajectory)
4. Zoom into *Plot* window to see there are differences

Note, that the test did not fail (see *Logs* window & dashboards). If you tighten tolerances – e.g., change the 32-Bit floating-point precision tolerances to the 64-Bit ones – it will fail.

eFMI Functional Mock-up Interface for embedded systems

Conduct SiL test of CATIA ESP generated production codes:

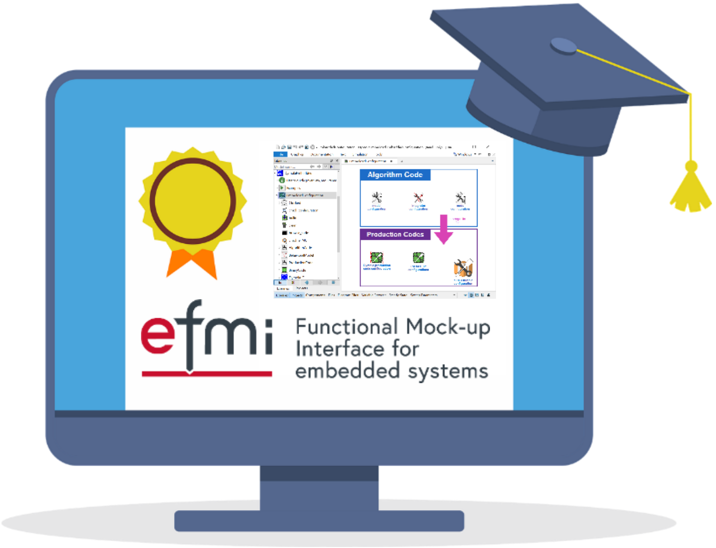


1. Double click `Test_SiL_Scenario_1` of the experiment package in *Package Browser / Projects* view
2. Switch to *Simulation* ribbon
   → Click *Simulate* button
3. Right click `'M_motor|match'` in diagram plot
   → *Plot Variable*
   → select *act* (actual SiL simulation trajectory)
   → select *ref* (expected reference trajectory)
4. Zoom into *Plot* window to see there are differences

Note, that the test did not fail (see *Logs* window & dashboards). If you tighten tolerances – e.g., change the 32-Bit floating-point precision tolerances to the 64-Bit ones – it will fail.

Functional Mock-up Interface for embedded systems

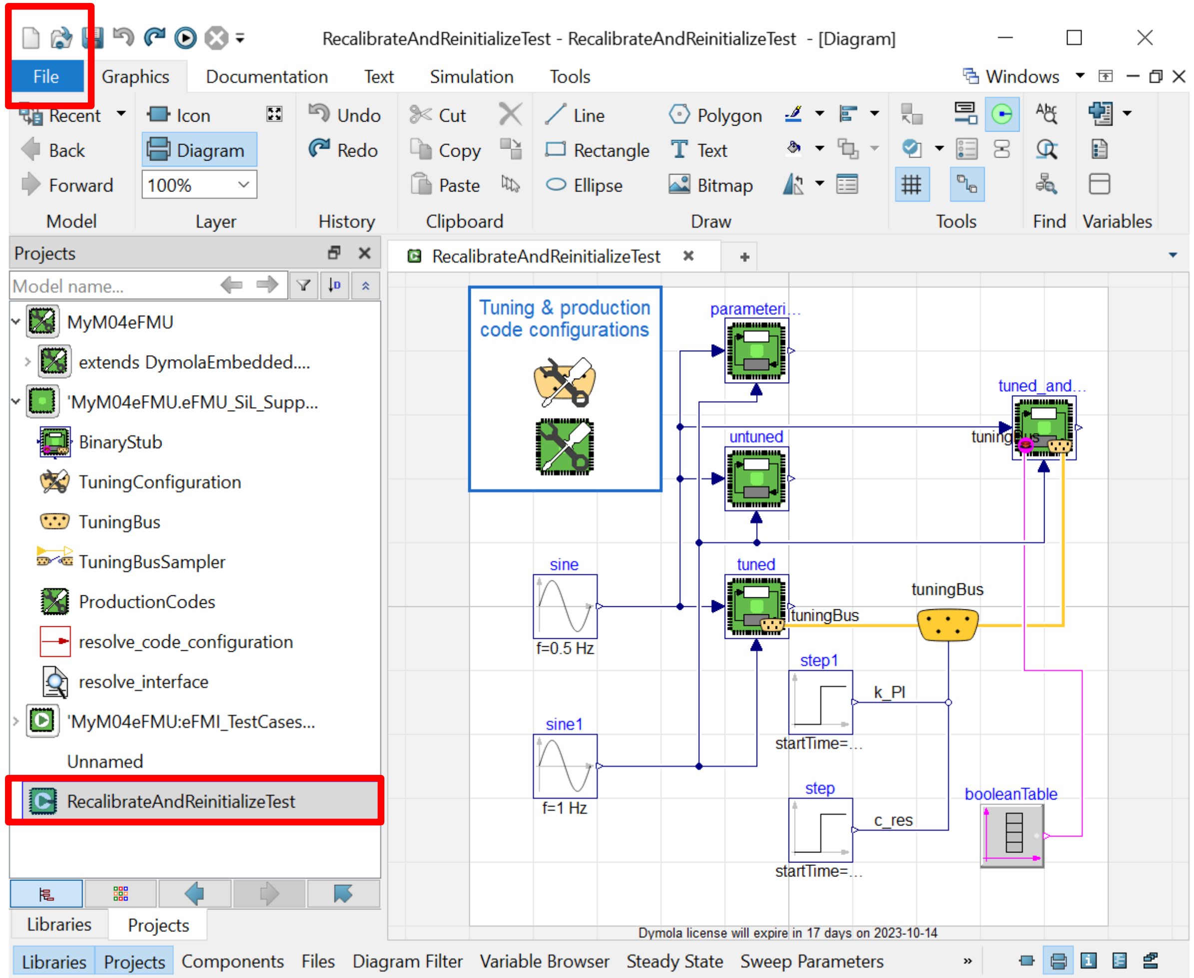
Congratulations, you did it!



