INtegrated TOol chain for model-based design of CPSs

INTO-CPS Tool Chain User Manual

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The INTO-CPS Association

http://into-cps.org

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Abstract

This user manual for the INTO-CPS tool chain, an update of Deliverable D4.3a [BLL$^+$17] that was developed inside the INTO-CPS H2020 project and it is now taken further inside the INTO-CPS association. It is targeted at those wishing to make use of the INTO-CPS technology to design and validate cyber-physical systems. This user manual is concerned with those aspects of the tool chain relevant to end-users, so it is necessarily high-level. Other deliverables from the INTO-CPS project discuss finer details of individual components, including theoretical foundations (Deliverables D4.3b [PBL$^+$17], D4.2c [BQ16], D4.3c [Bro17], D2.3a [ZCWO17], D2.2b [FCC$^+$16], D2.3b [CFT$^+$17], D2.3c [ZFC$^+$17]), methods and guidelines (Deliverables D3.3a [FGP17] and D3.6 [MGP$^+$17]) and software design decisions (Deliverables D4.3d [KLN$^+$17], D5.2a [PLM16], D5.3c [BH17], D5.3d [BHPG17], D5.3e [Gam17]).

Contents

1 Introduction

The tool chain supports the development and verification of Cyber-Physical Systems (CPSs) through collaborative modelling (co-modelling) and co-simulation [GTB+17]. Development of CPSs with the INTO-CPS technology proceeds with the development of constituent models using established and mature modelling tools. Development also benefits from support for Design Space Exploration (DSE). The analysis phase is primarily based on co-simulation of heterogeneous models compliant with version 2.0 of the Functional-Mockup Interface (FMI) standard for co-simulation [Blo14]. Other verification features supported by the tool chain include hardware- and software-in-the-loop (HiL and SiL) simulation and model-based testing through Linear Temporal Logic model checking.

All INTO-CPS tools can be obtained from

```
http://into-cps-association.github.io
```

This is the primary source of information and help for users of the INTO-CPS tool chain. The structure of the website follows the natural flow of CPS development with INTO-CPS, and serves as a natural aid in getting started with the technology. In case access to the individual tools is required, pointers to each are also provided.

Please note: This user manual assumes that the reader has a good understanding of the FMI standard. We therefore strongly encourage the reader to become familiar with Section 2 of Deliverable 4.1d [LLW+15] for background, concepts and terminology related to FMI.

The rest of this manual is structured as follows:

- Section 2 provides an overview of the different features and components of the INTO-CPS tool chain.
- Section 3 explains the different features of the main user interface of the INTO-CPS tool chain, called the INTO-CPS Application.
- Section 4 explains the relevant parts of the Modelio SysML modelling tool.
- Section 5 describes the separate modelling and simulation tools used to build and analyse the different constituent models of a multi-model.
- Section 6 describes Design Space Exploration (DSE) for INTO-CPS multi-models.

- Section 7 describes model-based test automation and model checking in the INTO-CPS context.
- Section 8 describes traceability along the INTO-CPS tool chain.
- Section 9 provides a short overview of code generation in the INTO-CPS context.
- Section 10 describes how issues with the INTO-CPS tool chain are reported and handled.
- Section 11 presents concluding remarks.
- The appendices are structured as follows:
  - Appendix A lists the acronyms used throughout this document.
  - Appendix B gives background information on the individual tools making up the INTO-CPS tool chain.
  - Appendix C gives background information on the various principles underlying the INTO-CPS tool chain.

2 Overview of the INTO-CPS Tool Chain

The INTO-CPS tool chain consists of several special-purpose tools from a number of different providers. Note that this is an open tool chain, so it is possible to incorporate other tools that also support the FMI standard for co-simulation. We have already tested this with numerous external tools (both commercial as well as open-source). The constituent tools are dedicated to the different phases of collaborative modelling activities. They are discussed individually through the course of this manual. An overview of the tool chain is shown in Figure 1. The main interface to INTO-CPS is the INTO-CPS Application. This is where the user can design co-simulations from scratch, assemble them using existing FMUs and configure how simulations are executed. The result is a *multi-model*. The multi-model can then be analysed through co-simulation, model checking and model-based testing.

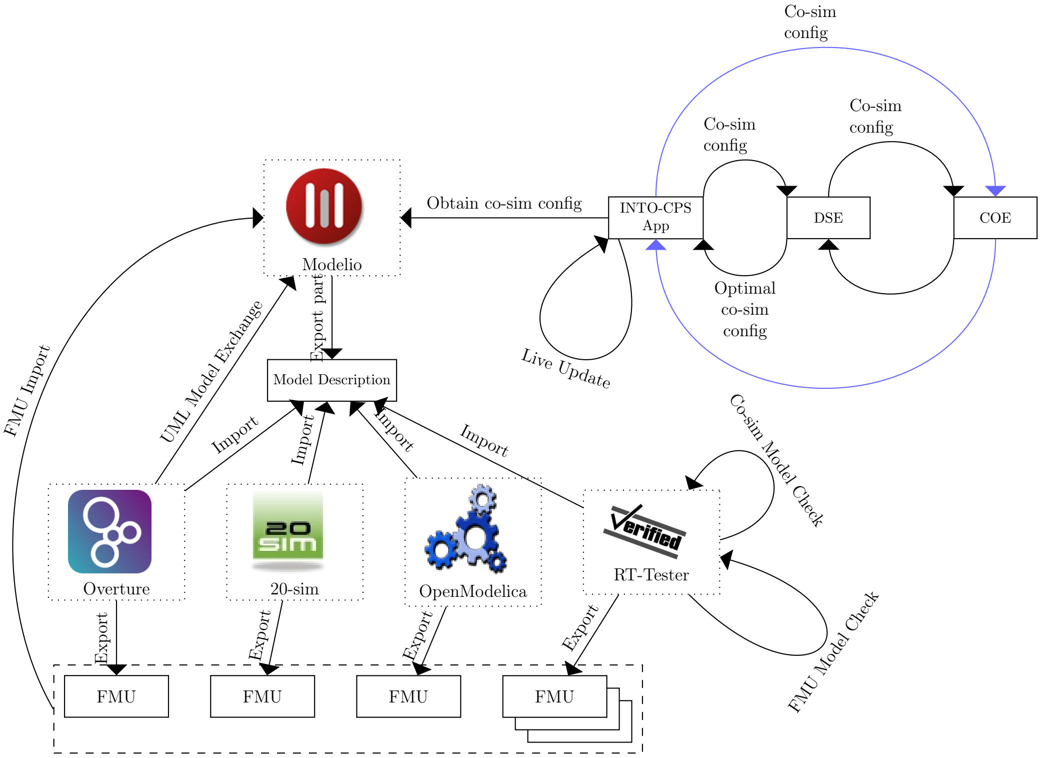


Figure 1: Overview of the structure of the INTO-CPS tool chain.

The design of a multi-model is carried out visually using the Modelio SysML tool, in accordance with the SysML/INTO-CPS profile described in D2.3a [ZCWO17]. Here one can either design a multi-model from scratch by specifying the characteristics and connection topology of Functional Mockup Units (FMUs) yet to be developed, or import existing FMUs so that the connections between them may be laid out visually. The result is a SysML architecture model of the multi-model, expressed in the SysML/INTO-CPS profile. In the former case, where no FMUs exist yet, a number of `modelDescription.xml` files are generated from this multi-model which serve as the starting point for constituent model construction inside each of the individual simulation tools, leading to the eventual FMUs.

Once a multi-model has been designed and populated with concrete FMUs, the Co-simulation Orchestration Engine (COE) can be invoked to execute a co-simulation. The COE controls all the individual FMUs in order to carry out the co-simulation. In the case of tool-wrapper FMUs, the model inside each FMU is simulated by its corresponding simulation tool. The tools involved are Overture [LBF$^+$10], 20-sim [Con13] and OpenModelica [Lin15]. RT-Tester is not under the direct control of the COE at co-simulation time, as its purpose is to carry out testing and model checking rather than simulation. The user can configure a co-simulation, for instance by running it with different simulation parameter values and observing the effect of the different values on the co-simulation outcome.

Alternatively, the user has the option of exploring optimal simulation parameter values by entering a DSE phase. In this mode, ranges are defined for various parameters which are explored, in an intelligent way, by a design space exploration engine that searches for optimal parameter values based on defined optimization conditions. This engine interacts directly with the COE and itself controls the conditions under which the co-simulation is executed.

3 The INTO-CPS Application

This section describes the INTO-CPS Application, the primary gateway to the INTO-CPS tool chain. Section 3.1 gives an introductory overview of the INTO-CPS Application. Section 3.2 describes how the INTO-CPS Application can be used to create new INTO-CPS co-simulation projects. Section 3.3 describes how multi-models can be assembled. Section 3.4 describes how co-simulations are configured, executed and visualized. Section 3.5 lists some additional useful features of the INTO-CPS Application, while Section 3.6 describes how the co-simulation engine itself can be started manually, for specialist use.

3.1 Introduction

The INTO-CPS Application is the front-end of the entire INTO-CPS tool chain. The INTO-CPS Application defines a common INTO-CPS project and it is the easiest way to configure and execute co-simulations. Certain features in the tool chain are only accessible through the INTO-CPS Application. Those features will be explained in their own sections of the user manual. This section introduces the INTO-CPS Application and its basic features only.

Releases of the INTO-CPS Application can be downloaded from:

`https://into-cps-association.github.io/into-cps/download`

Five variants are available:

- `-darwin-x64.zip` – MacOS version
- `-linux-ia32.zip` – Linux 32-bit version
- `-linux-x64.zip` – Linux 64-bit version
- `-win32-ia32.zip` – Windows 32-bit version
- `-win32-x64.zip` – Windows 64-bit version

The INTO-CPS Application itself has no dependencies and requires no installation. Simply unzip it and run the executable. However, certain INTO-

CPS Application features require Git[1], Java 8[2] and Python 2[3] to be already installed.

The main window of the INTO-CPS Application, with a project already loaded, is shown in Figure 2. The left panel shows the INTO-CPS project explorer. The central area of the window displays the contents of the current project's README file. The bottom of the main INTO-CPS Application window contains two navigation tabs. When clicked, their content is displayed immediately above. Figure 2 shows this for the "COE Console" tab. Elements of the main window are discussed in further detail below. The tabs are as follows:

- "COE Console" shows the output of the COE process and log messages with a log level of "error" or "warning". Furthermore, a dot shows whether the COE is online or offline. If the dot is green then the COE is online, whereas the dot is red when the COE is offline. The "Launch" and "Stop" buttons start and stop the COE process, respectively. If "Stream Redirect" is followed by a link icon (🔗) then the output of the COE is shown in this part of the main window, otherwise no COE output is shown.
- "COE log" shows the co-simulation log output according to the co-simulation configuration.

3.2 Projects

An INTO-CPS project contains all the artifacts used and produced by the tool chain. The project artifacts are grouped into folders. You can create as many folders as you want and they will all be displayed in the project browser. The default set of folders for a new project, shown in Figure 3, is:

DSES Scripts and configuration files for performing DSE experiments.

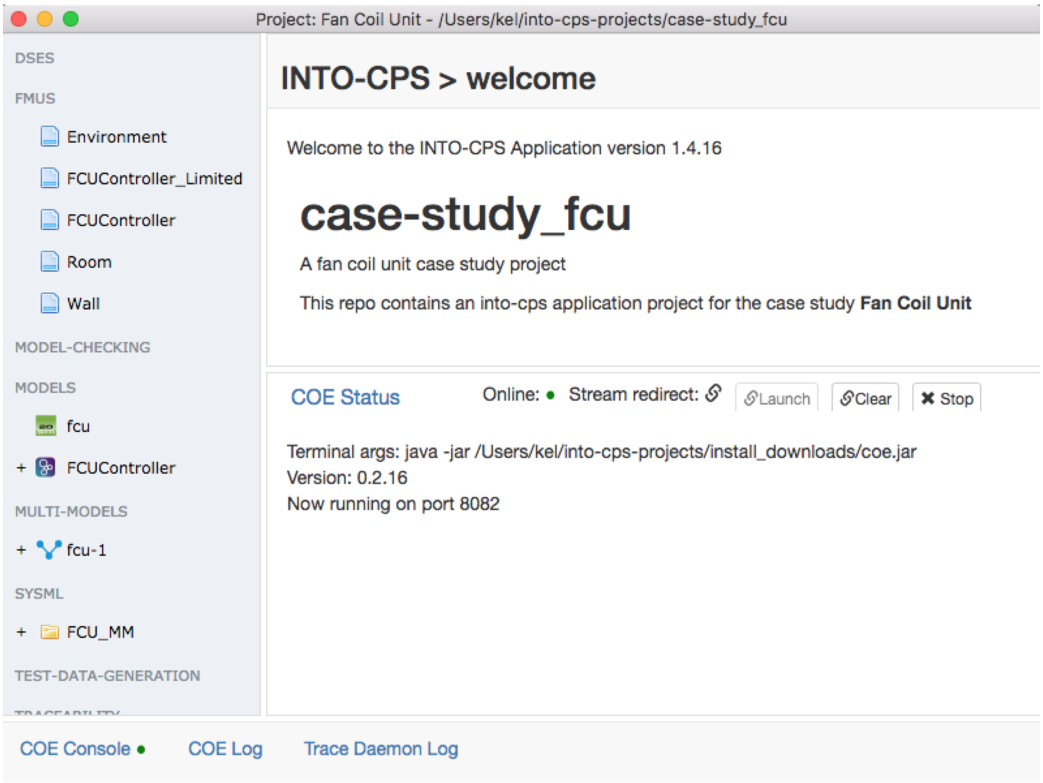
FMUs FMUs for the constituent models of the project.

Model-Checking Configuration files for performing Model Checking experiments.

[1] `https://git-scm.com/`

[2] `http://www.oracle.com/technetwork/java/javase/overview/java8-2100321.html`

[3] `http://www.python.org/downloads/`



Welcome to the INTO-CPS Application version 1.4.16

case-study_fcu

A fan coil unit case study project

This repo contains an into-cps application project for the case study **Fan Coil Unit**

```
Terminal args: java -jar /Users/kel/into-cps-projects/install_downloads/coe.jar
Version: 0.2.16
Now running on port 8082
```

Figure 2: INTO-CPS Application main window.

Models Sources for the constituent models of the project.

Multi-Models The multi-models of the project, using the project FMUs. This folder also holds configuration files for performing co-simulations.

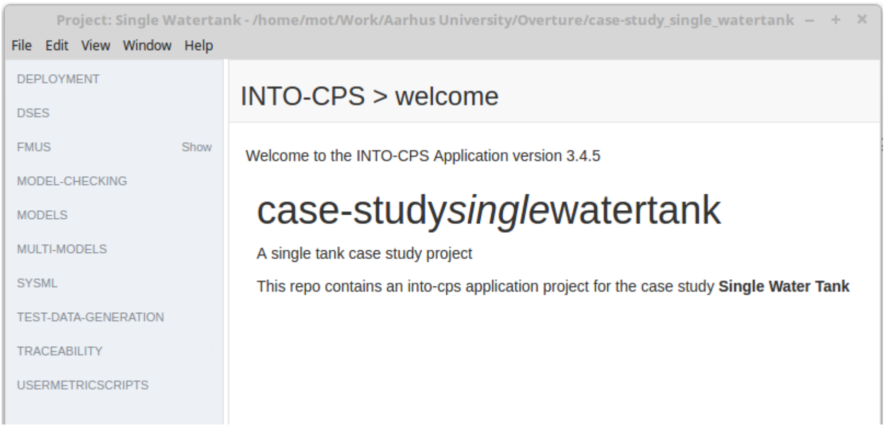
SysML Sources for the SysML model that defines the architecture and connections of the project multi-model.

Test-Data-Generation Configuration files for performing test data generation experiments.

Traceability Traceability-specific files plus context menu for traceability information.

userMetricScripts Data analysis scripts.

In order to create a new project, select *File* → *New Project*, as shown in Figure 4a. This opens the dialog shown in Figure 4b, where you must choose the project name and location – the chosen location will be the root of the project, so you should manually create a new folder for it. To open an existing



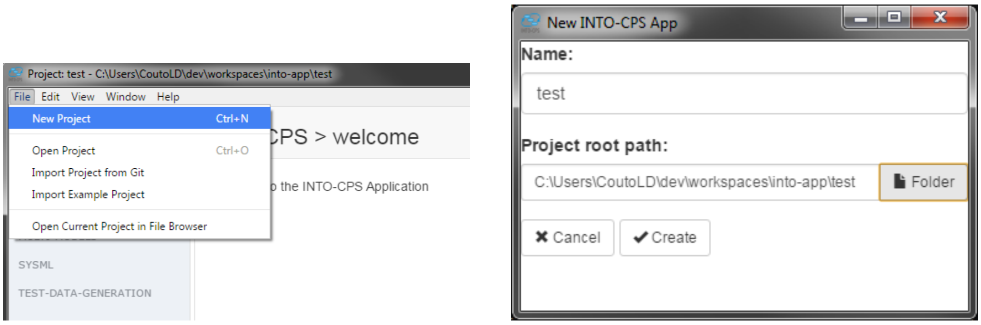
Welcome to the INTO-CPS Application version 3.4.5

case-study*single*watertank

A single tank case study project

This repo contains an into-cps application project for the case study **Single Water Tank**

Figure 3: INTO-CPS project shown in the project browser.



Name:

test

Project root path:

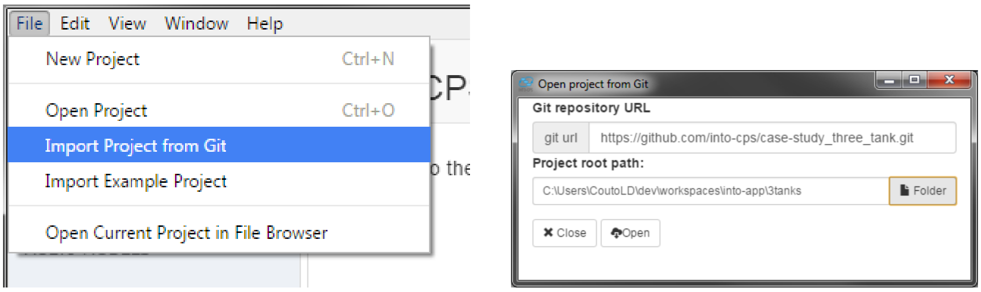
C:\Users\CoutoLD\dev\workspaces\into-app\test

(a) *New Project* menu entry. (b) *New Project* dialog.

Figure 4: Creating a new INTO-CPS project.

project, select *File* → *Open Project*, then navigate to the project's root folder and open it.

To import a project stored in the Git version control system, select *File* → *Import Project from Git*, as shown in Figure 5a. This opens the dialog shown in Figure 5b, where you must choose the project location and also provide the Git URL. The project is checked out using Git, so any valid Git URL will work. You must also have Git available in your PATH environment variable in order for this feature to work. It is possible to import several public example projects that show off the various features of the INTO-CPS tool chain. These examples are described in Deliverable D3.6 [MGP+17]. To import an example, select *File* → *Import Example Project*, as shown in Figure 6a. This opens the dialog box shown in Figure 6b, where you must select which example to import and a project location. The example is checked out via Git, so you must have Git available in your path in order for this feature



Git repository URL

git url https://github.com/into-cps/case-study_three_tank.git

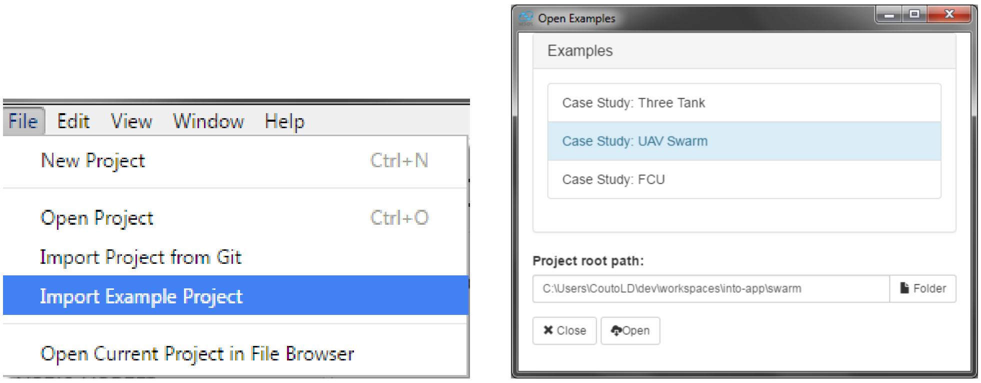
Project root path:

C:\Users\CoutoLD\dev\workspaces\into-app\3tanks

(a) *Import Git Project* menu entry. (b) *Import Git Project* dialog.

Figure 5: Importing a Git project.

to work. For both Git projects and examples, once you begin the import process, a process dialog is displayed, as shown in Figure 7.



Project root path:

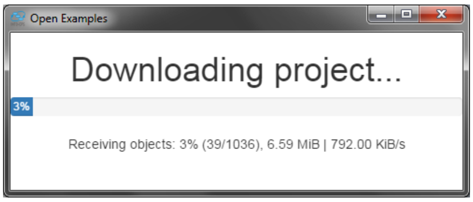
C:\Users\CoutoLD\dev\workspaces\into-app\swarm

(a) *Import Example Project* menu. (b) *Import Example Project* dialog.

Figure 6: Importing examples.

3.3 Multi-Models

For any given project, the INTO-CPS Application allows you to create and edit multi-models and co-simulation configurations. To create a new multi-model, right click the *Multi-models* node in the project browser and select *New multi-model*, as shown in Figure 8. After creation, the new multi-model is automatically opened for editing. To select an existing multi-model for editing, double-click it. Once a multi-model is open, the multi-model view, shown in Figure 9 is displayed. The top box, *Overview*, displays an overview of the input and output variables in the FMUs, as shown in Figure 10. The bottom box, *Configuration*, enables the user to configure the multi-model. In



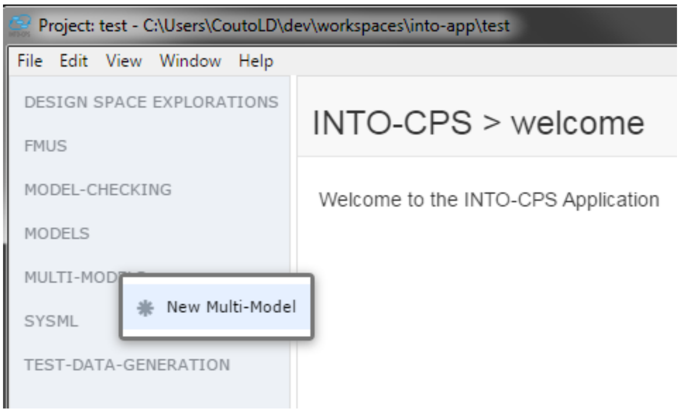
Open Examples

Downloading project...

3%

Receiving objects: 3% (39/1036), 6.59 MiB | 792.00 KiB/s

Figure 7: Progress of project imports through Git.

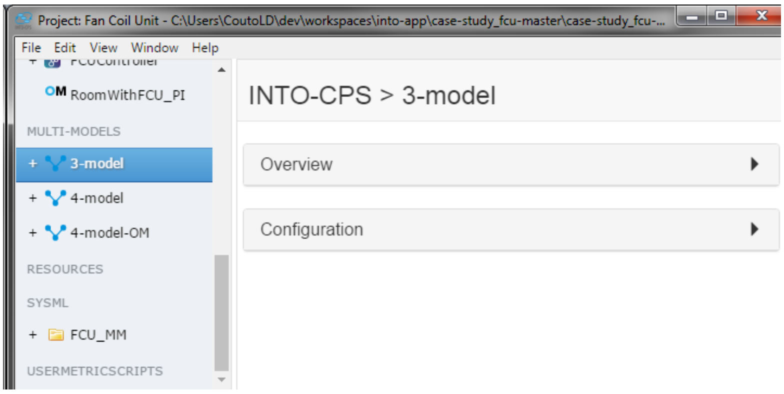


Project: test - C:\Users\CoutoLD\dev\workspaces\into-app\test

INTO-CPS > welcome

Welcome to the INTO-CPS Application

Figure 8: Creating a new multi-model.



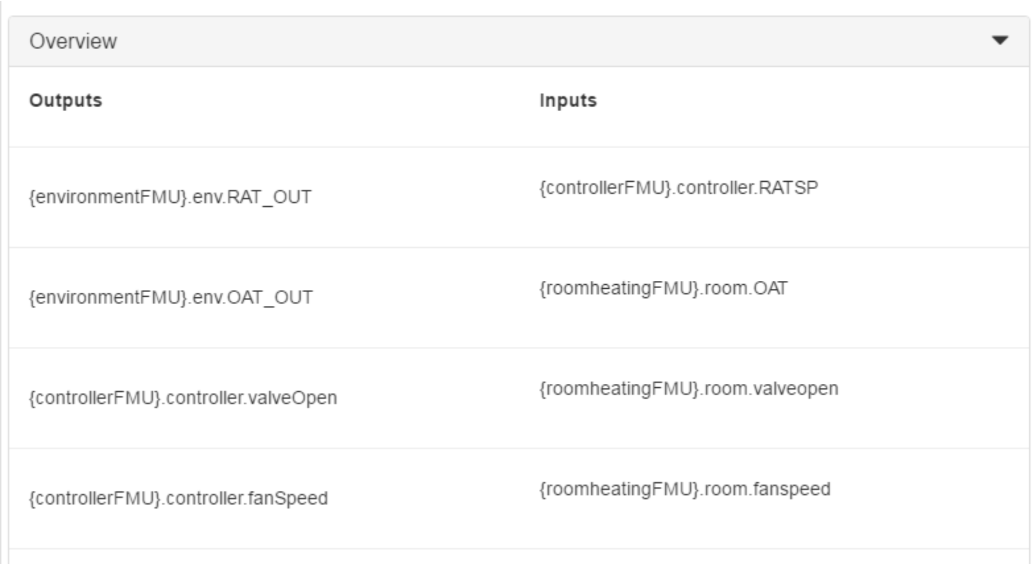
Project: Fan Coil Unit - C:\Users\CoutoLD\dev\workspaces\into-app\case-study_fcu-master\case-study_fcu-...

INTO-CPS > 3-model

Figure 9: Main multi-model view.

order to configure a multi-model, it must first be unlocked for editing by clicking the *Edit* button at the bottom of the *Configuration* box. There are four main areas dedicated to configuring various aspects of a multi-model.

The *FMUs* area, shown in Figure 11, allows you to remove or add FMUs and to associate the FMUs with their files by browsing to, or typing, the path of the FMU file. For each FMU file a marker is displayed indicating

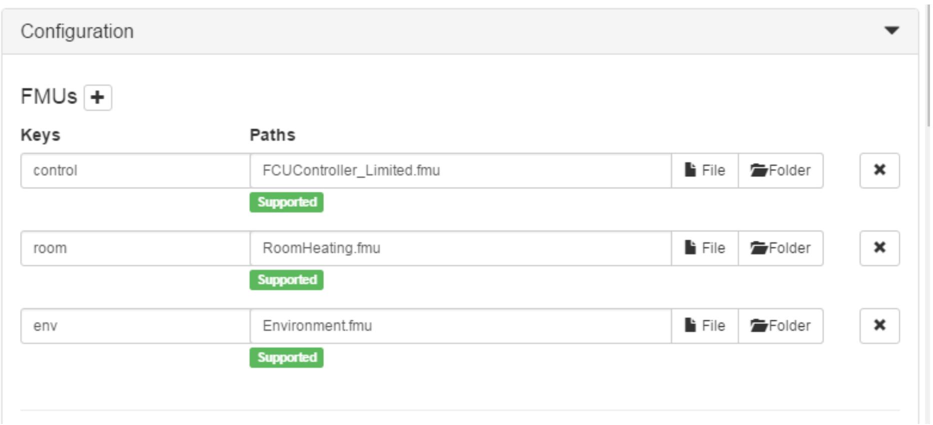


Overview

Outputs	Inputs
{environmentFMU}.env.RAT_OUT	{controllerFMU}.controller.RATSP
{environmentFMU}.env.OAT_OUT	{roomheatingFMU}.room.OAT
{controllerFMU}.controller.valveOpen	{roomheatingFMU}.room.valveopen
{controllerFMU}.controller.fanSpeed	{roomheatingFMU}.room.fanspeed

Figure 10: Multi-model overview.

whether the FMU is supported by the INTO-CPS Application and can be used for co-simulation on the current platform. The *FMU instances* area,



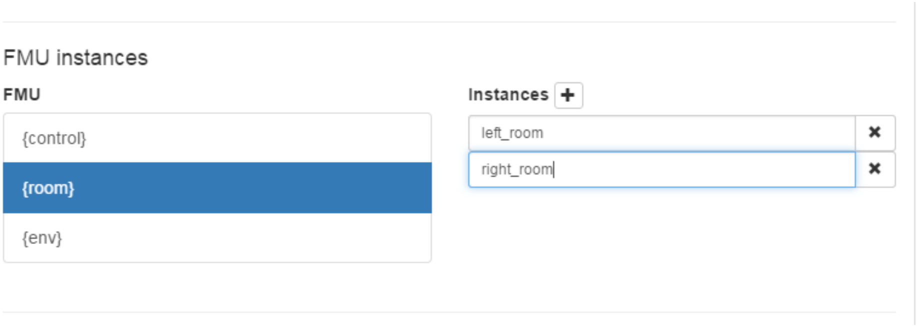
Configuration

FMUs +

Keys	Paths
control	FCUController_Limited.fmu Supported
room	RoomHeating.fmu Supported
env	Environment.fmu Supported

Figure 11: FMUs configuration.

shown in Figure 12, allows you to create or remove FMU instances and name them. A multi-model consists of one or more interconnected instances of various FMUs. More than one instance may be created for a given FMU. As a convenient workflow shortcut, the *Connections* area, shown in Figure 13, allows you to connect output variables from an FMU instance into input variables of another:



FMU instances

FMU	Instances
{control}	left_room
{room}	right_room
{env}	

Figure 12: FMU instances configuration.

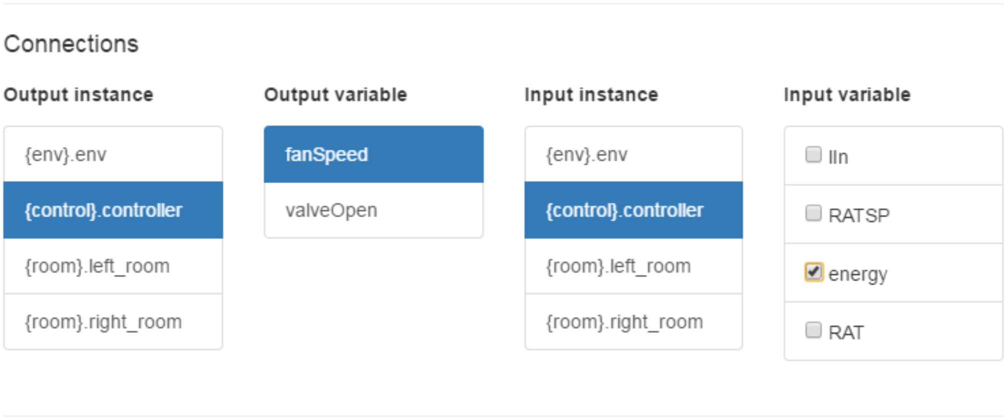
1. Click the desired output FMU instance in the first column. The output variables for the selected FMU appear in the second column.
2. Click the desired output variable in the second column. The input instances appear in the third column.
3. Click the desired FMU input instance in the third column. The input variables for the selected FMU appear in the fourth column.
4. Check the box for the desired input variable in the fourth column.

This facility makes it unnecessary to return to Modelio whenever small changes must be made to the connection topology of the multi-model[4]. The *Initial values of parameters* area, shown in Figure 14, allows you to set the initial values of any parameters defined in the FMUs:

1. Click the desired FMU instance in the *Instance Column*.
2. Select the desired parameter in the *Parameters* dropdown box and click *Add*.
3. Type the parameter value in the box that appears.

Once the multi-model configuration is complete, click the *Save* button at the bottom of the *Configuration* box.

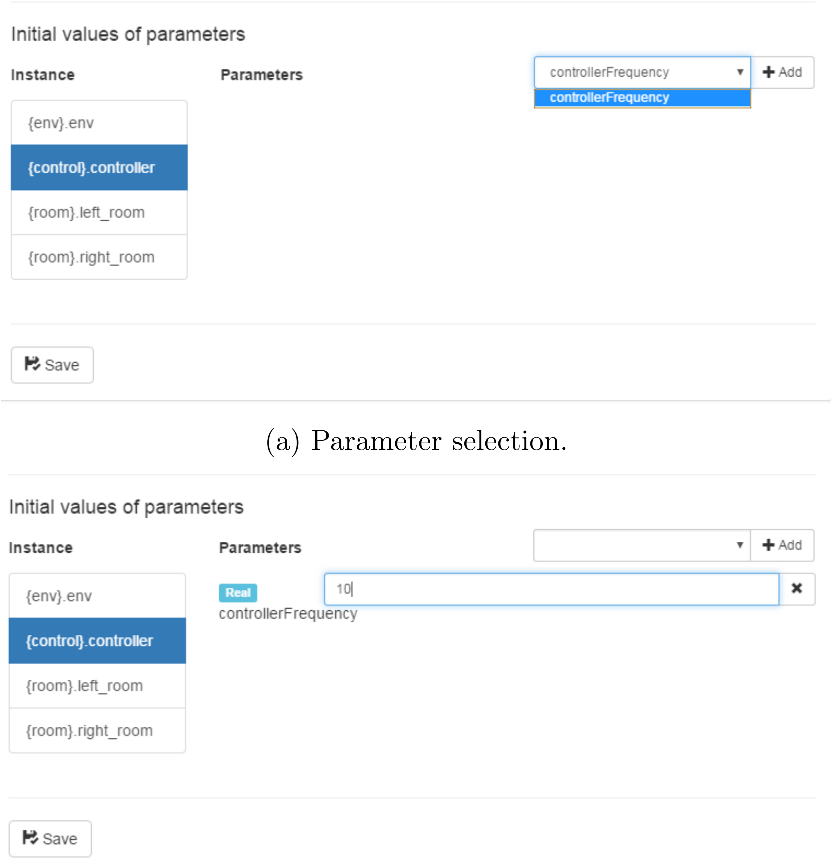
[4] Changes made to a multi-model or FMU outside of the INTO-CPS Application will cause internal CRC checks to fail. If this route is taken, it will be necessary to open the multi-model configuration again in the INTO-CPS Application and go through the edit-save procedure without making any changes. This will re-validate the multi-model configuration.



Connections

Output instance	Output variable	Input instance	Input variable
{env}.env	fanSpeed	{env}.env	□ lIn
{control}.controller	valveOpen	{control}.controller	□ RATSP
{room}.left_room		{room}.left_room	☑ energy
{room}.right_room		{room}.right_room	□ RAT

Figure 13: Connections configuration.



Initial values of parameters

Instance: {env}.env, {control}.controller, {room}.left_room, {room}.right_room

Parameters

controllerFrequency ▾ + Add

controllerFrequency

(a) Parameter selection.

Initial values of parameters

Instance: {env}.env, {control}.controller, {room}.left_room, {room}.right_room

Parameters

▾ + Add

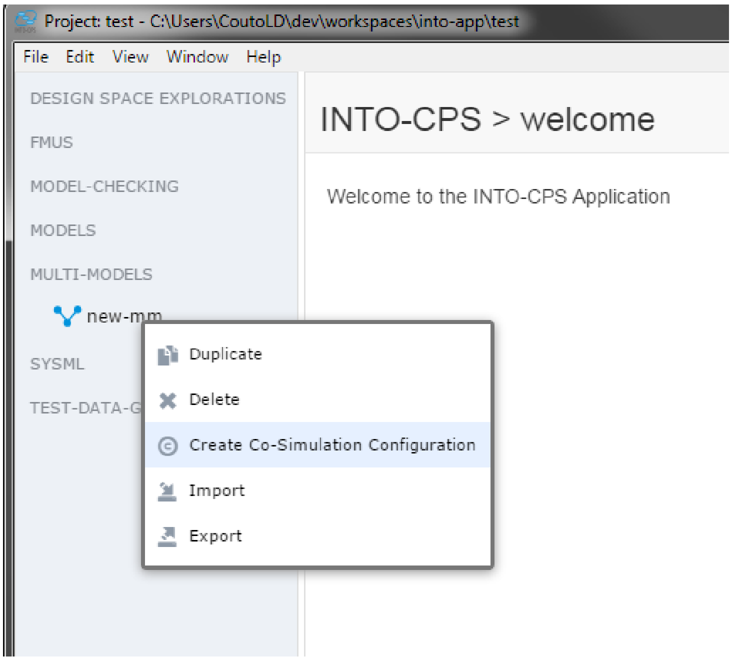
Real controllerFrequency: 10 ✖

(b) Parameter value input.

Figure 14: Initial values of parameters configuration.

3.4 Co-simulations

To execute co-simulations of a multi-model, a co-simulation configuration is needed. To create a co-simulation configuration, right click the desired multi-model and select *Create Co-Simulation Configuration*, as shown in Figure 15. After creation, the new configuration automatically opens for editing. To select an existing co-simulation configuration, double-click it. Once a configuration is open, the co-simulation configuration, shown in Figure 16, is displayed. The top box, *Configuration*, lets you configure the co-simulation. The bottom box, *Simulation*, lets you execute the co-simulation. In order to configure a co-simulation, the configuration must first be unlocked for editing by clicking the *Edit* button at the bottom of the *Configuration* box. There are seven things to configure for a co-simulation, discussed next.



Project: test - C:\Users\CoutoLD\dev\workspaces\into-app\test

INTO-CPS > welcome

Welcome to the INTO-CPS Application

Figure 15: Creating a co-simulation configuration.

Basic Configuration, shown in Figure 17, allows you to select the start and end time for the co-simulation as well as the master algorithm to be used. For every algorithm, there are configuration parameters that can be set. These are displayed below the top area, as shown in Figure 18. These parameters differ with the master algorithm chosen. Parameters are further documented in Deliverable D4.3b [PBL+17].

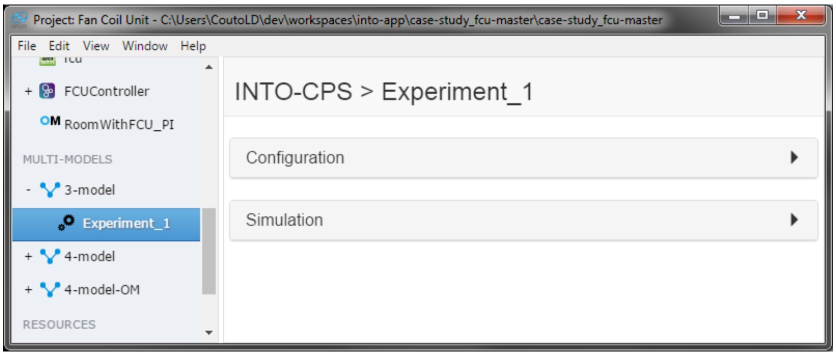
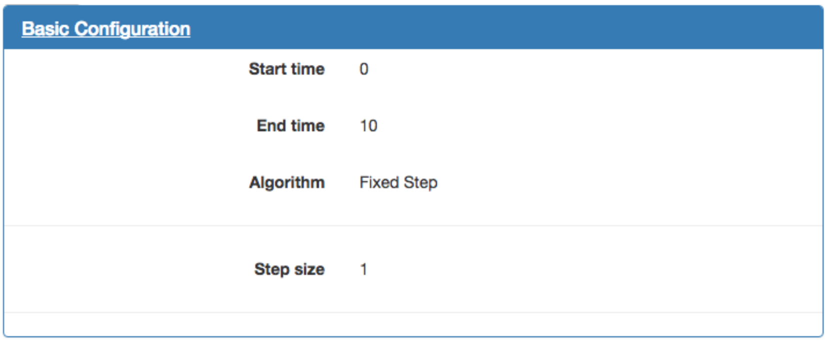


Figure 16: Main co-simulation configuration view.


Basic Configuration

Start time 0

End time 10

Algorithm Fixed Step

Step size 1

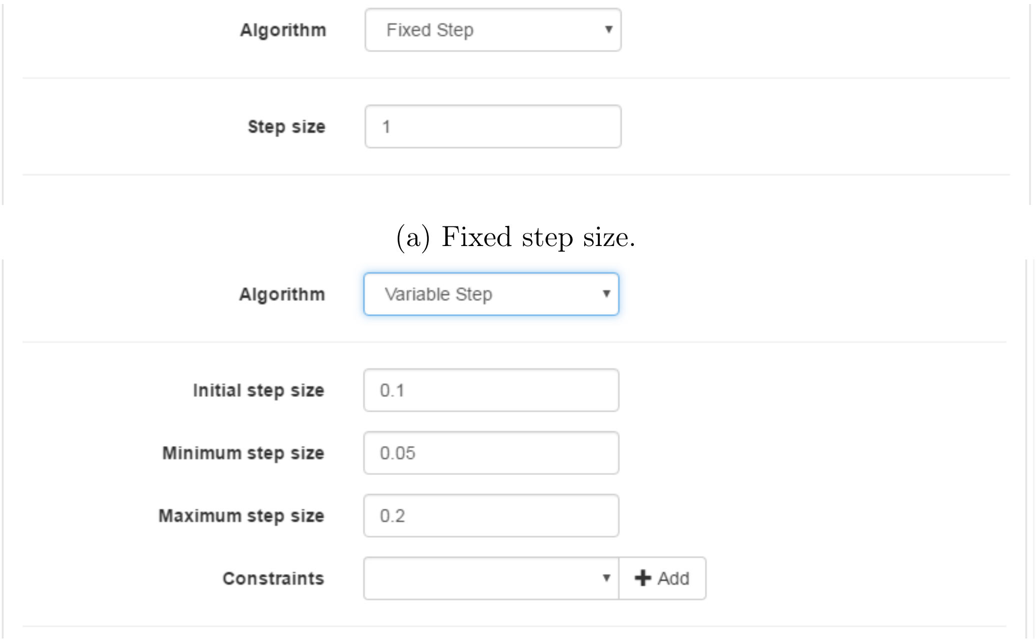
Figure 17: Start/End time and master algorithm configuration.

The *Visibility* area, shown in Figure 19, controls loggable FMU output. *Visible* indicates whether the FMU gives any visible feedback, *e.g.* graphs. *Logging on* indicates whether the FMU should use the logging system and send log info back to the COE. *Enable all log categories per instance* enables all log categories listed inside each FMU. *Global coe log level override* enables the user to override the pre-set log level in the COE. This is for debugging failing simulations and should be left unset or at “error” or “warning” level.

The *Stabilization* area, shown in Figure 20, allows the user to enable the global co-simulation stabilization feature. These parameters are passed to the NumPy `isclose()` function[5].

The *Live Plotting* area, shown in Figure 21, enables the user to define multiple graphs (currently this comes at a relatively high display cost.) Each graph can either be external (in its own window) or internal (embedded). The

[5] https://docs.scipy.org/doc/numpy-1.13.0/reference/generated/numpy.isclose.html



Algorithm: Fixed Step

Step size: 1

(a) Fixed step size.

Algorithm: Variable Step

Initial step size: 0.1

Minimum step size: 0.05

Maximum step size: 0.2

Constraints:

(b) Variable step size.

Figure 18: Master algorithm configuration.

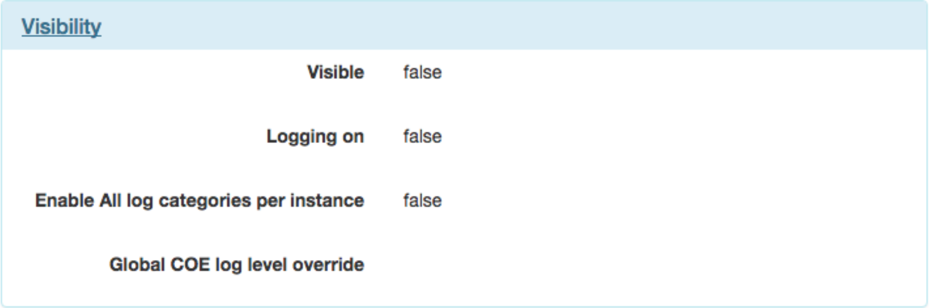
internal graphs are arranged in a configurable grid. The aim of the grid layout is to eliminate the need for scrolling. Additional rows are added if no space is left, but these introduce scrolling. When configuring the graphs, it is possible to use a filter on all available scalar variables to find the ones of interest.

The *Results Saving* area, shown in Figure 22, allows the user to select additional FMU variables to log in the global CSV log file. All connected variables are logged by default.

The *Others* area, shown in Figure 23, allows the user to slow the co-simulation down to wall time and to enable co-simulation parallelisation. Please note that parallelising a co-simulation does not always result in a speed-up [TL16].

The final area, *Post-Processing*, shown in Figure 24, allows the user to attach a post-processing script written in Python that can be executed at the end of co-simulations.

Once the co-simulation configuration is complete, click the *Save* button at the bottom of the *Configuration* box.



Visibility

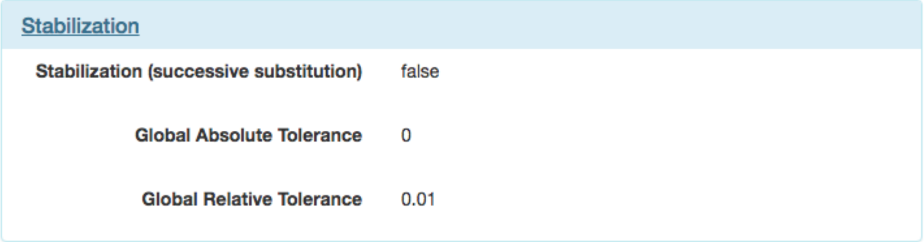
Visible false

Logging on false

Enable All log categories per instance false

Global COE log level override

Figure 19: Visibility configuration.



Stabilization

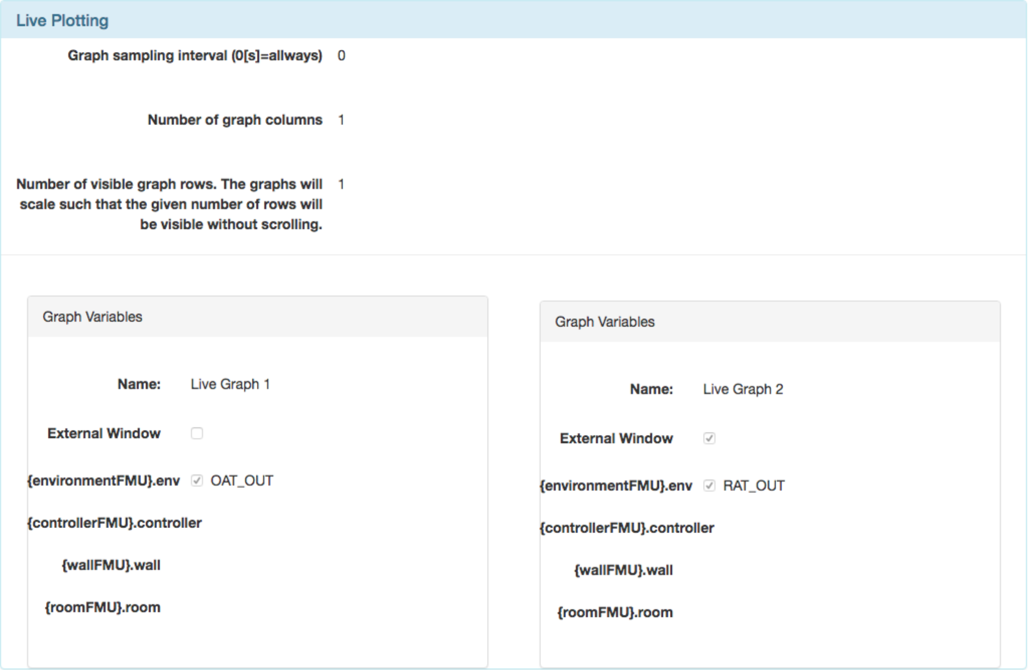
Stabilization (successive substitution) false

Global Absolute Tolerance 0

Global Relative Tolerance 0.01

Figure 20: Stabilization configuration.