Let’s do some advanced SiL stuff, like recalibration and reinitialization.

efmi Functional Mock-up Interface for embedded systems

Load prepared recalibration & reinitialization example for M04 controller:



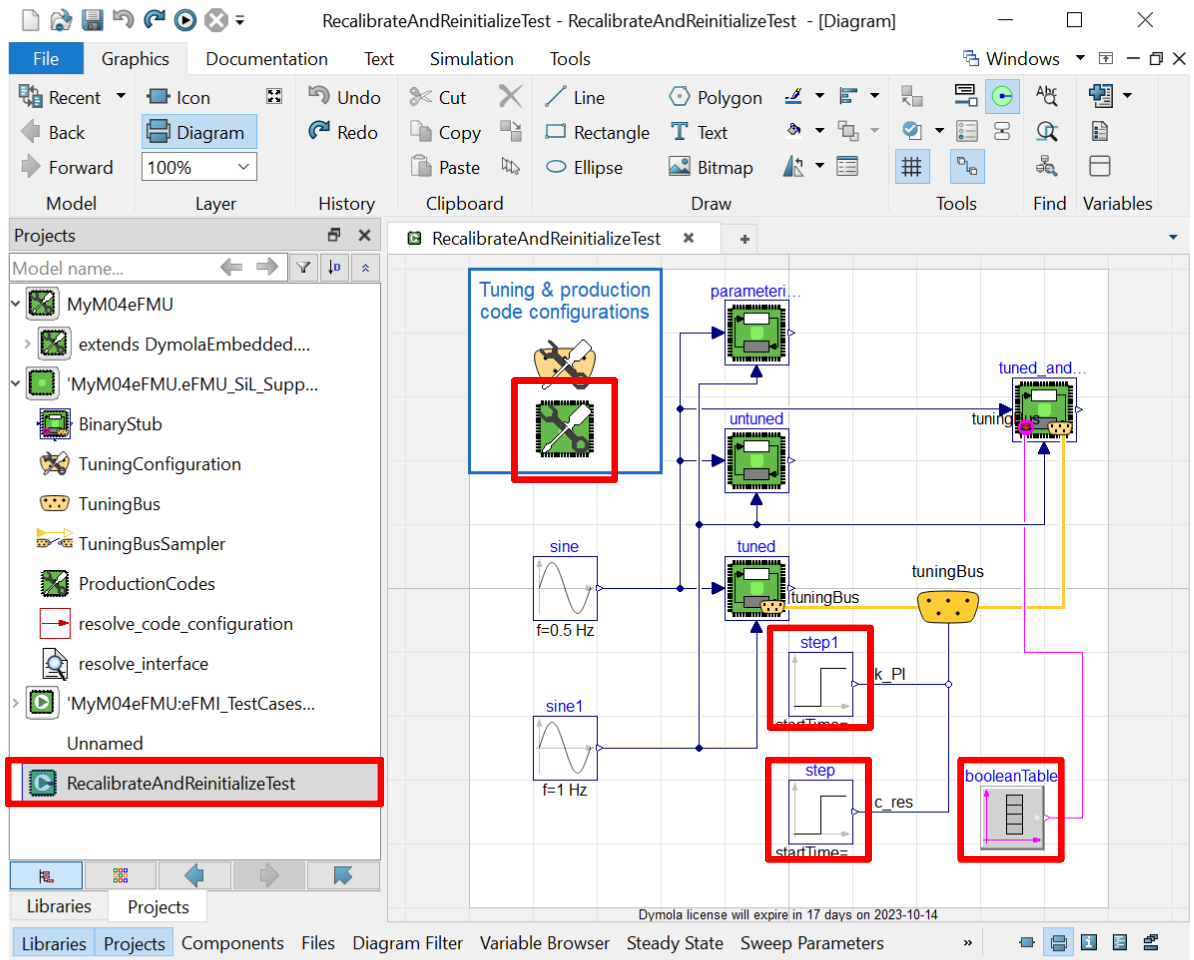
1. Either, drag and drop model `reference-models/Part-3/RecalibrateAndReinitializeTest.mo` in *Package Browser / Projects* view or load it via *File → Open → Load…*

The model has 4x M04 controller instances (eFMU co-simulation stub instances):

1. `untuned`: not modified, recalibrated nor reinitialized
2. `parameterized`: modified `c_res` & `k_PI` parameters, but not recalibrated nor reinitialized
3. `tuned`: unmodified, but via `tuningBus` runtime recalibrated `c_res` & `k_PI` parameters
4. `tuned_and_reinitialized`: like 3, but additionally at runtime reinitialized

Functional Mock-up Interface for embedded systems

Investigate recalibration & reinitialization example for M04 controller:



All 4 controllers use the same production code for simulation (`__defining_code` modification set by the global record parameter in the upper left of the diagram).

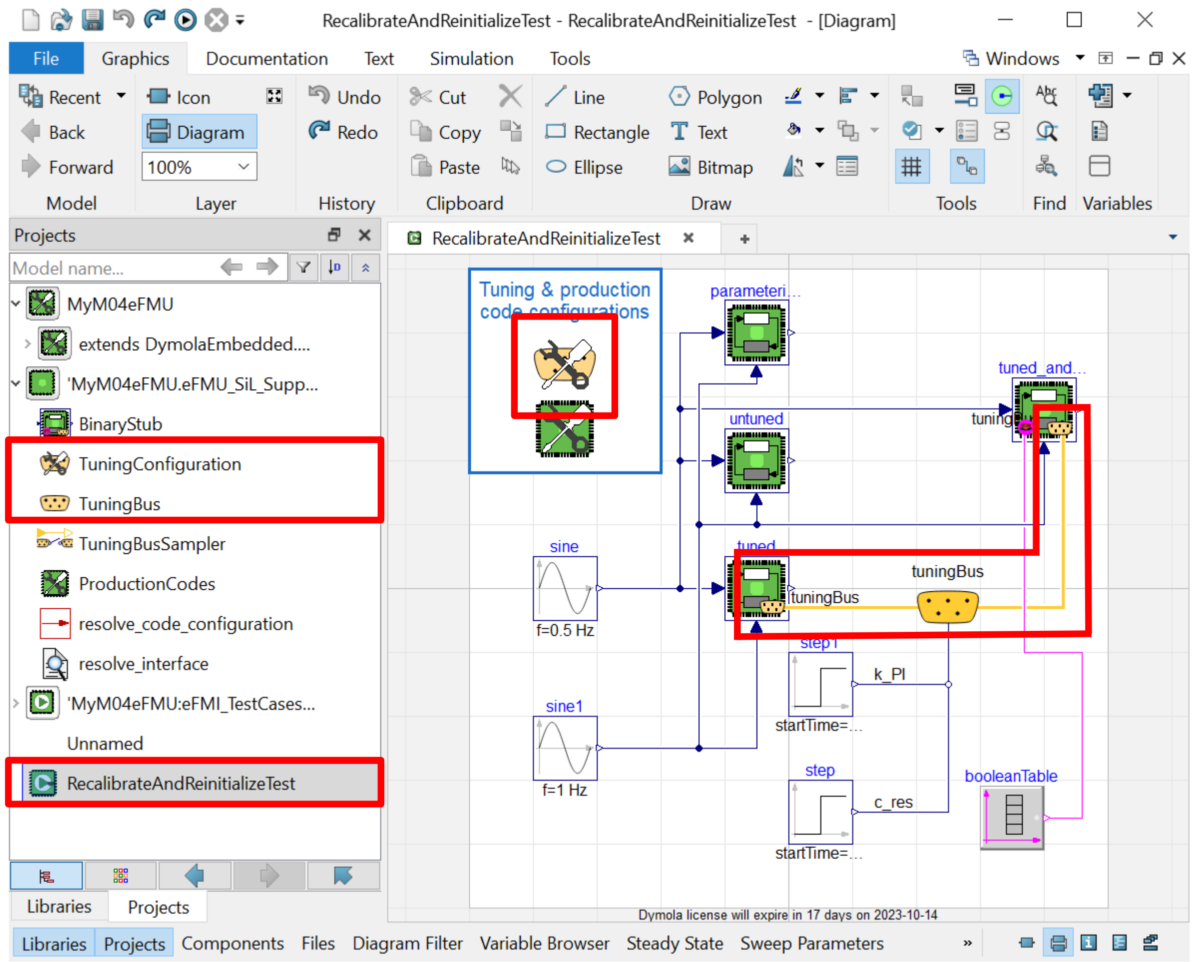
The `c_res` & `k_PI` parameter changes are all switches from the default value to the same new value, just at different time points (as modification before simulation or as recalibration during simulation):