The *Simulation* box, shown in Figure 25, allows you to launch a co-simulation. To run a co-simulation, the COE must be online. The area at the top of the *Simulation* box displays the status of the COE. If the COE is offline, you may click the *Launch* button to start it. Once a co-simulation is in progress, any variables chosen for live plotting are plotted in real time in the simulation box, as shown in Figure 26. A progress bar is also displayed. When the simulation is complete, the live stream plot can be explored or exported as a PNG image. In addition, an `outputs.csv` file is created containing the values of every variable marked for logging. This file can be double-clicked and it will open with the default system program for CSV files. It can also be imported into programs such as R, MATLAB or Excel for more complex analysis. Furthermore, it is possible to add a post-processing script that receives the CSV file name and the total simulation time respectively as arguments. It is also possible to configure the amount of logging performed by the COE.



Live Plotting

Graph sampling interval (0[s]=allways) 0

Number of graph columns 1

Number of visible graph rows. The graphs will scale such that the given number of rows will be visible without scrolling. 1

Graph Variables

Name: Live Graph 1

External Window □

{environmentFMU}.env ☑ OAT_OUT

{controllerFMU}.controller

{wallFMU}.wall

{roomFMU}.room

Graph Variables

Name: Live Graph 2

External Window ☑

{environmentFMU}.env ☑ RAT_OUT

{controllerFMU}.controller

{wallFMU}.wall

{roomFMU}.room

Figure 21: Live plotting configuration.

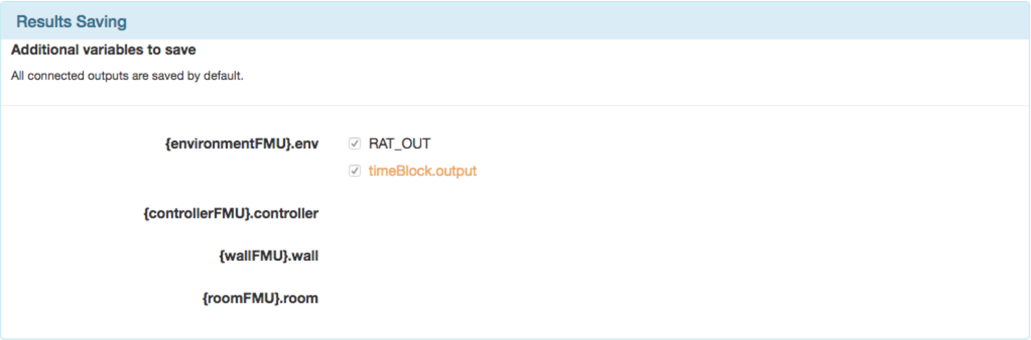
3.5 Additional Features

The INTO-CPS Application has several secondary features, most of them accessible through the *Window* menu, as shown in Figure 27. They are briefly explained below.

`Show Settings` Displays a settings page where various default paths and other options can be set. Development mode can also be enabled from this page, but this feature is primarily meant to be used by developers for testing. Documentation for each setting is found here.

`Show Download Manager` Displays a page where installers can be downloaded for the various tools of the INTO-CPS tool chain, including the COE.

`Show FMU Builder` Displays a page that links to a service where source code FMUs can be uploaded and cross-compiled for various platforms. Note that this is not a secure service and users are discouraged from uploading proprietary FMUs.



Results Saving

Additional variables to save

All connected outputs are saved by default.

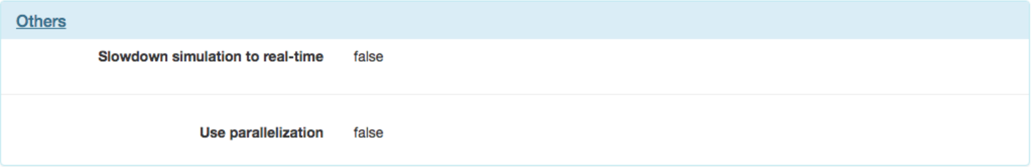
{environmentFMU}.env ☑ RAT_OUT
☑ timeBlock.output

{controllerFMU}.controller

{wallFMU}.wall

{roomFMU}.room

Figure 22: Results logging configuration.



Others

Slowdown simulation to real-time false

Use parallelization false

Figure 23: Miscellaneous configuration options.

3.6 The Co-Simulation Orchestration Engine

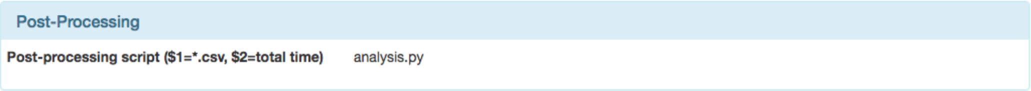
The heart of the INTO-CPS Application is the Co-Simulation Orchestration Engine (COE). This is the engine that orchestrates the various simulation tools (described below), carrying out their respective roles in the overall co-simulation. It runs as a stand-alone server hosting the co-simulation API on port 8080. It can be started from the INTO-CPS Application, but it may be started manually at the command prompt for testing and specialist purposes by executing:

```
java -jar coe.jar 8082
```

TCP port 8082 will be chosen by default if it is omitted in the command above. The COE is entirely hidden from the end user of the INTO-CPS Application, but parts of it are transparently configured through the main interface. The design of the COE is documented in Deliverable D4.1d [LLW+15].

The COE is controlled using simple HTTP requests. These are documented in the API manual, which can be obtained directly from the COE by navigating to `http://localhost:8082`, once the COE is running. Port 8082 should be changed to that specified when the COE is started.

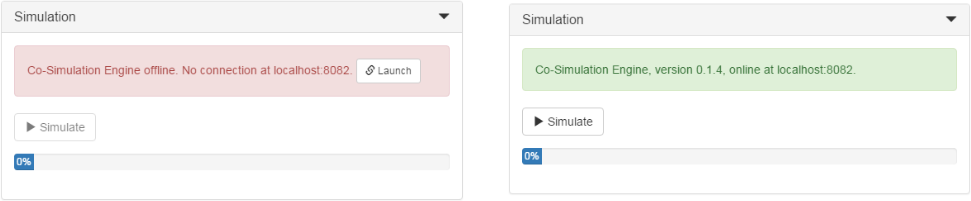
Following the protocol detailed in the API document, a co-simulation session can be controlled manually from the command prompt using, for example,



Post-Processing

Post-processing script ($1=*.csv, $2=total time) analysis.py

Figure 24: Attaching a post-processing script.



Co-Simulation Engine offline. No connection at localhost:8082.

Co-Simulation Engine, version 0.1.4, online at localhost:8082.

(a) COE offline.

(b) COE online.

Figure 25: Launching a co-simulation.

the curl utility, as demonstrated in the following example.

With the COE running, a session must first be created:

```
curl http://localhost:8082/createSession
```

This command will return a sessionID that is used in the following commands.

Next, assuming a COE configuration file called coeconf.json has been created as described in the API manual, the session must be initialized:

```
curl -H "Content-Type:  application/json"
--data @coeconf.json
http://localhost:8082/initialize/sessionID
```

Assuming start and end time information has been saved to a file, say startend.json, the co-simulation can now be started:

```
curl -H "Content-Type:  application/json"
--data @startend.json
http://localhost:8082/simulate/sessionID
```

Once the co-simulation run ends, the results can be obtained as follows:

```
curl -o results.zip
http://localhost:8082/result/sessionID/zip
```

The session can now be terminated:

```
curl http://localhost:8082/destroy/sessionID
```

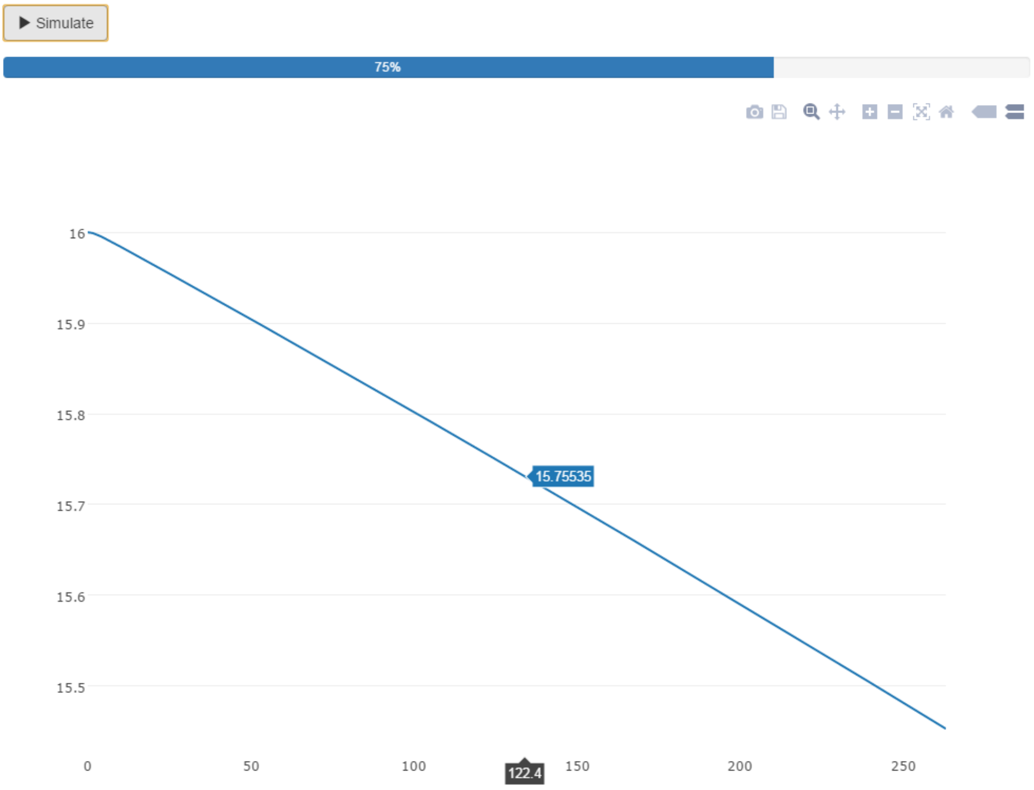


Figure 26: Live stream variable plot.

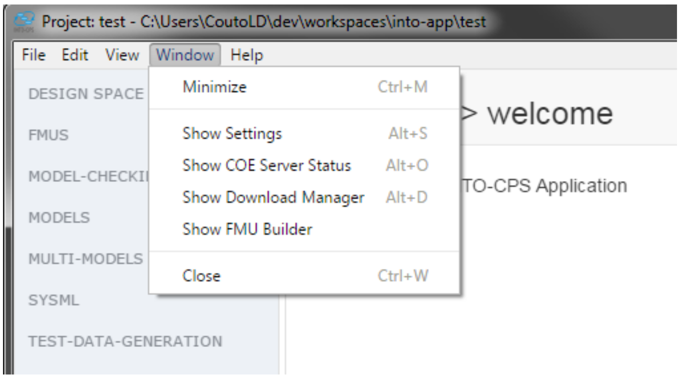


Figure 27: Additional features.

The INTO-CPS Application fundamentally controls the COE in this way.

Distributed co-simulations Presently the INTO-CPS Application can only control the COE in this way for non-distributed co-simulations. In order to run a distributed co-simulation, a distributed version of the COE, dcoe, must be controlled from the command prompt manually, as illustrated above. The distributed COE can be downloaded using the App's *Download Manager*.

In a distributed co-simulation the COE and (some) FMUs execute on physically different compute nodes. The FMUs local to the COE computing node are handled in the same way as in standard co-simulations.

Each FMU on the remote nodes is served externally by a daemon process. This process must be started on the remote node manually as follows:

```
java -jar daemon*-jar-with-dependencies.jar -host
<public-ip> -ip4
```

Here, <public-ip> is the IPv4 address of the compute node.

Next, the distributed COE process must be started manually from the command prompt on its own node, with options specific to distributed co-simulation:

```
java -Dcoe.fmu.custom.factory=
org.intocps.orchestration.coe.distribution.
DistributedFmuFactory
-jar dcoe*-jar-with-dependencies.jar
```

The second difference is the way in which the location of the remote FMUs is specified. For a standard co-simulation, the fmus clause of the co-simulation configuration file (coeconf.json, in our example) contains elements of the form

```
"file://fmu-1-path.fmu"
```

These must be modified for each remote FMU to the following URI scheme:

```
"uri://<public-ip>/FMU/#file://local-fmu-path.fmu"
```

The COE configuration file can, of course, be written manually in its entirety, but it is possible to take a faster route, as follows.

This configuration file is only generated when a co-simulation is executed. It is therefore possible to assemble a "dummy" co-simulation that is similar to the desired distributed version, but with a local FMU topology. Since it is likely that the remote FMUs are not supported on the COE platform itself, it is necessary here to construct "dummy" FMUs with the same interface. If this local co-simulation is then executed briefly, a COE configuration file will be emitted that can be easily modified as described above. The INTO-CPS Application will name this file config.json and emit it to the

`Multi-models` folder under each co-simulation run. This modified configuration can then be used to execute the distributed co-simulation.

4 Modelio and SysML

The INTO-CPS tool chain supports a model-based approach to the development and validation of CPS. The Modelio tool and its SysML/INTO-CPS profile extension provide the diagramming starting point. This section describes the Modelio extension that provides INTO-CPS-specific modelling functionality to the SysML modelling approach.

The INTO-CPS extension module is based on the Modelio SysML extension module, and extends it in order to fulfill INTO-CPS modelling requirements and needs. Figure 28 shows an example of a simple INTO-CPS Architecture Structure Diagram under Modelio. This diagram shows a *System*, named "System"[6], composed of two *EComponents* of kind *Subsystem*, named "SubSystem"[7]. These *Subsystems* have an internal *Variable* called "variable" of type *String* and expose two *FlowPorts* named "portIn" and "portOut". The type of data going through these ports is respectively defined by types *In* and *Out* of kind *StrtType*. More details on the SysML/INTO-CPS profile can be found in Deliverable D2.3a [ZCWO17].

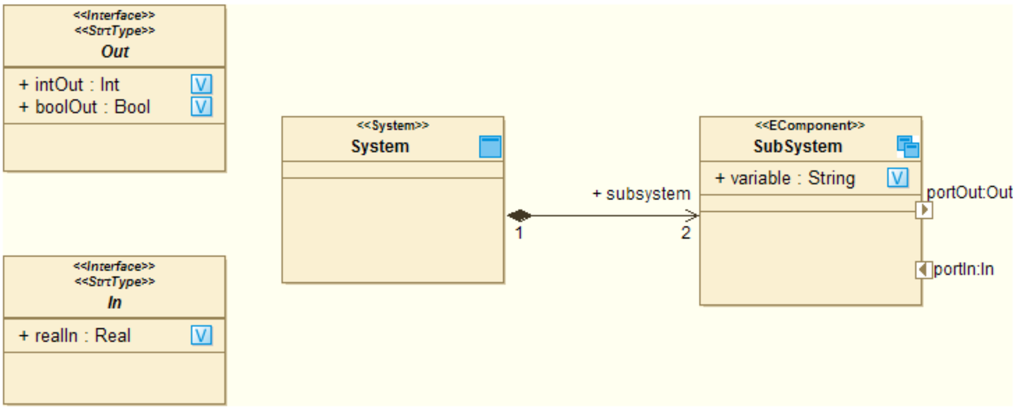


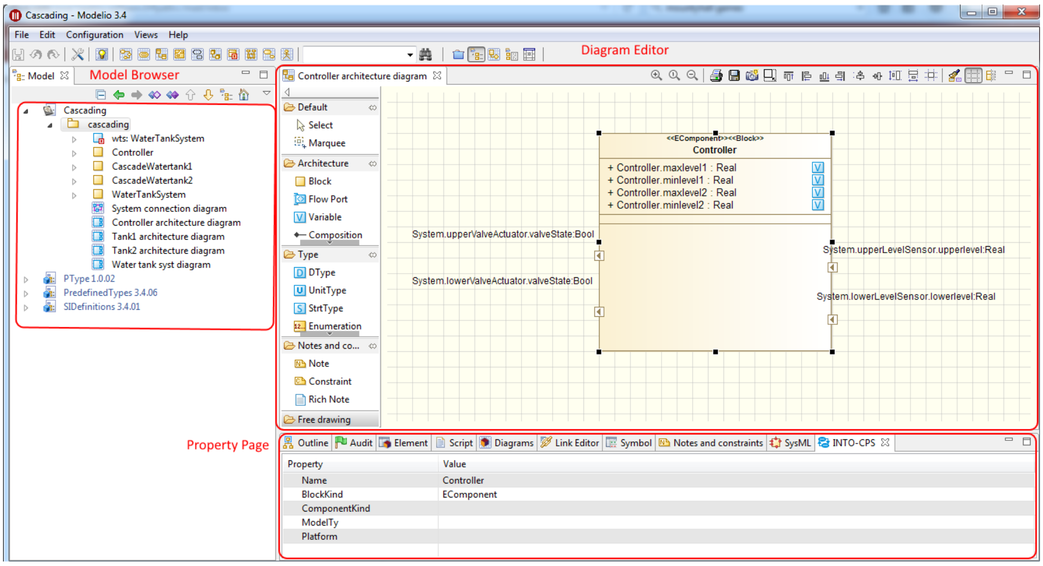
Figure 28: Example INTO-CPS multi-model.

Figure 29 illustrates the main graphical interface after Modelio and the INTO-CPS extension have been installed. Of all the panes, the following three are most useful in the INTO-CPS context.

1. The Modelio model browser, which lists all the elements of your model in tree form.

[6] An abstract description of an INTO-CPS multi-model.

[7] Abstract descriptions of INTO-CPS constituent models.


Cascading - Modelio 3.4
File Edit Configuration Views Help
Model Browser
Diagram Editor
Property Page
Model
Cascading
cascading
wts: WaterTankSystem
Controller
CascadeWatertank1
CascadeWatertank2
WaterTankSystem
System connection diagram
Controller architecture diagram
Tank1 architecture diagram
Tank2 architecture diagram
Water tank syst diagram
PType 1.0.02
PredefinedTypes 3.4.06
SIDefinitions 3.4.01
Controller architecture diagram
Default
Select
Marquee
Architecture
Block
Flow Port
Variable
Composition
Type
DType
UnitType
StrtType
Enumeration
Notes and co...
Note
Constraint
Rich Note
Free drawing
<<EComponent>><<Block>>
Controller
+ Controller.maxlevel1 : Real
+ Controller.minlevel1 : Real
+ Controller.maxlevel2 : Real
+ Controller.minlevel2 : Real
System.upperValveActuator.valveState:Bool
System.lowerValveActuator.valveState:Bool
System.upperLevelSensor.upperlevel:Real
System.lowerLevelSensor.lowerlevel:Real
Outline Audit Element Script Diagrams Link Editor Symbol Notes and constraints SysML INTO-CPS

Property	Value
Name	Controller
BlockKind	EComponent
ComponentKind	
ModelTy	
Platform	

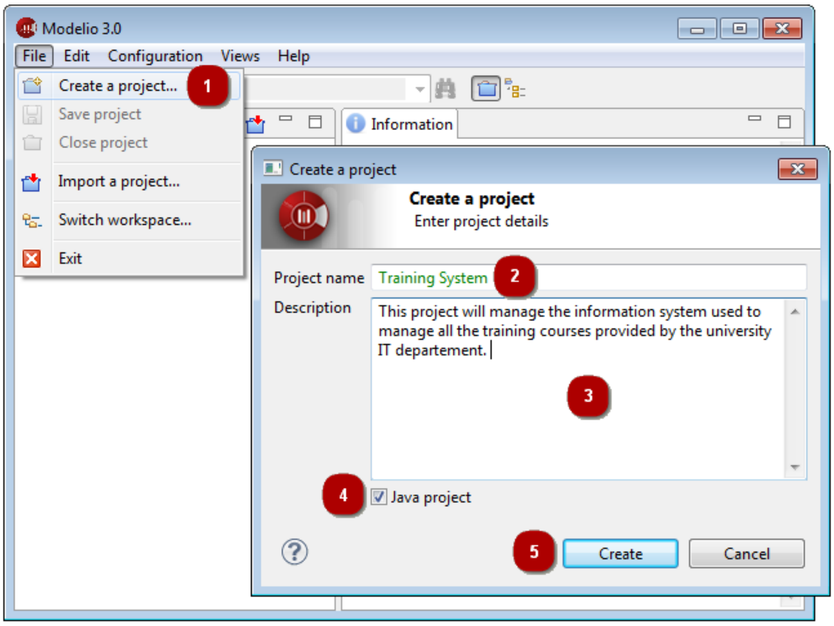
Figure 29: Modelio for INTO-CPS.

2. The diagram editor, which allows you to create INTO-CPS design architectures and connection diagrams.
3. The INTO-CPS property page, in which values for properties of INTO-CPS subsystems are specified.

4.1 Creating a New Project

In the INTO-CPS Modelling workflow described in Deliverable D3.3a [FGP17], the first step will be to create, as depicted in Figure 30, a Modelio project:

1. Launch Modelio.
2. Click on *File* → *Create a project...*.
3. Enter the name of the project.
4. Enter the description of the project.
5. If it is envisaged that the project will be connected to a Java development workflow in the future (unrelated to INTO-CPS), you can choose to include the Java Designer module by selecting *Java Project*, otherwise de-select this option.
6. Click on *Create* to create and open the project.



Project name: Training System

Description: This project will manage the information system used to manage all the training courses provided by the university IT departement.

☑ Java project

Figure 30: Creating a new Modelio project.

Once you have successfully created a Modelio project, you have to install the Modelio extensions required for INTO-CPS modelling, *i.e.* both Modelio SysML and INTO-CPS extensions, as described at

```
http://into-cps-association.github.io
```

If both modules have been correctly installed, you should be able to create, under any package, an INTO-CPS Architecture Structure Diagram in order to model the first subsystem of your multi-model. For that, in the Modelio model browser, right click on a *Package* element then in the *INTO-CPS* entry, choose *Architecture Structure Diagram* as shown in Figure 31. Once you are sure that the modules have been correctly installed. You are able to start your INTO-CPS SysML modelling.

4.2 INTO-CPS SysML modelling

INTO-CPS SysML modelling activitIES can be succinctly described as the creation and population of INTO-CPS SysML diagrams. Figure 31 shows you how to create an Architecture Structure Diagram. Figure 32 represents an example of an Architecture Structure Diagram. Besides creating an Architecture Structure Diagram from scratch and specifying by hand the *blocks* of your system, the INTO-CPS extension allows the user to create a block

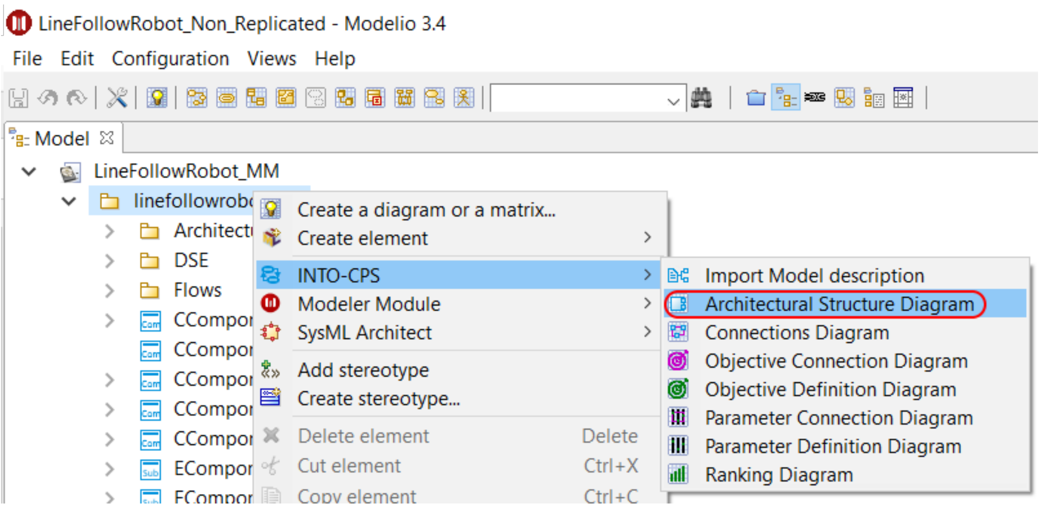


Figure 31: Creating an Architecture Structure diagram.

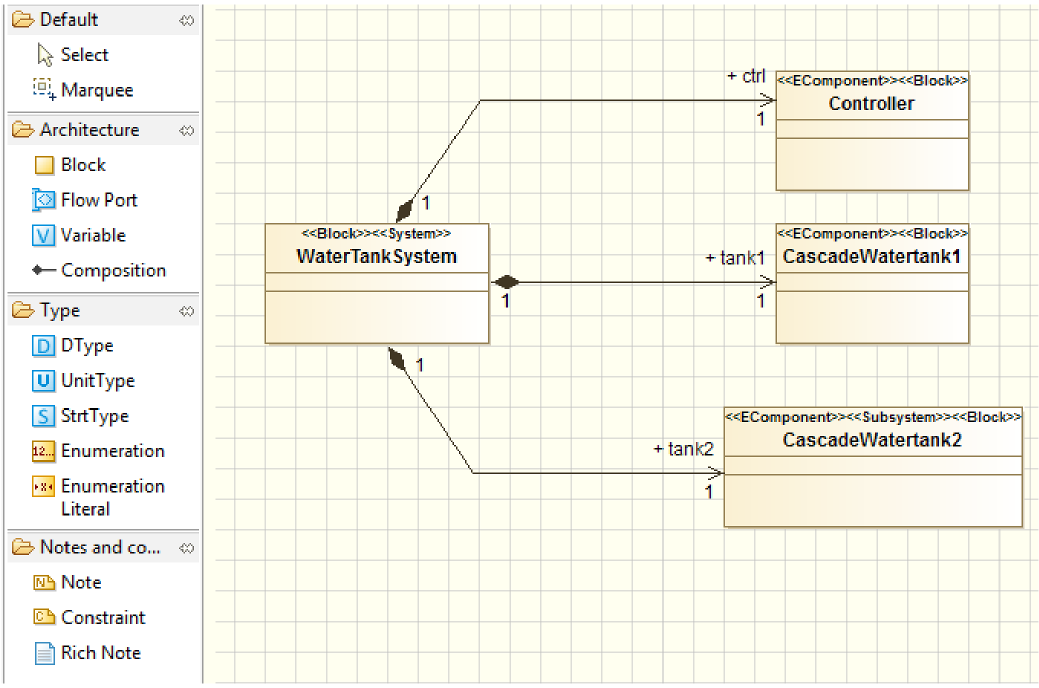


Figure 32: Example Architecture Structure diagram.

from an existing `modelDescription.xml` file . A `modelDescription.xml` file is an artifact defined in the FMI standard which specifies, in XML format, the public interface of an FMU. To import a `modelDescription.xml` file,

1. Right click in the Modelio model browser on a *Package* element, then in the *INTO-CPS* entry choose *Import Model description*, as shown in Figure 33.
2. Select the desired `modelDescription.xml` file (or the `.fmu` file that should contain a `modelDescription.xml` file) in your installation and click on *Import* (Figure 34).

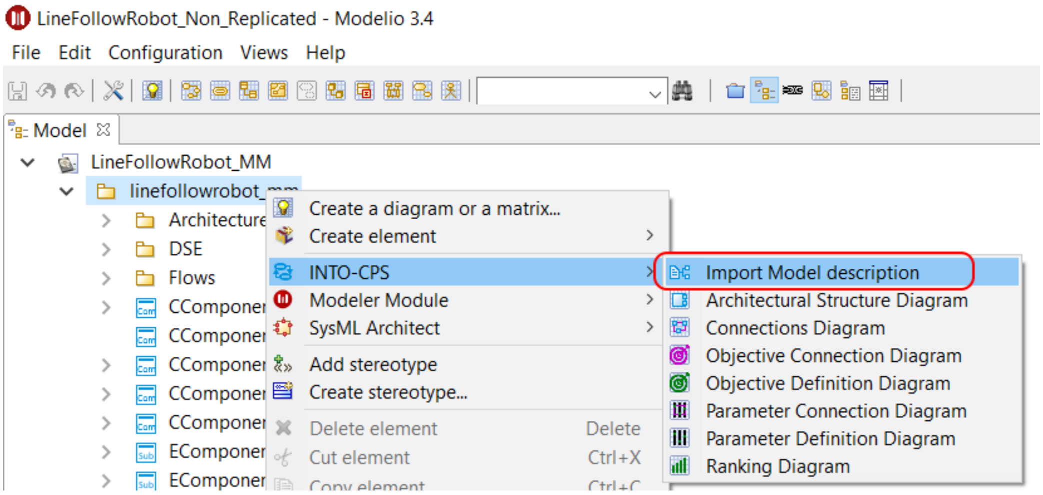
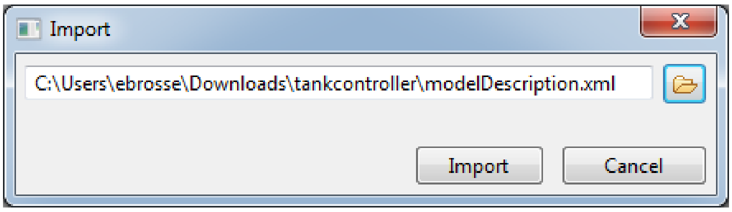


Figure 33: Importing an existing model description.



C:\Users\ebrosse\Downloads\tankcontroller\modelDescription.xml

Figure 34: Model description selection.

This import command creates an Architecture Structure Diagram describing the interface of an INTO-CPS block corresponding to the `modelDescription.xml` file imported, *cf.* Figure 35. Once you have created several such blocks, either from scratch or by importing `modelDescription.xml` files, you must eventually connect instances of them in an INTO-CPS Connection

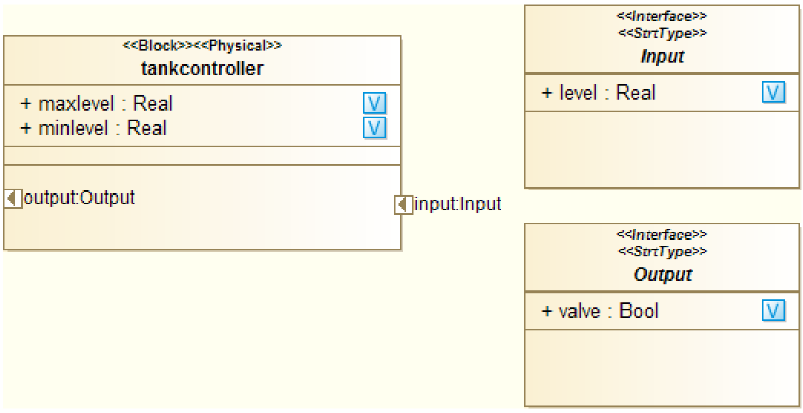


Figure 35: Result of model description import.

Diagram. To create an INTO-CPS Connection diagram, as for an INTO-CPS Architecture Structure Diagram, right click on a *Package* element, then in the *INTO-CPS* entry choose *Connection Diagram*, as shown in Figure 36. Figure 37 shows the result of creating such a diagram. Once you have created all desired block instances and their ports by using the dedicated command in the Connection Diagram palette, you will be able to model their connections by using the connector creation command (Figure 38). At this point your blocks have been defined and the connections have been set. The next step is to simulate your multi-model using the INTO-CPS Application. For that you must first generate a configuration file from your Connection diagram. Select

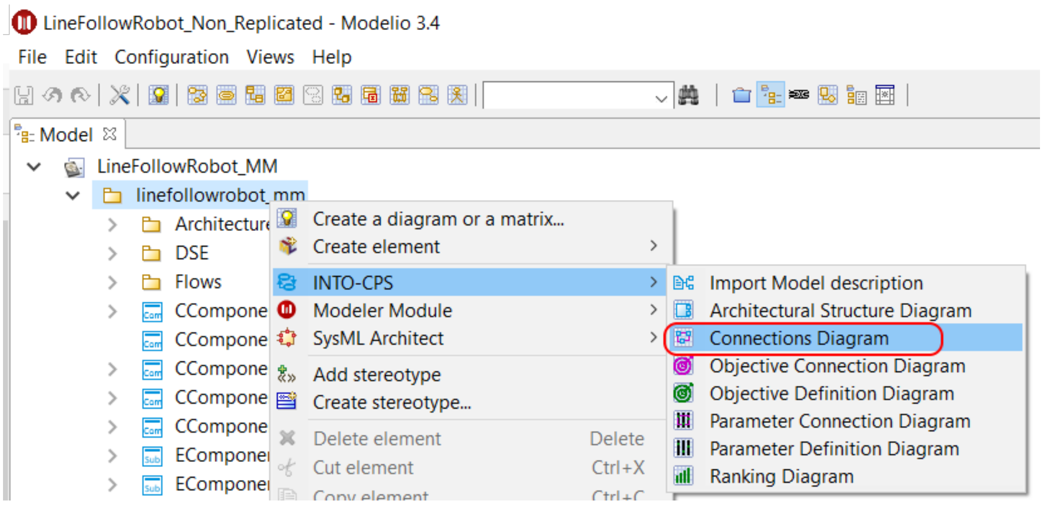
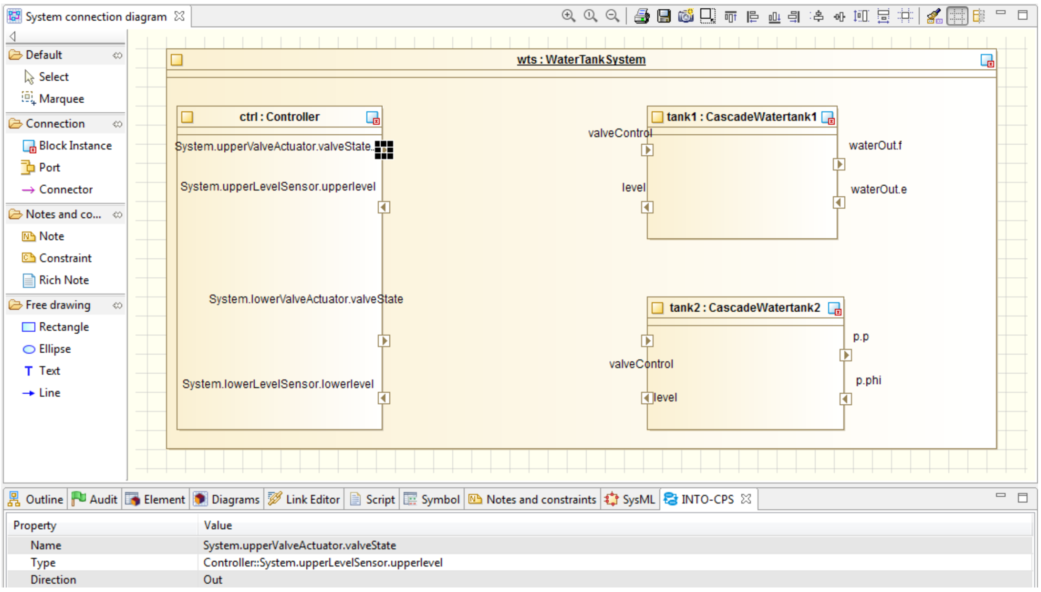


Figure 36: Creating a Connection diagram.



Property	Value
Name	System.upperValveActuator.valveState
Type	Controller::System.upperLevelSensor.upperlevel
Direction	Out

Figure 37: Unpopulated Connection diagram.

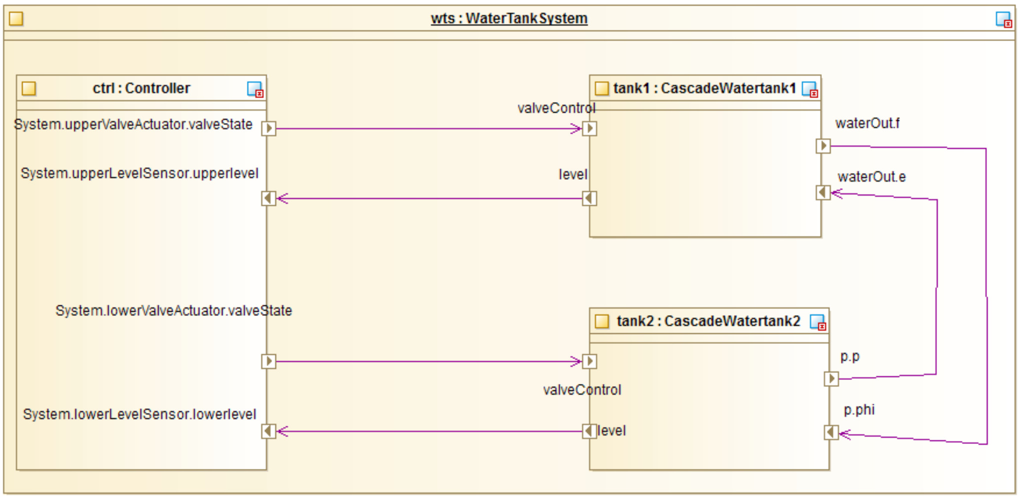

wts : WaterTankSystem
ctrl : Controller
System.upperValveActuator.valveState
System.upperLevelSensor.upperlevel
System.lowerValveActuator.valveState
System.lowerLevelSensor.lowerlevel
tank1 : CascadeWatertank1
valveControl
level
waterOut.f
waterOut.e
tank2 : CascadeWatertank2
valveControl
level
p.p
p.phi

Figure 38: Populated Connection diagram.

the top element in the desired Connection diagram, right click on it and in the *INTO-CPS* entry choose *Generate configuration*, as shown in Figure 39. In the final step, choose a relevant name and click on *Generate*.

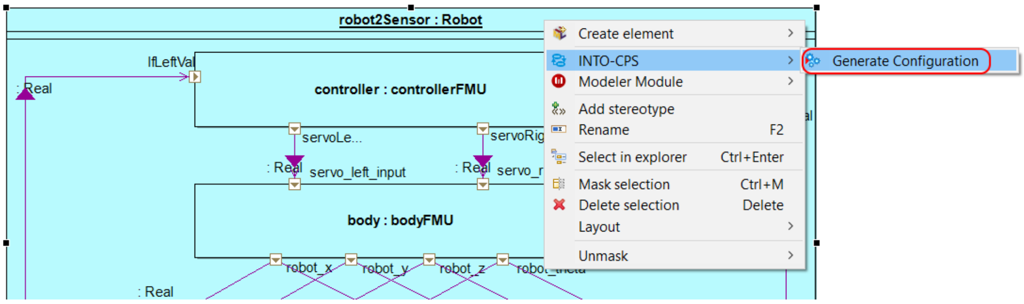


Figure 39: Generating a configuration file.

The SysML Connection diagram defines the components of the system and their connections. The internals of these block instances are created in the various modeling tools and exported as FMUs. The modeling tools Overture, 20-sim and OpenModelica support importing the interface definition (ports) of the blocks in the Connection diagram by importing a `modelDescription.xml` file containing the block name and its interface definition.

Follow these steps to export a `modelDescription.xml` file from Modelio:

1. In Modelio, right-click on the model block in the tree.
2. Select *INTO-CPS* → *Generate Model Description* (see Figure 40).
3. Choose a file name containing the text “modelDescription.xml” and click *Export* (see Figure 41).

4.3 DSE Modelling

For design space exploration (DSE) purposes, a DSE model can be constructed in Modelio as well. This modelling is done by specifying mainly a DSE analysis, its parameters, its objectives and a ranking method. Figure 42 depicts an example of a DSE objective definition. More details and examples can be found in Deliverable D4.2c [BQ16].

Once the DSE model has been created, the DSE analysis can be exported to the INTO-CPS Application. To do so, right-click on *DSE Analysis* in the

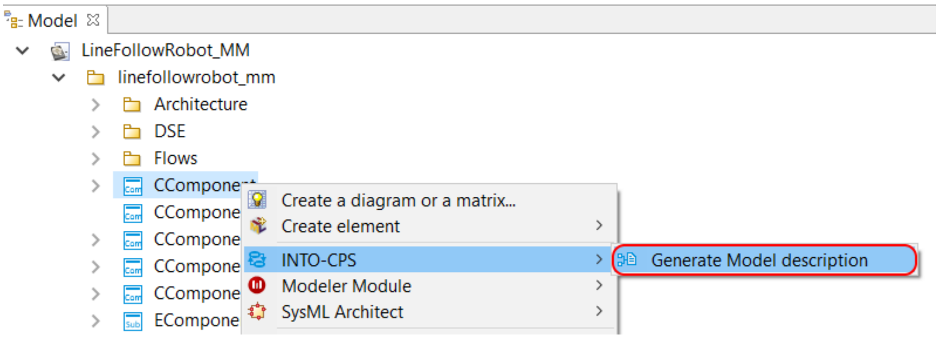
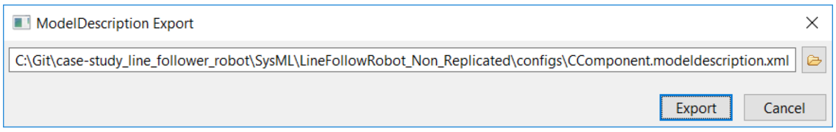


Figure 40: Exporting a `modelDescription.xml` file.



C:\Git\case-study_line_follower_robot\SysML\LineFollowRobot_Non_Replicated\configs\CComponent.modeldescription.xml

Figure 41: Naming the model description file.

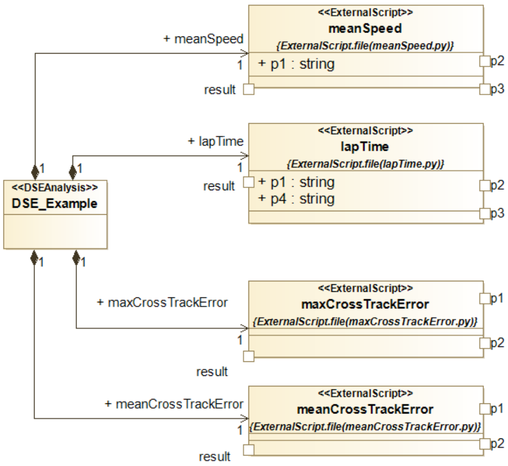


Figure 42: DSE Objective definition.

model tree as depicted in Figure 43. In the final step, choose a relevant name

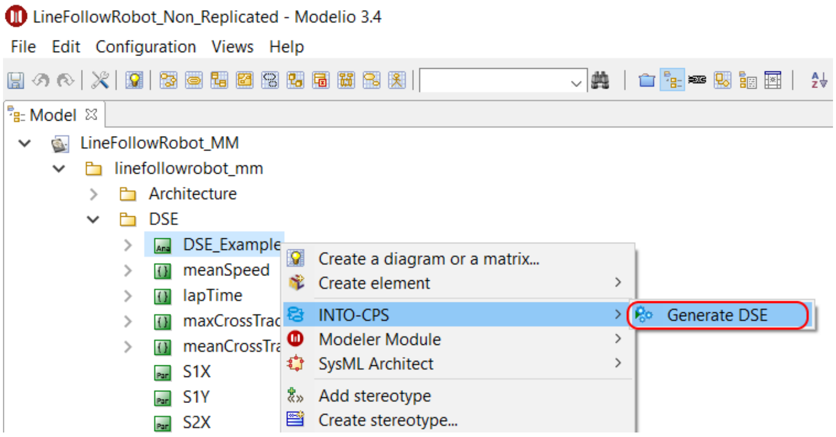


Figure 43: DSE Export command.

and click on *Export*.

4.4 Behavioural Modelling

For test generation and/or model-checking analysis, a behavioural model of the system is required. This is usually referred to as *test model* in order to indicate its purpose. It is typically not identical to the design model, because it can omit or abstract implementation details. The test model needs to capture all inputs and outputs and describe the system's reactions to inputs by means of one or more deterministic state machine diagram. Timing behaviour should be included by means of timers and timer-guarded transitions. For more details and examples refer to the RTT-MBT Manual [Ver15b].

Once the behavioural model has been specified, the *entire model* must be exported in XMI format. To do so, right-click on the *top package* in the model tree as depicted in Figure 44. Then select the file path by using the XMI export window, as shown in Figure 45. Note that compatibility must be set to "EMG UML 3.0.0" and the file extension to ".xmi".

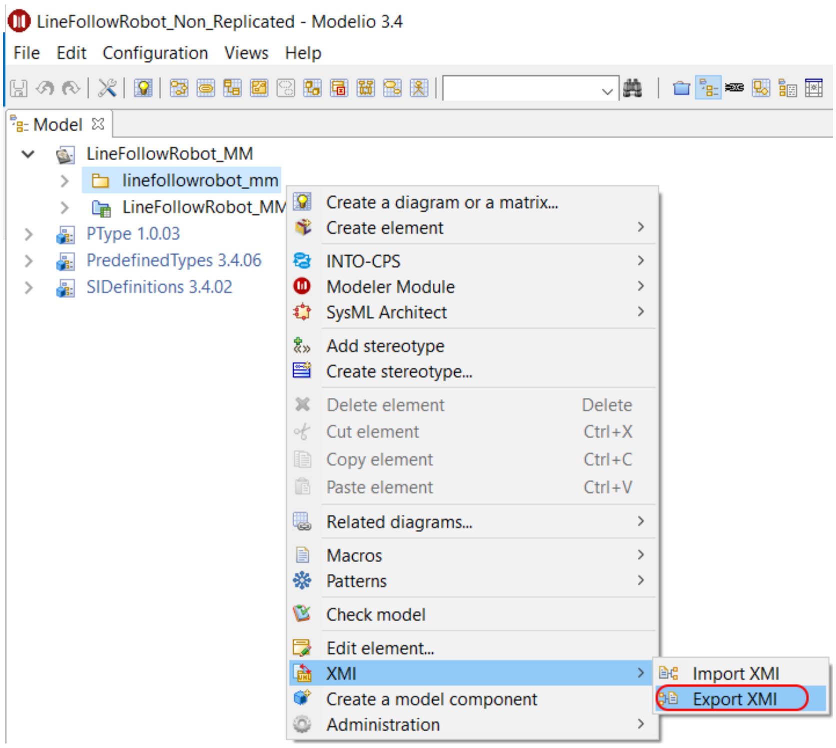
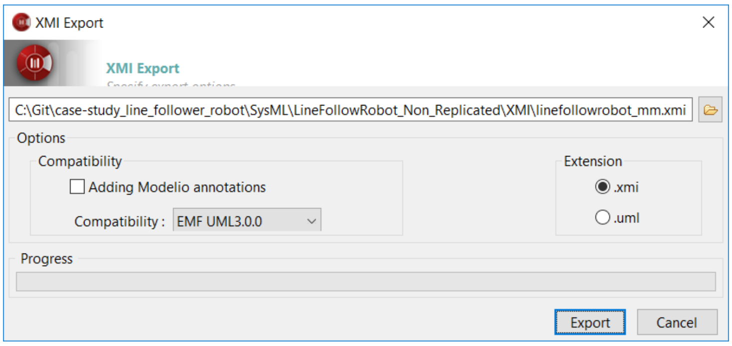


Figure 44: XMI Export command.