- `c_res`: `4710` → `2710` at t = 0s or 0.25s (`step` runtime value)
- `k_PI`: `-73` → `-10` at t = 0s or 0.6s (`step1` runtime value)

Reinitalization is done at t = 0.7005s (`booleanTable` runtime value).

Functional Mock-up Interface for embedded systems

Investigate recalibration & reinitialization example for M04 controller:



Tuning is enabled by modifying co-simulation subs:

- `__enable_tuning = true`
- selecting/activating the tuned parameters via `__tuning_configuration`

⇒ The tuning bus connector () is enabled.

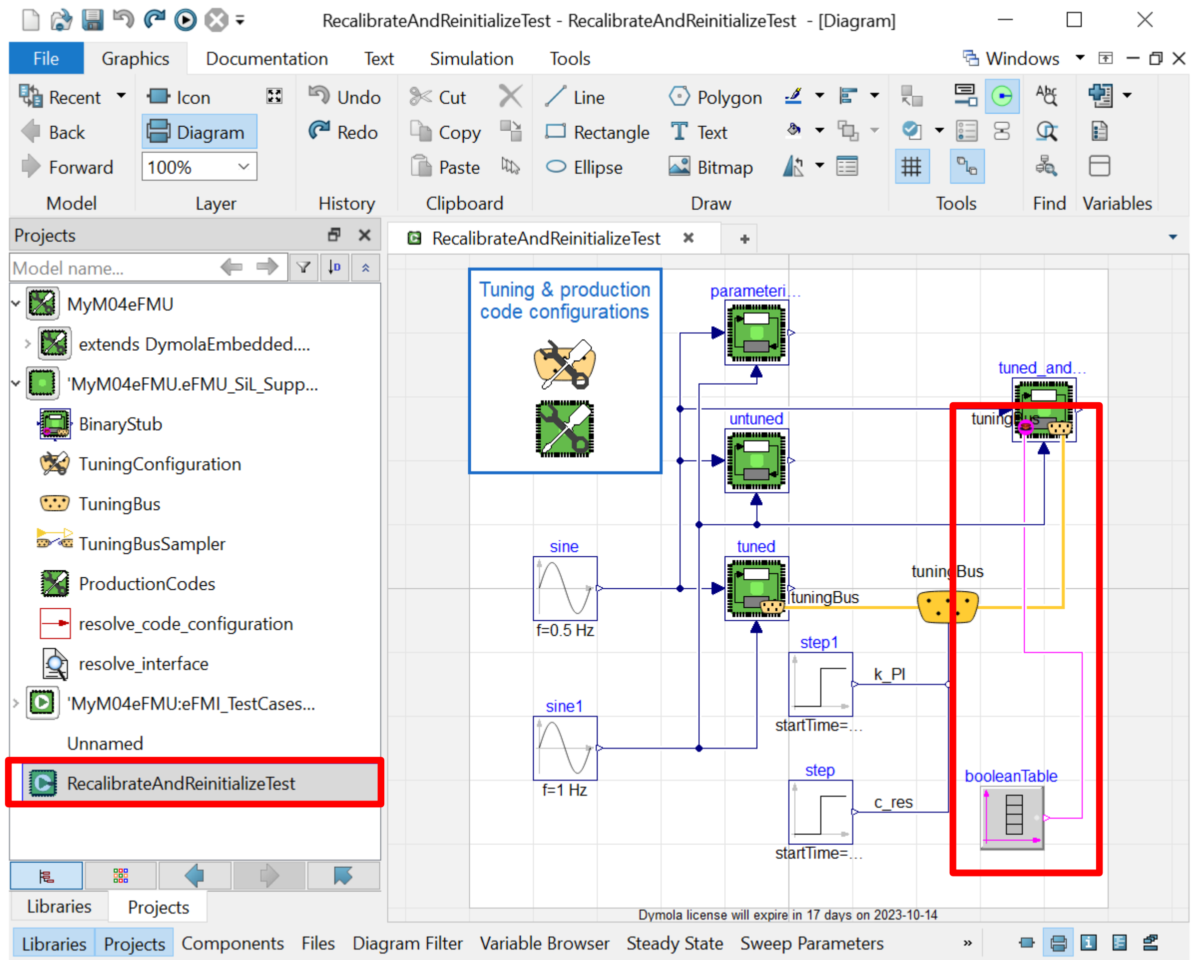
New recalibration parameter values are provided as runtime values connected to the tuning bus. Only tuning-activated parameters have to be provisioned.