C:\Git\case-study_line_follower_robot\SysML\LineFollowRobot_Non_Replicated\XMI\linefollowrobot_mm.xmi

Options

Compatibility

□ Adding Modelio annotations

Compatibility : EMF UML3.0.0

Extension

● .xmi

○ .uml

Progress

Figure 45: XMI export windows.

5 Using the Separate Modelling and Simulation Tools

This section provides a tutorial introduction to the FMI-specific functionality of each of the modelling and simulation tools. This functionality is centered on the role of FMUs for each tool. For more general descriptions of each tool, please refer to Appendix B.

5.1 Overture

Overture implements export of both tool-wrapper as well as standalone FMUs. It also has the ability to import a `modelDescription.xml` file in order to facilitate creating an FMI-compliant model from scratch. A typical workflow in creating a new FMI-compliant VDM-RT model starts with the import of a `modelDescription.xml` file created using Modelio. This results in a minimal project that can be exported as an FMU. The desired model is then developed in this context. This section discusses the complete workflow.

5.1.1 Installing the FMI import/export plugin for Overture

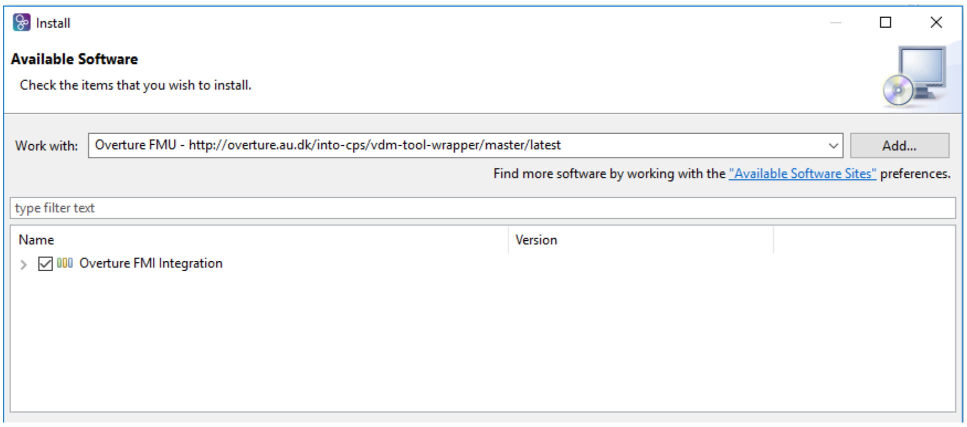
In order to use the FMI integration in Overture it is necessary to install a plugin. Below is a guide to install the plugin:

1. Open Overture.
2. Select *Help -> Install New Software*.
3. Click *Add...*
4. In the *Name:* field write *Overture FMU*.
5. In the *Location:* field there are two options:

   INTO-CPS Application: Download the *Overture FMU Import / Exporter - Overture FMI Support* using the Download Manager mentioned in Section 3.5. Locate the file using the *Archive...* button next to the *Location:* field.

   Update site: Enter the following URL in the *Location:* field: *http://overture.au.dk/into-cps/vdm-tool-wrapper/master/latest*.

6. Check the box next to *Overture FMI Integration* as shown in Figure 46.
7. Click *Next* or *Finish* to accept and install.


Install

Available Software

Check the items that you wish to install.

Work with: Overture FMU - http://overture.au.dk/into-cps/vdm-tool-wrapper/master/latest

Find more software by working with the "Available Software Sites" preferences.

type filter text

Name	Version
☑ Overture FMI Integration	

Figure 46: Installing Overture FMI Integration.

5.1.2 Import of `modelDescription.xml` File

A `modelDescription.xml` file is easily imported into an existing, typically blank, VDM-RT project from the project explorer context menu as shown in Figure 47. This results in the project being populated with the classes necessary for FMU export:

- A VDM-RT `system` class named "System" containing the system definition. The corresponding "System" class for the water tank controller FMU is shown in Listing 48.
- A standard VDM-RT class named "World". This class is conventional and only provides an entry point into the model. The corresponding "World" class for the water tank controller FMU is shown in Listing 49.
- A standard VDM-RT class named "HardwareInterface". This class contains the definition of the input and output ports of the FMU. Its structure is enforced, and a self-documenting annotation scheme[8] is used such that the "HardwareInterface" class may be hand-written. The

[8] The annotation scheme is documented on the INTO-CPS website `into-cps-association.github.io` under "*Constituent Model Development → Overture → FMU Import/Export*.

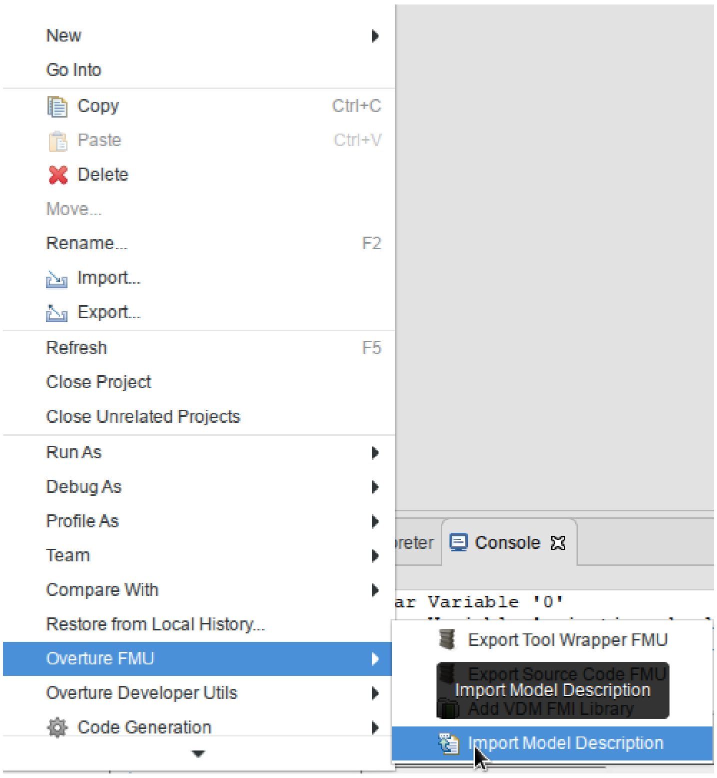


Figure 47: Importing a `modelDescription.xml` file.

corresponding “HardwareInterface” class for the water tank controller FMU is shown in Listing 50.

- The library file `Fmi.vdmrt` which defines the hardware interface port types used in “HardwareInterface”.

```
system System

instance variables

-- Hardware interface variable required by FMU Import/Export
public static hwi: HardwareInterface := new
    HardwareInterface();


instance variables

  public levelSensor : LevelSensor;
  public valveActuator : ValveActuator;
  public static controller : [Controller] := nil;

  cpu1 : CPU := new CPU(<FP>, 20);
operations

public System : () ==> System
System () ==
(
  levelSensor := new LevelSensor(hwi.level);
  valveActuator := new ValveActuator(hwi.valveState);

  controller := new Controller(levelSensor, valveActuator);

  cpu1.deploy(controller,"Controller");
);

end System
```

Figure 48: “System” class for water tank controller.

```
class World

operations

public run : () ==> ()
run() ==
 (start(System`controller);
  block();
 );

private block : () ==>()
block() ==
  skip;

sync

  per block => false;

end World
```

Figure 49: “World” class for water tank controller.

```
class HardwareInterface

values
  -- @ interface: type = parameter, name="minlevel";
  public minlevel : RealPort = new RealPort(1.0);
  -- @ interface: type = parameter, name="maxlevel";
  public maxlevel : RealPort = new RealPort(2.0);

instance variables
  -- @ interface: type = input, name="level";
  public level : RealPort := new RealPort(0.0);

instance variables
  -- @ interface: type = output, name="valve";
  public valveState : BoolPort := new BoolPort(false);

end HardwareInterface
```

Figure 50: “HardwareInterface” class for water tank controller.

The port structure used in the "HardwareInterface" class is a simple inheritance structure, with a top-level generic "Port", subclassed by ports for specific values: booleans, reals, integers and strings. The hierarchy is shown in Listing 51. When a model is developed without the benefit of an existing `modelDescription.xml` file, this library file can be added to the project from the project context menu, also under the category "Overture FMU".

With all the necessary FMU scaffolding in place, the VDM-RT model can be developed as usual.

5.1.3 Tool-Wrapper FMU Export

Models exported as tool-wrapper FMUs require the Overture tool to simulate. Export is implemented such that the VDM interpreter and its FMI interface are included in the exported FMU. Overture tool-wrapper FMUs currently support Win32, Win64, Linux64, Darwin64 and require Java 1.7 to be installed and available in the PATH environment variable.

A tool-wrapper FMU is easily exported from the project context menu as shown in Figure 52. The FMU will be placed in the `generated` folder.

```
class Port

types
  public String = seq of char;
  public FmiPortType = bool | real | int | String;

operations

  public setValue : FmiPortType ==> ()
  setValue(v) == is subclass responsibility;

  public getValue : () ==> FmiPortType
  getValue() == is subclass responsibility;

end Port

class IntPort is subclass of Port

instance variables
  value: int:=0;

operations
  public IntPort: int ==> IntPort
  IntPort(v)==setValue(v);

  public setValue : int ==> ()
  setValue(v) ==value :=v;

  public getValue : () ==> int
  getValue() == return value;

end IntPort

class BoolPort is subclass of Port

instance variables
  ...
```

Figure 51: Excerpt of "`Fmi.vdmrt`" library file defining FMI interface port hierarchy.

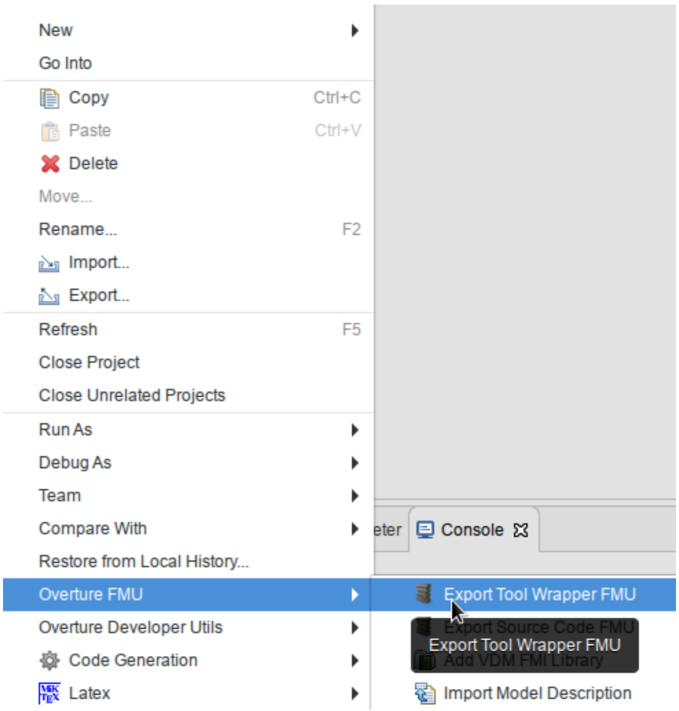


Figure 52: Exporting a tool-wrapper FMU.

5.1.4 Standalone FMU Export

In contrast to tool-wrapper FMUs, models exported as standalone FMUs do not require Overture in order to simulate. Instead, they are first passed through Overture's C code generator such that a standalone implementation of the model is first obtained. Once compiled, this executable model then replaces the combination of VDM interpreter and model, and the FMU executes natively on the co-simulation platform. Currently Mac OS, Windows and Linux are supported.

The export process consists of two steps. First, a source code FMU is obtained from Overture as shown in Figure 53. Second, the INTO-CPS Application must be used to upload the resulting FMU to the FMU compilation server using the built-in facility described in Section 3.5. This is accessed by navigating to *Window* → *Show FMU Builder*.

Please note that only some features of VDM-RT are currently supported by the C code generator. This is discussed in more detail in Section 9.

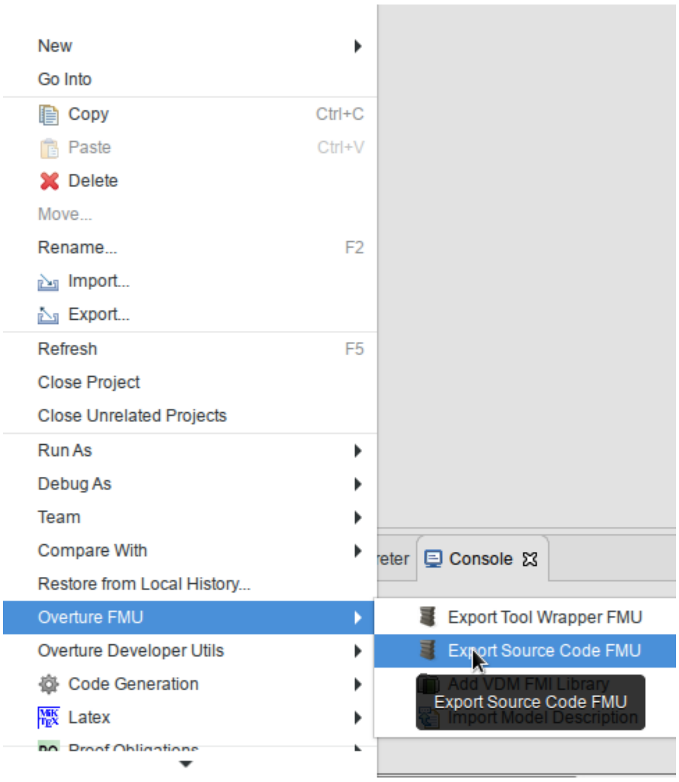


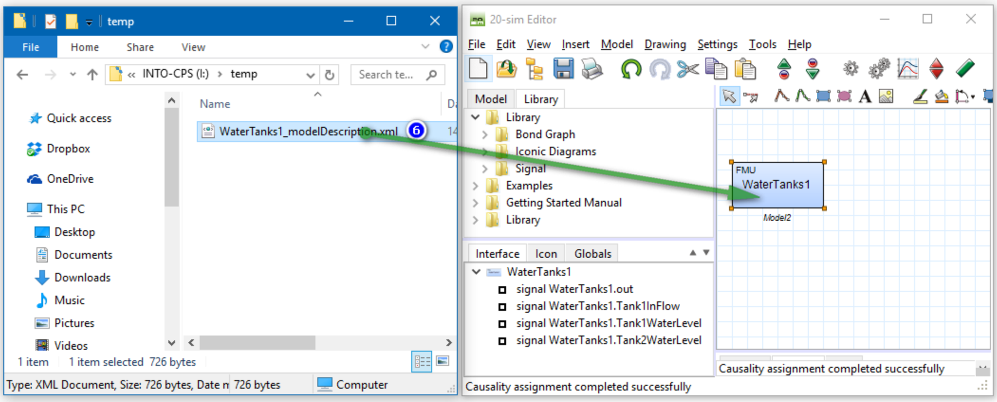
Figure 53: Exporting a standalone FMU.

5.2 20-sim

This section explains the FMI and INTO-CPS related features of 20-sim[9]. We focus on the import of `modelDescription.xml` files, standalone and tool-wrapper FMU export (FMU slave), 3D visualization of FMU operation and an experimental FMU import (FMU master) feature. The complete 20-sim tool documentation can be found in the 20-sim Reference Manual [KGD16].

5.2.1 Import of `modelDescription.xml` File

20-sim can automatically generate an empty 20-sim submodel [10] from a `modelDescription.xml` file. To use the `modelDescription.xml` import, you will need to use the special “4.6.4-intocps” version of 20-sim[11]. A `modelDescription.xml` file can be imported into 20-sim by using Windows Explorer to drag the `modelDescription.xml` file onto your 20-sim model (see Figure 54). This creates a new empty submodel with a blue icon that has the same inputs and outputs as defined in the `modelDescription.xml` file.



Type: XML Document, Size: 726 bytes, Date n 726 bytes

signal WaterTanks1.out
signal WaterTanks1.Tank1InFlow
signal WaterTanks1.Tank1WaterLevel
signal WaterTanks1.Tank2WaterLevel

Causality assignment completed successfully

Causality assignment completed successfully

Figure 54: Import a Model Description in 20-sim.

[9] Note that 20-sim is Windows-only. However, it can run fine using Wine [Win16] on other platforms. For details on using 20-sim under Wine, contact Controllab.

[10] Note that the term “submodel” here should not be confused with the INTO-CPS notion of a “constituent model”. A submodel here is a part in a graphical 20-sim model.

[11] You can download the INTO-CPS version of 20-sim using the Download Manager in the INTO-CPS Application.

5.2.2 Tool-wrapper FMU Export

A tool-wrapper FMU is a communication FMU that opens the original model in the modelling tool and takes care of remotely executing the co-simulation steps inside the modelling tool using some tool-supported communication mechanism. 20-sim supports co-simulation using the XML-RPC-based DESTECS co-simulation interface [LRVG11]. The generation of a tool-wrapper FMU involves two steps that will be explained below:

1. Extend the model with co-simulation inputs, outputs and shared design parameters.
2. Generate a model-specific tool-wrapper FMU.

The tool-wrapper approach involves communication between the co-simulation engine (COE) and the 20-sim model through the tool-wrapper FMU. The 20-sim model should be extended with certain variables that can be set or read by the COE. These variables are the co-simulation inputs and outputs. They can be defined in the model in an equation section called `externals`:

```
externals
    real global export mycosimOutput;
    real global import mycosimInput;
```

To make it possible to set or read a parameter by the co-simulation engine, it should be marked as `'shared'`:

```
parameters
    // shared design parameters
    real mycosimParameter ('shared') = 1.0;
```

The next step is to generate a tool-wrapper FMU for the prepared model. This requires at least the "4.6.3-intocps" version of 20-sim[12]. This version of 20-sim comes with a Python script that generates a tool-wrapper FMU for the loaded model.

To generate the tool-wrapper FMU:

1. Make sure that the tool-wrapper prepared 20-sim model is saved at a writable location. The tool-wrapper FMU will be generated in the same folder as the model.

[12] You can download the INTO-CPS version of 20-sim using the Download Manager in the INTO-CPS Application.

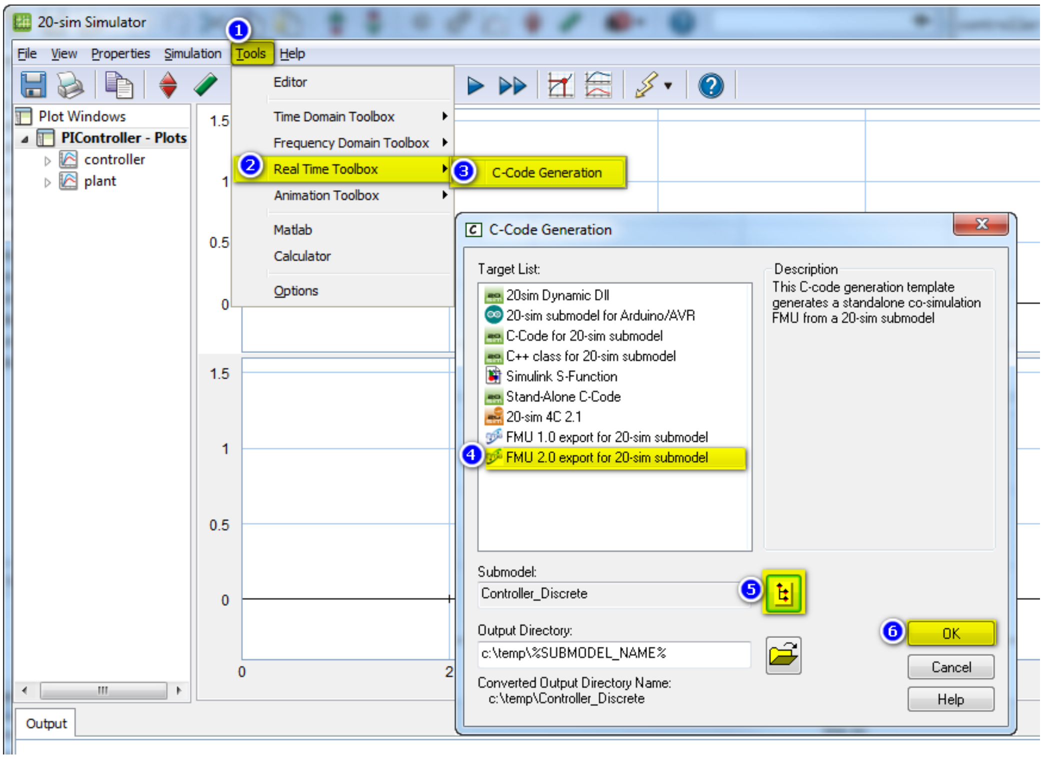
2. Open the prepared 20-sim model in 20-sim.
3. In the 20-sim Editor window, open the menu *Tools* and select the menu option *Generate Toolwrapper FMU*.
4. You can find the generated tool-wrapper FMU as *<modelname>.fmu* in the same folder as your model.

5.2.3 Standalone FMU Export

Starting with 20-sim version 4.6, the tool has a built-in option to generate standalone co-simulation FMUs for both FMI 1.0 and 2.0.

To export a 20-sim submodel as a standalone FMU, make sure that the part of the model that you want to export as an FMU is contained in a submodel and simulate your model to confirm that it behaves as desired.

Next, follow these steps (see also Figure 55):



Description: This C-code generation template generates a standalone co-simulation FMU from a 20-sim submodel

Submodel: Controller_Discrete

Output Directory: c:\temp\%SUBMODEL_NAME%

Converted Output Directory Name: c:\temp\Controller_Discrete

Figure 55: Export an FMU from 20-sim.

1. In the Simulator window, choose from the menu: *Tools*.

2. Select *Real Time Toolbox*.
3. Click *C-Code Generation*.
4. Select the *FMU 2.0 export for 20-sim submodel* target.
5. Select the submodel to export as an FMU.
6. Click OK to generate the FMU. This will pop-up a blue window.

Note that to automatically compile the FMU, you will need the Microsoft Visual C++ 2010, 2013 or 2015 compiler installed (normally included with Microsoft Visual Studio, either Express or Community edition). If 20-sim can find one of the supported VC++ compilers, it starts the compilation and reports where you can find the newly generated FMU. The 20-sim FMU export also generates a *Makefile* that allows you to compile the FMU on Windows using Cygwin, MinGW, MinGW64 or on Linux or MacOS X.

20-sim can currently export only a subset of the supported modelling language elements as standalone C-code. Full support for all 20-sim features is only possible through the tool-wrapper FMU approach (described shortly in Section 5.2.2). The original goal for the 20-sim code generator was to export control systems into ANSI-C code to run the control system under a real-time operating system. As a consequence, 20-sim currently only allows code generation for discrete-time submodels or continuous-time submodels using a fixed-step integration method. Support for variable step size integration methods is not yet included by default in the official 20-sim 4.6 release, but it is already included in the 20-sim "4.6.2-intocps" release and on GitHub (see below). Other language features that are not supported, (or are only partly supported) for code generation, are:

- **Hybrid models:** Models that contain both discrete- and continuous-time sections cannot be generated at once. However, it is possible to export the continuous and discrete blocks separate.
- **File I/O:** The 20-sim "Table2D" block is supported; the "datafromfile" block is not yet supported.
- **External code:** Calls to external code are not supported. Examples are: `DLL()`, `DLLDynamic()` and the MATLAB functions.
- **Variable delays:** The `tdelay()` function is not supported due to the requirement for dynamic memory allocation.
- **Event functions:** `timeevent()`, `frequencyevent()` statements are ignored in the generated code.

- **Fixed-step integration methods:** *Euler*, *Runge-Kutta 2* and *Runge-Kutta 4* are supported.
- **Implicit models:** Models that contain unsolved algebraic loops are not supported.
- **Variable-step integration methods:** *Vode-Adams* and *Modified Backward Differential Formula* (MeBDF) are available on GitHub (see below for the link).

The FMU export feature of 20-sim is being improved continuously based on feedback from INTO-CPS members and other customers. To benefit from bug fixes and to try the latest FMU export features like variable step size integration methods (*e.g.* Vode-Adams and MeBDF), you can download the latest version of the 20-sim FMU export template from:

`https://github.com/controllab/fmi-export-20sim`

Detailed instructions for the installation of the GitHub version of the 20-sim FMU export template can be found on this GitHub page. The GitHub FMU export template can be installed alongside the existing built-in FMU export template.

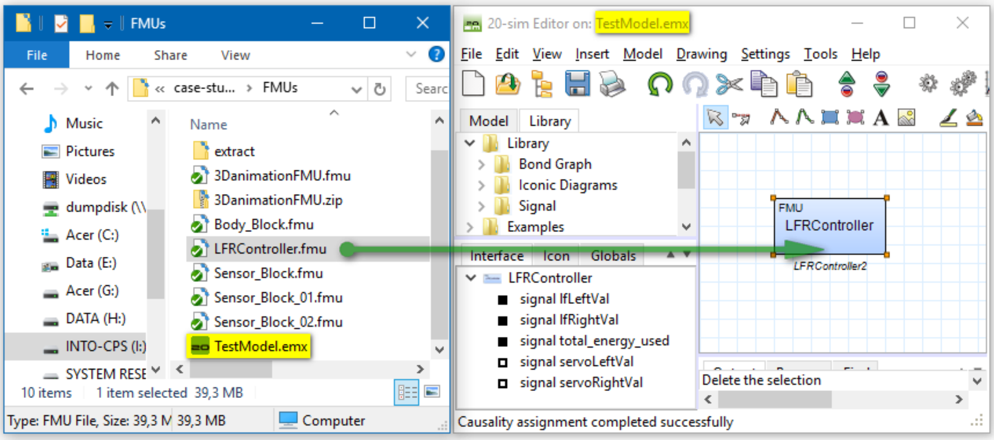
5.2.4 FMI 2.0 Import

The “4.6.4-intocps” version of 20-sim has an experimental option to import an FMU directly in 20-sim for co-simulation within 20-sim itself. This is useful for quickly testing exported FMUs without the need to set-up a full co-simulation experiment in the INTO-CPS application. Presently it can only import FMI 1.0 and 2.0 *co-simulation* FMUs can be imported.

The procedure for importing an FMU as 20-sim submodel is similar to importing a `modelDescription.xml` file. Follow these steps to import an FMU in 20-sim:

1. Copy/move the FMU to the same folder as your model. This is not required but recommended to prevent embedding hardcoded paths in your model.
2. Using Windows Explorer, drag the FMU file on your 20-sim model (see Figure 56).

This creates a new submodel with a blue icon that acts as an FMU wrapper. FMU inputs and outputs are translated into 20-sim submodel input



Causality assignment completed successfully

Figure 56: Importing an FMU in 20-sim.

and output signals. FMU parameters (scalar variables with causality “parameter”) are also available in 20-sim. This means that you can alter the default values of these FMU parameters in 20-sim. The altered FMU parameters are transferred to the FMU during the initialization mode phase of the FMU.

5.3 20-sim 4C

This section describes the features of 20-sim 4C [Con17] [13] developed specifically in support of INTO-CPS and FMI. 20-sim 4C is a rapid prototyping tool that facilitates running C code on hardware to control machines and systems. 20-sim 4C imports models (as generated C code) from multiple sources (*e.g.* 20-sim) and runs them on hardware targets such as embedded ARM boards (*e.g.* Raspberry Pi), PCs running real-time Linux and industrial PLCs.

One of the goals of the INTO-CPS project is to extend the capabilities of the INTO-CPS tool chain toward executing part of a co-simulation on real hardware in real-time. This is known as Hardware-in-the-Loop (HiL) simulation. This section explains how the FMI import and export features of 20-sim 4C can be used to execute source code FMUs on hardware targets in co-simulation under the control of the COE. The complete 20-sim tool documentation can be found in the 20-sim 4C Reference Manual [Kle13]. All

[13] Note that 20-sim 4C is Windows-only, but it can be executed using Wine [Win16] on other platforms.

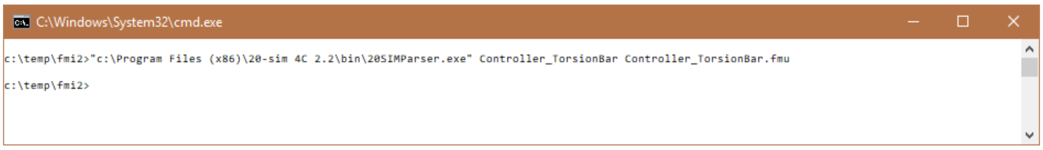
details of the implementation of FMI support in 20-sim 4C can be found in Deliverable D4.3b [PBL+17].

5.3.1 Source Code FMU Import

To import an FMU in 20-sim 4C, it must first be converted to a valid 20-sim 4C project. This is currently done via a command line call at the Windows Command prompt. The command to import a source code FMU in 20-sim 4C is:

```
C:\Program Files (x86)\20-sim 4C 2.2\bin\
20simparser.exe newfmuProjectName fmuFilename.fmu
```

where `newfmuProjectName` is the name of a new directory in which 20-sim 4C will generate the new project. This directory is created as a subdirectory of the current directory. An example is shown in Figure 57. This example creates a new directory in `C:\Temp\fmi2` named `Controller_TorsionBar` and briefly shows the import dialog from Figure 58. After successfully extracting and importing the FMU, 20-sim 4C will start.



```
c:\temp\fmi2>"c:\Program Files (x86)\20-sim 4C 2.2\bin\20SIMParser.exe" Controller_TorsionBar Controller_TorsionBar.fmu

c:\temp\fmi2>
```

Figure 57: Import a source code FMU in 20-sim 4C.

Source code FMUs are deployed to a real-time target as follows:

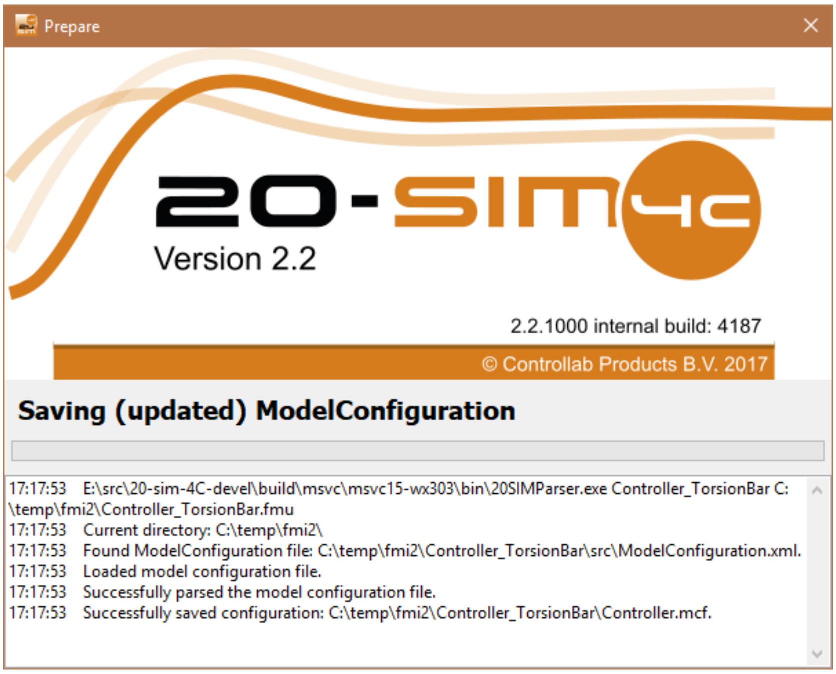
1. The 20-sim 4C window (Figure 59) shows the name of the FMU and its public variables and parameters in the tree at the left side.

2. Use the *Select* button in the *Target Template Selection* box to select the hardware target for the FMU. This shows the *Select Target Configuration* dialog (Figure 60.)

3. Select the *Raspberry Pi 3 (Raspbian, Xenomai 2.6.5)* target.

4. Press the *OK* button to confirm. This will automatically trigger a network scan to find the Raspberry Pi on the network.

5. In case multiple targets are found, select the desired target in the *Please select a target* dialog (Figure 61) and press *OK*.



Prepare
20-sim 4c
Version 2.2
2.2.1000 internal build: 4187
© Controllab Products B.V. 2017

Saving (updated) ModelConfiguration

```
17:17:53   E:\src\20-sim-4C-devel\build\msvc\msvc15-wx303\bin\20SIMParser.exe Controller_TorsionBar C:
\temp\fmi2\Controller_TorsionBar.fmu
17:17:53   Current directory: C:\temp\fmi2\
17:17:53   Found ModelConfiguration file: C:\temp\fmi2\Controller_TorsionBar\src\ModelConfiguration.xml.
17:17:53   Loaded model configuration file.
17:17:53   Successfully parsed the model configuration file.
17:17:53   Successfully saved configuration: C:\temp\fmi2\Controller_TorsionBar\Controller.mcf.
```

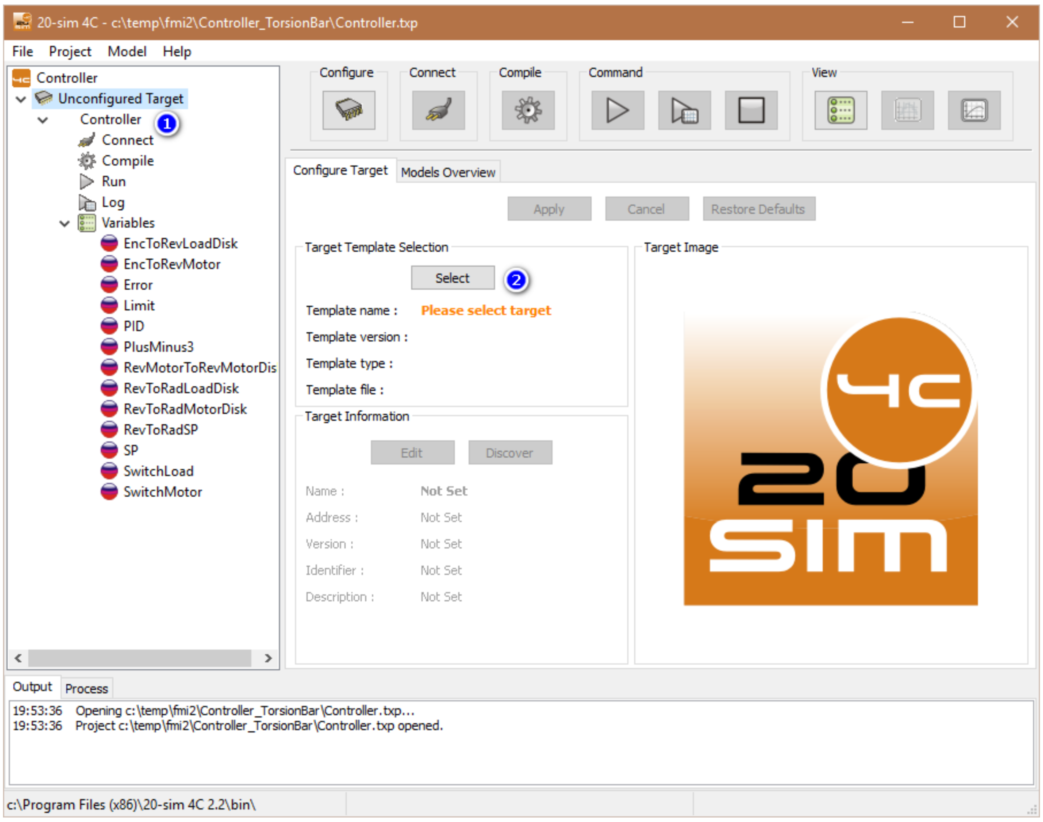
Figure 58: 20-sim 4C FMU importer.

6. In the main 20-sim 4C window, press *Apply* to confirm the target settings. 20-sim 4C will now try to connect to the Raspberry Pi. When the connection is successful, the *Configure* button will turn green. See Figure 62.

7. Click the *Connect* button to go to the connection phase. This will show the inputs and outputs of the FMU and 20-sim 4C allows you to connect them to the on-board I/O pins.

8. To connect an input or output, select the signal and press the *Connect* button or double-click the signal (Figure 63.) This will show the *Connection* dialog as shown in Figure 64.

9. The connection dialog allows you to select an I/O component (*e.g.* GPIO for digital I/O or PWM; see Figure 64) and a port within this component (typically a physical pin or connector on the target device; see Figure 65). Select *OK* to confirm the connection. The I/O available depends on the selected target device. The Raspberry Pi 3 provides by default only digital inputs and outputs and 2 PWM outputs. Extension boards are needed for other I/O.
   Note: In case you would like to use an extension board or external I2C or SPI based I/O chip or other I/O, feel free to ask Controllab for



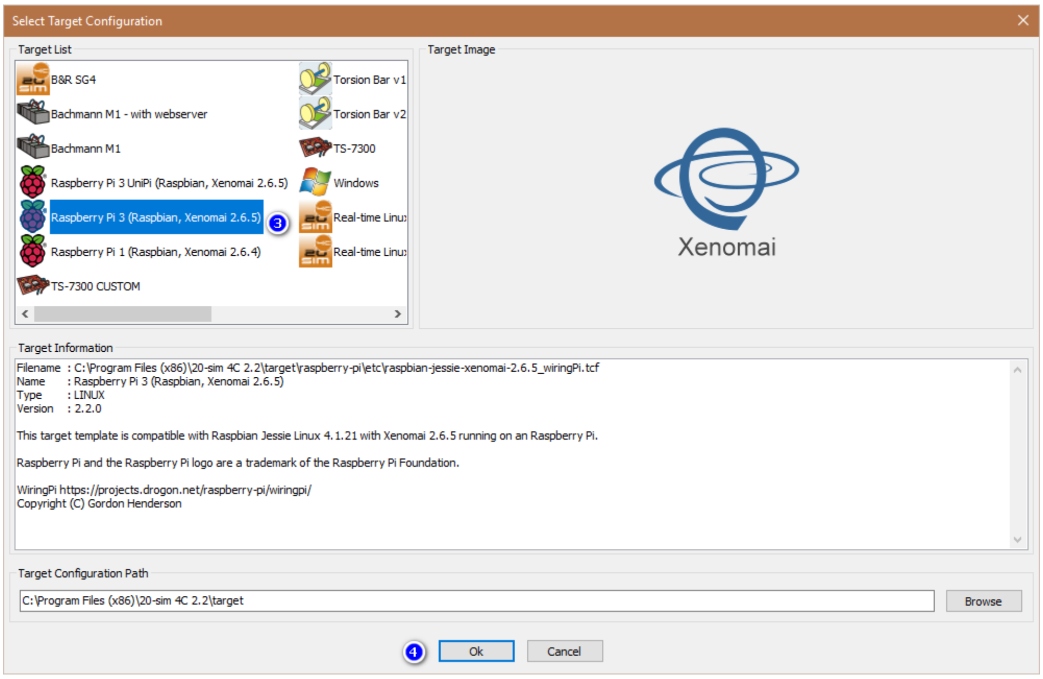
Template name : Please select target
Template version :
Template type :
Template file :

Name : Not Set
Address : Not Set
Version : Not Set
Identifier : Not Set
Description : Not Set

```
19:53:36   Opening c:\temp\fmi2\Controller_TorsionBar\Controller.txp...
19:53:36   Project c:\temp\fmi2\Controller_TorsionBar\Controller.txp opened.
```

c:\Program Files (x86)\20-sim 4C 2.2\bin\

Figure 59: 20-sim 4C project with imported FMU.


Select Target Configuration
Target List
B&R SG4
Bachmann M1 - with webserver
Bachmann M1
Raspberry Pi 3 UniPi (Raspbian, Xenomai 2.6.5)
Raspberry Pi 3 (Raspbian, Xenomai 2.6.5)
3
Raspberry Pi 1 (Raspbian, Xenomai 2.6.4)
TS-7300 CUSTOM
Torsion Bar v1
Torsion Bar v2
TS-7300
Windows
Real-time Linu
Real-time Linu
Target Image
Xenomai
Target Information
Target Configuration Path
Browse
4
Ok
Cancel

Filename : C:\Program Files (x86)\20-sim 4C 2.2\target\raspberry-pi\etc\raspbian-jessie-xenomai-2.6.5_wiringPi.tcf
Name : Raspberry Pi 3 (Raspbian, Xenomai 2.6.5)
Type : LINUX
Version : 2.2.0

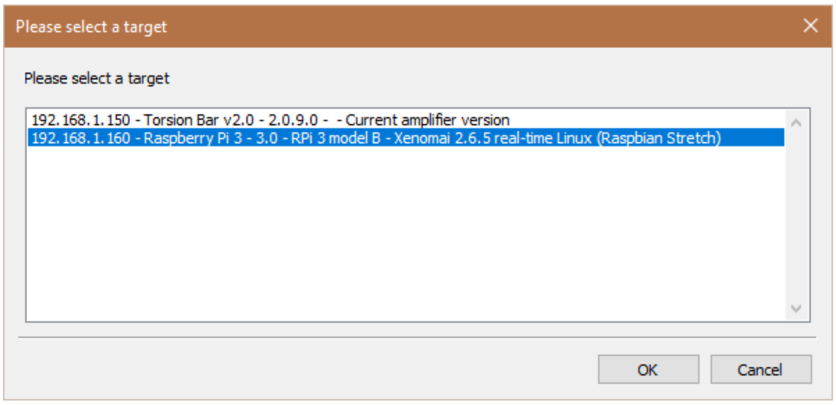
This target template is compatible with Raspbian Jessie Linux 4.1.21 with Xenomai 2.6.5 running on an Raspberry Pi.

Raspberry Pi and the Raspberry Pi logo are a trademark of the Raspberry Pi Foundation.

WiringPi https://projects.drogon.net/raspberry-pi/wiringpi/
Copyright (C) Gordon Henderson

C:\Program Files (x86)\20-sim 4C 2.2\target

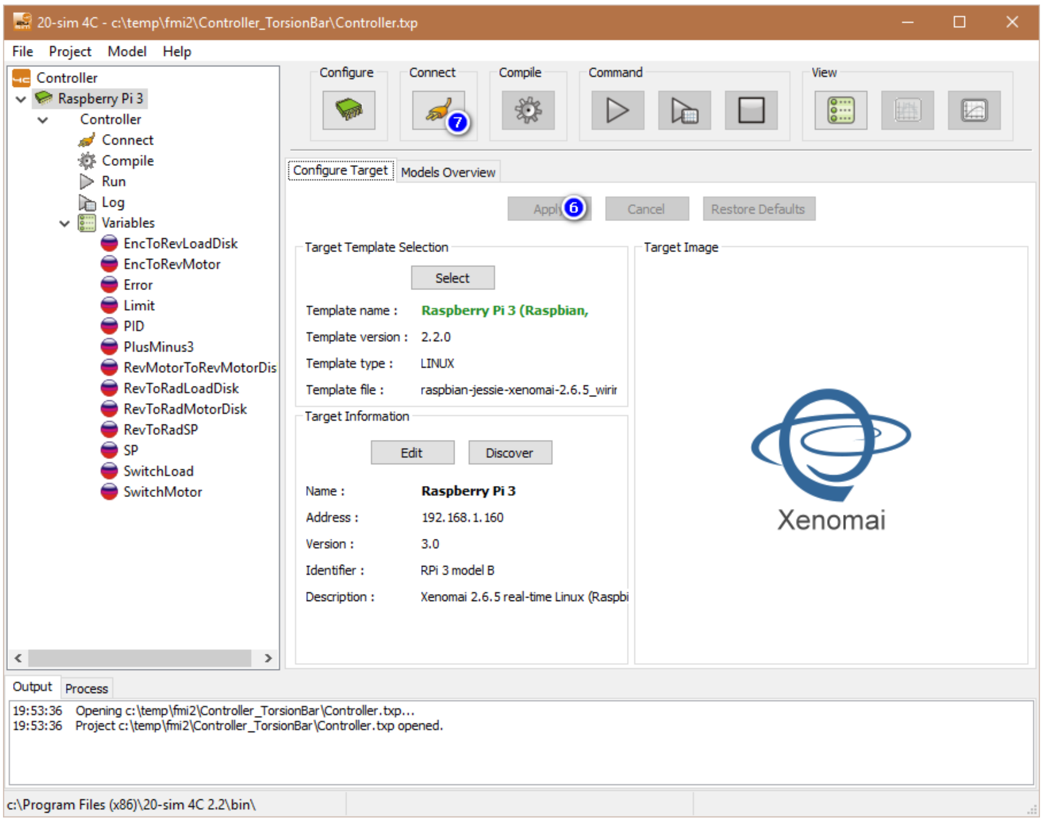
Figure 60: Select the Raspberry Pi target.



Please select a target

192.168.1.150 - Torsion Bar v2.0 - 2.0.9.0 - - Current amplifier version
192.168.1.160 - Raspberry Pi 3 - 3.0 - RPi 3 model B - Xenomai 2.6.5 real-time Linux (Raspbian Stretch)

Figure 61: Select the right target.



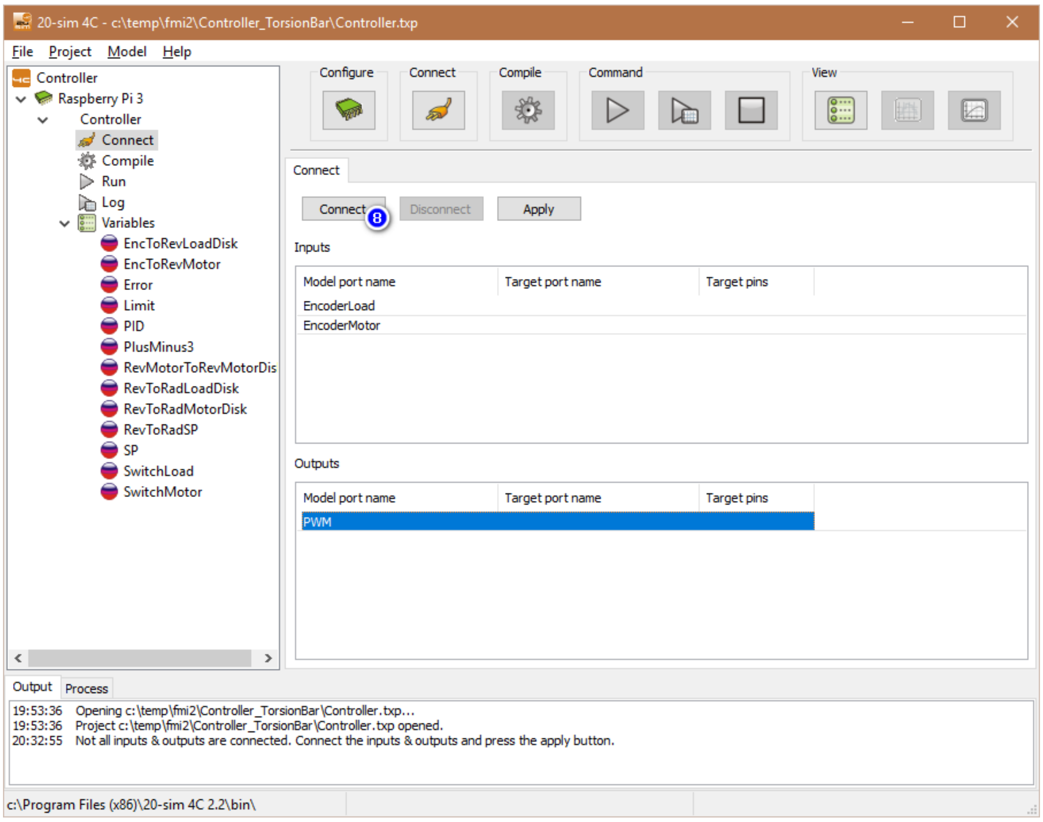
Template name : Raspberry Pi 3 (Raspbian,
Template version : 2.2.0
Template type : LINUX
Template file : raspbian-jessie-xenomai-2.6.5_wirir

Name : Raspberry Pi 3
Address : 192.168.1.160
Version : 3.0
Identifier : RPi 3 model B
Description : Xenomai 2.6.5 real-time Linux (Raspbi

```
19:53:36   Opening c:\temp\fmi2\Controller_TorsionBar\Controller.txp...
19:53:36   Project c:\temp\fmi2\Controller_TorsionBar\Controller.txp opened.
```

c:\Program Files (x86)\20-sim 4C 2.2\bin\

Figure 62: Accept target settings and go to the connection phase.