Tuning configuration & bus types are provided in the generated eFMU co-simulation stub (drag and drop).

In this model: Tuneable parameters are selected by the global `__tuning_configuration` record parameter in the upper left of the diagram.

Functional Mock-up Interface for embedded systems

Investigate recalibration & reinitialization example for M04 controller:



Reinitialization is enabled by modifying eFMI co-simulation subs:

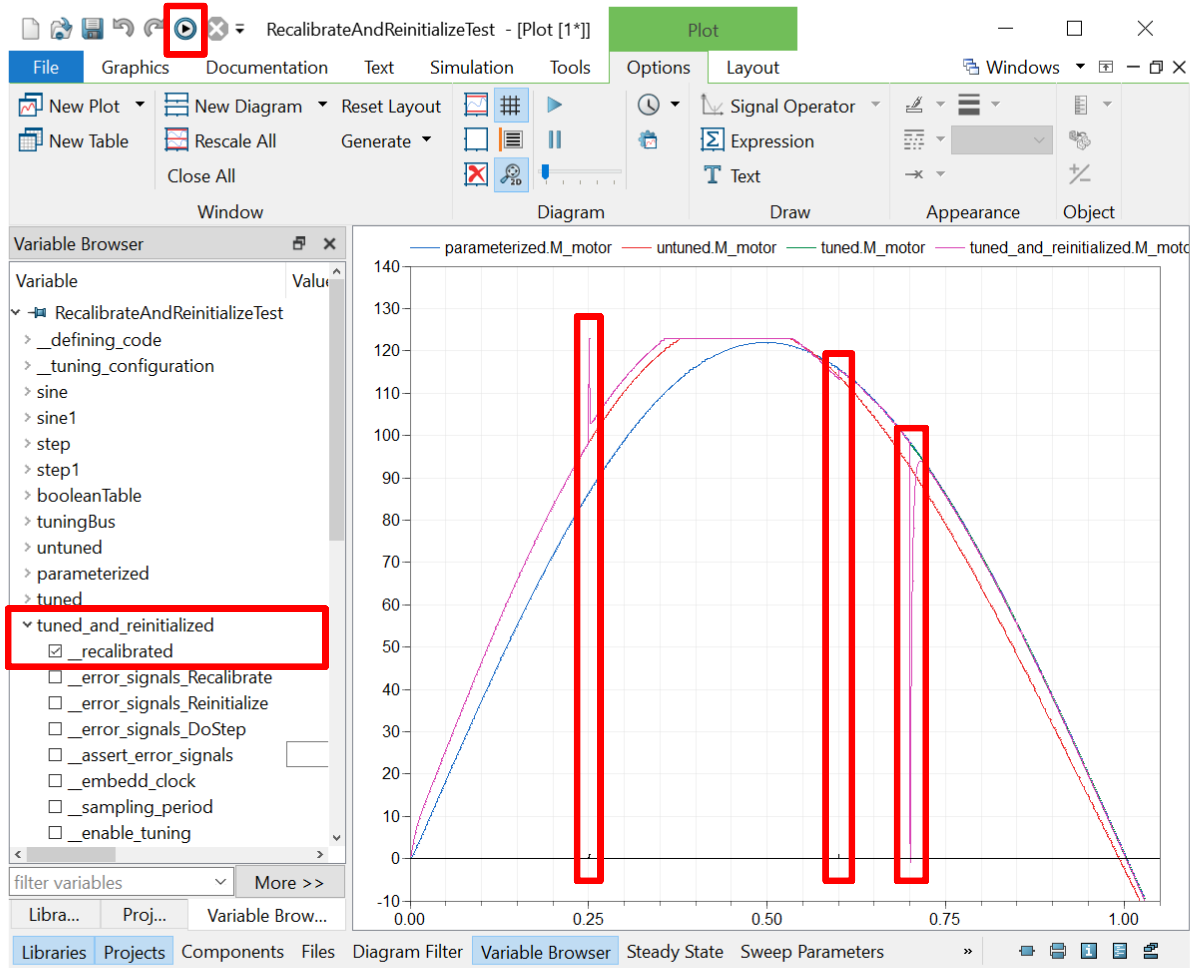
- `__enable_reinitialization = true`

⇒ The "stop push button" ( ) is enabled.

New reinitialization requests are provided as runtime values connected to the "stop push button". Such are locked until the next sampling; it is sufficient to signal at any point inbetween two samplings that a reinitialization is requested – it is not necessary to ensure `__reinitialize == true` exactly at the sampling.

Functional Mock-up Interface for embedded systems

Investigate recalibration & reinitialization example for M04 controller:



1. Simulate `RecalibrateAndReinitializeTest`
2. Plot `M_motor` of all 4 co-simulation stubs
3. Plot `__recalibrated` (true, iff recalibration done)
4. Zoom into the plot at $0.0 \leq t \leq 1.05$

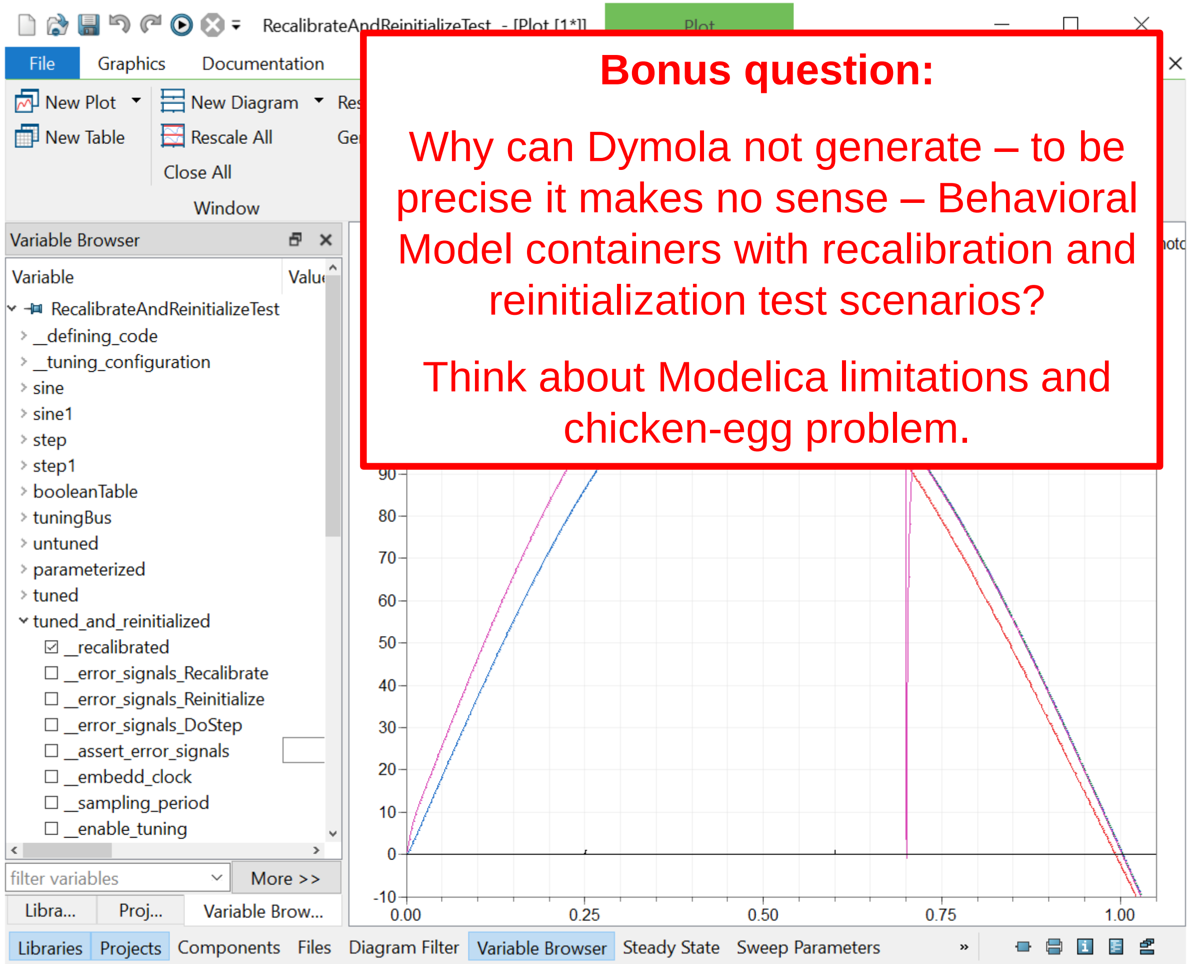
When do `parameterized` and `tuned` plots align? When does `untuned` align? Is the controller fast adapting in case of errors that require a system restart?