Inputs

Model port name	Target port name	Target pins
EncoderLoad		
EncoderMotor		

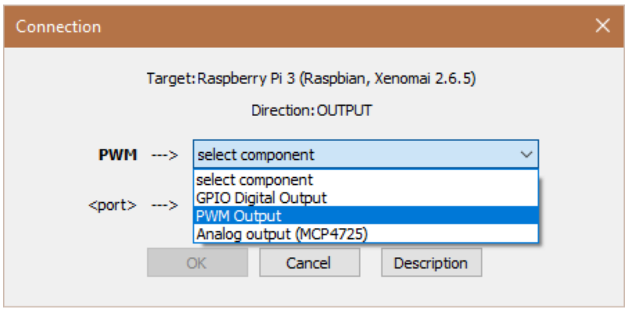
Outputs

Model port name	Target port name	Target pins
PWM		

```
19:53:36   Opening c:\temp\fmi2\Controller_TorsionBar\Controller.txp...
19:53:36   Project c:\temp\fmi2\Controller_TorsionBar\Controller.txp opened.
20:32:55   Not all inputs & outputs are connected. Connect the inputs & outputs and press the apply button.
```

Figure 63: Select an input or output and press *Connect*.

options to support this in 20-sim 4C.



Connection

Target: Raspberry Pi 3 (Raspbian, Xenomai 2.6.5)

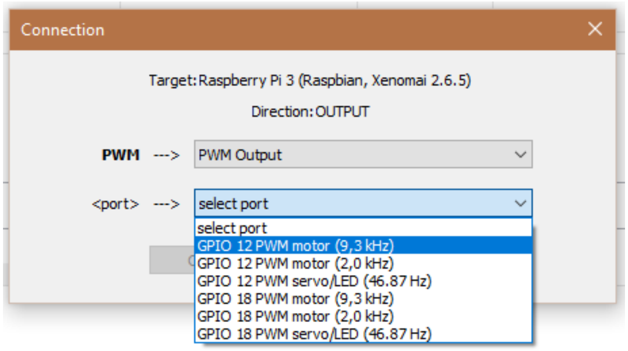
Direction: OUTPUT

PWM ---> select component

<port> --->

select component
GPIO Digital Output
PWM Output
Analog output (MCP4725)

Figure 64: Select a component.



Connection

Target: Raspberry Pi 3 (Raspbian, Xenomai 2.6.5)

Direction: OUTPUT

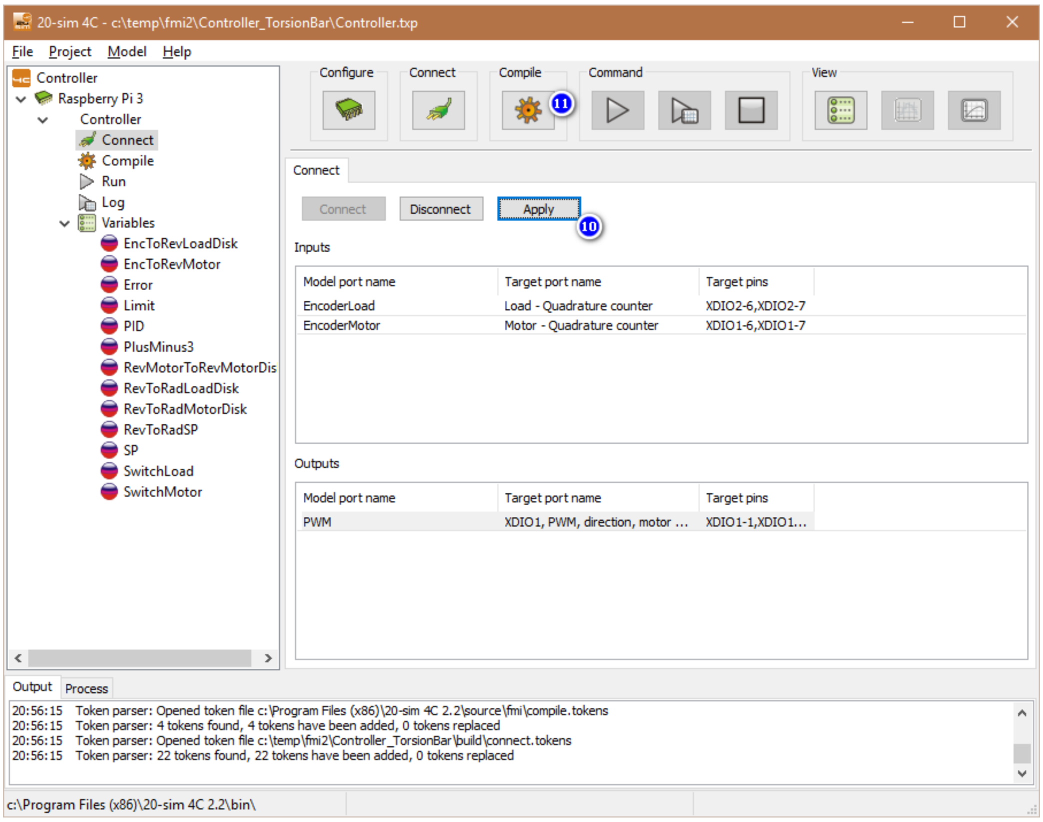
PWM ---> PWM Output

<port> ---> select port

select port
GPIO 12 PWM motor (9,3 kHz)
GPIO 12 PWM motor (2,0 kHz)
GPIO 12 PWM servo/LED (46.87 Hz)
GPIO 18 PWM motor (9,3 kHz)
GPIO 18 PWM motor (2,0 kHz)
GPIO 18 PWM servo/LED (46.87 Hz)

Figure 65: Select a port.

10. When you have connected all desired inputs and outputs to the I/O, press the *Apply* button (Figure 66.) The *Connect* button will turn green and 20-sim 4C will extend the FMU source code with additional files to provide support for the Raspberry Pi Xenomai real-time Linux and the Raspberry Pi I/O.
    Note: It is not required to connect all inputs and outputs to real I/O. 20-sim 4C will show a warning when some inputs or outputs are not connected. Unconnected inputs will read a zero (0) value by default. A special real-time toolwrapper FMU can be generated from 20-sim 4C that will allow you to write to unconnected inputs from a co-simulation experiment (see section 5.3.2). This toolwrapper FMU will also allow you to read all FMU exported variables including all inputs and outputs even when inputs and outputs are connected to the I/O. This toolwrapper FMU is the basis for INTO-CPS HiL simulation with the Raspberry Pi as the real-time target.



Inputs

Model port name	Target port name	Target pins
EncoderLoad	Load - Quadrature counter	XDIO2-6,XDIO2-7
EncoderMotor	Motor - Quadrature counter	XDIO1-6,XDIO1-7

Outputs

Model port name	Target port name	Target pins
PWM	XDIO1, PWM, direction, motor ...	XDIO1-1,XDIO1...

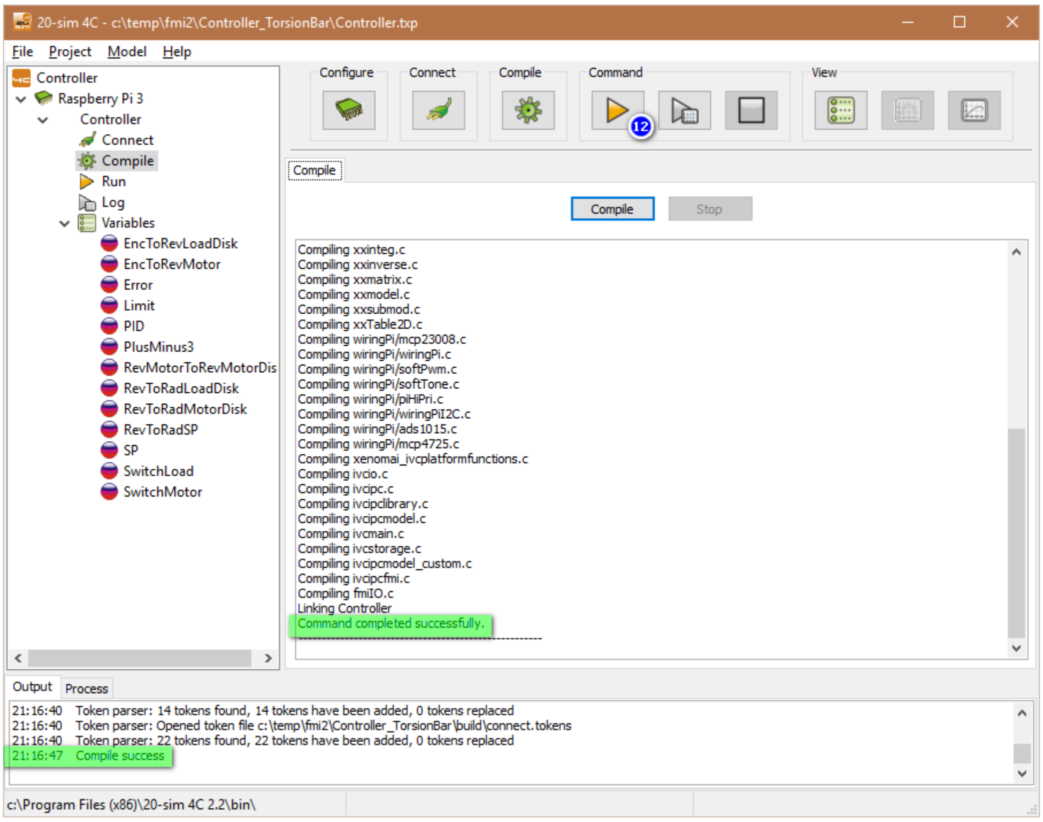
```
20:56:15   Token parser: Opened token file c:\Program Files (x86)\20-sim 4C 2.2\source\fmi\compile.tokens
20:56:15   Token parser: 4 tokens found, 4 tokens have been added, 0 tokens replaced
20:56:15   Token parser: Opened token file c:\temp\fmi2\Controller_TorsionBar\build\connect.tokens
20:56:15   Token parser: 22 tokens found, 22 tokens have been added, 0 tokens replaced
```

c:\Program Files (x86)\20-sim 4C 2.2\bin\

Figure 66: Apply the connections and compile the code.

11. Press the orange *Compile* button (Figure 66) to go to the *Compile* phase. This will compile the FMU source code and the additional 20-sim 4C source code into a real-time application.

12. When the compilation process is ready and successful, click the orange *Command* button to configure the last task settings before uploading the compiled FMU to the Raspberry Pi (Figure 67.)



```
Compiling xxinteg.c
Compiling xxinverse.c
Compiling xxmatrix.c
Compiling xxmodel.c
Compiling xxsubmod.c
Compiling xxTable2D.c
Compiling wiringPi/mcp23008.c
Compiling wiringPi/wiringPi.c
Compiling wiringPi/softPwm.c
Compiling wiringPi/softTone.c
Compiling wiringPi/piHiPri.c
Compiling wiringPi/wiringPiI2C.c
Compiling wiringPi/ads1015.c
Compiling wiringPi/mcp4725.c
Compiling xenomai_ivcplatformfunctions.c
Compiling ivcio.c
Compiling ivcipc.c
Compiling ivcipclibrary.c
Compiling ivcipcmodel.c
Compiling ivcmain.c
Compiling ivcstorage.c
Compiling ivcipcmodel_custom.c
Compiling ivcipcfmi.c
Compiling fmiIO.c
Linking Controller
Command completed successfully.
------------------------------------------------------------
```

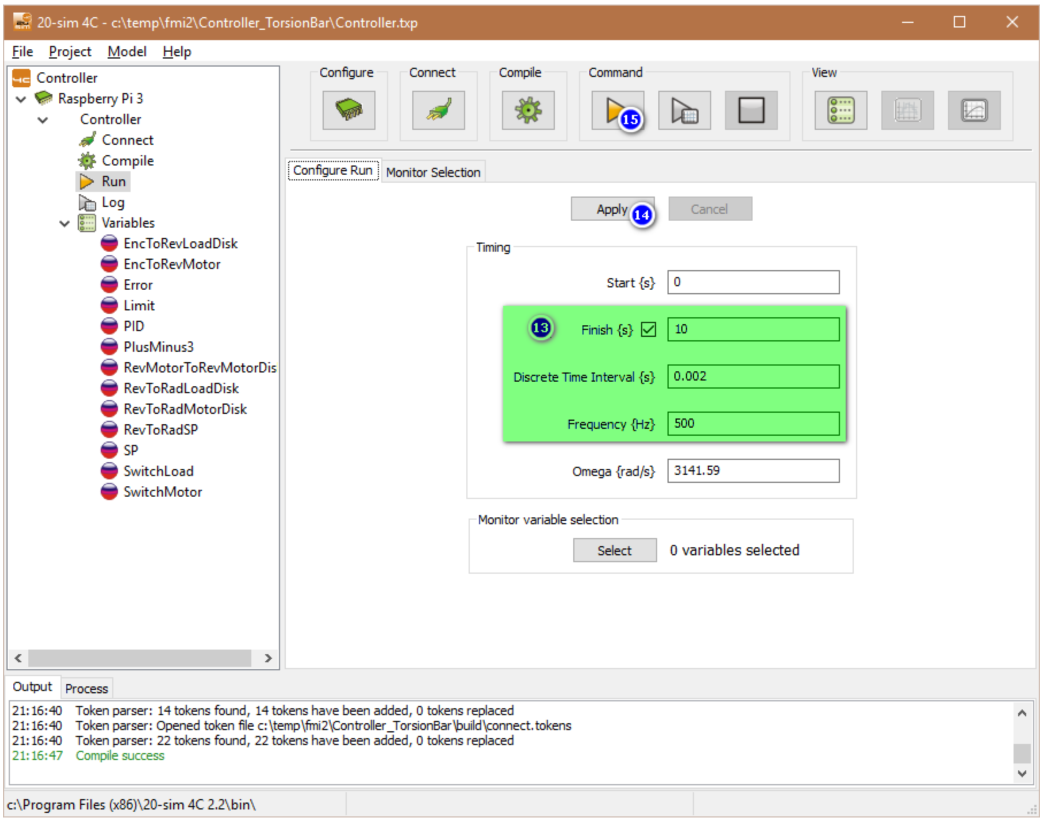
```
21:16:40   Token parser: 14 tokens found, 14 tokens have been added, 0 tokens replaced
21:16:40   Token parser: Opened token file c:\temp\fmi2\Controller_TorsionBar\build\connect.tokens
21:16:40   Token parser: 22 tokens found, 22 tokens have been added, 0 tokens replaced
21:16:47   Compile success
```

c:\Program Files (x86)\20-sim 4C 2.2\bin\

Figure 67: Compilation phase.

13. On the *Configure Run* tab (Figure 68), you can specify the finish time of the FMU or disable it if it should run forever (until reboot/shutdown). Ensure that the *Discrete Time Interval* has a step size larger than 0. This value is used as the time (step size) between two FMU "doStep" calls and determines the FMU calculation frequency. The Raspberry Pi 3 is able to support step sizes as low as 0.00005 (20 kHz), but this depends on the FMU computation load and number of connected I/O pins.

14. Press the *Apply* button to store the run settings. The *Command* button



20-sim 4C - c:\temp\fmi2\Controller_TorsionBar\Controller.txp

Timing

Start {s}: 0

Finish {s} ☑: 10

Discrete Time Interval {s}: 0.002

Frequency {Hz}: 500

Omega {rad/s}: 3141.59

Monitor variable selection: 0 variables selected

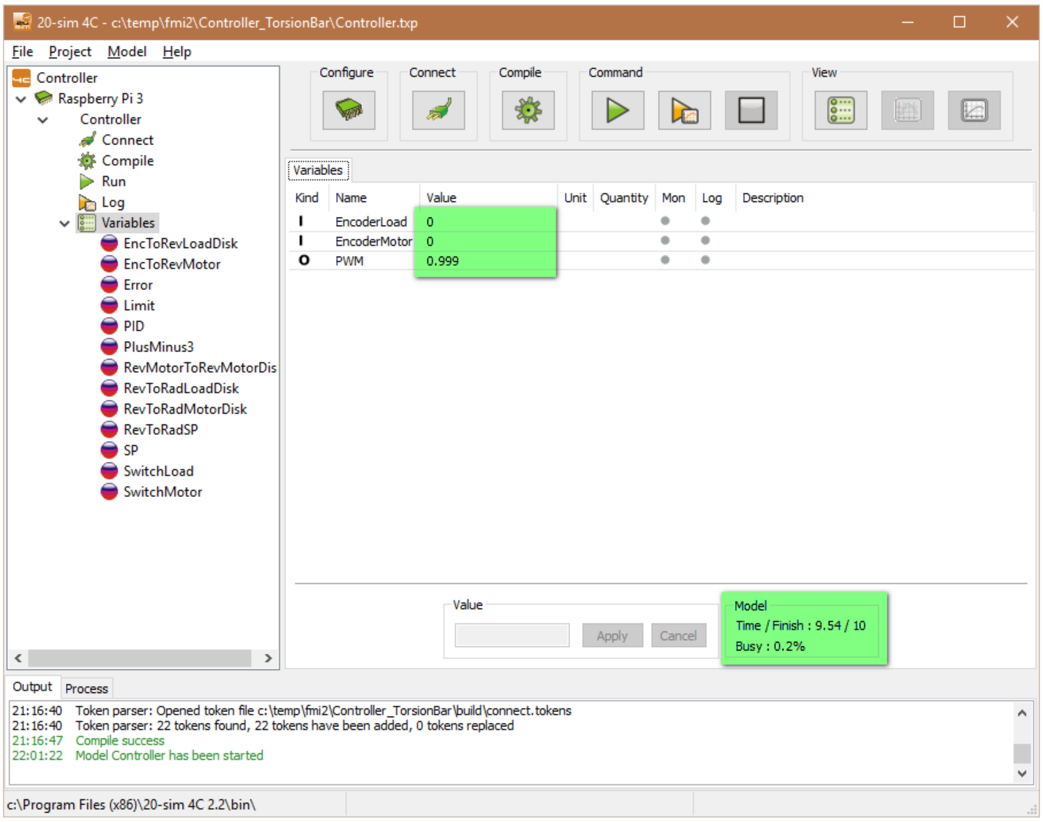
```
21:16:40   Token parser: 14 tokens found, 14 tokens have been added, 0 tokens replaced
21:16:40   Token parser: Opened token file c:\temp\fmi2\Controller_TorsionBar\build\connect.tokens
21:16:40   Token parser: 22 tokens found, 22 tokens have been added, 0 tokens replaced
21:16:47   Compile success
```

c:\Program Files (x86)\20-sim 4C 2.2\bin\

Figure 68: Configure task run settings.

will turn green.

15. Click the *Command* button to upload and start your FMU on the Raspberry Pi. If everything is configured correctly, the FMU will start and 20-sim 4C will monitor its progress and the current value of the FMU variables.



Kind	Name	Value	Unit	Quantity	Mon	Log	Description
I	EncoderLoad	0			●	●	
I	EncoderMotor	0			●	●	
O	PWM	0.999			●	●	

Value

Model
Time / Finish : 9.54 / 10
Busy : 0.2%

```
21:16:40   Token parser: Opened token file c:\temp\fmi2\Controller_TorsionBar\build\connect.tokens
21:16:40   Token parser: 22 tokens found, 22 tokens have been added, 0 tokens replaced
21:16:47   Compile success
22:01:22   Model Controller has been started
```

c:\Program Files (x86)\20-sim 4C 2.2\bin\

Figure 69: FMU is running.

16. It is also possible to show selected variables in a monitor plot. You can enable monitoring of a signal by toggling the dot icon in the *Mon* column to a monitor icon.

17. Click the large monitor icon on the button bar to show the monitor plot. An example of the monitor plot with three I/O signals is shown in Figure 70.

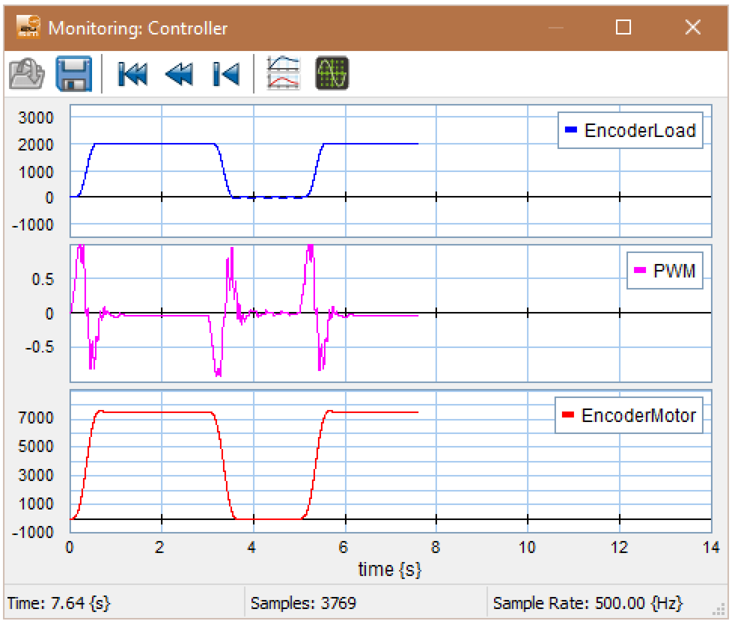


Figure 70: Variable monitor.

5.3.2 Real-time toolwrapper FMU export

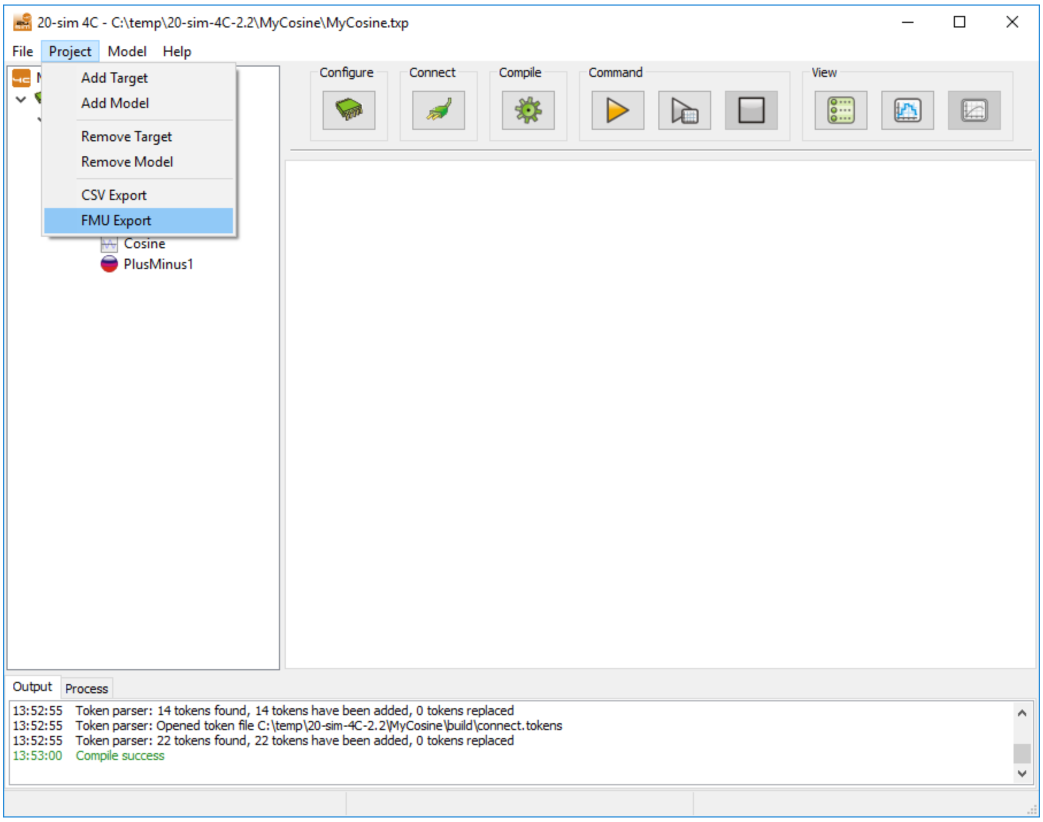
For HiL simulation with a Raspberry Pi, 20-sim 4C is extended with FMU export functionality. The 20-sim 4C FMU export option generates a real-time toolwrapper FMU for the currently loaded 20-sim 4C project. This FMU can be used in the COE to interface the real-time FMU running on the Raspberry Pi with a standard COE co-simulation experment. Assuming a running application on the Raspberry Pi, FMU export can be performed as follows:

1. Co-simulation using a toolwrapper FMU uses the unconnected 20-sim 4C inputs. Make sure that the desired co-simulation inputs are not connected during the 20-sim 4C *Connect* phase (Figure 66).

2. Export an FMU using the *FMU Export* menu item. Make sure that the "Raspberry Pi 3" target, or the 20-sim 4C project (your FMU name,) is selected in the left tree. This is required so that the FMU exporter can find the right 20-sim 4C project.

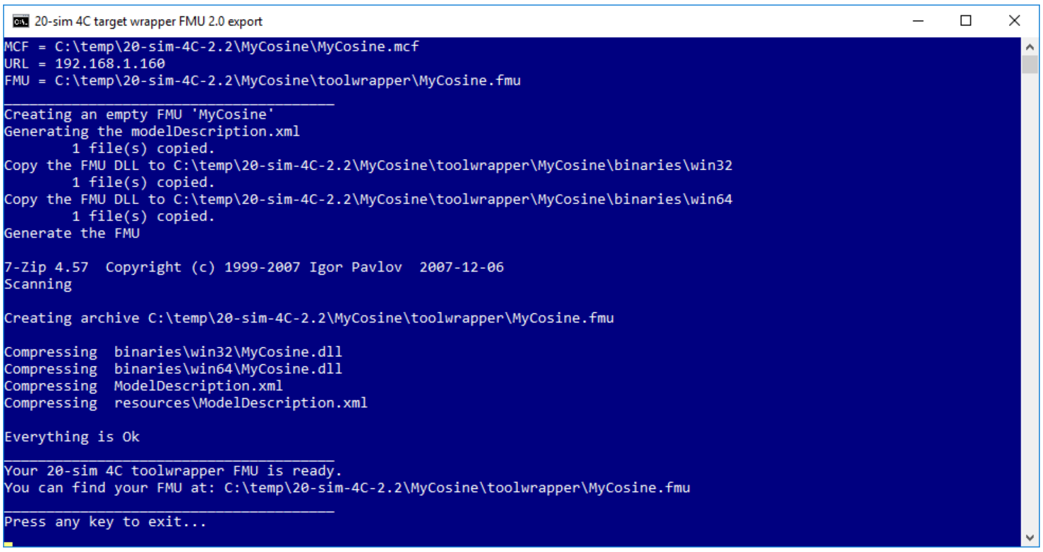
3. Select *Export FMU* from the *Project* menu item. See Figure 71.

4. A command-line window will be displayed showing status information of the FMU toolwrapper creation process. See Figure 72.



```
13:52:55   Token parser: 14 tokens found, 14 tokens have been added, 0 tokens replaced
13:52:55   Token parser: Opened token file C:\temp\20-sim-4C-2.2\MyCosine\build\connect.tokens
13:52:55   Token parser: 22 tokens found, 22 tokens have been added, 0 tokens replaced
13:53:00   Compile success
```

Figure 71: Export toolwrapper FMU.



```
MCF = C:\temp\20-sim-4C-2.2\MyCosine\MyCosine.mcf
URL = 192.168.1.160
FMU = C:\temp\20-sim-4C-2.2\MyCosine\toolwrapper\MyCosine.fmu
_______________________________________
Creating an empty FMU 'MyCosine'
Generating the modelDescription.xml
        1 file(s) copied.
Copy the FMU DLL to C:\temp\20-sim-4C-2.2\MyCosine\toolwrapper\MyCosine\binaries\win32
        1 file(s) copied.
Copy the FMU DLL to C:\temp\20-sim-4C-2.2\MyCosine\toolwrapper\MyCosine\binaries\win64
        1 file(s) copied.
Generate the FMU

7-Zip 4.57  Copyright (c) 1999-2007 Igor Pavlov  2007-12-06
Scanning

Creating archive C:\temp\20-sim-4C-2.2\MyCosine\toolwrapper\MyCosine.fmu

Compressing  binaries\win32\MyCosine.dll
Compressing  binaries\win64\MyCosine.dll
Compressing  ModelDescription.xml
Compressing  resources\ModelDescription.xml

Everything is Ok
_______________________________________
Your 20-sim 4C toolwrapper FMU is ready.
You can find your FMU at: C:\temp\20-sim-4C-2.2\MyCosine\toolwrapper\MyCosine.fmu
_______________________________________
Press any key to exit...
```

Figure 72: Toolwrapper FMU status.

5. This window can be closed after noting the location of the generated FMU.

6. The newly created FMU can be used in 32-bit and 64-bit Windows FMI co-simulators like the INTO-CPS COE. Linux and MacOS X compatible versions are not yet available.

5.4 OpenModelica

This section explains the FMI and INTO-CPS related features of OpenModelica. The focus is on import of `modelDescription.xml` files and standalone and tool-wrapper FMU export.

5.4.1 Import of `modelDescription.xml` Files

OpenModelica can import `modelDescription.xml` interface files created using Modelio and create Modelica models from them. To use the `modelDescription.xml` import feature, you will need to use OpenModelica nightly-builds versions, as this extension is new. Nightly builds can be obtained through the main INTO-CPS GitHub site:

`http://into-cps-association.github.io`

To import a `modelDescription.xml` file in OpenModelica one can use:

1. The OpenModelica Connection Editor GUI (OMEdit): *FMI* → *Import FMI Model Description*.

2. A MOS script, *i.e.* `script.mos`, see below.

```
// start script.mos
// import the FMU modelDescription.xml
importFMUModeldescription("path/to/modelDescription.xml");
   getErrorString();
// end script.mos
```

The MOS script can be executed from command line via:

```
// on Linux and Mac OS
> path/to/omc script.mos
// on Windows
> %OPENMODELICAHOME%\bin\omc script.mos
```

The result is a generated file with a Modelica model containing the inputs and outputs specified in `modelDescription.xml`. For instance:

```
model Modelica_Blocks_Math_Gain_cs_FMU "Output the product
   of a gain value with the input signal"
  Modelica.Blocks.Interfaces.RealInput u "Input signal
     connector" annotation(Placement(transformation(extent
     ={{-120,60},{-100,80}})));
  Modelica.Blocks.Interfaces.RealOutput y "Output signal
     connector" annotation(Placement(transformation(extent
     ={{100,60},{120,80}})));
end Modelica_Blocks_Math_Gain_cs_FMU;"
```

5.4.2 FMU Export

All FMUs exported from OpenModelica are standalone. There are two ways to export an FMU:

1. From a command prompt.
2. From OMEdit (OpenModelica Connection Editor).

FMU export from a command prompt To export an FMU for co-simulation from a Modelica model, a Modelica script file `generateFMU.mos` containing the following calls to the OMC compiler can be used:

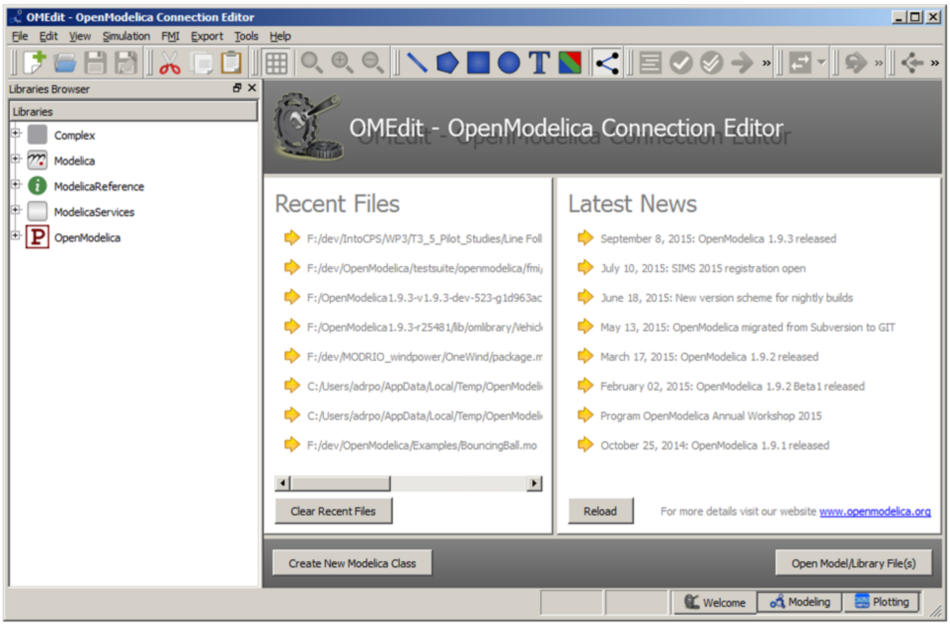
```
// load Modelica library
loadModel(Modelica); getErrorString();

// load other libraries if needed
// loadModel(OtherLibrary); getErrorString();

// generate the FMU: PathTo.MyModel.fmu
translateModelFMU(PathTo.MyModel, "2.0", "cs");
   getErrorString();
```

Next, the OMC compiler must be invoked on the `generateFMU.mos` script:

```
// on Linux and Mac OS
> path/to/omc generateFMU.mos
// on Windows
> %OPENMODELICAHOME%\bin\omc generateFMU.mos
```

FMU export from OMEdit One can also use OMEdit to export an FMU, as detailed in the figures below.

- Open OMEdit (see Figure 73.)
- Load the model in OMEdit (see Figure 74.)
- Open the model in OMEdit (see Figure 75.)
- Use the menu to export the FMU (see Figure 76.)
- The FMU is now generated (see Figure 77.)


OMEdit - OpenModelica Connection Editor
File Edit View Simulation FMI Export Tools Help
Libraries Browser
Libraries
Complex
Modelica
ModelicaReference
ModelicaServices
OpenModelica
OMEdit - OpenModelica Connection Editor
Recent Files
Latest News
Clear Recent Files
Reload
Create New Modelica Class
Open Model/Library File(s)
Welcome
Modeling
Plotting

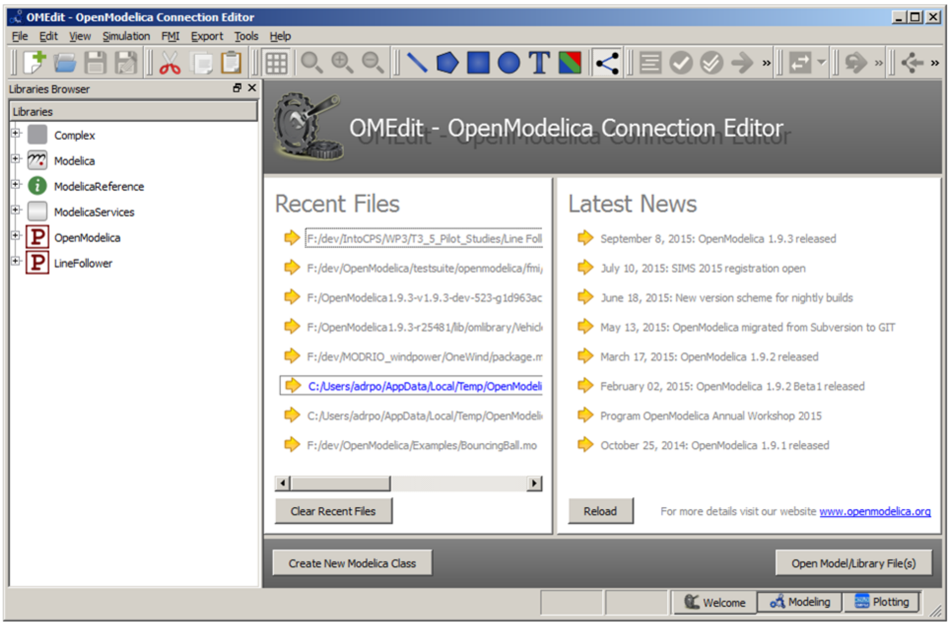
F:/dev/IntoCPS/WP3/T3_5_Pilot_Studies/Line Foll
F:/dev/OpenModelica/testsuite/openmodelica/fmi
F:/OpenModelica1.9.3-v1.9.3-dev-523-g1d963ac
F:/OpenModelica1.9.3-r25481/lib/omlibrary/Vehicl
F:/dev/MODRIO_windpower/OneWind/package.m
C:/Users/adrpo/AppData/Local/Temp/OpenModeli
C:/Users/adrpo/AppData/Local/Temp/OpenModeli
F:/dev/OpenModelica/Examples/BouncingBall.mo

September 8, 2015: OpenModelica 1.9.3 released
July 10, 2015: SIMS 2015 registration open
June 18, 2015: New version scheme for nightly builds
May 13, 2015: OpenModelica migrated from Subversion to GIT
March 17, 2015: OpenModelica 1.9.2 released
February 02, 2015: OpenModelica 1.9.2 Beta1 released
Program OpenModelica Annual Workshop 2015
October 25, 2014: OpenModelica 1.9.1 released

For more details visit our website www.openmodelica.org

Figure 73: Opening OMEdit.

The generated FMU will be saved to `%TEMP%\OpenModelica\OMEdit`.


OMEdit - OpenModelica Connection Editor
File Edit View Simulation FMI Export Tools Help
Libraries Browser
Libraries
Complex
Modelica
ModelicaReference
ModelicaServices
OpenModelica
LineFollower
OMEdit - OpenModelica Connection Editor
Recent Files
Latest News
Clear Recent Files
Reload
Create New Modelica Class
Open Model/Library File(s)
Welcome
Modeling
Plotting

F:/dev/IntoCPS/WP3/T3_5_Pilot_Studies/Line Foll
F:/dev/OpenModelica/testsuite/openmodelica/fmi
F:/OpenModelica1.9.3-v1.9.3-dev-523-g1d963ac
F:/OpenModelica1.9.3-r25481/lib/omlibrary/Vehicl
F:/dev/MODRIO_windpower/OneWind/package.m
C:/Users/adrpo/AppData/Local/Temp/OpenModeli
C:/Users/adrpo/AppData/Local/Temp/OpenModeli
F:/dev/OpenModelica/Examples/BouncingBall.mo

September 8, 2015: OpenModelica 1.9.3 released
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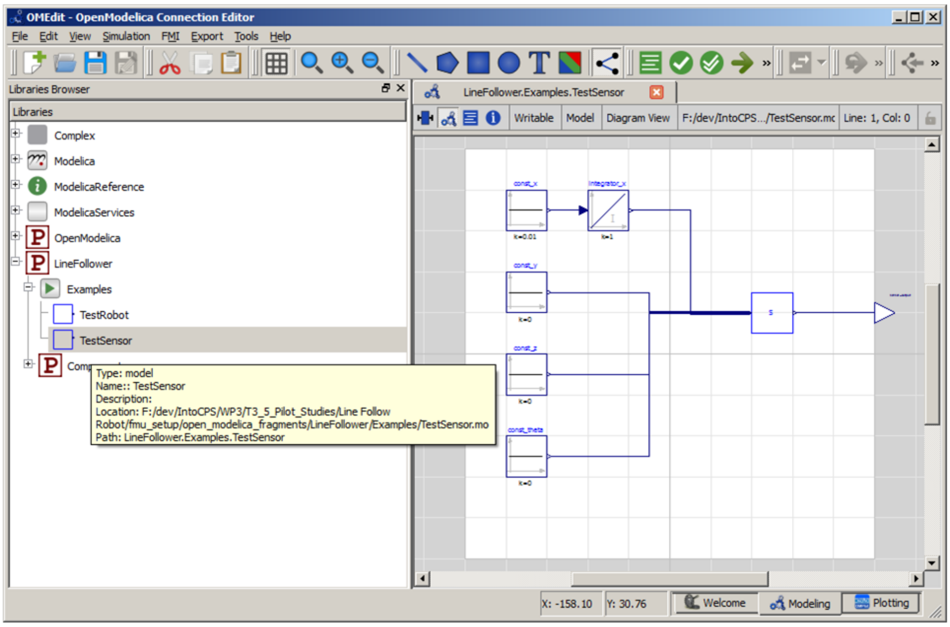
February 02, 2015: OpenModelica 1.9.2 Beta1 released
Program OpenModelica Annual Workshop 2015
October 25, 2014: OpenModelica 1.9.1 released

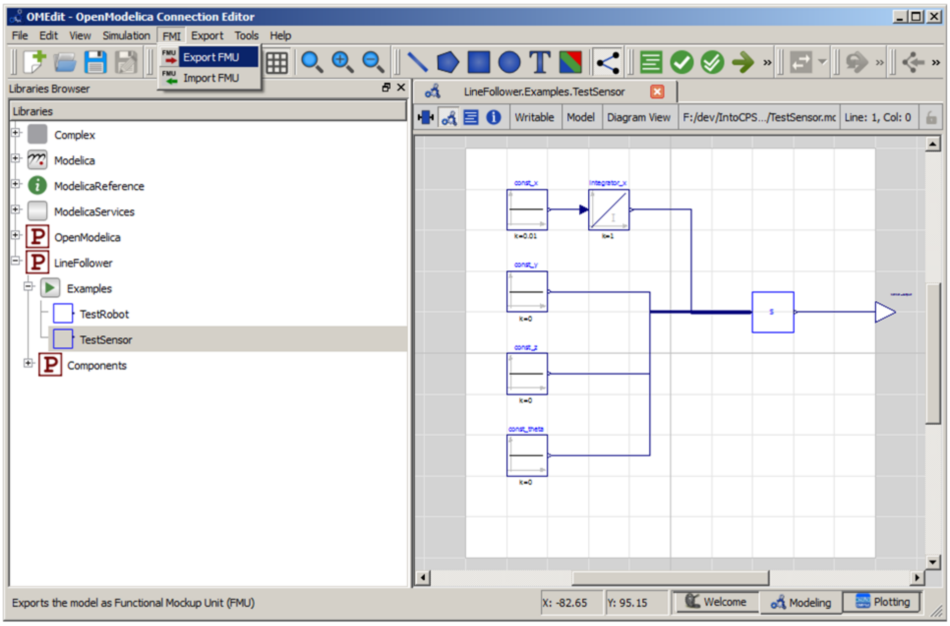
For more details visit our website www.openmodelica.org

Figure 74: Loading the Modelica model in OMEdit.



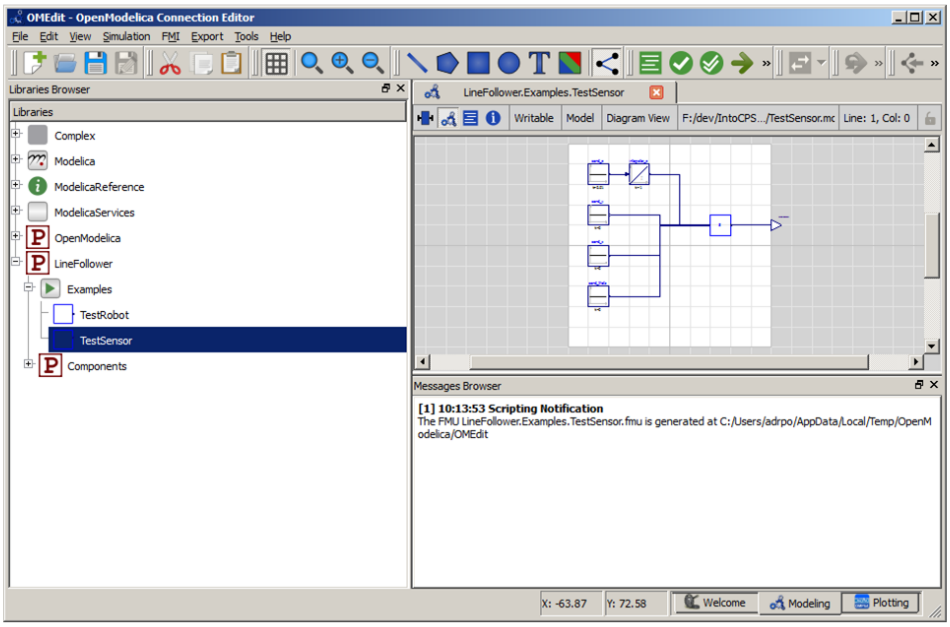
Type: model
Name:: TestSensor
Description:
Location: F:/dev/IntoCPS/WP3/T3_5_Pilot_Studies/Line Follow Robot/fmu_setup/open_modelica_fragments/LineFollower/Examples/TestSensor.mo
Path: LineFollower.Examples.TestSensor

Figure 75: Opening the Modelica model in OMEdit.


OMEdit - OpenModelica Connection Editor
File Edit View Simulation FMI Export Tools Help
Export FMU
Import FMU
Libraries Browser
Libraries
Complex
Modelica
ModelicaReference
ModelicaServices
OpenModelica
LineFollower
Examples
TestRobot
TestSensor
Components
LineFollower.Examples.TestSensor
Writable Model Diagram View F:/dev/IntoCPS.../TestSensor.mo Line: 1, Col: 0
X: -82.65 Y: 95.15 Welcome Modeling Plotting

Exports the model as Functional Mockup Unit (FMU)

Figure 76: Exporting the FMU.


OMEdit - OpenModelica Connection Editor
File Edit View Simulation FMI Export Tools Help
Libraries Browser
Libraries
Complex
Modelica
ModelicaReference
ModelicaServices
OpenModelica
LineFollower
Examples
TestRobot
TestSensor
Components
LineFollower.Examples.TestSensor
Writable Model Diagram View F:/dev/IntoCPS.../TestSensor.mo Line: 1, Col: 0
Messages Browser
X: -63.87 Y: 72.58 Welcome Modeling Plotting

[1] 10:13:53 Scripting Notification
The FMU LineFollower.Examples.TestSensor.fmu is generated at C:/Users/adrpo/AppData/Local/Temp/OpenModelica/OMEdit

Figure 77: Final step of FMU export.

5.5 Unity

This section describes the 3D visualisation functionality of the INTO-CPS tool chain. This capability is encapsulated into a Unity-based FMU that is configured and loaded into co-simulations in the usual manner. Unity is a professional game engine. It can be downloaded from the Unity website [Tec16].

5.5.1 Importing the Unity Package into Unity

To create a 3D animation FMU using Unity, first create a new project or open an existing Unity project. A Unity package was made by CLP that can be imported into Unity to expand Unity with FMU export options. This Unity package can be downloaded via the Download Manager in the INTO-CPS application or by contacting CLP. First, drag-and-drop this package into the *Assets* folder in Unity (in the *Project* tab). See Figure 78 on how to import the package from the explorer into Unity. A pop-up will open, like the one shown in Figure 79. Press the *Import* button, as shown in Figure 79. Since the package contains scripts that will modify the Unity editor, it is necessary to restart the Unity project after importing the package.

5.5.2 Importing the FMUBuilder *gameobject*

After restarting Unity, go to the *Hierarchy* tab. Right click within the blank part of the hierarchy (*i.e.* do not select any objects in the hierarchy) and select *FMU →FMUBuilder* (see Figure 80). This will create a new object in the hierarchy named FMUBuilder. When selecting this FMUBuilder object in the hierarchy, a few options will be shown in the *Inspector* (see Figure 81). There are three components visible: *Transform*, *FMU Builder (Script)* and *Scenery Conversion (Script)*. The latter two are unique to the INTO-CPS Unity FMU package. *FMU Builder (Script)* is the component that will eventually build the 3D animation FMU, which will be covered later in this section. The other component, *Scenery Conversion (Script)*, is used to convert existing 20-sim sceneries into Unity sceneries. This will also be covered later in this section.

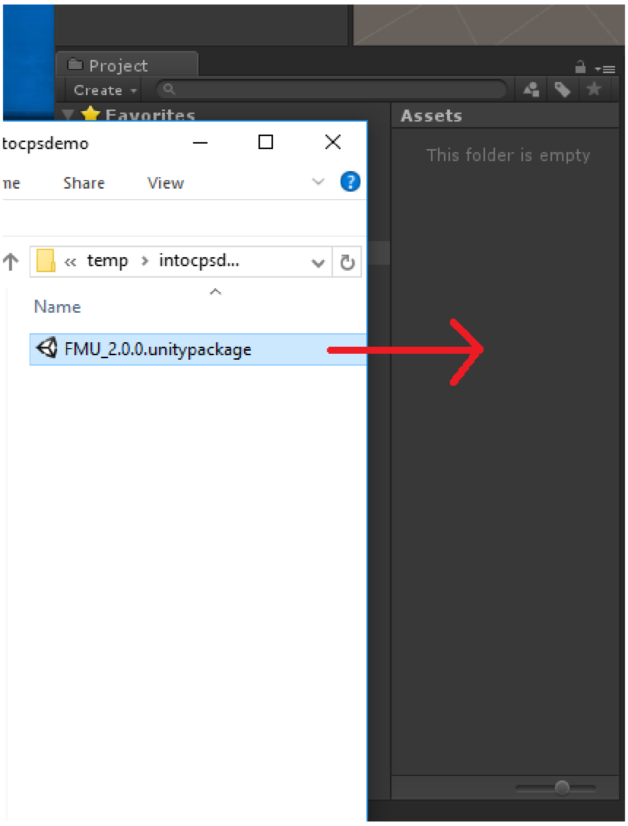
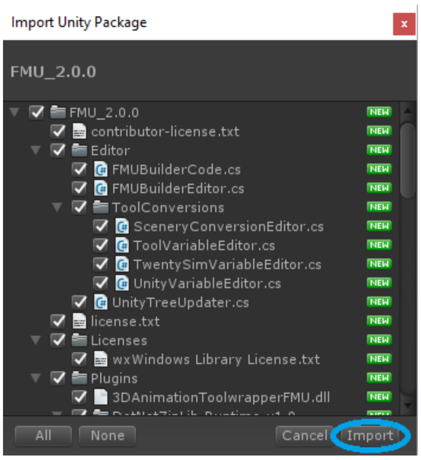


Figure 78: Importing the Unity package into Unity.

5.5.3 Assigning FMU Variables to Unity *gameobjects*

To be able to connect variables from a co-simulation to an object in Unity, a *gameobject* is needed. For example, as shown in Figure 80, a cube object can be created by right-clicking in the hierarchy tab in a blank space of the hierarchy, but now selecting *3D Object →Cube*. When the newly created object is selected in the hierarchy, all components currently attached to this cube can be seen in the *Inspector* tab. At the bottom of this tab there is a button named *Add Component*. Press this button, go to *FMU variables* and choose between *20-sim coordinates* or *Unity coordinates*. The first one means that the axes are part of a right-handed frame, that the Z-axis is pointing up, and that the order of rotation for Euler angles is X-Y-Z. The latter is the Unity convention, in which the frame is left-handed, the Y-axis is pointing up, and the rotation for Euler angles is Z-X-Y. See Figure 82 on how to do this. If there is doubt about which of the two types of variables should be chosen, choose the 20-sim option, as this is the reference frame used in



```
▼ ☑ FMU_2.0.0                                   NEW
    ☑ contributor-license.txt                   NEW
  ▼ ☑ Editor                                    NEW
      ☑ FMUBuilderCode.cs                       NEW
      ☑ FMUBuilderEditor.cs                     NEW
    ▼ ☑ ToolConversions                         NEW
        ☑ SceneryConversionEditor.cs            NEW
        ☑ ToolVariableEditor.cs                 NEW
        ☑ TwentySimVariableEditor.cs            NEW
        ☑ UnityVariableEditor.cs                NEW
      ☑ UnityTreeUpdater.cs                     NEW
    ☑ license.txt                               NEW
  ▼ ☑ Licenses                                  NEW
      ☑ wxWindows Library License.txt           NEW
  ▼ ☑ Plugins                                   NEW
      ☑ 3DAnimationToolwrapperFMU.dll           NEW
```

Figure 79: Summary of what will be imported into the Unity project.

most modeling tools like 20-sim. Once one is selected, two additional scripts become available in the *Inspector* tab. These are *GUID (Script)* and either *Twenty Sim Variable (Script)* or *Unity Variable (Script)*. The *GUID* script should not be touched. The *Variable* script, however, is the script that will describe the interface variables of the to-be-generated FMU. Choose an FMU variable name and an axis, and press the *Add Axis* button. Multiple axes can be defined for one *gameobject*. Figure 83 shows the axes dropdown menu and the *Twenty Sim Variable (Script)* and *GUID (Script)* components.

5.5.4 Converting a 20-sim Scenery into a Unity Scenery

If a 20-sim scenery already exists, then it is possible to import it into Unity. If there is a 3D animation window in the 20-sim model, then double click the plot to open the *3D Properties* window. Then go to *File* →*Save Scene* (see Figure 84). If 20-sim asks to save the whole scenery, select *Yes*. Remember where the scenery file is located and go back to Unity. Go to the hierarchy tab, select *FMUBuilder* and enter under the *Scene Conversion (Script)* the location of the scenery file, by pressing *Find scenery*. Afterwards, press the *Build scenery* button and the 20-sim scene will be loaded underneath the *FMUBuilder* object in the hierarchy (this can be drag-dropped to other places in the hierarchy if needed), see Figure 85 for the hierarchy that is created. Note that the Cube seen in Figure 84 in the hierarchy is now created in Unity as well. Furthermore, the *Default Lights and Cameras* frame is converted into Unity, which is a default set of lights and cameras in every 20-sim 3D scene.

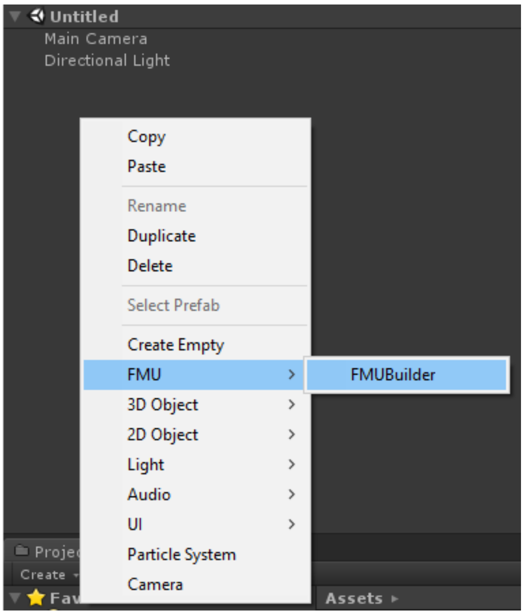
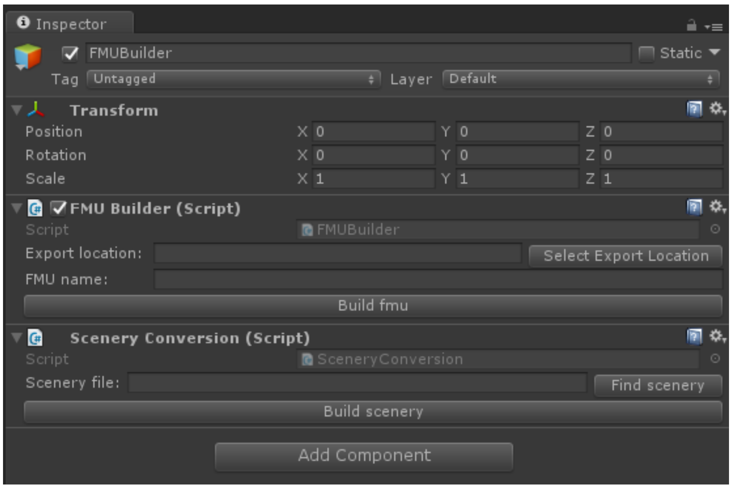


Figure 80: Creating the FMUBuilder *gameobject* in the hierarchy tab.

5.5.5 Exporting an FMU

The final step in the process of creating a 3D animation FMU in Unity is the build process itself. The variables that were added by manually assigning FMU variables to *gameobjects* and by importing 20-sim scenery files will now be used to generate the FMU itself. Every variable name (either the ones manually entered, or automatically generated by the import 20-sim scenery option) will be the input variables of this FMU. Select the *FMUBuilder* in the hierarchy and go to the *Inspector* tab. Under *FMU Builder (Script)* select the export location and the name of the to-be-exported FMU, then press *Build FMU*. Once the build process is done, the FMU will be present in the export location selected, with the given name. Note that for larger Unity scenes this can take a while to build.



☑ FMUBuilder

Tag Untagged Layer Default

Position X 0 Y 0 Z 0

Rotation X 0 Y 0 Z 0

Scale X 1 Y 1 Z 1

Script FMUBuilder

Export location:

FMU name:

Script SceneryConversion

Scenery file:

Figure 81: Components of the FMUBuilder in the *Inspector* tab in Unity.

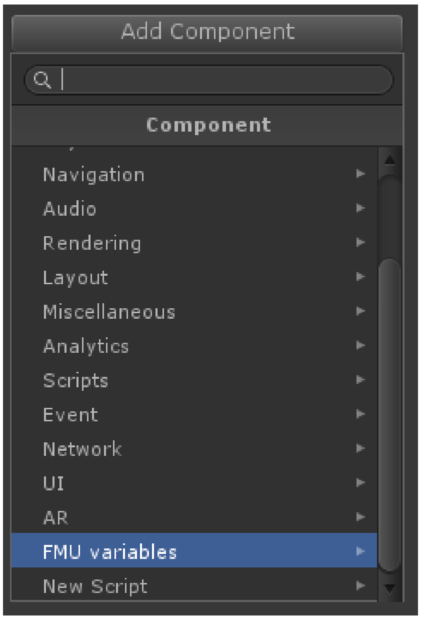
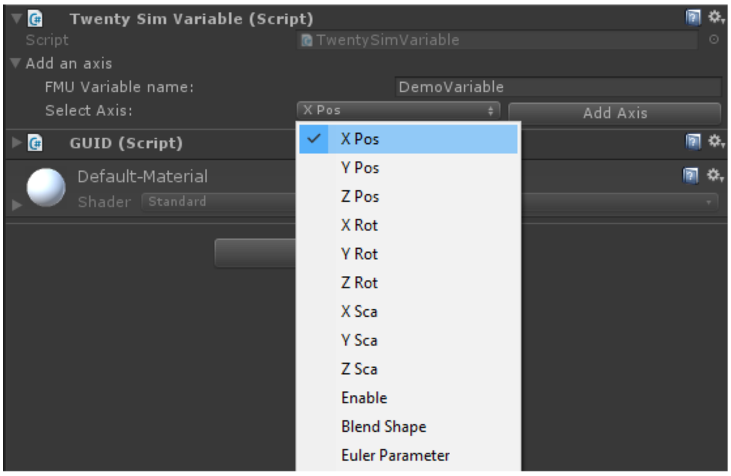


Figure 82: Adding new FMU variables to the Unity scene.



Script: TwentySimVariable

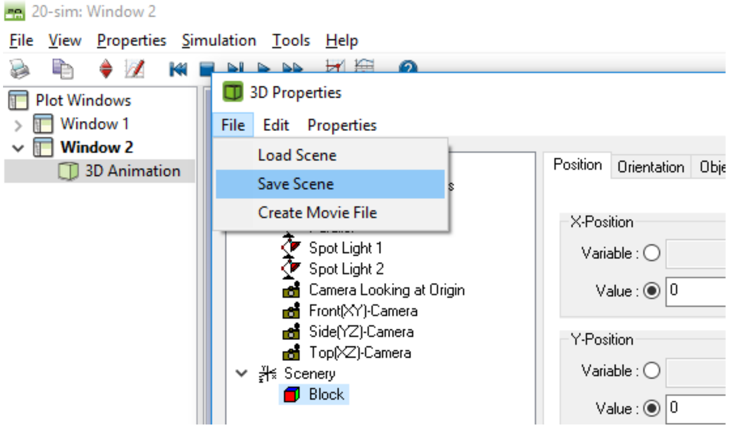
Add an axis

FMU Variable name: DemoVariable

Select Axis: X Pos

Shader: Standard

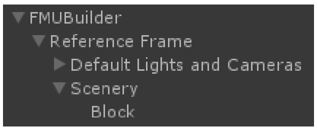
Figure 83: Adding the variable named "DemoVariable" for the x-position axis to the newly generated cube object.



X-Position
Variable : ○
Value : ● 0

Y-Position
Variable : ○
Value : ● 0

Figure 84: Exporting a 20-sim 3D scenery from a 3D animation plot.



```
▼ FMUBuilder
  ▼ Reference Frame
    ▶ Default Lights and Cameras
    ▼ Scenery
        Block
```

Figure 85: Importing a 20-sim scenery file into Unity.

5.6 AutoFOCUS3

AutoFOCUS3 (AF3) is an open source model based development tool for distributed, reactive and embedded software systems. It uses models to develop systems. From the requirements to the hardware architecture, passing by the design of the logical architecture, the deployment and the scheduling. It provides advanced features to support the user ensuring the quality of their system: formal analyses, synthesis methods, space exploration visualization, etc.

Co-simulation feature supports for now only Functional Mockup Unit (FMU) export satisfying the following constraints:

- FMI 2.0
- 32/64bit
- GCC compilation
- Input and output values cannot carry NoVal but instead contain default values (0 for integers and reals, false for booleans, first item for enumerations) Note: This behavior is different from AF3 simulation

FMI export is done at the level of component with logical architecture (in the future, we might implement this feature for deployments as well). To export your component with logical architecture to the FMU, right-click on it in the model navigator and select "Export to FMU2.0" as shown in Figure 86.

AF3 works with logical time, however co-simulation is generally achieved with tools modeling reality and therefore working with real time. Therefore, the FMI standard requires that AF3 notion of time is translated to real time. Consequently, you will have to define the sampling time (in seconds) for the component as a function with name "samplingTime()" in the data dictionary as shown in Figure 87. Otherwise, you will be asked to provide the frequency of the component in Hertz as shown in Figure 88.

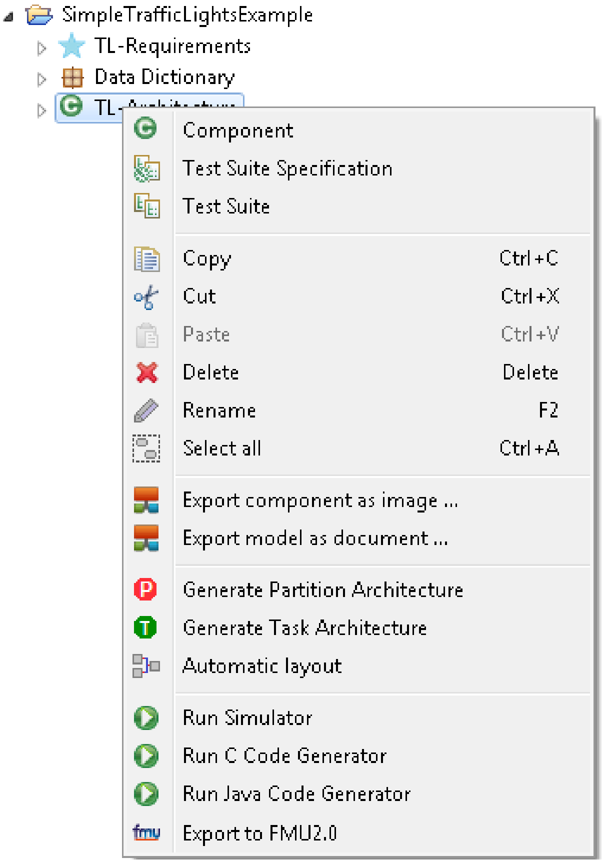
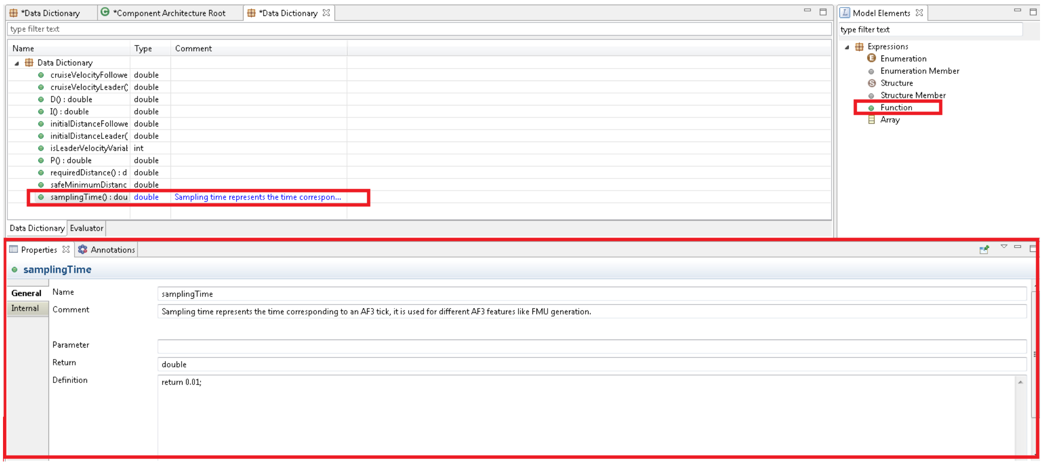


Figure 86: Exporting component architecture to FMU.



Name	Type	Comment
Data Dictionary		
cruiseVelocityFollowe	double	
cruiseVelocityLeader(	double	
D() : double	double	
I() : double	double	
initialDistanceFollowe	double	
initialDistanceLeader(	double	
isLeaderVelocityVariat	int	
P() : double	double	
requiredDistance() : d	double	
safeMinimumDistanc	double	
samplingTime() : dou	double	Sampling time represents the time correspon...

samplingTime

Name: samplingTime

Comment: Sampling time represents the time corresponding to an AF3 tick, it is used for different AF3 features like FMU generation.

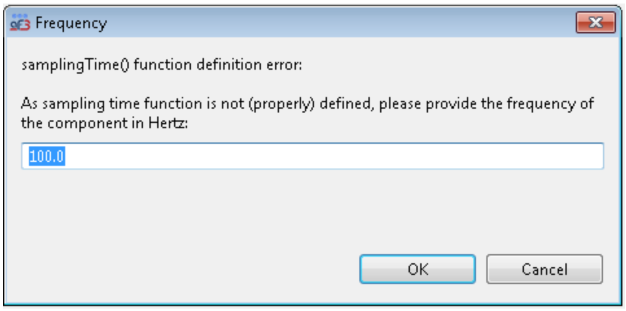
Parameter:

Return: double

Definition:

```
return 0.01;
```

Figure 87: Defining the sampling time function in data dictionary.



samplingTime() function definition error:

As sampling time function is not (properly) defined, please provide the frequency of the component in Hertz:

100.0

Figure 88: Providing the component frequency in case of samplingtime() function not defined.

6 Design Space Exploration

This section provides a description of INTO-CPS tool chain support for design space exploration (DSE.) This section is split into four parts. In Section 6.1 the installation procedure is outlined. Section 6.2 describes how the INTO-CPS Application can be used to launch a DSE using an existing configuration file and Section 6.3 describes how the results from DSE are generated and stored. Section 6.4 describes the structure of the DSE configuration file, giving enough detail for the user to be able to edit one for their purposes.

6.1 Installing DSE Scripts

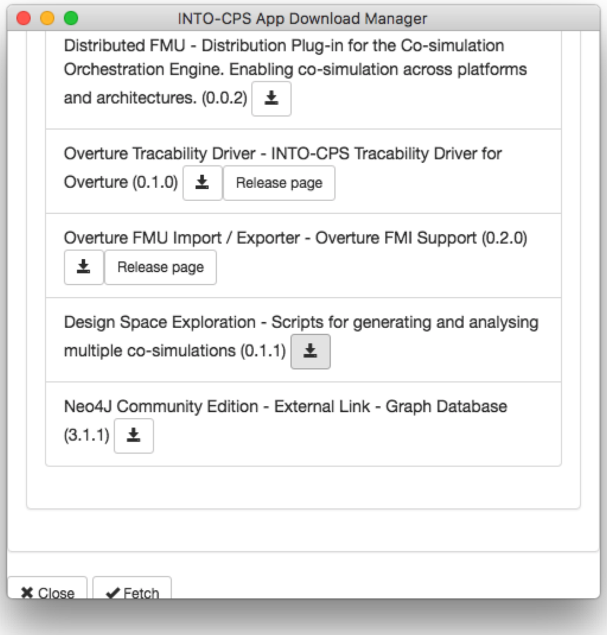
Before we launch a DSE, we must install the DSE scripts for the various search algorithms and objective evaluation. In the INTO-CPS Application, select *Window → Show Download Manager*. This opens the download manager as shown in Figure 89. Select the most recent release and download *Design Space Exploration - Scripts for generating and analysing multiple co-simulations*. Python version 2.7 must be installed, along with the matplotlib library.

This will download a Zip archive – extract this into the directory in which the archive was downloaded. DSEs may now be launched.

6.2 How to Launch a DSE

To launch a DSE we need to provide the INTO-CPS Application with the path to two files. The first is the DSE configuration, defining the parameters of the design space, how it should be searched, measured and the results compared. The second is the multi-model configuration, defining the base model that will be used for the search. A DSE configuration is selected by double clicking on one of the configurations listed in the *DSES* section of the INTO-CPS Application project explorer; these configurations are identified with the () icon. Hint: several of the downloadable examples have predefined DSE configurations.

To launch the DSE, we must first select the multi-model to use. One can be selected by clicking the *Set multi-model* button and selecting one from the drop-down list, as shown in Figures 90 and 91. Once selected, your choice



Distributed FMU - Distribution Plug-in for the Co-simulation Orchestration Engine. Enabling co-simulation across platforms and architectures. (0.0.2)

Overture Tracability Driver - INTO-CPS Tracability Driver for Overture (0.1.0) Release page

Overture FMU Import / Exporter - Overture FMI Support (0.2.0) Release page

Design Space Exploration - Scripts for generating and analysing multiple co-simulations (0.1.1)

Neo4J Community Edition - External Link - Graph Database (3.1.1)

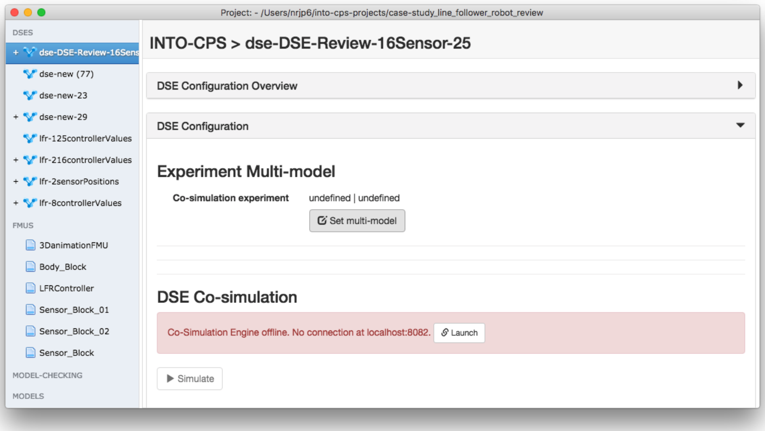
Figure 89: Download Manager.

must be saved to parse the DSE configuration with respect to the multi-model of choice by clicking on the *Save multi-model choice* button, as shown in Figure 91.

If the COE is not already running, the bottom of the DSE page is shown with a red "*Co-Simulation Engine offline. No connection at localhost:8082*" status, as shown in Figure 92. If this is the case, click on the *Launch* button to start the COE. This results in a green co-simulation engine status (see Figure 93). Pressing the *Simulate* button starts the DSE background process.

6.3 Results of a DSE

The DSE scripts store their results in a folder named for the date and time at which the DSE was started. This folder may be found underneath the name of the DSE script selected, as shown in Figure 94. When the DSE has finished, we can find both a graphs folder and an HTML results page inside the results folder. It may be necessary to refresh the project view to see these new items. The results HTML file is identified by the (📈) icon,


Project: - /Users/nrjp6/into-cps-projects/case-study_line_follower_robot_review

INTO-CPS > dse-DSE-Review-16Sensor-25

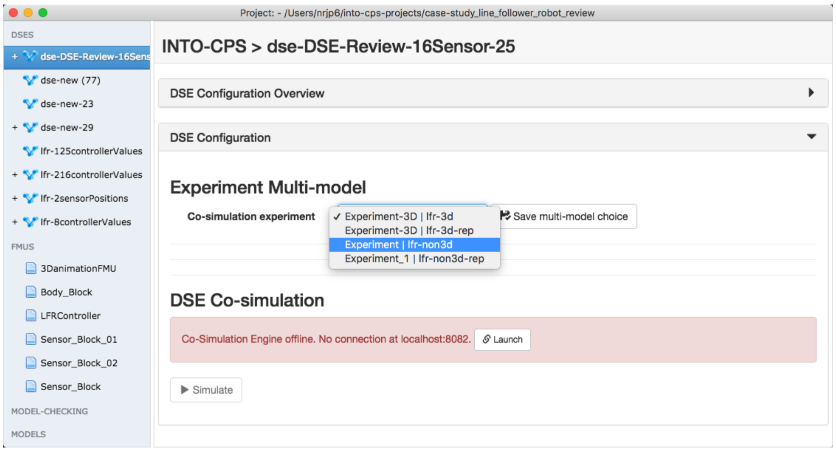
Experiment Multi-model

Co-simulation experiment: undefined | undefined

DSE Co-simulation

Co-Simulation Engine offline. No connection at localhost:8082.

Figure 90: Selecting a multi-model.


Project: - /Users/nrjp6/into-cps-projects/case-study_line_follower_robot_review

INTO-CPS > dse-DSE-Review-16Sensor-25

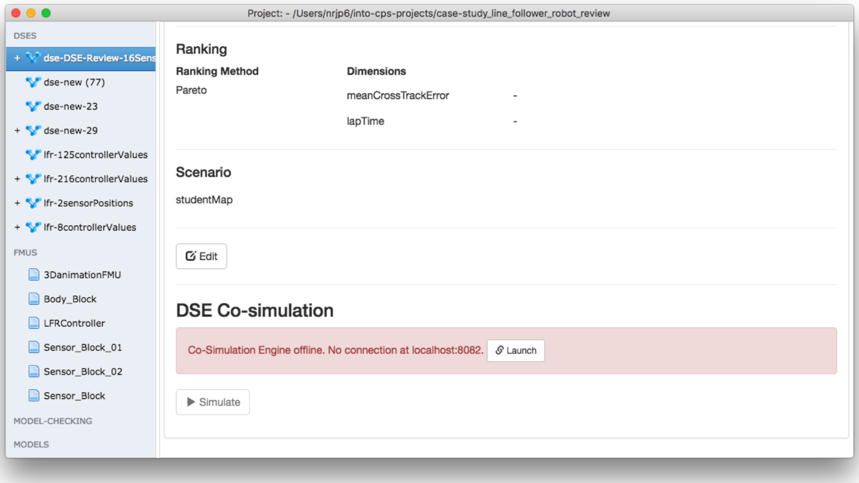
Experiment Multi-model

Co-simulation experiment:
- ✓ Experiment-3D | lfr-3d
- Experiment-3D | lfr-3d-rep
- Experiment | lfr-non3d
- Experiment_1 | lfr-non3d-rep

DSE Co-simulation

Co-Simulation Engine offline. No connection at localhost:8082.

Figure 91: Setting a multi-model.



Ranking

Ranking Method	Dimensions	
Pareto	meanCrossTrackError	-
	lapTime	-

Scenario

studentMap

DSE Co-simulation

Co-Simulation Engine offline. No connection at localhost:8082.

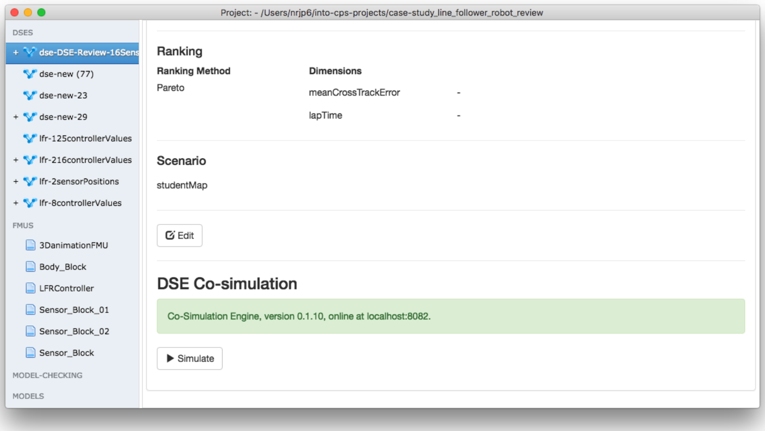
Figure 92: Status when COE is not running.

and double clicking on it opens the results page in the computer's default browser.

The results, shown in Figure 95, contain two elements. The first element is a Pareto graph showing the results of all simulations on a single plot, with each point on the graph representing a single simulation. The best designs, referred to as the non-dominated set, are shown in blue, with ranks of progressively worse designs coloured alternately red and yellow. The second element is a table of these results, with the rank in the left hand column, followed by the objective values and finally the design parameters that produced the result.

6.4 How to Edit a DSE Configuration

A DSE configuration comprises several elements. In Section 6.4.1 we outline the content of each element and their role in a DSE. There are three methods for producing DSE configurations; through the use of the INTO-SysML DSE profile (Section 6.4.2), through the INTO-CPS Application (this method may also be used to edit an existing configuration) (Section 6.4.3), or manually editing a text configuration document (Section 6.4.13). In this section we outline each approach.



Ranking

Ranking Method	Dimensions	
Pareto	meanCrossTrackError	-
	lapTime	-

Scenario

studentMap

DSE Co-simulation

Co-Simulation Engine, version 0.1.10, online at localhost:8082.

Figure 93: Status when COE is running.

6.4.1 DSE Configuration Overview

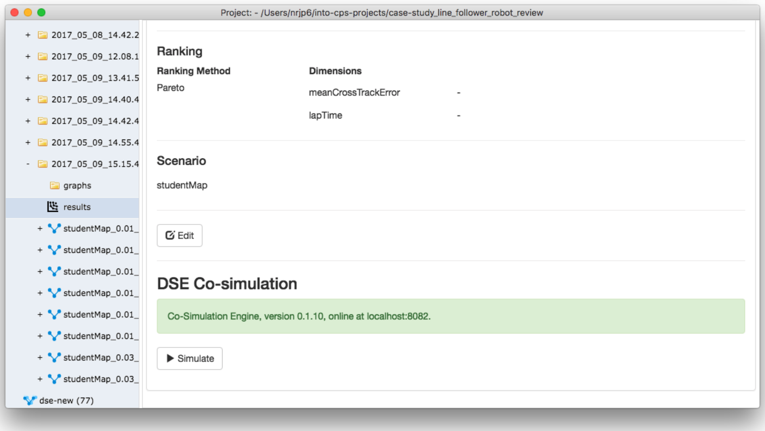
A DSE configuration comprises several elements: the search algorithm to use; parameters; parameter constraints; objectives; objective constraints; a ranking; and a set of scenarios.

Search Algorithm

The algorithm section allows a user to choose between DSE search algorithms implemented in INTO-CPS. There are two options at present: *exhaustive* and *genetic*. The exhaustive approach will simulate the whole design space as dictated by the choice of parameters and scenarios. The genetic algorithm uses an approach to selecting the designs to simulate based upon genetic breeding and mutations. For more information on the search algorithms, see Deliverable D3.2a [FGPP16].

Parameters

The parameters section is used to define a list of values for each parameter to be explored. If a parameter is included in the DSE configuration file, then it must have at least one value defined. The order of the values in the list is not important.



Project: - /Users/nrjp6/into-cps-projects/case-study_line_follower_robot_review

Ranking

Ranking Method: Pareto

Dimensions: meanCrossTrackError -, lapTime -

Scenario: studentMap

DSE Co-simulation

Co-Simulation Engine, version 0.1.10, online at localhost:8082.

Figure 94: Icon shown when DSE results are ready.

Parameter Constraints

It may be the case that not all combinations of the parameter values defined in the previous section are valid. So, it is necessary to be able to define constraints over the design parameters such that no time is wasted simulating invalid designs. For example, in the Line Follower Robot project [MGP^{+}17] we define ranges for the x and y co-ordinates of the left and right sensors separately, and running all combinations of these leads to asymmetric designs that do not have the same turning behaviour on left and right turns. To prevent this we can define boolean expressions based upon the design parameters and evaluate these before a simulation is launched.

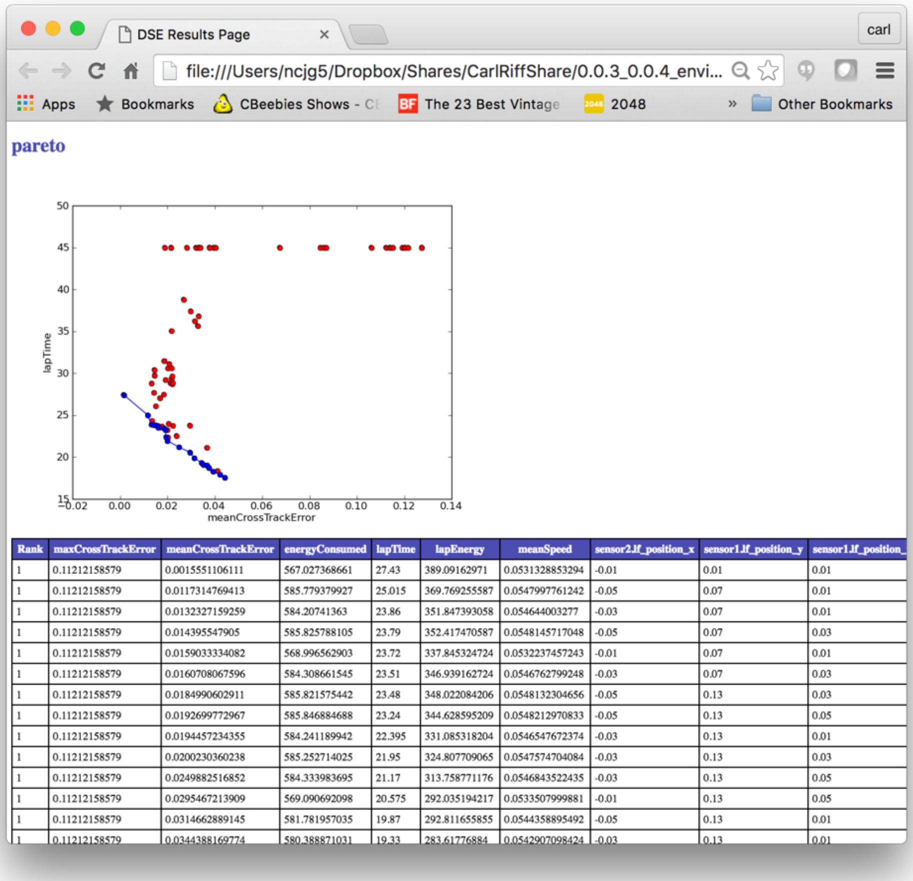
Objective Definitions: Internal

There are two means for defining the objectives used to assess the performance of a simulated model. The first of these, described here, is using the internal functions included in the DSE scripts. This is a set of simple functions that can be applied to any of the values recorded by the COE during simulation. The current set of internal functions is:

max Returns the maximum value of a variable during a simulation.

min Returns the minimum value of a variable during a simulation.

mean Returns the mean value of a variable during a simulation (*n.b.*, a fixed simulation step size is assumed.)



Rank	maxCrossTrackError	meanCrossTrackError	energyConsumed	lapTime	lapEnergy	meanSpeed	sensor2.lf_position_x	sensor1.lf_position_y	sensor1.lf_position_
1	0.11212158579	0.0015551106111	567.027368661	27.43	389.09162971	0.0531328853294	-0.01	0.01	0.01
1	0.11212158579	0.0117314769413	585.779379927	25.015	369.769255587	0.0547997761242	-0.05	0.07	0.01
1	0.11212158579	0.0132327159259	584.20741363	23.86	351.847393058	0.054644003277	-0.03	0.07	0.01
1	0.11212158579	0.014395547905	585.825788105	23.79	352.417470587	0.0548145717048	-0.05	0.07	0.03
1	0.11212158579	0.0159033334082	568.996562903	23.72	337.845324724	0.0532237457243	-0.01	0.07	0.01
1	0.11212158579	0.0160708067596	584.308661545	23.51	346.939162724	0.0546762799248	-0.03	0.07	0.03
1	0.11212158579	0.0184990602911	585.821575442	23.48	348.022084206	0.0548132304656	-0.05	0.13	0.03
1	0.11212158579	0.0192699772967	585.846884688	23.24	344.628595209	0.0548212970833	-0.05	0.13	0.05
1	0.11212158579	0.0194457234355	584.241189942	22.395	331.085318204	0.0546547672374	-0.03	0.13	0.01
1	0.11212158579	0.0200230360238	585.252714025	21.95	324.807709065	0.0547574704084	-0.03	0.13	0.03
1	0.11212158579	0.0249882516852	584.333983695	21.17	313.758771176	0.0546843522435	-0.03	0.13	0.05
1	0.11212158579	0.0295467213909	569.090692098	20.575	292.035194217	0.0533507999881	-0.01	0.13	0.05
1	0.11212158579	0.0314662889145	581.781957035	19.87	292.811655855	0.0544358895492	-0.05	0.13	0.01
1	0.11212158579	0.0344388169774	580.388871031	19.33	283.61776884	0.0542907098424	-0.03	0.13	0.01

Figure 95: A page of DSE results.

Objective Definitions: External Scripts

The second form of objective definition makes use of user-defined Python scripts to allow bespoke analysis of simulation results to be launched automatically and results recorded using the common format. The definition has two parts: the construction of the Python script to perform the analysis and the definition of the script's required parameters in the DSE configuration file. These two steps are described below.

Construction of the Script The outline functionality of an analysis script is that, at the appropriate times, a DSE script calls it, passing four or more arguments. The script uses these arguments to locate a raw simulation results file (`results.csv`), process those results and then write the objective values into an objectives file (`objectives.json`) for that simulation.

The first three arguments sent to the script are common to all scripts. These are listed below.

argv 1 The absolute path to the folder containing the `results.csv` results file. This is also the path where the script finds the `objectives.json` file.

argv 2 The name of the objective. This is the key against which the script should save its results in the objectives file.

argv 3 The name of the scenario.

With this information the script can find the raw simulation data and also determine where to save its results. The name of the scenario allows the script to locate any data files it needs relating to the scenario. For example, in the case of the script measuring cross track error for the line following robot, the script makes use of a data file that contains a series of coordinates that represent the line to be followed. The name of this data file is `map1px.csv`. It is placed into a folder with the same name as the scenario, which in this case is `studentMap`. That folder is located in the `userMetricScripts` folder, as shown in Figure 96. Using this method, the developer of an external analysis script needs only to define the name of the data file they will need and know that at runtime the script will be passed a path to a folder containing the data file suitable for the scenario under test.

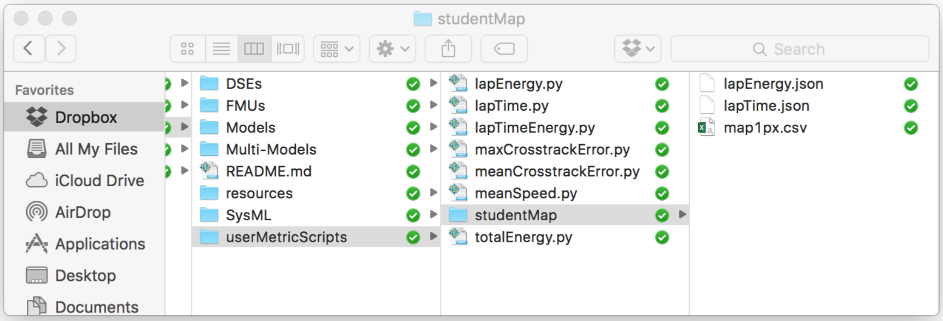
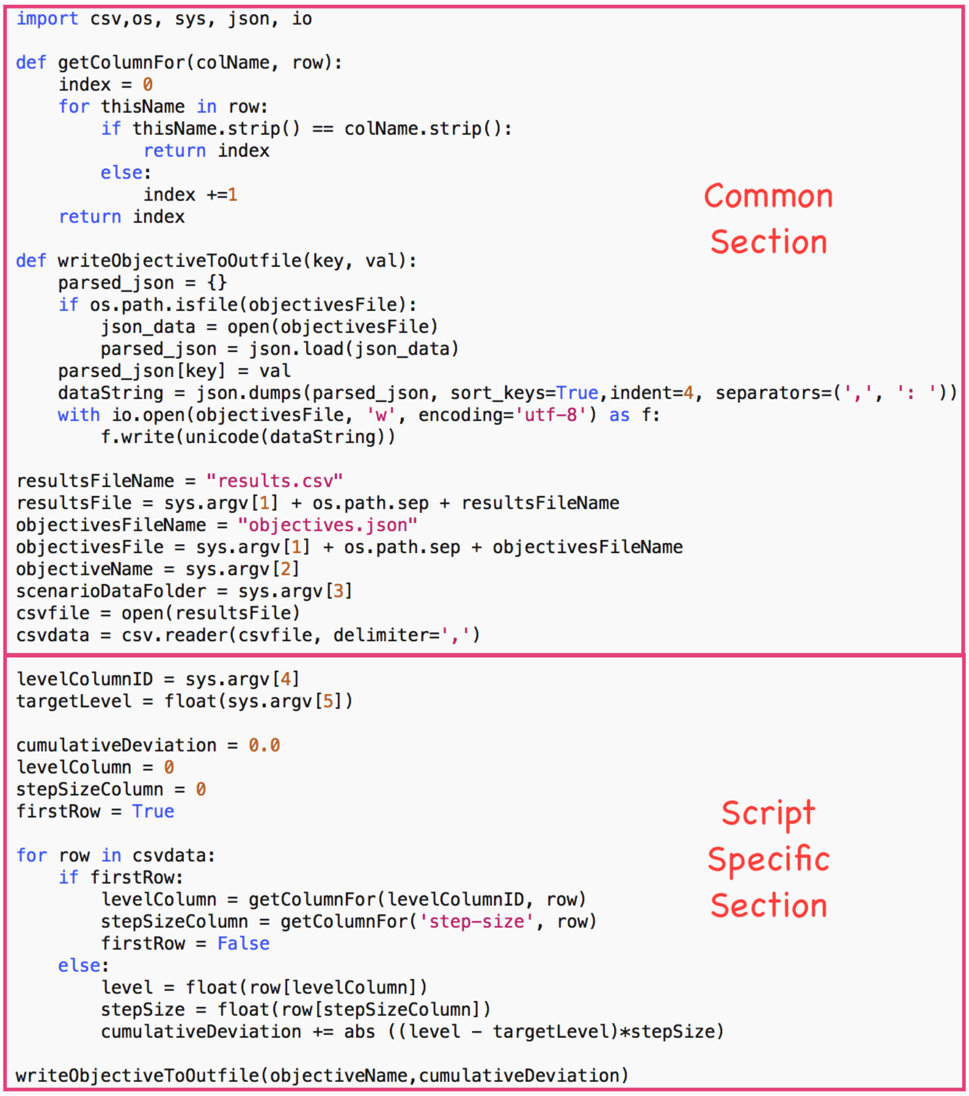


Figure 96: External analysis script data files for the “studentMap” scenario.

Figure 97 shows an example of an external analysis script. In this case it computes the cumulative deviation of the water level from some target level.



```
import csv,os, sys, json, io

def getColumnFor(colName, row):
    index = 0
    for thisName in row:
        if thisName.strip() == colName.strip():
            return index
        else:
            index +=1
    return index

def writeObjectiveToOutfile(key, val):
    parsed_json = {}
    if os.path.isfile(objectivesFile):
        json_data = open(objectivesFile)
        parsed_json = json.load(json_data)
    parsed_json[key] = val
    dataString = json.dumps(parsed_json, sort_keys=True,indent=4, separators=(',', ': '))
    with io.open(objectivesFile, 'w', encoding='utf-8') as f:
        f.write(unicode(dataString))

resultsFileName = "results.csv"
resultsFile = sys.argv[1] + os.path.sep + resultsFileName
objectivesFileName = "objectives.json"
objectivesFile = sys.argv[1] + os.path.sep + objectivesFileName
objectiveName = sys.argv[2]
scenarioDataFolder = sys.argv[3]
csvfile = open(resultsFile)
csvdata = csv.reader(csvfile, delimiter=',')
```

```
levelColumnID = sys.argv[4]
targetLevel = float(sys.argv[5])

cumulativeDeviation = 0.0
levelColumn = 0
stepSizeColumn = 0
firstRow = True

for row in csvdata:
    if firstRow:
        levelColumn = getColumnFor(levelColumnID, row)
        stepSizeColumn = getColumnFor('step-size', row)
        firstRow = False
    else:
        level = float(row[levelColumn])
        stepSize = float(row[stepSizeColumn])
        cumulativeDeviation += abs ((level - targetLevel)*stepSize)

writeObjectiveToOutfile(objectiveName,cumulativeDeviation)
```

Figure 97: External analysis script to calculate cumulative deviation in the Water Tank example.

There are two distinct sections in the file, we shall refer to them as the "common" and "script specific" sections.

The common section contains core functions that are common to all external scripts. It reads in the three arguments that are common to all scripts, and contains functions to help the user retrieve the data needed by the analysis script, and to write the computed objective value into the `objectives.json` file. It is recommended that this section be copied to form the basis of any new external analysis scripts.

The second part of the example script shown is specific to the analysis to be performed. The purpose of this section is to actually compute the value of the objective from the results of a simulation. Generally it will have three parts: reading in any analysis specific arguments such as the ID of data in the results that it needs, using the data in `results.csv` to calculate the value of the objective and finally write the objective value into `objectives.json`.

In the 'Script Specific Section' of Figure 97 we see the example of the script calculating the cumulative deviation of the water level from a target level in the water tank model. It starts by reading a further two arguments passed when the script is launched and initializes the variables. The script then iterates through all rows of data in `results.csv` to calculate the cumulative deviation which is then written to the `objectives.json` file in the final line.

Ranking

The final part of a DSE configuration file concerns the placing of designs in a partial order according to their performance. The DSE currently supports a Pareto method of ranking, as was shown earlier in Figure 95. The purpose of the ranking section of the configuration is to define the pair of objectives that will be used to rank the designs, and whether to maximise or minimise each.