Good to remember:

- All controllers use same production code
- `c_res` & `k_PI` parameters change consistently:
  - `c_res` at t = 0s or 0.25s (`step`)
  - `k_PI` at t = 0s or 0.6s (`step1`)
- Reinitalization at t = 0.7005s (`booleanTable`)

Functional Mock-up Interface for embedded systems

Investigate recalibration & reinitialization example for M04 controller:



Bonus question:

Why can Dymola not generate – to be precise it makes no sense – Behavioral Model containers with recalibration and reinitialization test scenarios?

Think about Modelica limitations and chicken-egg problem.

1. Simulate `RecalibrateAndReinitializeTest`
2. Plot `M_motor` of all 4 co-simulation stubs
3. Plot `__recalibrated` (true, iff recalibration done)
4. Zoom into the plot at 0.0 ≤ t ≤ 1.05

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Good to remember:

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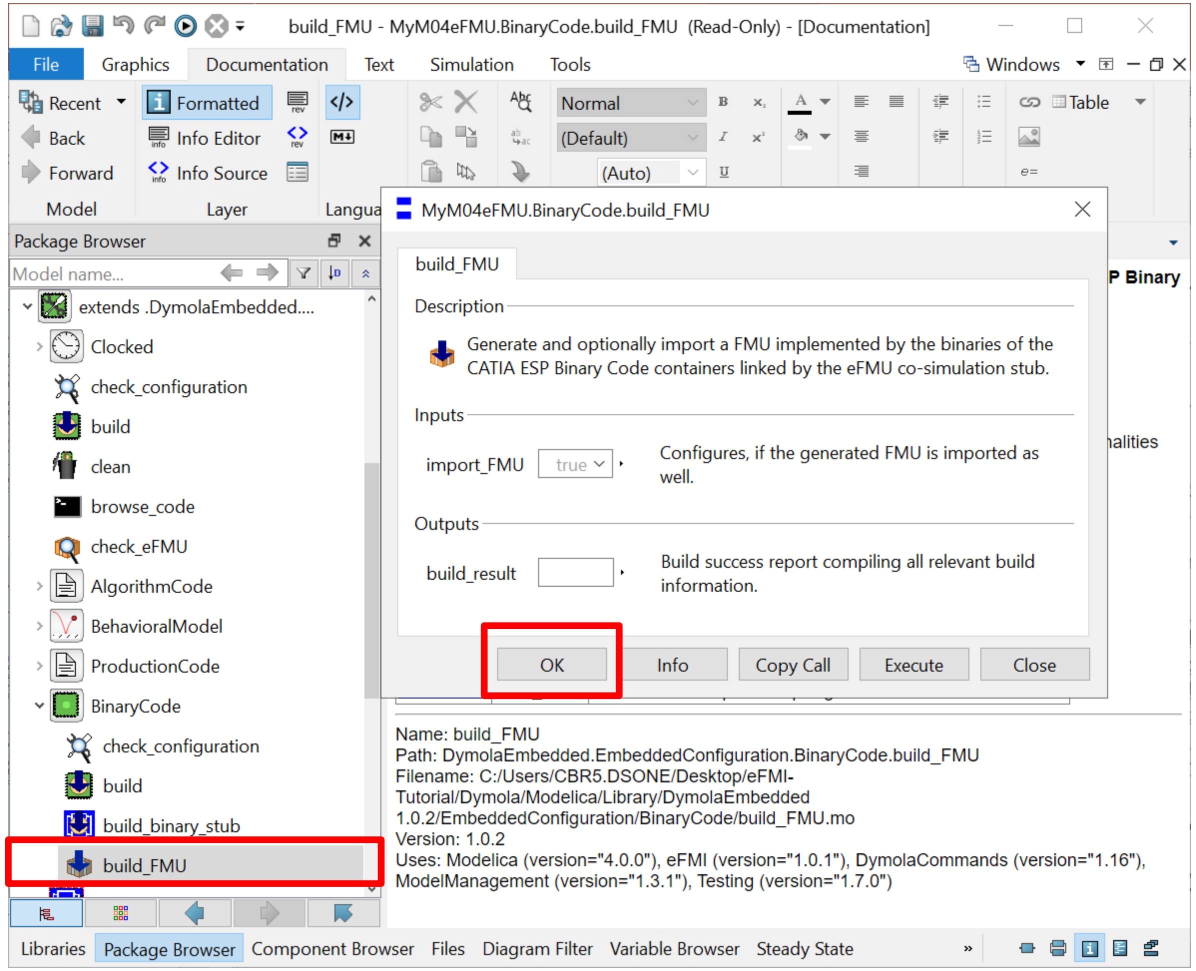
Functional Mock-up Interface for embedded systems