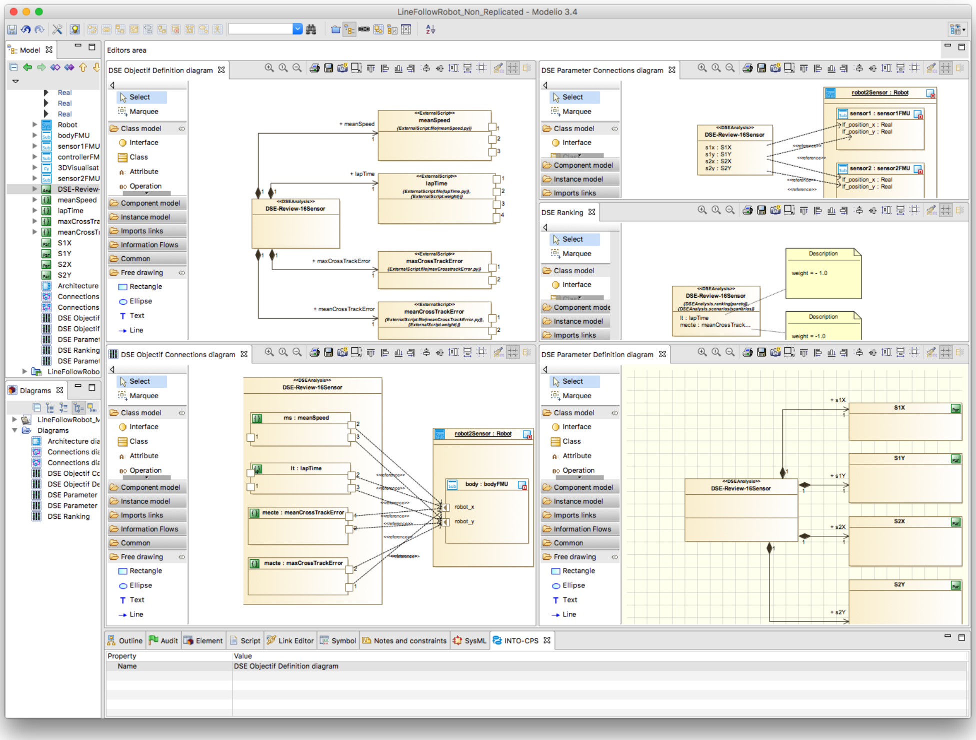
Scenario List

The DSE scripts currently have limited support for scenarios referring to a specific set of conditions against which the multi-model is to be tested. In the example of the line following robot, the scenario refers to the map the robot has to follow, along with its starting co-ordinates. For instance, in one scenario the robot would go around a circular track in one direction, predominantly turning left, whereas in a different scenario the same track would be followed in the opposite direction, predominantly turning right. In both scenarios the map of the track is the same.

6.4.2 Using the INTO-SysML DSE Profile

The INTO-CPS DSE SysML profile is defined in Deliverable D4.2c [BQ16], with an example of its use in Deliverable D3.3a [FGP17]. Here we describe the steps to export the configuration from Modelio and import it into the INTO-CPS Application.

Given a complete DSE SysML model, as shown in Figure 98, we generate a DSE configuration by right-clicking on the `DSEAnalysis` object in the model browser and selecting *INTO-CPS* → *GenerateDSE*, as in Figure 99.



Property | Value
Name | DSE Objectif Definition diagram

Figure 98: SysML model of DSE analysis experiment.

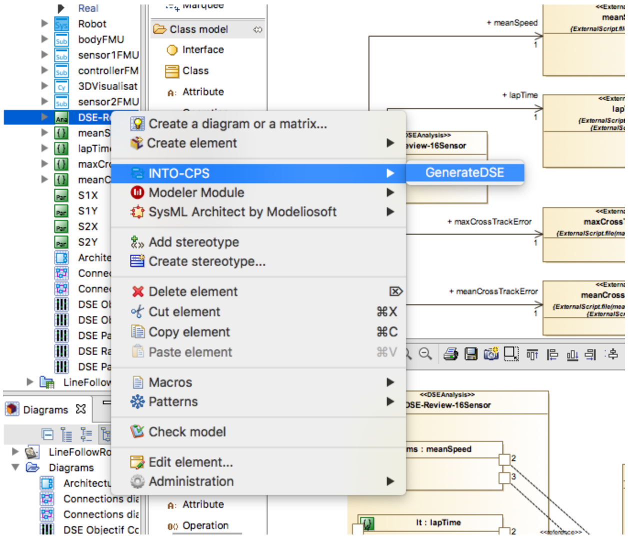
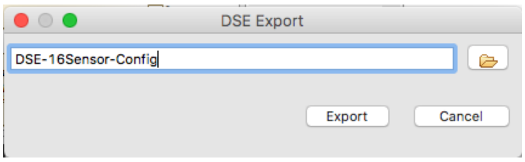


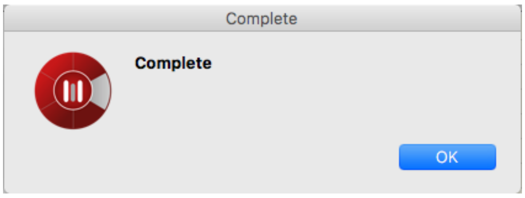
Figure 99: Menu option for generating DSE configuration.

Simply supply an appropriate name and select *Export* (Figure 100). When the export is complete, click *OK* (Figure 101).


DSE Export

DSE-16Sensor-Config

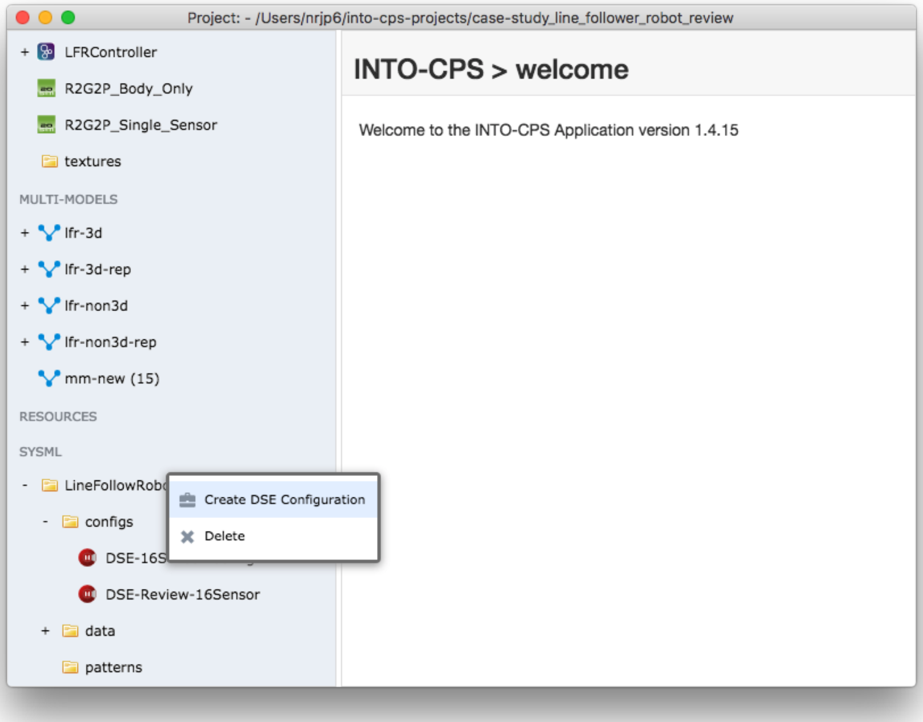
Figure 100: Enter DSE configuration name.


Complete

Complete

Figure 101: Export complete.

Moving to the INTO-CPS Application, we start to import the configuration. Expand the generated configurations in project's SysML model: *Model* → *configs*, right click on the configuration name as defined above and select *Create DSE Configuration* (see Figure 102). When complete, the configuration screen is displayed, and can be launched according to instructions in Section 6.2.



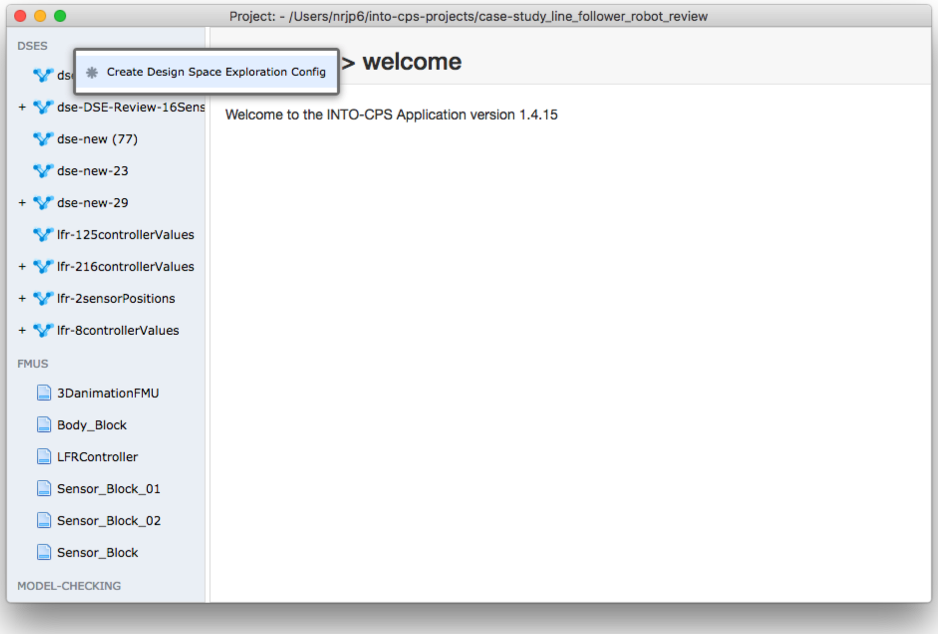
INTO-CPS > welcome

Welcome to the INTO-CPS Application version 1.4.15

Figure 102: Create configuration in INTO-CPS Application.

6.4.3 Using the INTO-CPS Application DSE Editor

To create a new DSE configuration in the INTO-CPS Application, right click on the DSES section of the project browser and select *Create Design Space Exploration Config*, as in Figure 103. This will create a new configuration with a name in the form `dse-new(xx)` with a random number. This can be renamed by right-clicking on the new config in the project browser. When opened, one must first select the multi-model to use. Follow the same steps as given earlier for launching a DSE (Figures 90 and 91). When selected, the DSE configuration may be edited.



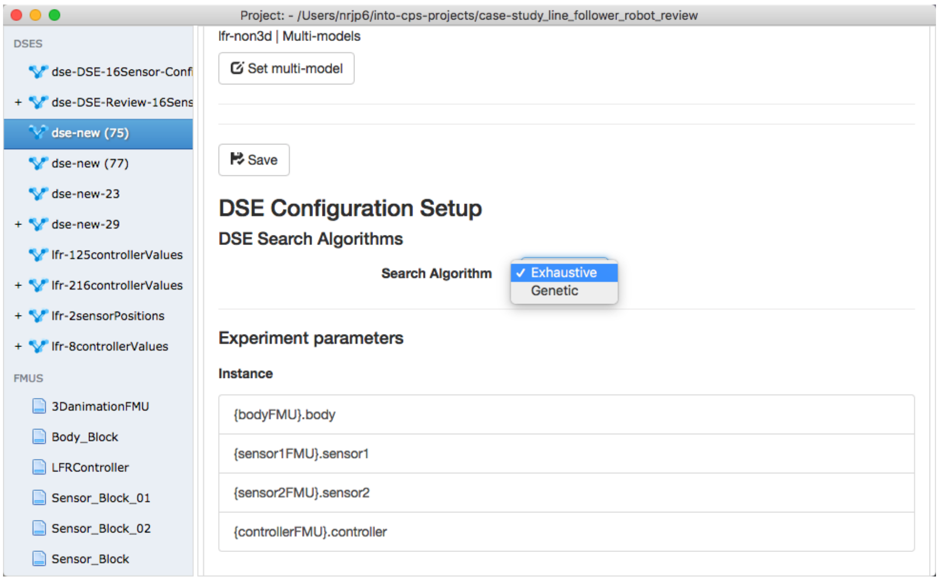
Welcome to the INTO-CPS Application version 1.4.15

Figure 103: Create new DSE configuration.

6.4.4 Search Algorithm

The first element to define is the search algorithm. A choice is given between *Exhaustive* and *Genetic* searches, as shown in Figure 104. The exhaustive option has no further options, whist a genetic search requires data concerning: the *initial population*; *initial population distribution*; *mutation probability*;

parent selection strategy; and *maximum generations without improvement* – these are shown in Figure 105.



DSE Configuration Setup

DSE Search Algorithms

Search Algorithm ✓ Exhaustive

Experiment parameters

Instance

{bodyFMU}.body

{sensor1FMU}.sensor1

{sensor2FMU}.sensor2

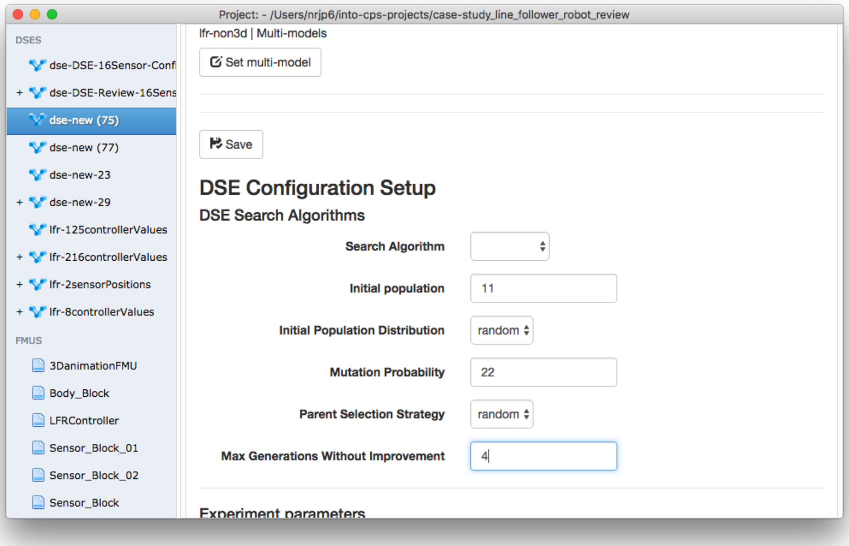
{controllerFMU}.controller

Figure 104: Choosing the DSE search algorithm.

6.4.5 Parameters

Design parameters may be defined in a multi-model. In addition, a DSE configuration may define a range of values to be used in the DSE. The DSE editor allows users to browse the multi-model parameters (Figure 106) and edit those parameters defined in the multi-model (Figure 107).

Parameters may be removed from the DSE configuration (they will not be removed from the multi-model) by clicking the *Remove DSE Parameter* button – see Figure 108. Additional DSE parameters may be added by selecting the parameter name from the drop down and clicking the *Add DSE Parameter* button – see Figure 109.



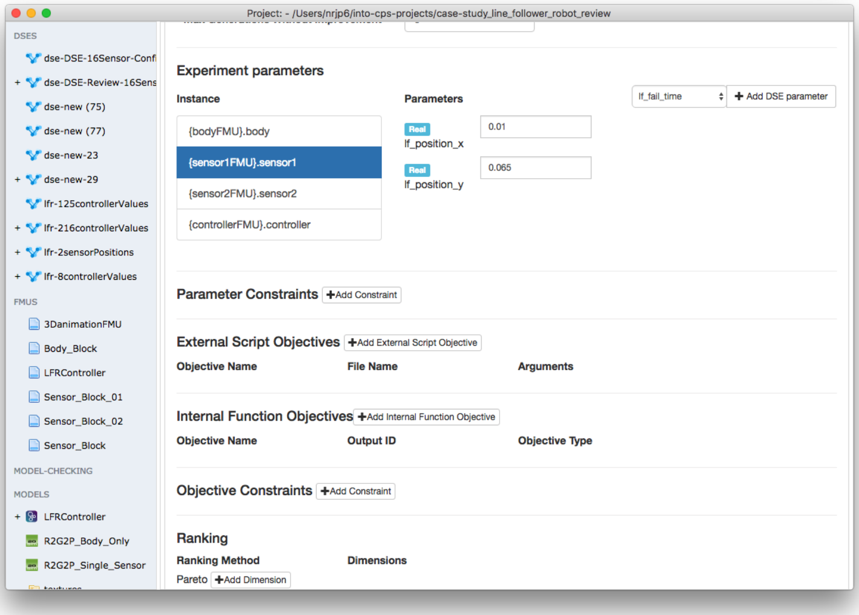
DSE Configuration Setup

DSE Search Algorithms

Search Algorithm	
Initial population	11
Initial Population Distribution	random
Mutation Probability	22
Parent Selection Strategy	random
Max Generations Without Improvement	4

Experiment parameters

Figure 105: Options for the genetic algorithm.



Experiment parameters

Instance: {bodyFMU}.body, {sensor1FMU}.sensor1, {sensor2FMU}.sensor2, {controllerFMU}.controller

Parameters (lf_fail_time):

Real lf_position_x	0.01
Real lf_position_y	0.065

Parameter Constraints

External Script Objectives

Objective Name	File Name	Arguments

Internal Function Objectives

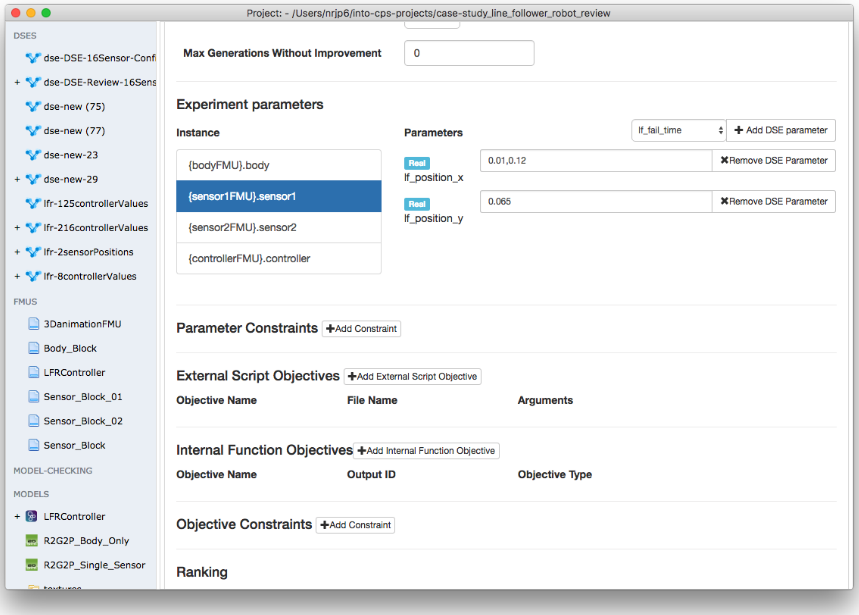
Objective Name	Output ID	Objective Type

Objective Constraints

Ranking

Ranking Method	Dimensions
Pareto	

Figure 106: Browsing the multi-model parameters.



Max Generations Without Improvement 0

Experiment parameters

Instance

{bodyFMU}.body
{sensor1FMU}.sensor1
{sensor2FMU}.sensor2
{controllerFMU}.controller

Parameters lf_fail_time

Real lf_position_x 0.01,0.12

Real lf_position_y 0.065

Parameter Constraints

External Script Objectives

Objective Name	File Name	Arguments

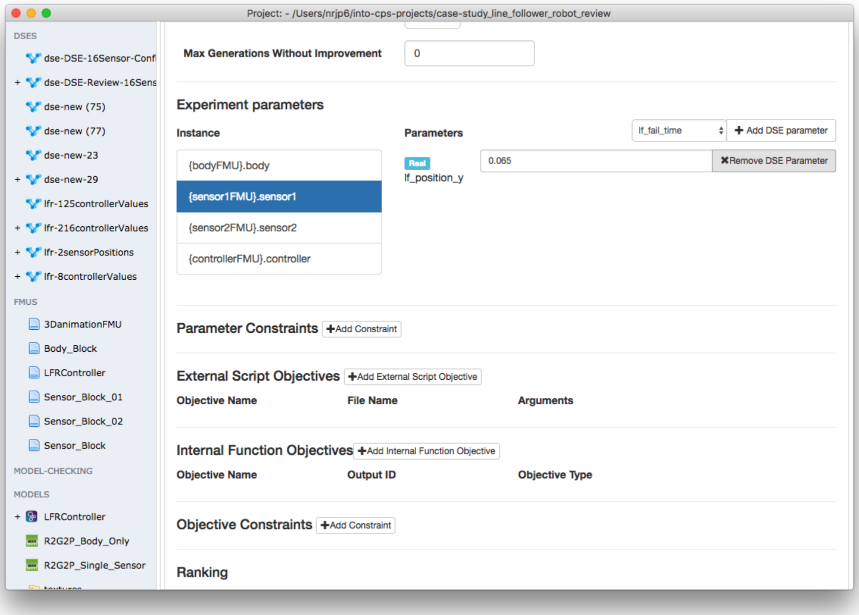
Internal Function Objectives

Objective Name	Output ID	Objective Type

Objective Constraints

Ranking

Figure 107: Editing parameters for DSE run.



Max Generations Without Improvement 0

Experiment parameters

Instance

{bodyFMU}.body
{sensor1FMU}.sensor1
{sensor2FMU}.sensor2
{controllerFMU}.controller

Parameters lf_fail_time

Real lf_position_y 0.065

Parameter Constraints

External Script Objectives

Objective Name	File Name	Arguments

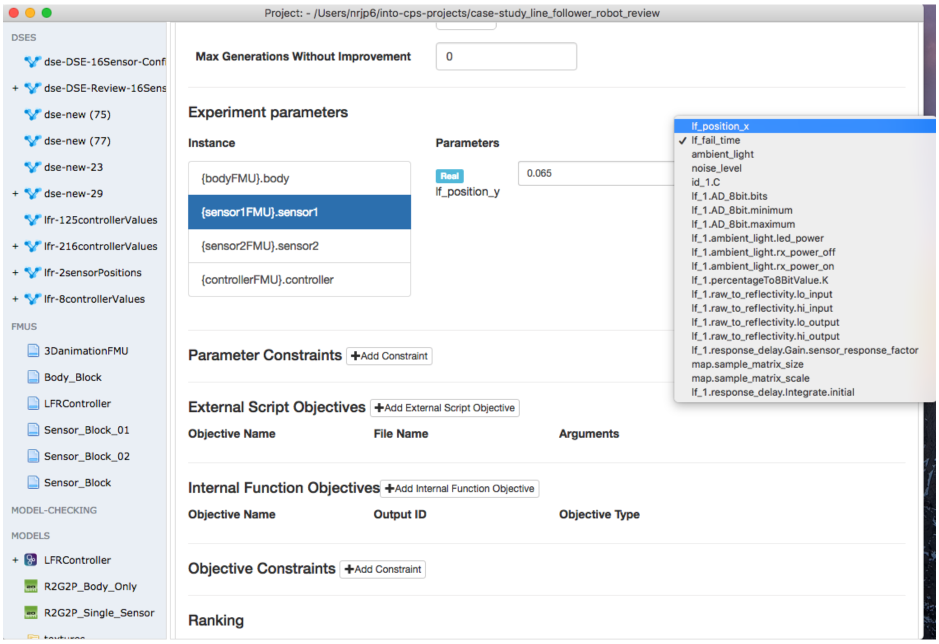
Internal Function Objectives

Objective Name	Output ID	Objective Type

Objective Constraints

Ranking

Figure 108: Removing a DSE parameter.



Max Generations Without Improvement: 0

Experiment parameters

Instance	Parameters	
{bodyFMU}.body	Real lf_position_y	0.065
{sensor1FMU}.sensor1		
{sensor2FMU}.sensor2		
{controllerFMU}.controller		

Parameter Constraints

External Script Objectives

Objective Name	File Name	Arguments

Internal Function Objectives

Objective Name	Output ID	Objective Type

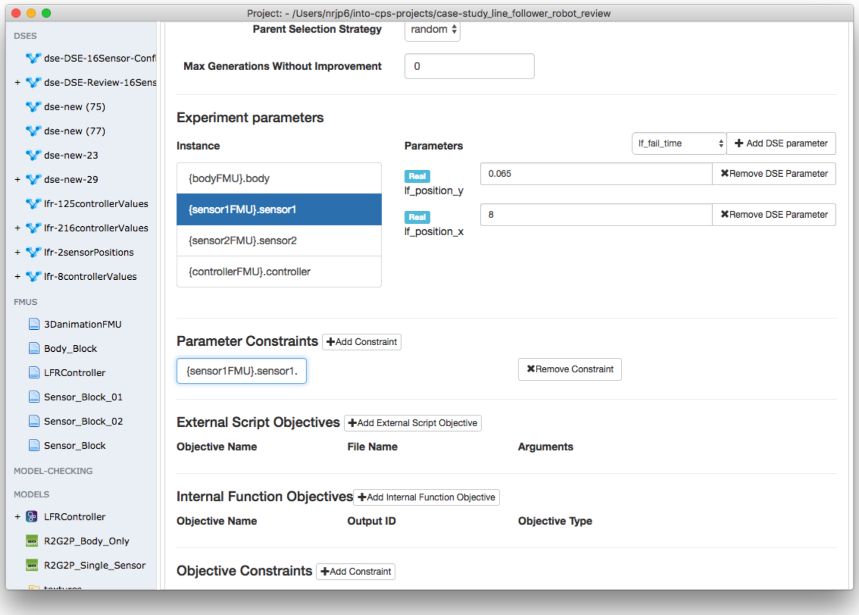
Objective Constraints

Ranking

Figure 109: Add a model parameter for DSE.

6.4.6 Parameter Constraints

Clicking the *Add Constraint* button in the Parameter Constraints section adds a text box where free text may be added, shown in Figure 110. The constraint must be defined according to the description in Section 6.4.16.



Project: - /Users/nrjp6/into-cps-projects/case-study_line_follower_robot_review

Parent Selection Strategy: random

Max Generations Without Improvement: 0

Experiment parameters

Instance	Parameters	
{bodyFMU}.body	Real lf_position_y	0.065
{sensor1FMU}.sensor1	Real lf_position_x	8
{sensor2FMU}.sensor2		
{controllerFMU}.controller		

Parameter Constraints: {sensor1FMU}.sensor1.

External Script Objectives

Objective Name	File Name	Arguments

Internal Function Objectives

Objective Name	Output ID	Objective Type

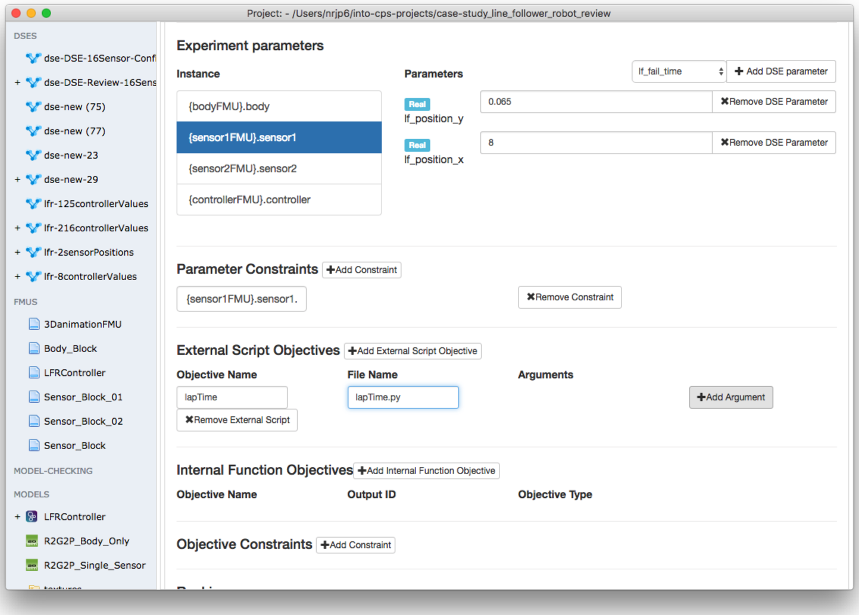
Objective Constraints

Figure 110: Defining a parameter constraint.

6.4.7 Objective Definitions: External Scripts

An external script can be added by clicking the *Add External Script Objective* button. Two text boxes are added; first a name for the objective and the file name of the objective script. In Figure 111, the new objective is given the name *lapTime* and uses the *lapTime.py* Python script. Note: external scripts must be included in the *userMetricScripts* folder of the INTO-CPS project.

Once added, the required arguments must be given. Clicking the *Add Argument* button adds several elements (shown in Figure 112) – the first text box indicates the argument order; the second drop down indicates the type of value, which is either a model output (refers to an output port of a constituent element of the multi-model), a simulation value (either `step-size`



Project: - /Users/nrjp6/into-cps-projects/case-study_line_follower_robot_review

Experiment parameters

Instance: {sensor1FMU}.sensor1

Parameters:

- Real lf_position_y: 0.065
- Real lf_position_x: 8

Parameter Constraints: {sensor1FMU}.sensor1.

External Script Objectives

Objective Name: lapTime

File Name: lapTime.py

Figure 111: Adding a new external script.

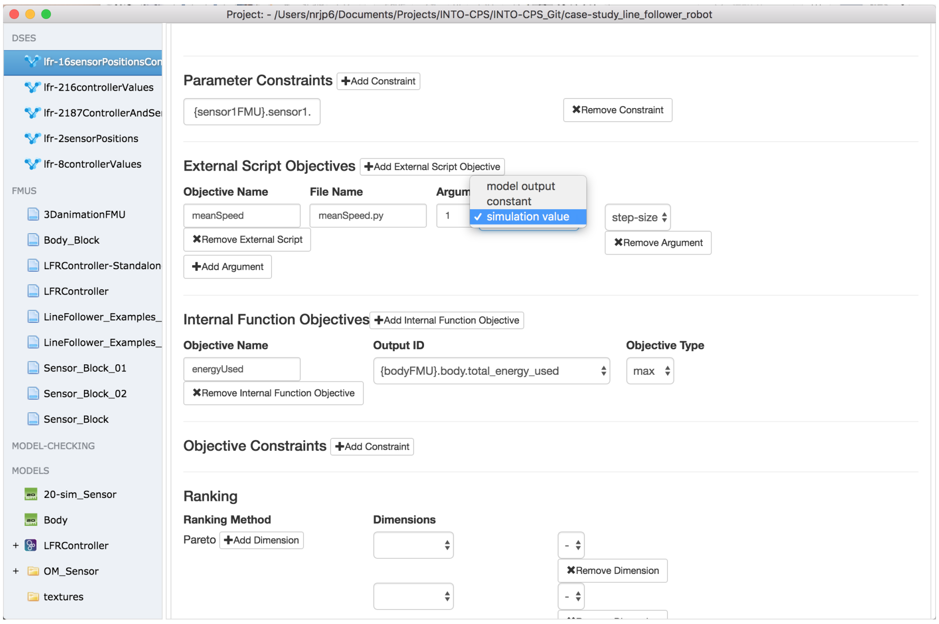
or time), or some constant; the third is the argument to pass to the script. The argument may be a user defined constant value, or one of the predefined values depending on the type selected. A complete definition is shown in Figure 113.

6.4.8 Objective Definitions: Internal Functions

Internal functions are added by clicking the *Add Internal Function Objective* button. This adds a text box to provide the name of the objective, a drop down to specify which model output to use (this refers to an output port of a constituent element of the multi-model) and a drop down to select the type of function. Currently three exist: *max*, *min* and *mean*. This is shown in Figure 114.

6.4.9 Objective Constraints

Objective constraints are similar to parameter constraints. A constraint is added by clicking the *Add Constraint* button in the Objective Constraints



Project: - /Users/nrjp6/Documents/Projects/INTO-CPS/INTO-CPS_Git/case-study_line_follower_robot

Parameter Constraints

{sensor1FMU}.sensor1.

External Script Objectives

Objective Name	File Name	Argum
meanSpeed	meanSpeed.py	1

✓ simulation value

step-size

Internal Function Objectives

Objective Name	Output ID	Objective Type
energyUsed	{bodyFMU}.body.total_energy_used	max

Objective Constraints

Ranking

Ranking Method	Dimensions
Pareto	

Figure 112: Add argument to external script.

section. This adds a text box where free text may be added, shown in Figure 115. The constraint must be expressed in valid Python code.

6.4.10 Ranking

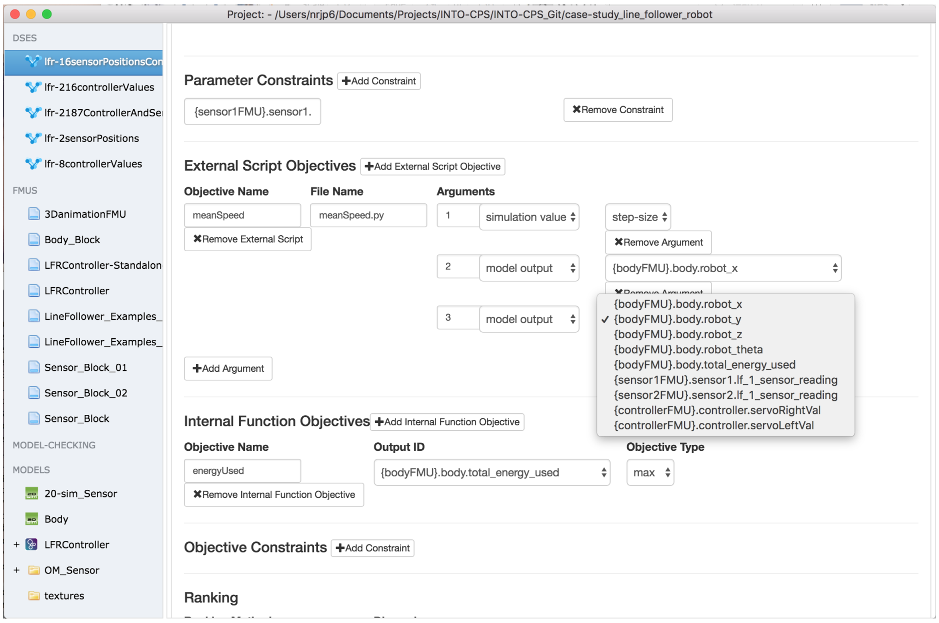
At present, DSE uses only 2-way Pareto rankings. As such, a maximum of two dimensions may be added by clicking the *Add Dimension* button. When clicked, the user may select one of the defined objectives and a direction – either + or −. This is shown in Figure 116.

6.4.11 Scenario List

The support for scenarios is currently limited. At present the user may define a collection of named scenarios, which are passed to all external scripts (the external scripts need not use this). This is shown in Figure 117.

6.4.12 Saving the Configuration

When the configuration editing is finished, it may be saved by clicking the *Save* button at the top or bottom of the configuration description, as in Fig-



Project: - /Users/nrjp6/Documents/Projects/INTO-CPS/INTO-CPS_Git/case-study_line_follower_robot

Parameter Constraints

{sensor1FMU}.sensor1.

External Script Objectives

Objective Name	File Name	Arguments		
meanSpeed	meanSpeed.py	1	simulation value	step-size
		2	model output	{bodyFMU}.body.robot_x
		3	model output	{bodyFMU}.body.robot_y

Internal Function Objectives

Objective Name	Output ID	Objective Type
energyUsed	{bodyFMU}.body.total_energy_used	max

Objective Constraints

Ranking

Figure 113: Complete external script.

ure 118. Note this will overwrite the previous version of the json configuration file – any non-DSE tags will be lost.

6.4.13 Manual Configuration Creation

The recommended procedure for creating a new configuration is to make a copy of an existing one and then to edit the required sections. The individual configurations are located in their own folders within the *Design Space Exploration* folder of the INTO-CPS Application project directory, such as the pilot study with the line following robot "LFR-2SensorPositions" configuration shown in Figure 119 (see [PGP+16]). Using your OS's file browser, create a new folder under *DSEs* and then copy in and rename a DSE configuration. The names of the new folder and configuration folder can be chosen at will, but the configuration file must have the extension `.dse.json` .

6.4.14 Algorithm

The algorithm section dictates the DSE search algorithm to employ in a DSE. There are two types (although if no algorithm is defined, it is assumed to be an exhaustive search):

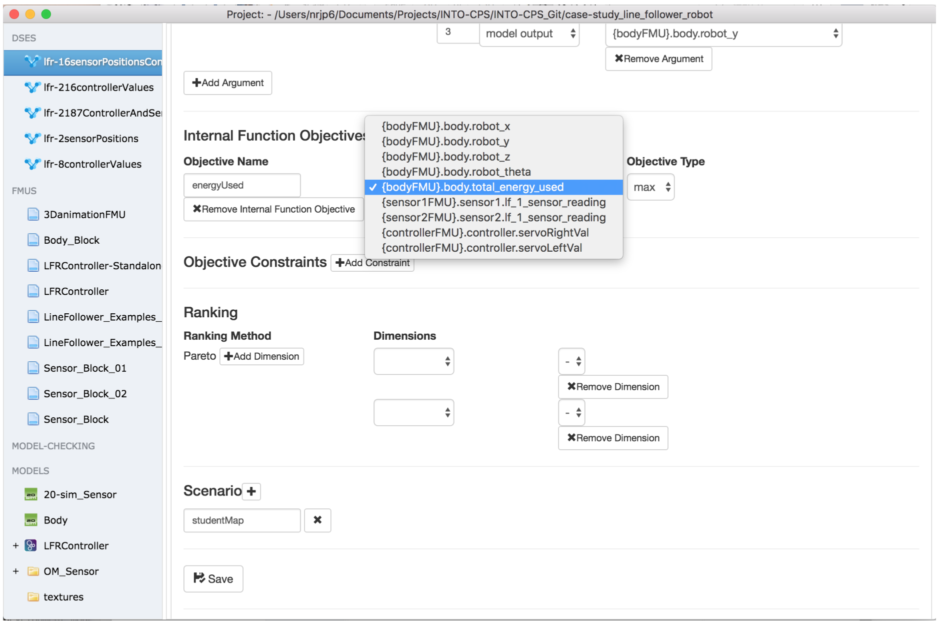


Figure 114: Defining an internal function.

Exhaustive No further values are required.

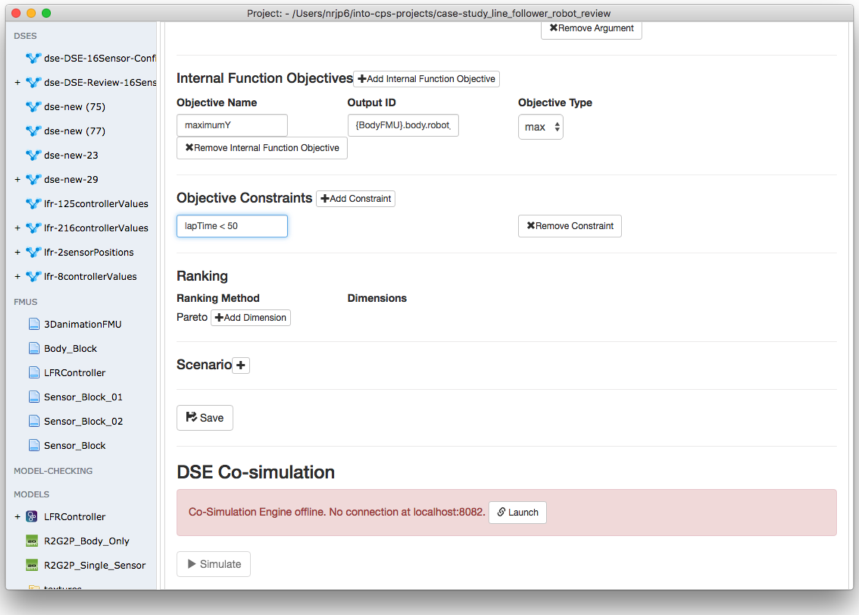
Genetic The genetic approach requires several additional values; initialPopulation (number); initialPopulationDistribution (currently only “random” is supported); mutationProbablity (number – 0-100); parentSelectionStrategy (currently only “random” is supported); and maxGenerationsWithoutImprovement (number).

An example is given in Figure 120.

6.4.15 Parameters

The parameters section is used to define a list of values for each parameter to be explored. Figure 121 shows the definition of four parameters, each with two values. If a parameter is included in the DSE configuration file, then it must have at least one value defined. The order of the values in the list is not important. If a parameter that is to be explored is not in the list, its ID may be found in the three ways listed below.

1. If the parameter is listed in the multi-model configuration, then copy it from there.
2. If the parameter is not in the multi-model parameters list then its name



Objective Name: maximumY
Output ID: {BodyFMU}.body.robot
Objective Type: max

lapTime < 50

Ranking Method: Pareto
Dimensions

Co-Simulation Engine offline. No connection at localhost:8082.

Figure 115: Defining an objective constraint.

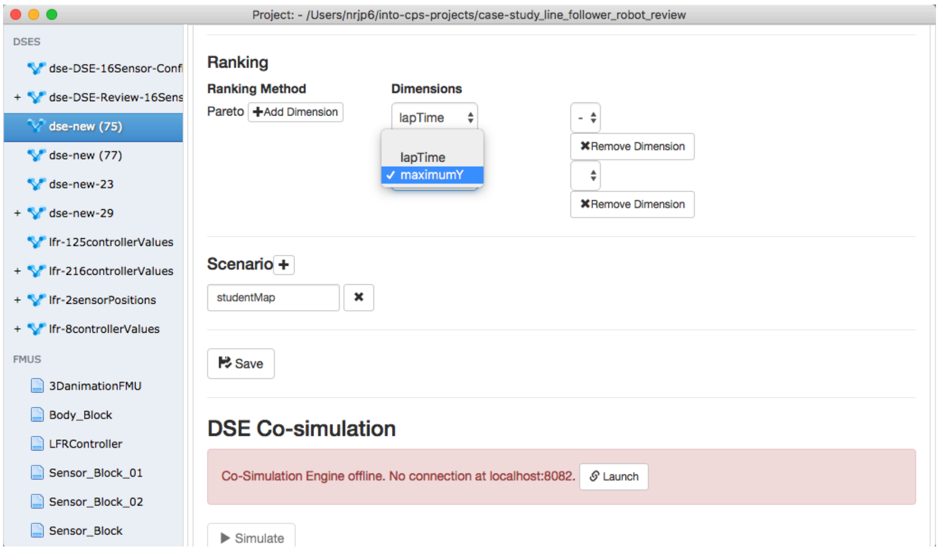
may be found by examining the model description file in the associated FMU. In this case it will be necessary to prepend the parameter ID with the ID for the FMU and the instance ID of the FMU, for example in "`{sensor1FMU}.sensor1.lf_position_x`".

- the ID of the FMU is `{sensor1FMU}`.
- the instance ID of the FMU in the multi-model is `sensor1`.
- the parameter ID is `lf_position_x`.

3. The IDs for each parameter may also be found on the Architecture Structure Diagram in the SysML models of the system. The full name for use in the multi-model may then be constructed as above.

6.4.16 Parameter Constraints

Figure 122 shows two constraints defined for the line follower DSE experiment that ensure only symmetrical designs are allowed. The first constraint ensures the y co-ordinates of both sensors are the same, while the second constraint ensures that the x co-ordinate of the left sensor is the same, but negated as



Co-Simulation Engine offline. No connection at localhost:8082.

Figure 116: Defining the Pareto ranking.

the x co-ordinate of the right sensor. Note that the names used when defining such constraints have the same `FMU_ID.instance_ID.parameter_ID` format as used when defining a parameter range (see Section 6.4.15)

Since the constraints are processed using the Python `eval` function, any boolean expression compatible with this may be used here.

6.4.17 Objective Definitions: Internal

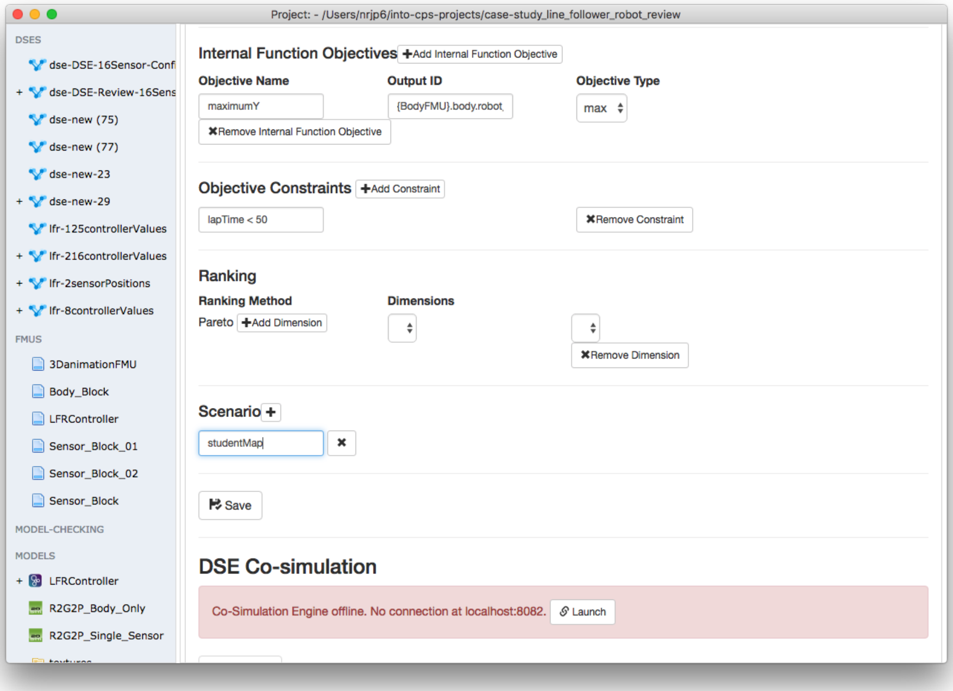
Defining an internal objective requires three pieces of information:

name This is the name that the objective value will be stored under in the objectives file.

type This selects the function to be applied. The key `objectiveType` is used in the DSE configuration file.

variable This defines the variable to which the function is to be applied. The key `columnID` is used to denote this parameter in the DSE configuration file.

Figure 123 shows the definition of an objective named `energyConsumed`, which records the maximum value of the variable `{bodyFMU}.body.total_energy_used`. This objective is recorded and may be used later, primarily for the purpose of ranking designs, but it could



Internal Function Objectives

Objective Name	Output ID	Objective Type
maximumY	{BodyFMU}.body.robot	max

Objective Constraints

lapTime < 50

Ranking

Ranking Method: Pareto

Dimensions

Scenario +

studentMap

DSE Co-simulation

Co-Simulation Engine offline. No connection at localhost:8082.

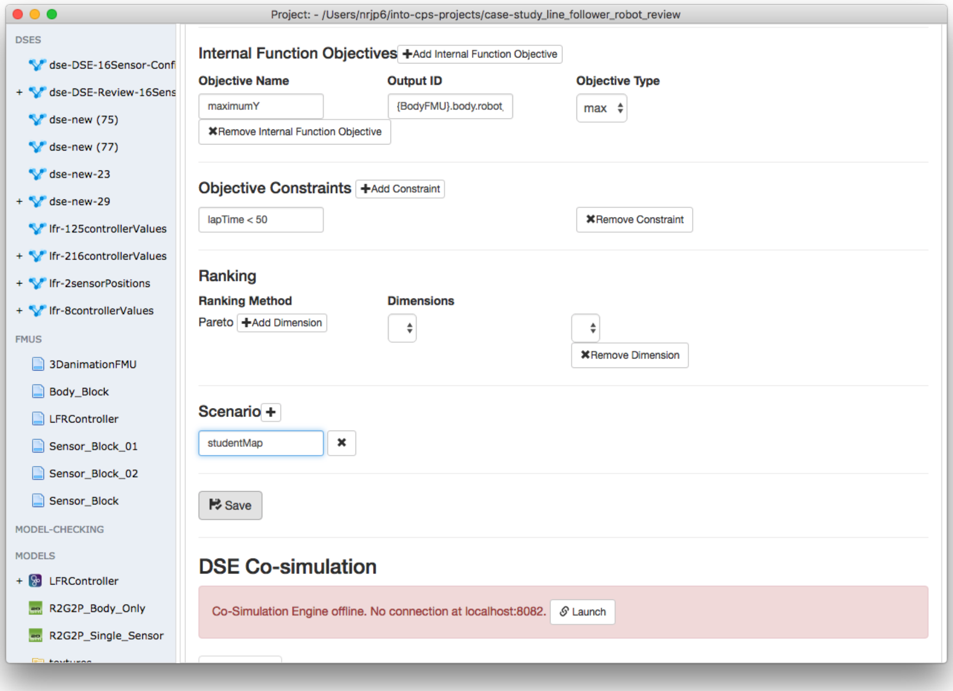
Figure 117: Adding a DSE scenario.

also be used for any other analysis required.

6.4.18 Objective Definitions: External Scripts

Using external scripts in a configuration requires three parts; a name for the objective, the file name of the script and a list of arguments to pass. The name given to the objective allows it to be referenced in the objectives constraints and ranking sections of the DSE configuration. The file name tells the DSE scripts which script to launch and the arguments define additional data (over the standard three arguments described earlier) that the script needs, such as the names of data it needs or constant values.

In Figure 124 we find the definition of the external analysis used in the Three Water Tank example. There are two analyses defined, the first is named “cumulativeDeviation” and the second is “vCount”. In each there are two parameters defined: “scriptFile” contains the file name of the script file to run in each case, while “scriptParameters” contains the list of additional arguments each needs.



Project: - /Users/nrjp6/into-cps-projects/case-study_line_follower_robot_review

Internal Function Objectives

Objective Name	Output ID	Objective Type
maximumY	{BodyFMU}.body.robot_	max

Objective Constraints

lapTime < 50

Ranking

Ranking Method: Pareto

Dimensions

Scenario

studentMap

DSE Co-simulation

Co-Simulation Engine offline. No connection at localhost:8082.

Figure 118: Save DSE configuration.

The purpose of both internal and external analysis functions is to populate the `objectives.json` file with values that characterise the performance of the designs being explored. Figure 125 shows an example objectives file generated during a DSE of the Three Water Tank example. There is an instance of the objectives file created for each simulation in DSE, its primary use being to inform the ranking of designs, but it may be used for any other analysis a user wishes to define.

6.4.19 Ranking

Figure 126 shows an example of a ranking definition from the line following robot example. Here the user has specified that the lap time and mean cross track error objectives will be used for ranking. The use of '-' after each indicates that the aim is to minimise both, whereas a '+' indicates the desire to maximise.

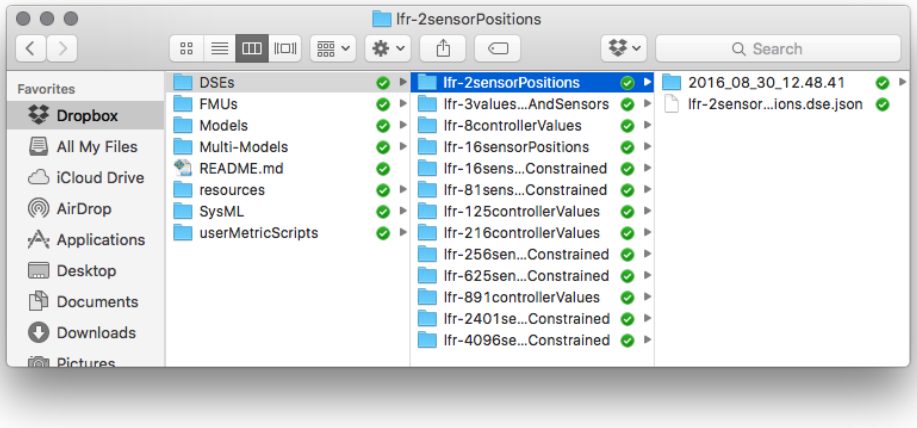


Figure 119: Location of DSE configurations.

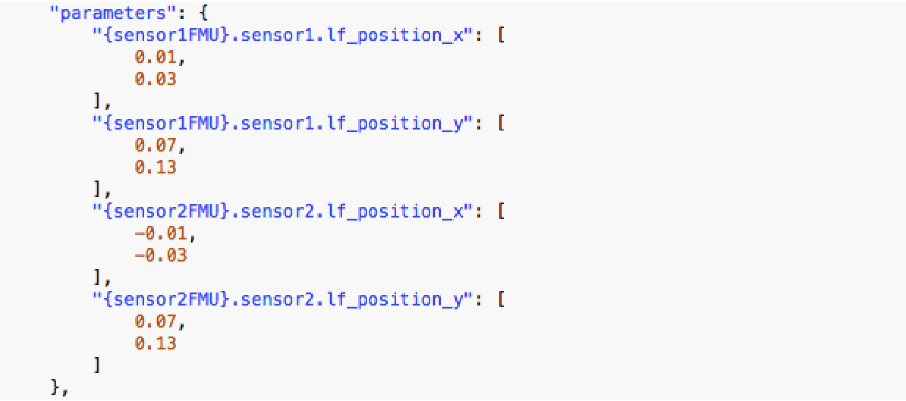
```
"algorithm": {
    "type": "genetic",
    "initialPopulation": 2,
    "initialPopulationDistribution": "random",
    "mutationProbability" : 95,
    "parentSelectionStrategy": "random",
    "maxGenerationsWithoutImprovement": 5
},
```

Figure 120: Example genetic algorithm.

6.4.20 Scenario List

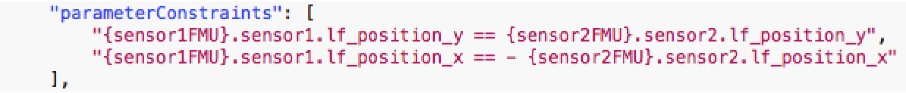
Changing a scenario may involve changing one or more different parts of the multi-model and its analysis, such as the specific FMUs used, parameters passed to an FMU, the multi-model the DSE is based upon, along with any data files used by the objective scripts (Section 6.4.18) to evaluate performance. This feature is currently under development and so only the objective data file selection is implemented presently. As such, scenarios are simply passed to objectives.

Combining all these sections results in a complete DSE configuration, as shown in Figure 127.



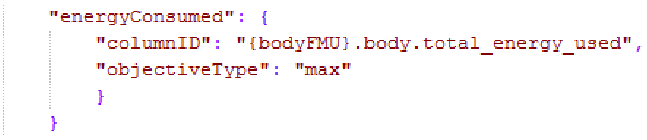
```
"parameters": {
    "{sensor1FMU}.sensor1.lf_position_x": [
        0.01,
        0.03
    ],
    "{sensor1FMU}.sensor1.lf_position_y": [
        0.07,
        0.13
    ],
    "{sensor2FMU}.sensor2.lf_position_x": [
        -0.01,
        -0.03
    ],
    "{sensor2FMU}.sensor2.lf_position_y": [
        0.07,
        0.13
    ]
},
```

Figure 121: Example parameter definitions.



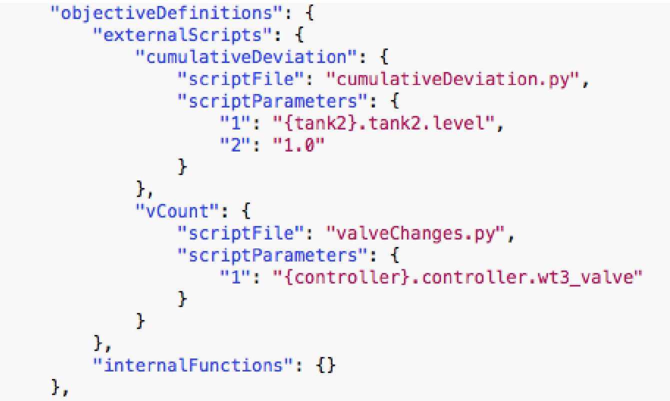
```
"parameterConstraints": [
    "{sensor1FMU}.sensor1.lf_position_y == {sensor2FMU}.sensor2.lf_position_y",
    "{sensor1FMU}.sensor1.lf_position_x == - {sensor2FMU}.sensor2.lf_position_x"
],
```

Figure 122: Example parameter constraints.



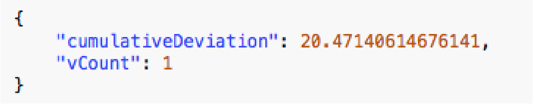
```
"energyConsumed": {
    "columnID": "{bodyFMU}.body.total_energy_used",
    "objectiveType": "max"
    }
}
```

Figure 123: Definition of an internal objective.



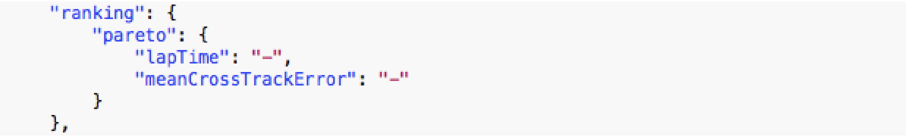
```
"objectiveDefinitions": {
    "externalScripts": {
        "cumulativeDeviation": {
            "scriptFile": "cumulativeDeviation.py",
            "scriptParameters": {
                "1": "{tank2}.tank2.level",
                "2": "1.0"
            }
        },
        "vCount": {
            "scriptFile": "valveChanges.py",
            "scriptParameters": {
                "1": "{controller}.controller.wt3_valve"
            }
        }
    },
    "internalFunctions": {}
},
```

Figure 124: Definition of the external analysis functions for the Three Water Tank model.



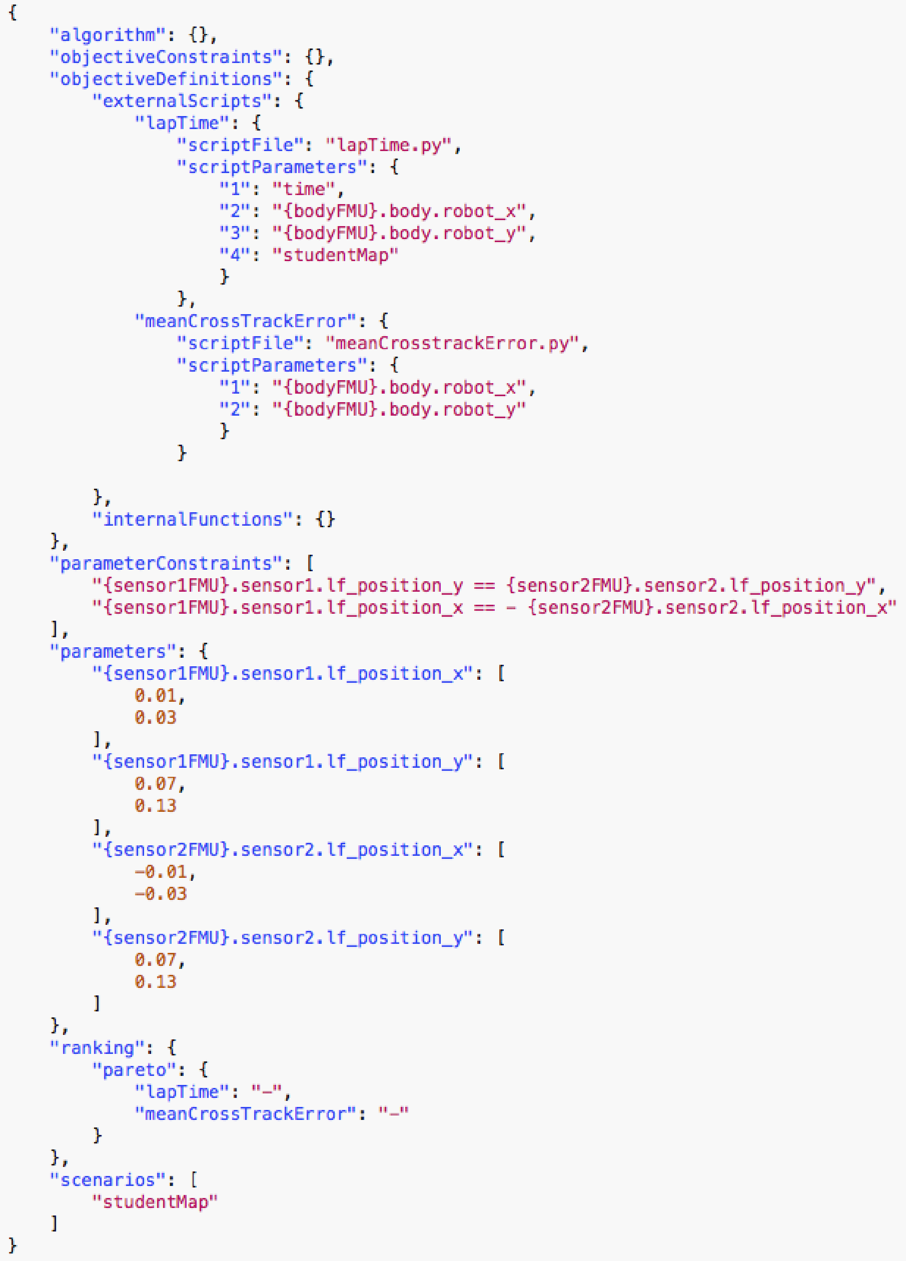
```
{
    "cumulativeDeviation": 20.47140614676141,
    "vCount": 1
}
```

Figure 125: Contents of `objectives.json` file for a single simulation of the Three Water Tank model.



```
    "ranking": {
        "pareto": {
            "lapTime": "-",
            "meanCrossTrackError": "-"
        }
    },
```

Figure 126: Defining parameters and their preferred directions for ranking.



```
{
    "algorithm": {},
    "objectiveConstraints": {},
    "objectiveDefinitions": {
        "externalScripts": {
            "lapTime": {
                "scriptFile": "lapTime.py",
                "scriptParameters": {
                    "1": "time",
                    "2": "{bodyFMU}.body.robot_x",
                    "3": "{bodyFMU}.body.robot_y",
                    "4": "studentMap"
                }
            },
            "meanCrossTrackError": {
                "scriptFile": "meanCrosstrackError.py",
                "scriptParameters": {
                    "1": "{bodyFMU}.body.robot_x",
                    "2": "{bodyFMU}.body.robot_y"
                }
            }

        },
        "internalFunctions": {}
    },
    "parameterConstraints": [
        "{sensor1FMU}.sensor1.lf_position_y == {sensor2FMU}.sensor2.lf_position_y",
        "{sensor1FMU}.sensor1.lf_position_x == - {sensor2FMU}.sensor2.lf_position_x"
    ],
    "parameters": {
        "{sensor1FMU}.sensor1.lf_position_x": [
            0.01,
            0.03
        ],
        "{sensor1FMU}.sensor1.lf_position_y": [
            0.07,
            0.13
        ],
        "{sensor2FMU}.sensor2.lf_position_x": [
            -0.01,
            -0.03
        ],
        "{sensor2FMU}.sensor2.lf_position_y": [
            0.07,
            0.13
        ]
    },
    "ranking": {
        "pareto": {
            "lapTime": "-",
            "meanCrossTrackError": "-"
        }
    },
    "scenarios": [
        "studentMap"
    ]
}
```

Figure 127: A complete DSE configuration for the Line Follower Robot example.

7 Test Automation and Model Checking

Test Automation and Model Checking for INTO-CPS is provided by the RT-Tester RTT-MBT tool. This section first describes installation and configuration of RT-Tester MBT in Section 7.1. It then describes test automation in Section 7.2 and model checking in Section 7.3. Note, that these features are explained in more detail in the deliverables D5.2a [PLM16] and D5.3c [BH17], respectively. Section 7.4 describes modelling guidelines for model checking and model-based testing.

7.1 Installation of RT-Tester RTT-MBT

In order to use RTT-MBT, a number of software packages must be installed. These software packages have been bundled into two installers:

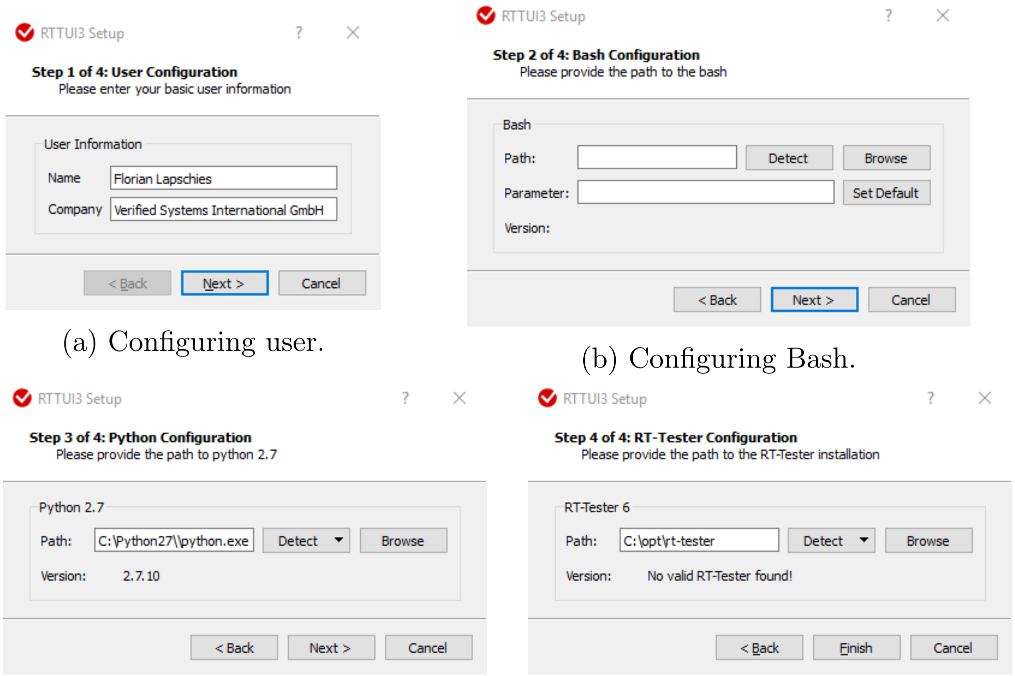
- **VSI tools dependencies bundle:**
  This bundle is required on the Windows platform and installs the following third party software:
  - Python 2.7.
  - GCC 4.9 compiler suite, used to compile FMUs.
- **VSI tools – VSI Test Tool Chain:**
  - RT-Tester 6.0, a stripped version of the RT-Tester core test system that contains the necessary functionality for INTO-CPS.
  - RT-Tester MBT 9.0, the model-based testing extension of RT-Tester.
  - RTTUI 3.9, the RT-Tester graphical user interface.
  - Utility scripts to run RTT-MBT.
  - Examples for trying out RTT-MBT.

These bundles can be downloaded via the download manager of the INTO-CPS Application.

7.1.1 Setup of the RT-Tester User Interface

When the RT-Tester User Interface (RTTUI) is first started, a few configuration settings must be made.

- User name and company name (Figure 128a).
- Location of Bash shell (Figure 128b). This step can be safely skipped by clicking *Next*.
- Path to Python 2.7 executable (Figure 128c): Click *Detect* and then *Installation Path* for auto-detection, or *Browse* to select manually.
- Location of RT-Tester (Figure 128d): Click *Browse* to select the directory of your RT-Tester installation. Note that if you did not specify the Bash shell location in step 7.1.1, the version number might not be detected properly.



RTTUI3 Setup

Step 1 of 4: User Configuration
Please enter your basic user information

User Information
Name: Florian Lapschies
Company: Verified Systems International GmbH

(a) Configuring user.

RTTUI3 Setup

Step 2 of 4: Bash Configuration
Please provide the path to the bash

Bash
Path:
Parameter:
Version:

(b) Configuring Bash.

RTTUI3 Setup

Step 3 of 4: Python Configuration
Please provide the path to python 2.7

Python 2.7
Path: C:\Python27\\python.exe
Version: 2.7.10

(c) Configuring Python.

RTTUI3 Setup

Step 4 of 4: RT-Tester Configuration
Please provide the path to the RT-Tester installation

RT-Tester 6
Path: C:\opt\rt-tester
Version: No valid RT-Tester found!

(d) Configuring RT-Tester.

Figure 128: RT-Tester GUI configuration.

7.2 Test Automation

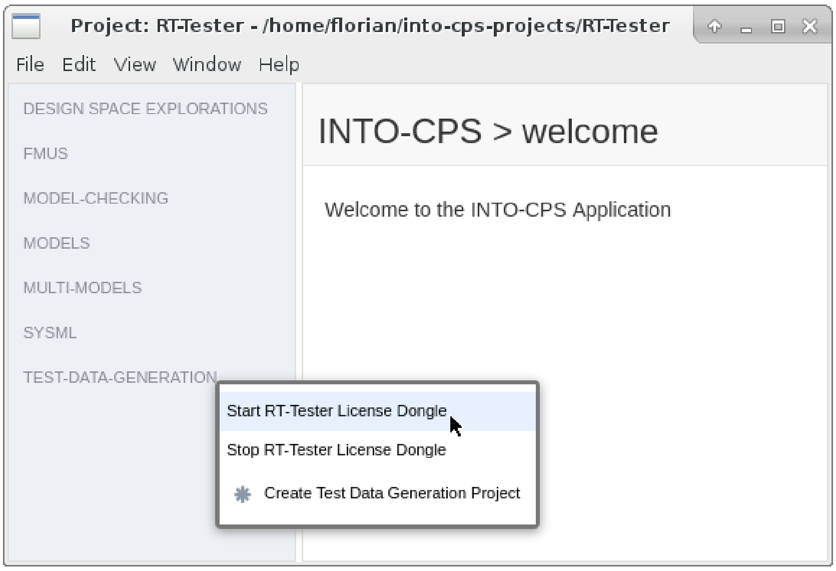
Configuring and using a Test Project involves several activities. These are:

- Creating a test project.
- Defining tests.

- Compiling test driver FMUs.
- Setting up test runs.
- Running tests.
- Evaluating test results.

These activities can be performed either solely using the RT-Tester graphical user interface, or using a combination of the INTO-CPS Application and the RT-Tester GUI. In this section we focus on describing the latter, since it supports the complete set of features necessary for test automation. A more comprehensive description of the test automation workflow can be found in Deliverable D5.2a [PLM16].

In the INTO-CPS Application, test automation functionality can be found below the main activity *Test-Data-Generation* in the project browser. Before using most of the test automation utilities, the license management process has to be started. To this end, right-click on *Test-Data-Generation* and select *Start RT-Tester License Dongle* (see Figure 129).


Project: RT-Tester - /home/florian/into-cps-projects/RT-Tester
File Edit View Window Help
DESIGN SPACE EXPLORATIONS
FMUS
MODEL-CHECKING
MODELS
MULTI-MODELS
SYSML
TEST-DATA-GENERATION
Start RT-Tester License Dongle
Stop RT-Tester License Dongle
Create Test Data Generation Project

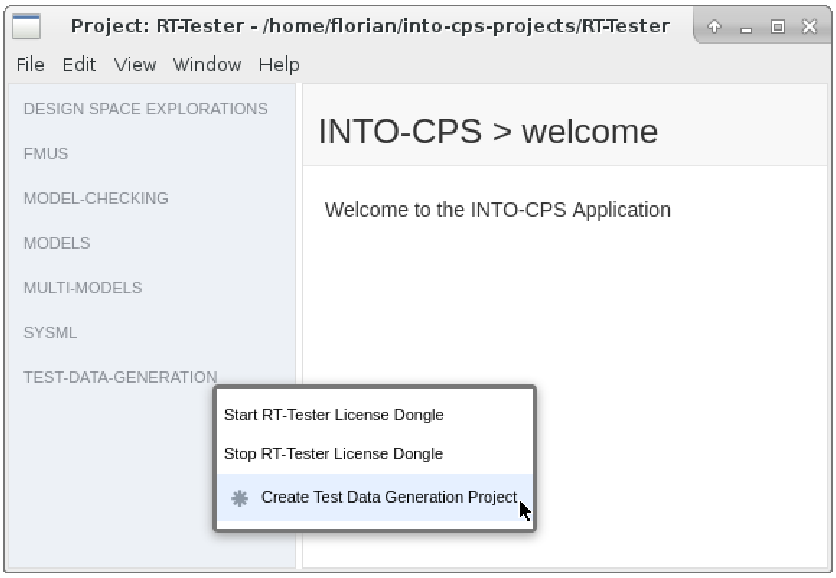
INTO-CPS > welcome

Welcome to the INTO-CPS Application

Figure 129: Starting the license management process.

After developing the behavioural model in Modelio and exporting it to an XMI file (see section 4.4), test automation projects can be created from the INTO-CPS Application. Such a project is then added as a sub-project within a containing INTO-CPS Application project. To create a project, do the following:

1. Right-click on *Test-Data-Generation* in the project browser and select *Create Test Data Generation Project* (see Figure 130).
2. Specify a name for the project, select the XMI file containing the test model and press *Create*, as shown in Figure 131.


Project: RT-Tester - /home/florian/into-cps-projects/RT-Tester

INTO-CPS > welcome

Welcome to the INTO-CPS Application

File
Edit
View
Window
Help
DESIGN SPACE EXPLORATIONS
FMUS
MODEL-CHECKING
MODELS
MULTI-MODELS
SYSML
TEST-DATA-GENERATION
Start RT-Tester License Dongle
Stop RT-Tester License Dongle
Create Test Data Generation Project

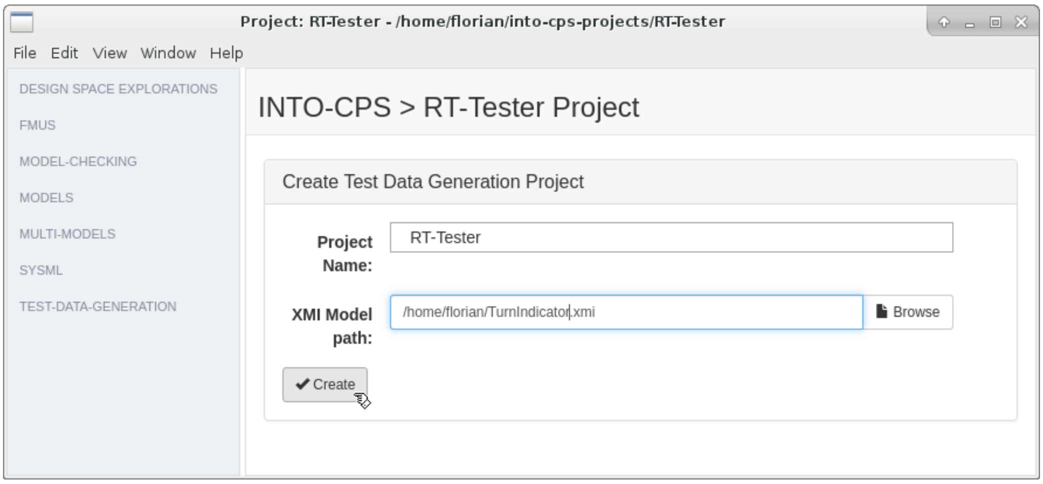
Figure 130: Creating a test automation project.

The newly created sub-project and its directory hierarchy is displayed in the project browser. The following two folders are of special significance:

- `TestProcedures` contains symbolic test procedures where test objectives are specified in an abstract way, for example by specifying Linear Temporal Logic (LTL) formulas.
- From these symbolic test procedures, concrete executable (RT-Tester 6) test procedures are generated, which then reside in the folder `RTT_TestProcedures`.

The specification of test objectives is done using the RT-Tester GUI. The relevant files can be opened in the RT-Tester GUI directly from the INTO-CPS Application by double-clicking them:

- `conf/generation.mbtconf` allows you to specify the overall test objectives of the test procedure. Test objectives can be specified as LTL formulas, which must then be fulfilled during a test run. Test goals can also be specified by selecting structural elements from a tree representation of the test model and then choosing a coverage metric


Project: RT-Tester - /home/florian/into-cps-projects/RT-Tester
File Edit View Window Help
DESIGN SPACE EXPLORATIONS
FMUS
MODEL-CHECKING
MODELS
MULTI-MODELS
SYSML
TEST-DATA-GENERATION
INTO-CPS > RT-Tester Project
Create Test Data Generation Project
Browse
Create

Project Name: RT-Tester

XMI Model path: /home/florian/TurnIndicator.xmi

Figure 131: Test automation project specifics.

for that element. For example, the user might select a sub-component of the System Under Test (SUT) and specify that all Basic Control States (BCS) must be reached (see Figure 132), or that all transitions must be exercised (TR) in a test run.

- `conf/signalmap.csv` allows you to configure the input and output signals of the system under test (see Figure 133). This includes defining the admissible signal latencies for checking the SUT's outputs in a test run. This file also allows you to restrict the range of the signals in order to constrain these values during test data generation.

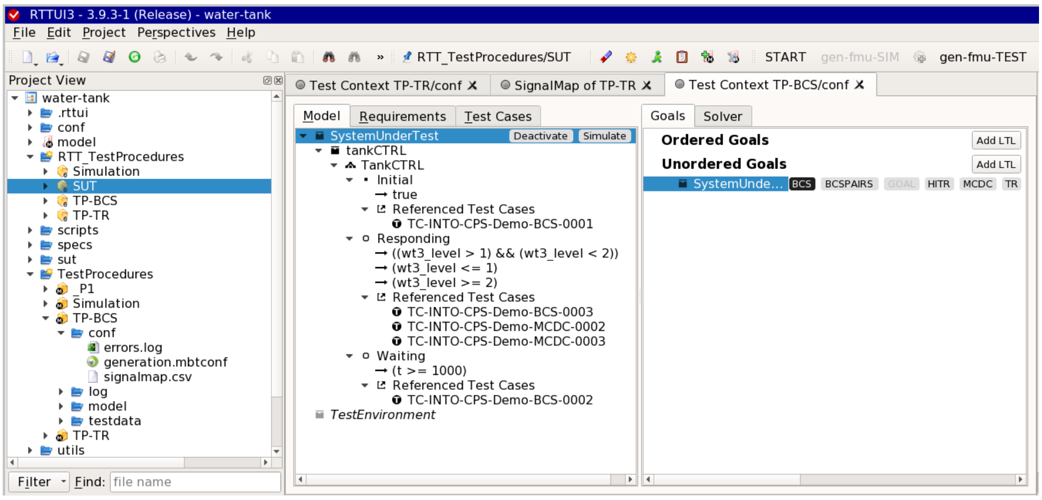
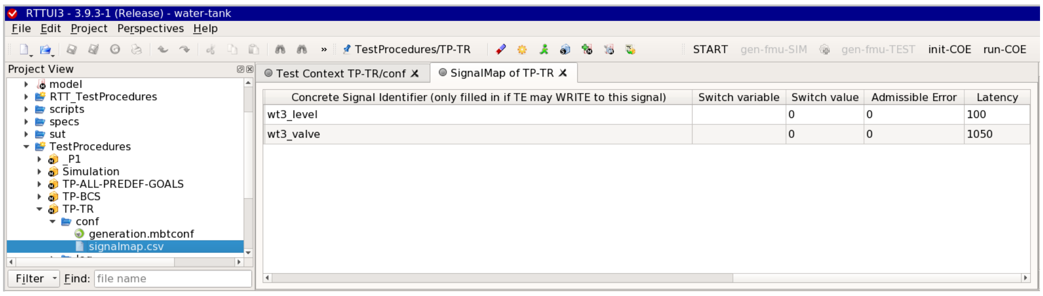


Figure 132: Configuring a test goal.



Concrete Signal Identifier (only filled in if TE may WRITE to this signal)	Switch variable	Switch value	Admissible Error	Latency
wt3_level		0	0	100
wt3_valve		0	0	1050

Figure 133: Configuring signals.

More details on the definition of tests can be found in Deliverable D5.2a [PLM16].

After defining the test objectives, a concrete test case can be created by right-clicking on the symbolic test case under *TestProcedures* and then selecting *Solve* (see Figure 134).

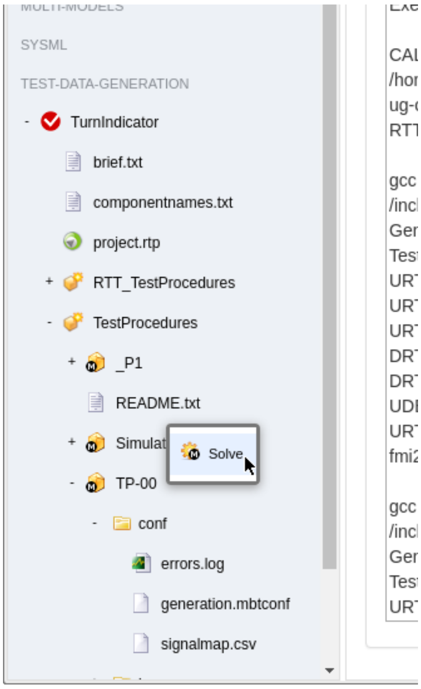
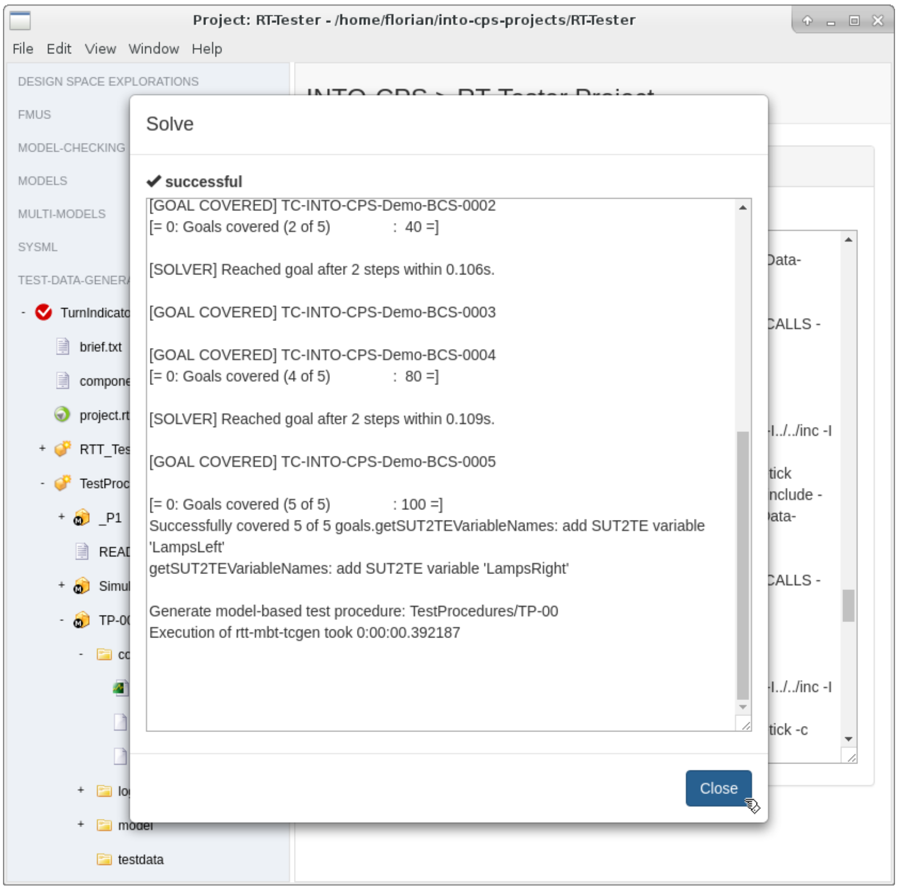


Figure 134: Generating a concrete test procedure.

A solver component then computes the necessary timed inputs to realize the test objectives. A concrete test procedure is generated that feeds a system under test with these inputs and observes its outputs against expected results derived from the test model. This test procedure will be placed in `RTT_TestProcedures` and has the same name as the symbolic test procedure. Figure 135 shows how test generation progresses.



```
[GOAL COVERED] TC-INTO-CPS-Demo-BCS-0002
[= 0: Goals covered (2 of 5)            :  40 =]

[SOLVER] Reached goal after 2 steps within 0.106s.

[GOAL COVERED] TC-INTO-CPS-Demo-BCS-0003

[GOAL COVERED] TC-INTO-CPS-Demo-BCS-0004
[= 0: Goals covered (4 of 5)            :  80 =]

[SOLVER] Reached goal after 2 steps within 0.109s.

[GOAL COVERED] TC-INTO-CPS-Demo-BCS-0005

[= 0: Goals covered (5 of 5)            : 100 =]
Successfully covered 5 of 5 goals.getSUT2TEVariableNames: add SUT2TE variable
'LampsLeft'
getSUT2TEVariableNames: add SUT2TE variable 'LampsRight'

Generate model-based test procedure: TestProcedures/TP-00
Execution of rtt-mbt-tcgen took 0:00:00.392187
```

Figure 135: Test data generation progress.

A generated test procedure can be cast into an FMU, which can then be run in a co-simulation against the system under test. To this end, right click on the concrete test procedure and select *Generate Test FMU* (see Figure 136). In cases where a real and perhaps physical system under test is not available, a simulation of the system under test can be generated from the behavioural model. To generate such an FMU, right-click on *Simulation* an select *Generate Simulation FMU* as depicted in Figure 137.

In order to run a test, right-click on the test procedure and select *Run Test*

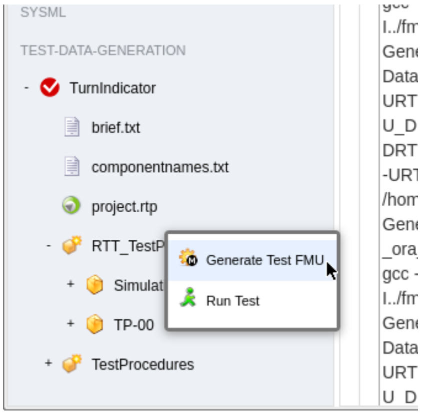


Figure 136: Generating a test FMU.

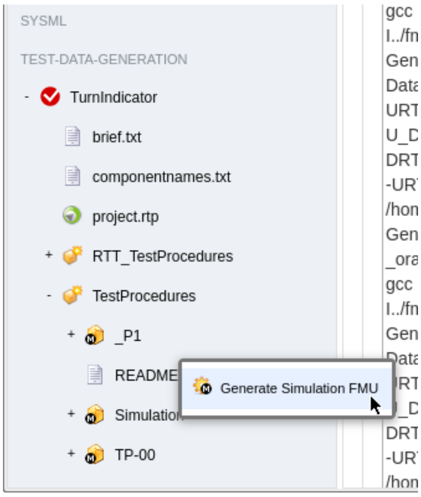
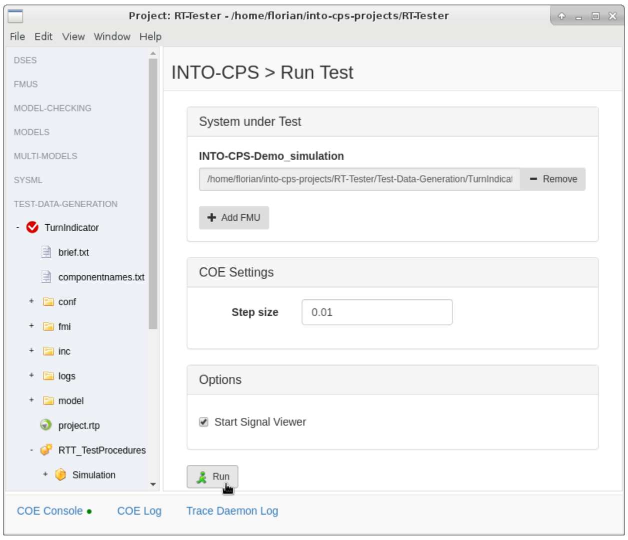


Figure 137: Generating a simulation FMU.

(see Figure 138). Then, the FMUs that constitute the system under test must be added by pressing the respective *Add FMU* button. When running a test, this list of FMUs is further augmented by an FMU representing the test driver. The connections between these FMUs are automatically derived by matching the names of inputs and outputs. The duration of the test is derived during test data generation and does not need to be manually specified. However, an appropriate step size must be set. Finally, after making sure the COE is running, press *Run* to start the test (see Figure 139).

Every test execution yields as its result an evaluation of test cases, *i.e.*, each is



Project: RT-Tester - /home/florian/into-cps-projects/RT-Tester

INTO-CPS > Run Test

System under Test

INTO-CPS-Demo_simulation

/home/florian/into-cps-projects/RT-Tester/Test-Data-Generation/TurnIndicat

COE Settings

Step size 0.01

Options

☑ Start Signal Viewer

Figure 138: Running a test.

associated with a verdict of PASS, FAIL, or INCONCLUSIVE.[14] The details are found in the test log files below the folder `testdata`. See the RT-Tester user manual [Ver15a] for details.

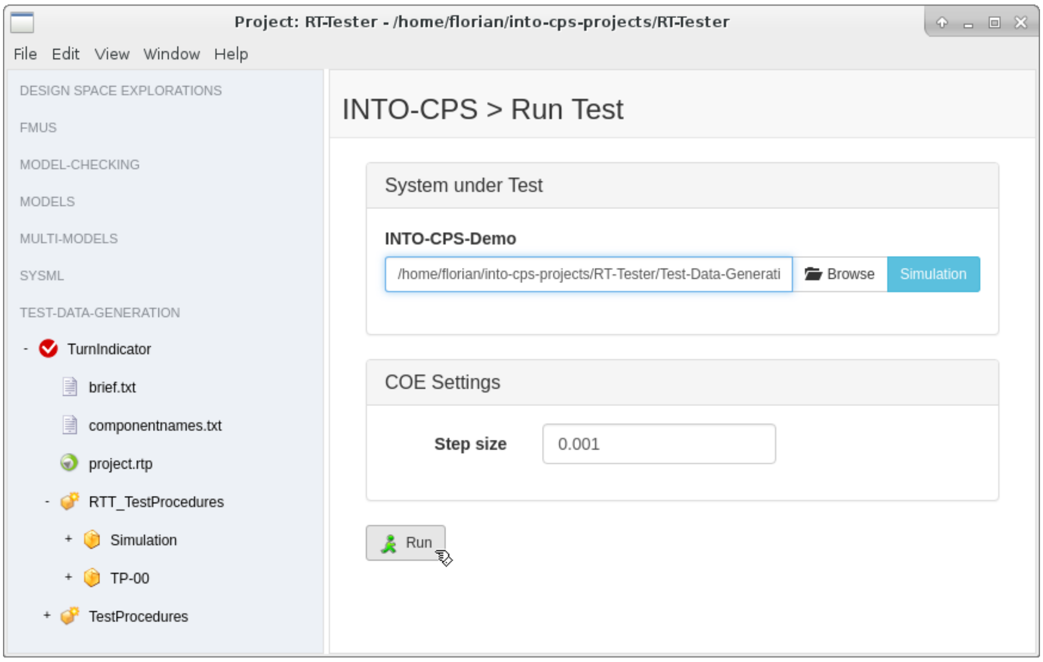
The file `testcase_tags.txt` gives a condensed record of test case, verdict, and point in a `*.log` file where a corresponding PASS, FAIL, or—in case of INCONCLUSIVE—test case occurrence without assertion can be found. The project-wide test-case verdict summary as well the requirement verdict summary can be found in the folder `RTT_TestProcedures/verification`. More details on the evaluation of test runs can be found in Deliverable D5.2a [PLM16].

7.3 Model Checking

This section describes how to use the INTO-CPS Application as a front-end to the LTL model checker of RT-Tester RTT-MBT. More details on the algorithms used and the syntax of LTL formulas can be found in Deliverable D5.3c [BH17].

Once an INTO-CPS project has been created (see Section 3.2), model checking functionality can be found under the top-level activity *Model Checking* in

[14] The verdict can also be NOT TESTED. This means a test case has been included in a test procedure, but a run that reaches it is still missing.



/home/florian/into-cps-projects/RT-Tester/Test-Data-Generati

Step size 0.001

Figure 139: Configuring a test.

the project browser. Before getting started, the RT-Tester license management process must be launched. To this end, right-click on *Model Checking* and select *Start RT-Tester License Dongle* (see Figure 140). Model checking projects are presented as sub-projects of INTO-CPS Application projects. In order to add a new project,

1. Right-click on the top-level activity *Model Checking* in the project browser and select *Create Model Checking Project* (see Figure 141).
2. Provide a project name and the behavioural model that has been exported to XMI from Modelio (see section 4.4).

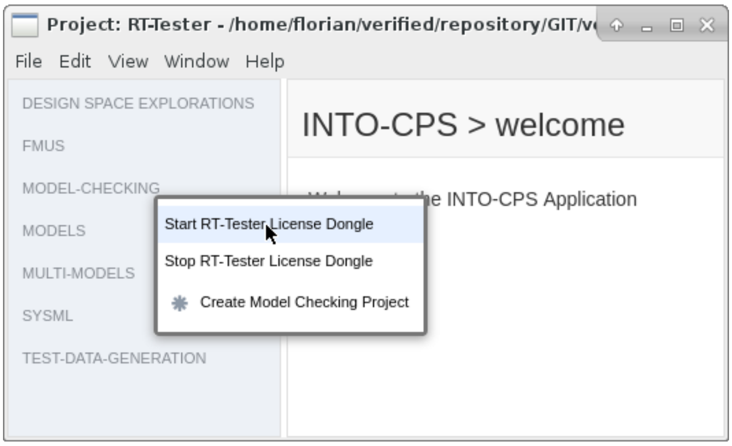

Project: RT-Tester - /home/florian/verified/repository/GIT/v
File
Edit
View
Window
Help
DESIGN SPACE EXPLORATIONS
FMUS
MODEL-CHECKING
MODELS
MULTI-MODELS
SYSML
TEST-DATA-GENERATION
INTO-CPS > welcome
e INTO-CPS Application
Start RT-Tester License Dongle
Stop RT-Tester License Dongle
Create Model Checking Project

Figure 140: Starting the RT-Tester license dongle.

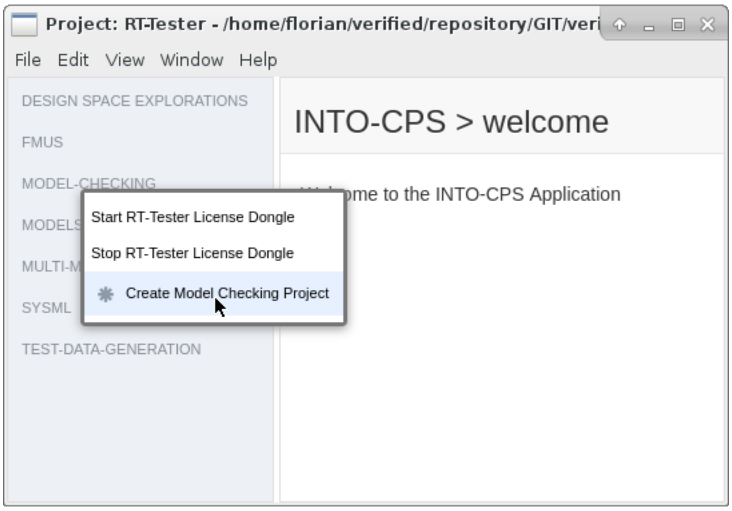
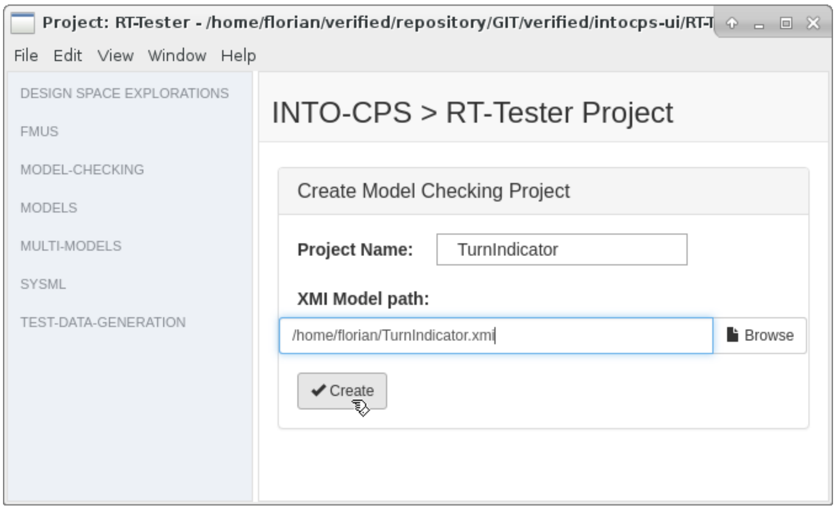

Project: RT-Tester - /home/florian/verified/repository/GIT/veri
File
Edit
View
Window
Help
DESIGN SPACE EXPLORATIONS
FMUS
MODEL-CHECKING
MODELS
MULTI-M
SYSML
TEST-DATA-GENERATION
INTO-CPS > welcome
ome to the INTO-CPS Application
Start RT-Tester License Dongle
Stop RT-Tester License Dongle
Create Model Checking Project

Figure 141: Creating a model checking project.