Final touch – export eFMU as FMU:



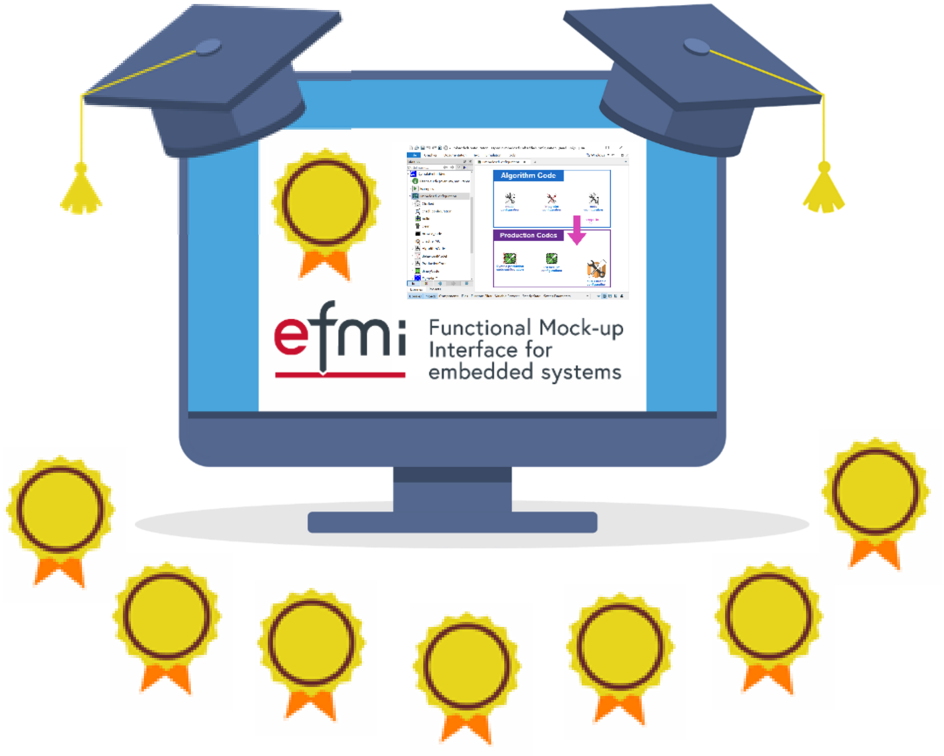
1. Right click `MyM04eFMU.BinaryCode.build_FMU` in *Package Browser / Projects* view
   → *Call Function…*
   → *OK*

The exported FMU has all conditional parameters of the eFMU co-simulation stub fixed to their defaults:

- Floating-point precision: precision of `__defining_code` production code
- Recalibration & reinitialization: disabled, i.e., `__enable_tuning = false`, `__enable_reinitialization = false`
- Error signals: asserted, i.e., `__assert_error_signals = true`
- Internal sampling: embedded & fixed, i.e., `__embedd_clock = true`

Functional Mock-up Interface for embedded systems

Congratulations, you did it like a PRO!



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eFMI® Tutorial – Agenda

Part 1: eFMI® motivation and overview (40 min)

Part 2: Running use-case introduction (10 min)

Part 3: Hands-on demonstration in Dymola and CATIA ESP (25 min)

Coffee break (30 min)

Part 3: Hands-on demonstration in Dymola and CATIA ESP (35 min)

Part 4: Live demonstration in TargetLink (30 min)

Part 5: Short presentation of further tooling (5 min)

Part 6: Conclusion (5 min)

Tutorial leader:
Christoff Bürger

DASSAULT SYSTEMES

Presenter:
Oliver Lenord

BOSCH
Invented for life

Presenter:
Jörg Niere

dSPACE

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