Project: RT-Tester - /home/florian/verified/repository/GIT/verified/intocps-ui/RT-T
File Edit View Window Help
DESIGN SPACE EXPLORATIONS
FMUS
MODEL-CHECKING
MODELS
MULTI-MODELS
SYSML
TEST-DATA-GENERATION
INTO-CPS > RT-Tester Project
Create Model Checking Project
Browse
✔ Create

Project Name: TurnIndicator

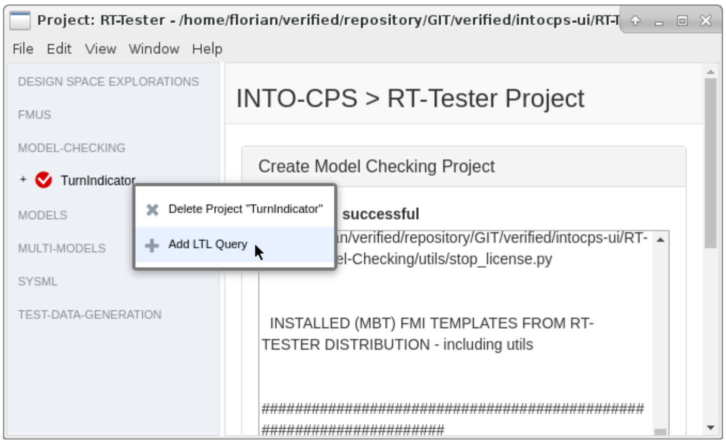
XMI Model path: /home/florian/TurnIndicator.xml

Figure 142: Specifying the model checking project.

After pressing *Create*, a new node representing the model checking project is added to the project browser.

The next step is to add LTL queries to the project:

1. Right click on the project and select *Add LTL Query* (see Figure 143).
2. Enter a name for the new query (see Figure 144).
3. To edit the LTL query, double click on the corresponding node in the project browser (see Figure 145). The LTL formula can then be edited in a text field. In addition to all variables occurring in the model a special variable called *_stable* which is true *iff* the system resides in a stable state is available. This variable can be used to rule out spurious counter-examples involving transient states that are immediately left in zero time. Note that the editor supports auto-completion for variable names and LTL operators (see Figure 146).
4. Specify a comma-separated list of requirements and select whether a model checking result should be linked to either verify or violate these requirements in the traceability database.
5. Provide the upper bound for the bounded model checking query.


Project: RT-Tester - /home/florian/verified/repository/GIT/verified/intocps-ui/RT-T

File
Edit
View
Window
Help
DESIGN SPACE EXPLORATIONS
FMUS
MODEL-CHECKING
+ TurnIndicator
MODELS
MULTI-MODELS
SYSML
TEST-DATA-GENERATION
Delete Project "TurnIndicator"
Add LTL Query
INTO-CPS > RT-Tester Project
Create Model Checking Project

successful

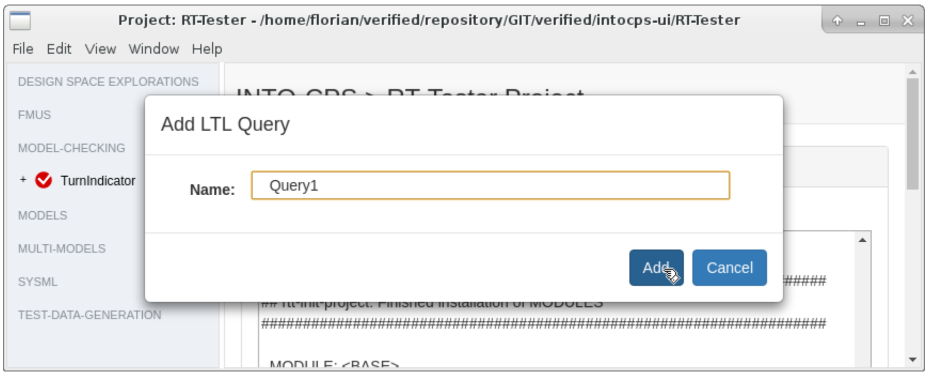
```
n/verified/repository/GIT/verified/intocps-ui/RT-
el-Checking/utils/stop_license.py


 INSTALLED (MBT) FMI TEMPLATES FROM RT-
TESTER DISTRIBUTION - including utils


################################################
#######################
```

Figure 143: Adding an LTL formula.

To check the query, press *Save & Check*. After a while the tool either reports that the query holds within the specified number of steps or it prints a counterexample to demonstrate that the property does not hold — as depicted in Figure 147. The user then has to manually inspect the model-checking result for spurious counter examples that might have been introduced by abstractions that are too coarse. Finally, if the user is satisfied with the result, the

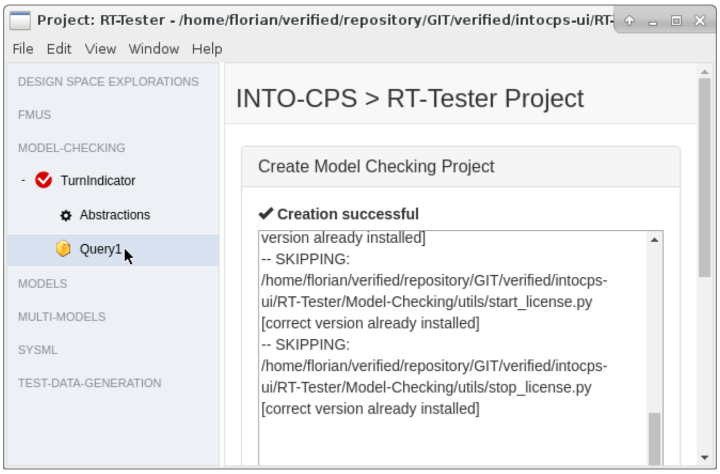

Project: RT-Tester - /home/florian/verified/repository/GIT/verified/intocps-ui/RT-Tester
File Edit View Window Help
DESIGN SPACE EXPLORATIONS
FMUS
MODEL-CHECKING
+ TurnIndicator
MODELS
MULTI-MODELS
SYSML
TEST-DATA-GENERATION
INTO-CPS > RT-Tester Project
Add
Cancel

Add LTL Query

Name: Query1

```
## rtt-init-project: Finished installation of MODULES
##########################################################################
MODULE: <BASE>
```

Figure 144: Naming the new LTL formula.


Project: RT-Tester - /home/florian/verified/repository/GIT/verified/intocps-ui/RT-
File Edit View Window Help
DESIGN SPACE EXPLORATIONS
FMUS
MODEL-CHECKING
- TurnIndicator
Abstractions
Query1
MODELS
MULTI-MODELS
SYSML
TEST-DATA-GENERATION
INTO-CPS > RT-Tester Project
Create Model Checking Project

✔ **Creation successful**

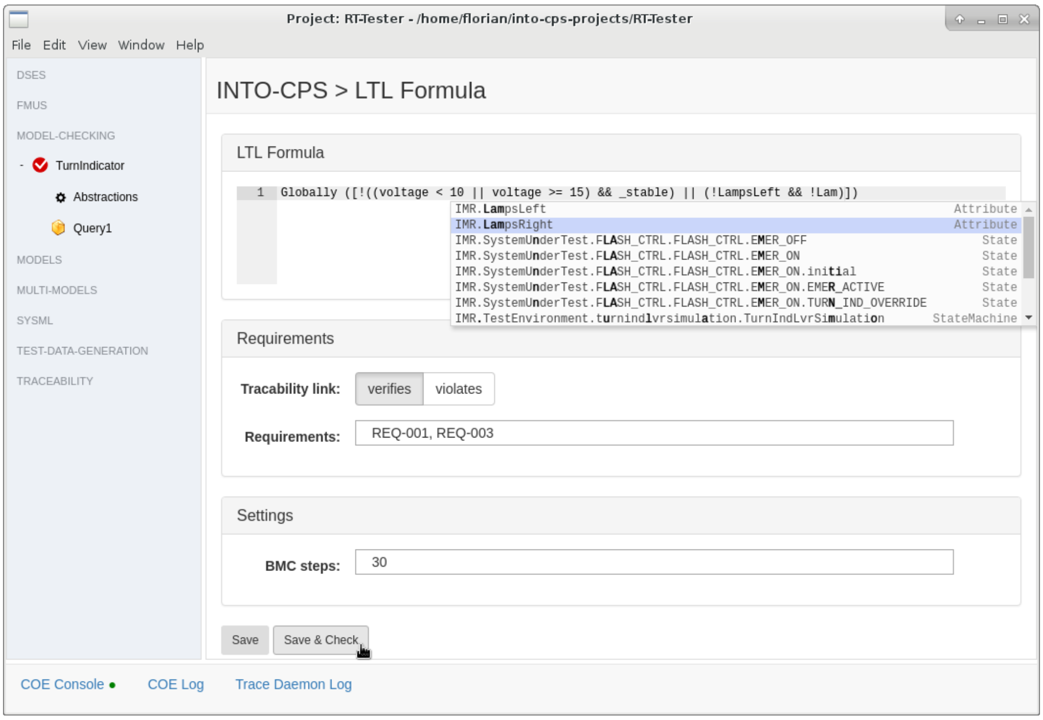
```
version already installed]
-- SKIPPING:
/home/florian/verified/repository/GIT/verified/intocps-
ui/RT-Tester/Model-Checking/utils/start_license.py
[correct version already installed]
-- SKIPPING:
/home/florian/verified/repository/GIT/verified/intocps-
ui/RT-Tester/Model-Checking/utils/stop_license.py
[correct version already installed]
```

Figure 145: Opening the LTL formula editor.

traceability information associated with the result can be committed to the traceability database by pressing *Commit Traceability Data*.

It is possible to configure abstractions[15] for a particular model checking project. To do so, double-click on the corresponding *Abstractions* node below that project in the project browser. It is then possible to choose an abstraction method for each output variable of an environment component along with making the associated setting. In Figure 148 the interval abstraction has been selected for the output variable `voltage`. This abstraction has further been configured to restrict the variable's value within the interval $[10, 12]$. After pressing *Save*, this abstraction is applied to all model checking queries in the current model checking project.

[15] Information on abstractions and their associated configuration items can be found in Deliverable D5.2b [BLM16].



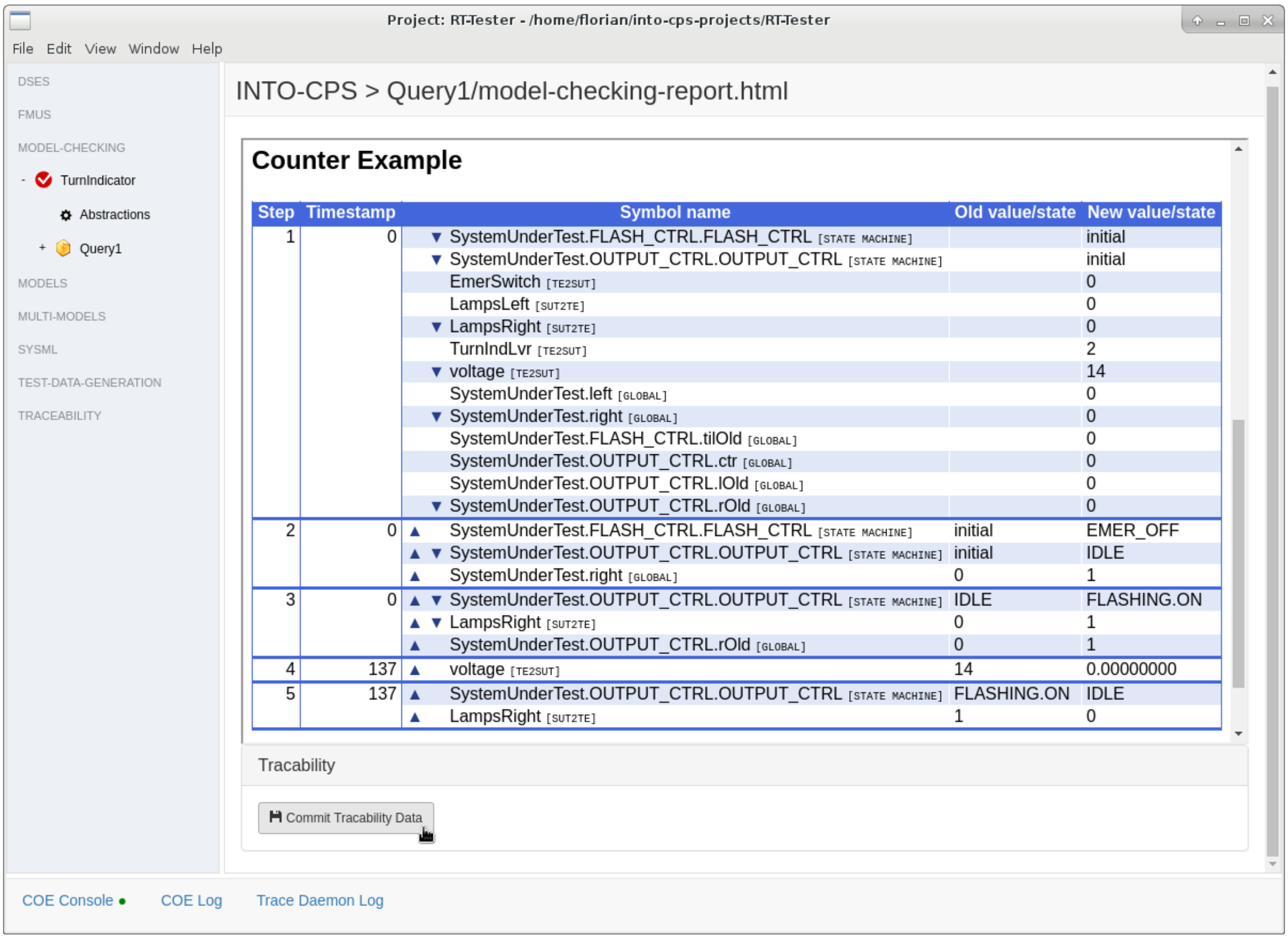
```
Globally ([!((voltage < 10 || voltage >= 15) && _stable) || (!LampsLeft && !Lam)])
IMR.LampsLeft                                                          Attribute
IMR.LampsRight                                                         Attribute
IMR.SystemUnderTest.FLASH_CTRL.FLASH_CTRL.EMER_OFF                         State
IMR.SystemUnderTest.FLASH_CTRL.FLASH_CTRL.EMER_ON                          State
IMR.SystemUnderTest.FLASH_CTRL.FLASH_CTRL.EMER_ON.initial                  State
IMR.SystemUnderTest.FLASH_CTRL.FLASH_CTRL.EMER_ON.EMER_ACTIVE              State
IMR.SystemUnderTest.FLASH_CTRL.FLASH_CTRL.EMER_ON.TURN_IND_OVERRIDE        State
IMR.TestEnvironment.turnindlvrsimulation.TurnIndLvrSimulation       StateMachine
```

Tracability link: [✓ verifies] violates

Requirements: REQ-001, REQ-003

BMC steps: 30

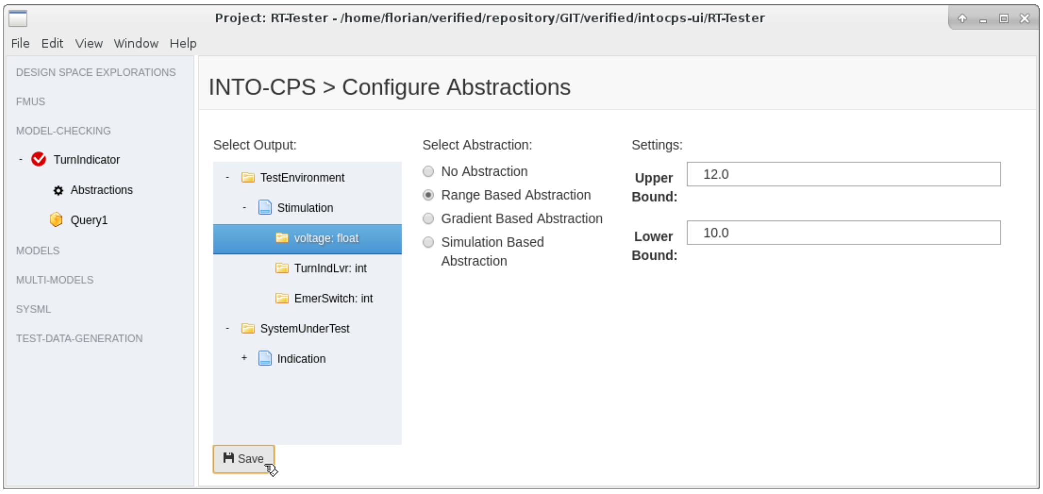
Figure 146: LTL formula editor.



Counter Example

Step	Timestamp	Symbol name	Old value/state	New value/state
1	0	▼ SystemUnderTest.FLASH_CTRL.FLASH_CTRL [STATE MACHINE]		initial
		▼ SystemUnderTest.OUTPUT_CTRL.OUTPUT_CTRL [STATE MACHINE]		initial
		EmerSwitch [TE2SUT]		0
		LampsLeft [SUT2TE]		0
		▼ LampsRight [SUT2TE]		0
		TurnIndLvr [TE2SUT]		2
		▼ voltage [TE2SUT]		14
		SystemUnderTest.left [GLOBAL]		0
		▼ SystemUnderTest.right [GLOBAL]		0
		SystemUnderTest.FLASH_CTRL.tilOld [GLOBAL]		0
		SystemUnderTest.OUTPUT_CTRL.ctr [GLOBAL]		0
		SystemUnderTest.OUTPUT_CTRL.lOld [GLOBAL]		0
		▼ SystemUnderTest.OUTPUT_CTRL.rOld [GLOBAL]		0
2	0	▲ SystemUnderTest.FLASH_CTRL.FLASH_CTRL [STATE MACHINE]	initial	EMER_OFF
		▲ ▼ SystemUnderTest.OUTPUT_CTRL.OUTPUT_CTRL [STATE MACHINE]	initial	IDLE
		▲ SystemUnderTest.right [GLOBAL]	0	1
3	0	▲ ▼ SystemUnderTest.OUTPUT_CTRL.OUTPUT_CTRL [STATE MACHINE]	IDLE	FLASHING.ON
		▲ ▼ LampsRight [SUT2TE]	0	1
		▲ SystemUnderTest.OUTPUT_CTRL.rOld [GLOBAL]	0	1
4	137	▲ voltage [TE2SUT]	14	0.00000000
5	137	▲ SystemUnderTest.OUTPUT_CTRL.OUTPUT_CTRL [STATE MACHINE]	FLASHING.ON	IDLE
		▲ LampsRight [SUT2TE]	1	0

Figure 147: Model checking result.



Select Abstraction:

○ No Abstraction
● Range Based Abstraction
○ Gradient Based Abstraction
○ Simulation Based Abstraction

Settings:

Upper Bound: 12.0

Lower Bound: 10.0

Figure 148: Configuring abstractions.

7.4 Modeling Guidelines (for TA and MC purposes)

When creating a model for test automation (TA) or model checking (MC), it is important to keep in mind that it will be input to a *solver* that explores the state space of the model. It is not helpful to have a very precise state machine model which the solver cannot handle.[16]

A *"good"* model tries to find a balance between precision and solver time, *i.e.*, it aims to represent all important logical aspects (that may contain design errors,) but abstract away from details where the implementation can be trusted to handle data correctly. This section contains some guidelines on how to avoid common modelling pitfalls.

(G.1) Model independent parts as separate machines. When you can think of two parts of the system as individual entities, then you should have one state machine for each part. This is much easier to maintain than a state machine that "merges" two (or more) behaviours.

(G.2) Reset auxiliary variables. If you use "auxiliary" variables in your model (*e.g.* to remember some situation) then they should have a limited lifetime where they can be of relevance. Reset them (to "0") when they have fulfilled their purpose. This modelling trick will not influence the relevant behaviour of your model, but make the solver's task easier.

(G.3) Keep the diameter of state machines small (if possible). The number of steps that are necessary to reach a certain situation can be a serious limitation in finding solutions. If your state machine includes long sequences of transitions that need to be taken in order to reach a certain situation, consider simplifying it by

- breaking this state machine down into several state machines
- "merging" several similar states along this path into a single, more abstract state (*i.e.* make your model less precise)

(G.4) Use abstractions whenever specific (payload) data is of no interest. If the logical state depends on input data, try to model this as

[16] *I.e.*, resources on time, memory or user patience will be depleted before completion of the "solving" task.

simply as possible. Consider omitting data sanitation steps (like plausibility checks, interpolation of values, data sanitation) that may exist in your specific system but only serve as countermeasures to unreliable sensor inputs. In the modelling world, inputs are always "perfect" and "reliable". **Example**: When modelling a protocol, avoid modelling the payload. Also, do not put payload and addressing (housekeeping) information in the same variable.

(G.5) Try to think of "logical states" rather than of "data driven states". Variables can be used to "encode" the states of your system. Try to find a balance where state machine states actually represent "logical states" (that are distinguished by their behaviour). This will make the guard conditions smaller and more maintainable.

(G.6) Keep a list of modelling parameters. Keep an overview on what immutable "parameters" your modelling depends on, *i.e.*, what values they have and where they are used. This will make it easier to revise your model consistently when required.

(G.7) Dare to approximate complex values. In particular *continuous flows* may need to be broken down into manageable components. **Example**: A physical accumulator can be approximated by a scalar value. Using a (scaled) integer instead of a floating-point number may be good enough and make the task of the solver much easier.

(G.8) Dare to approximate complex behaviour. A common modelling mistake is to "model as precise as possible". In particular, capturing continuous states can be very expensive (in terms of state space). Whenever possible, you should consider simplifying things, even if this means sacrificing precision. Remember that testing aims to find "logical errors" and not to "represent the most precise approximation of the system". **Example**: When modelling a water tank with (continuous) in-flow and state change, it may suffice to create a "coarse" model of it which changes state only once per second, based in input value, water level, and maximal output capacity.

(G.9) Start with small versions of your system. Do not start modelling with a full-blown version of a complete system. Rather start with one relevant component, say, one controller and explore testing a small system before moving to "many controllers, many other components".

8 Traceability Support

This section describes tool support for traceability along the INTO-CPS tool chain.

8.1 Overview

Traceability support is divided into two steps: sending data from the tools to the Neo4J traceability database, and retrieving information from the database. In the following we first describe how information is sent to the database and then how it is retrieved.

It shall be noted that the traceability features of INTO-CPS require Git[17] to be installed. Furthermore, the project folder must be under Git version control.

8.2 INTO-CPS Application

Information is stored in the traceability database via the traceability daemon. The traceability daemon is integrated in the INTO-CPS Application and it starts automatically when the Application is started. Only Neo4J has to be downloaded, which can be done through the Download Manager. When downloaded, Neo4J must be extracted by hand into the folder `<user_home>/into-cps-projects/install` (the archive file is located at `<user_home>/into-cps-projects/install_downloads` after download.) Note that Neo4J is a singleton, so ensure all other instances of Neo4J are down before starting the INTO-CPS Application.

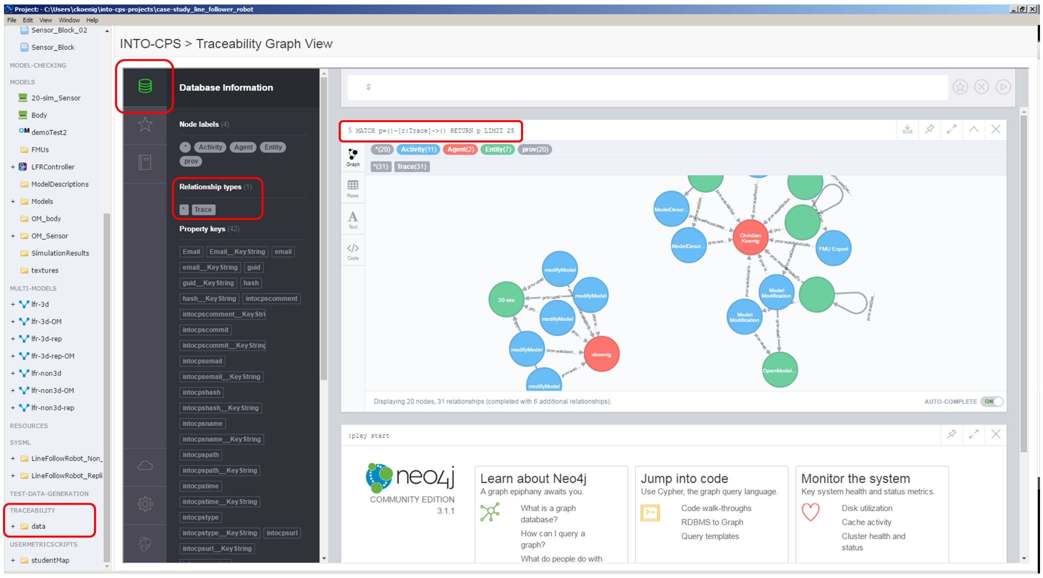
Please note: the daemon only runs while the INTO-CPS Application is running. Therefore, to record traceability data while using any of the other tools, the INTO-CPS Application must be running.

Treaceability information is captured by the traceability daemon and stored in a Neo4J database. The database is project-specific and is deployed on project change within the INTO-CPS Application. When running, Neo4J is accessible at `http://localhost:7474`. Here one can view the current traceability graph. Username and password of the databases are always:

[17] `https://git-scm.com/`

username = intoCPSApp
password = KLHJiK8k2378HKsg823jKKLJ89sjklJHBNf8j8JH7FxE

To view the raw data from the database, right-click on *Traceability* in the INTO-CPS Application project browser and select *View Traceability Graph* (see Figure 149). Select the database symbol and click under *Relationship types* click on *Trace*. This shows the graph database. By default, the view is limited to 25 entries. To change this, edit the line `MATCH p=()-[r:Trace]->() RETURN p LIMIT 25` and set the limit to a different value. When starting the INTO-CPS Application, Neo4J needs to be started as well. Sometimes this is very slow and the startup operation is aborted. To force the Neo4J database to start, repeat the *View Traceability Graph* action until the Neo4J view shows, as illustrated in Figure 149. Alternatively, start the INTO-CPS Application from the command line to monitor the status of the Neo4J database. Please note: this view of traceability relationships is not meant for end users, but rather for developers.



```
$ MATCH p=()-[r:Trace]->() RETURN p LIMIT 25
```

```
:play start
```

Displaying 20 nodes, 31 relationships (completed with 6 additional relationships).

Figure 149: Current view of traceability in the INTO-CPS Application.

8.3 Modelio

The latest Modelio module can be downloaded here: http://forge.modelio.org/projects/intocps-modelio34/files. Note that currently the INTO-CPS module is only compatible with Modelio 3.4. Modelio currently (INTO-CPS module 1.3.15) supports traceability for the following modelling activities:

- Model creation
- Model modification
- Model Description export
- Configuration export
- Requirements creation

To install the module go to *Configuration* → *Modules*, select *INTO-CPS* and set the parameters for:

- The daemon connection, *i.e.* the daemon IP address and its connection port (7474). By default these values are, respectively, 127.0.0.1 and 8083
- The Git user identification, *i.e.* its Git ID, the related e-mail address and the path to the local Git repository (*i.e.* the path to the location of the `.git` folder).

The traceability information is sent automatically to the daemon, either right after performing a traced action (Model Description Export and Configuration Export) or after closing the project.

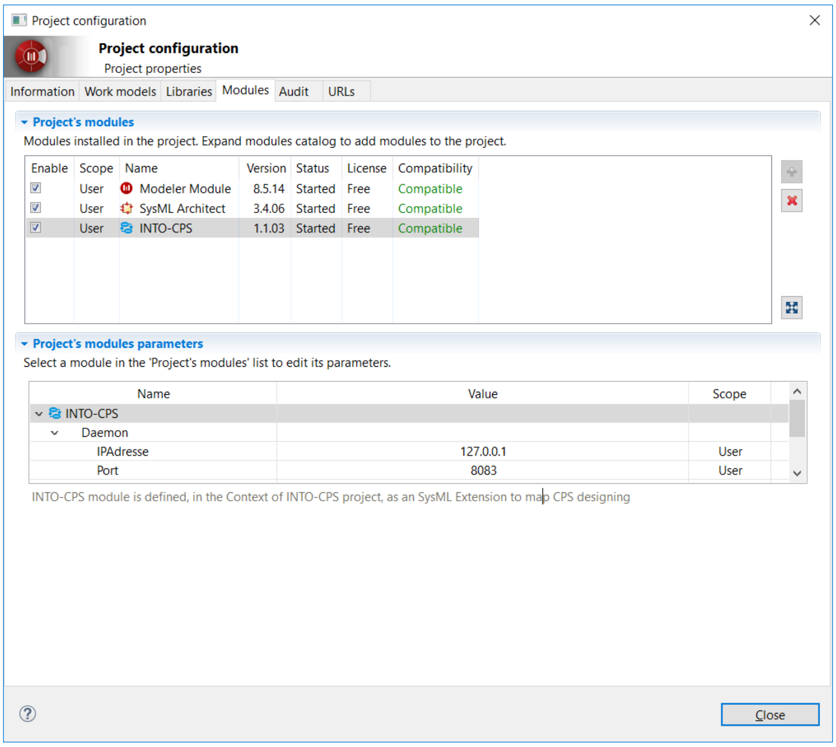
Regarding requirements tracing, currently only the relations *Satisfy* and *Verify* are supported for traceability, as shown in Figure 151. Hint: To push an older model (*i.e.*, one made before the deployment of the traceabilty feature) to the traceability database, you can use the following Jython script inside the Modelio *Script* tab as depicted in Figure 152.

```
peerModule = Modelio.getInstance().getModuleService().
    getPeerModule(IINTOCPSPeerModule.MODULE_NAME);
peerModule.pushModel();
```

8.4 Overture

The latest version of the Overture traceability driver can be found on the GitHub site[18] or in the download manager of the INTO-CPS Application.

[18] see `https://github.com/overturetool/intocps-tracability-driver/releases`



Project configuration

Project properties

Project's modules

Modules installed in the project. Expand modules catalog to add modules to the project.

Enable	Scope	Name	Version	Status	License	Compatibility
☑	User	Modeler Module	8.5.14	Started	Free	Compatible
☑	User	SysML Architect	3.4.06	Started	Free	Compatible
☑	User	INTO-CPS	1.1.03	Started	Free	Compatible

Project's modules parameters

Select a module in the 'Project's modules' list to edit its parameters.

Name	Value	Scope
INTO-CPS		
Daemon		
IPAdresse	127.0.0.1	User
Port	8083	User

INTO-CPS module is defined, in the Context of INTO-CPS project, as an SysML Extension to map CPS designing

Figure 150: Configuration of traceability features in Modelio.

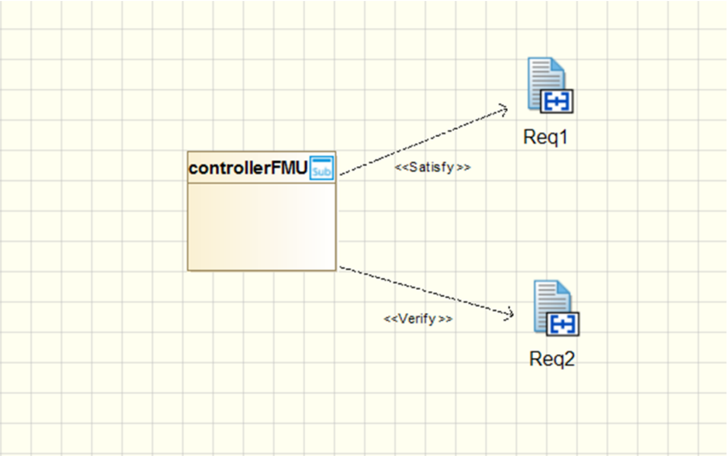
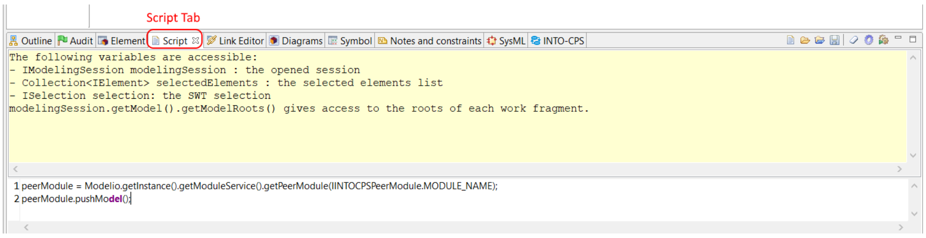


Figure 151: Requirements related to a SysML Block in Modelio.



```
The following variables are accessible:
- IModelingSession modelingSession : the opened session
- Collection<IElement> selectedElements : the selected elements list
- ISelection selection: the SWT selection
modelingSession.getModel().getModelRoots() gives access to the roots of each work fragment.
```

```
peerModule = Modelio.getInstance().getModuleService().getPeerModule(IINTOCPSPeerModule.MODULE_NAME);
peerModule.pushModel();
```

Figure 152: Pushing Jython script.

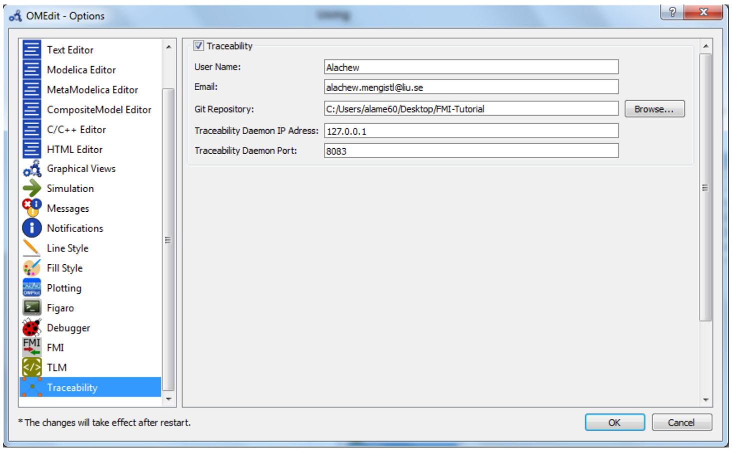
All traces can be extracted from the traceability driver and sent to the daemon. To do so, please follow the description on the GitHub site above.

8.5 OpenModelica

The latest INTO-CPS targeted nightly builds of OpenModelica support traceability. They can be downloaded from `https://build.openmodelica.org/omc/builds/windows/nightly-builds/intocps/`. OpenModelica supports tracing the following modeling activities:

- Model creation
- Model modification
- FMU export
- FMU import
- Model description XML import

As a prerequisite for traceability support, Git should be installed in the system. To configure traceability support, go to *Tools* → *Options* → *Traceability*, select the traceability checkbox and set all the fields, the traceability daemon IP address and port (7474) (see Figure 153). By default, the port is 8083. Then, go to *Tools* → *Options* → *General* and set the working directory to which you would like to export the FMU (see Figure 154). Create a Modelica model via *File* → *New Modelica Class* or load a model via *File* → *Open Model/LibraryFile(s)*, as in Figure 155. After modification of the model/class, click the *File* → *Save* button, press `Ctrl-s` or click the *Save* button from the menu bar, as shown in Figure 156. A dialog as shown below in Figure 157 will appear to enter the commit description. To trace the export of an FMU, load the Modelica model or create a new model, then go to *FMI* → *Export FMU* (see Figure 158). OpenModelica generates the FMU, commits and sends the traceability information to the daemon automatically.



☑ Traceability

User Name: Alachew

Email: alachew.mengistl@liu.se

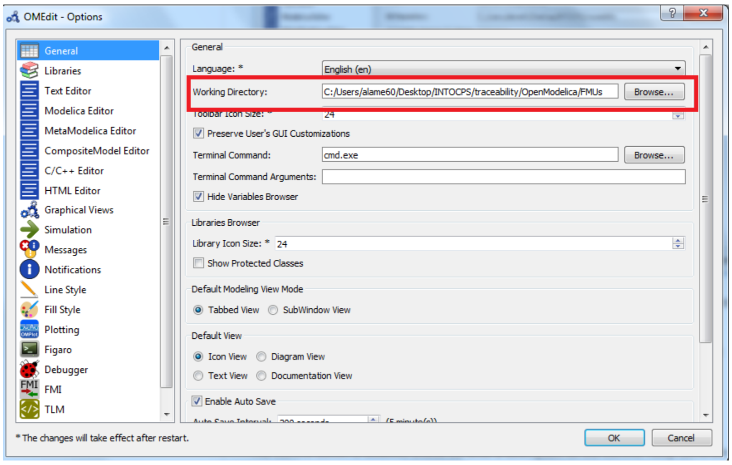
Git Repository: C:/Users/alame60/Desktop/FMI-Tutorial

Traceability Daemon IP Adress: 127.0.0.1

Traceability Daemon Port: 8083

* The changes will take effect after restart.

Figure 153: Traceability settings in OpenModelica.



General

Language: * English (en)

Working Directory: C:/Users/alame60/Desktop/INTOCPS/traceability/OpenModelica/FMUs

Toolbar Icon Size: * 24

☑ Preserve User's GUI Customizations

Terminal Command: cmd.exe

Terminal Command Arguments:

☑ Hide Variables Browser

Libraries Browser

Library Icon Size: * 24

☐ Show Protected Classes

Default Modeling View Mode

● Tabbed View ○ SubWindow View

Default View

● Icon View ○ Diagram View

○ Text View ○ Documentation View

☑ Enable Auto Save

* The changes will take effect after restart.

Figure 154: FMU export directory in OpenModelica.

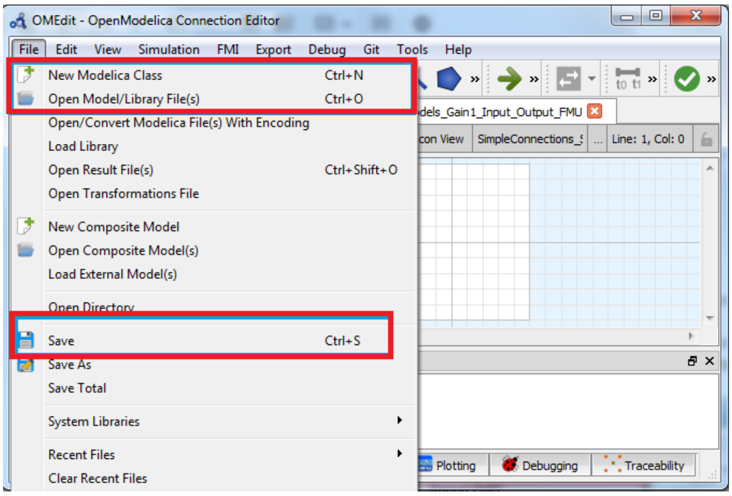


Figure 155: Create or open a Class in OpenModelica.

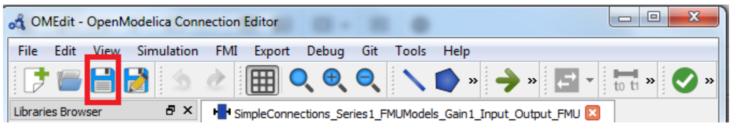
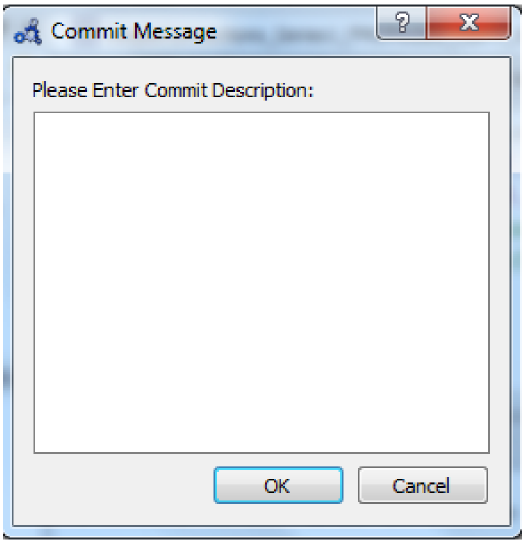

OMEdit - OpenModelica Connection Editor
File
Edit
View
Simulation
FMI
Export
Debug
Git
Tools
Help
Libraries Browser
SimpleConnections_Series1_FMUModels_Gain1_Input_Output_FMU

Figure 156: Save a model in OpenModelica.


Commit Message

Please Enter Commit Description:

Figure 157: The commit message in OpenModelica.

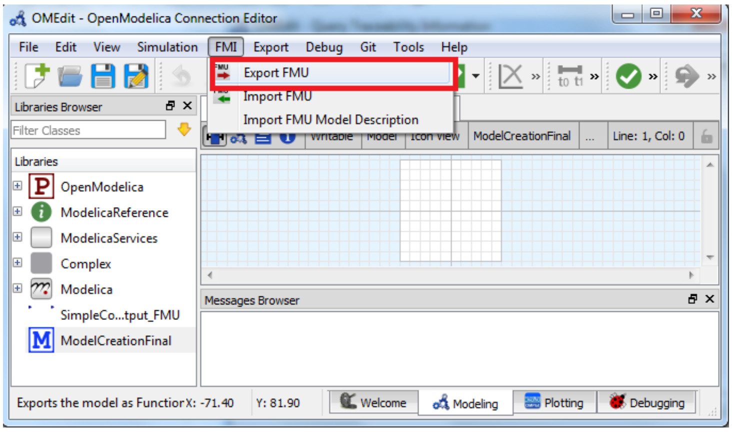


Figure 158: FMU export in OpenModelica.

To import a `modelDescription.xml` file, go to *FMI → Import FMU Model Description*. A dialog as shown in Figure 159 will appear. Select the `modelDescription.xml` file and the output directory then press *OK*. The Modelica model with SysML block inputs and outputs will be generated and automatically loaded (see the left part of Figure 159). To visualize the traceability graph, click the *Traceability* perspective button as shown below.

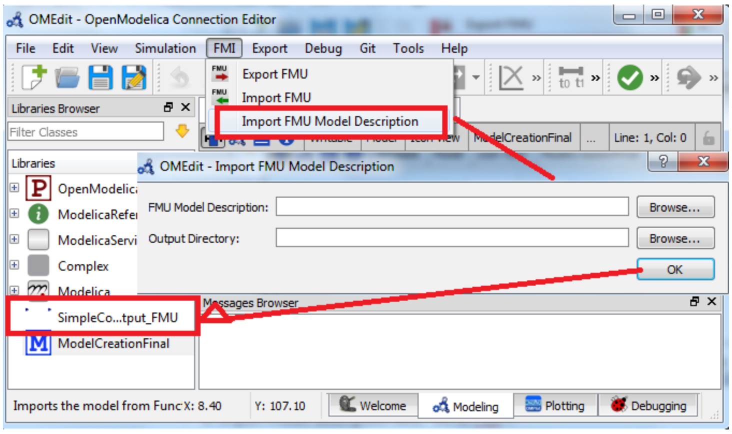


Figure 159: FMI model description import in OpenModelica.

8.6 20-sim

To record traceability information from within 20-sim, 20-sim 4.6.3-intocps or higher is required. A version of 20-sim that supports traceability can be found

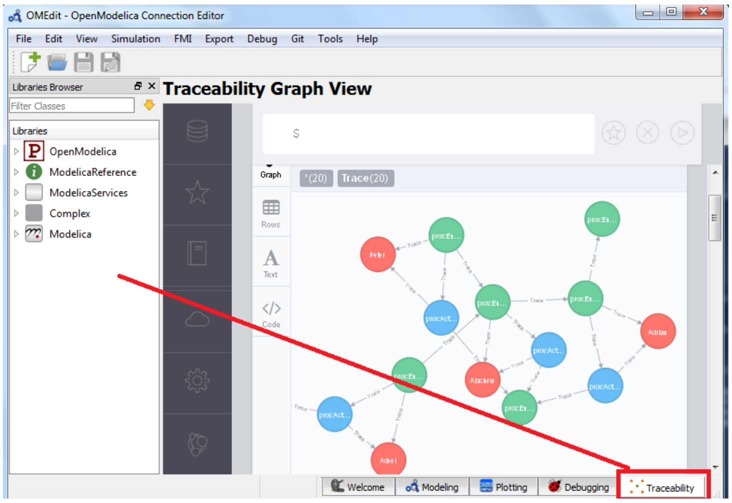


Figure 160: View traceability data in OpenModelica.

in the INTO-CPS application download manager. Please keep the checkbox to install Python enabled during the installation process of 20-sim.

When the installation process of 20-sim is done, open 20-sim. The traceability settings dialog can be found by going to *Tools* →*Version Control Toolbox* →*Traceability* (see Figure 161). A window will pop up, like the one shown in Figure 162. If no changes have been made with respect to traceability within the settings of the INTO-CPS Application, then these are the default settings that should be used. Please note that the Git Repository can be changed to another folder on your PC. Furthermore, *GIT username* and *GIT email address* should be altered to match the Git user account and Git email address with which the commit should be made. For an explanation of all options that are available in this dialog, please refer to Deliverable D4.3d [KLN$^+$17].

20-sim has support for several traceable actions:

- Model creation
- Model modification
- FMU export
- FMU import
- Model description XML import

Performing any of these actions will automatically trigger a trace event. Model creation and model modification are triggered by a *Save As* action and

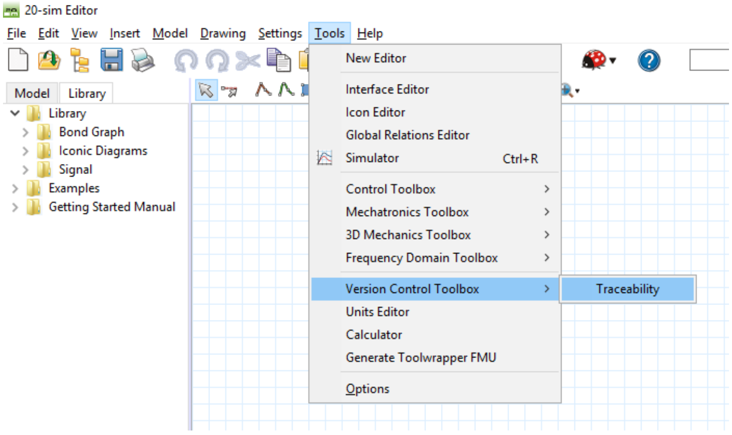


Figure 161: Opening the traceability dialog in 20-sim.

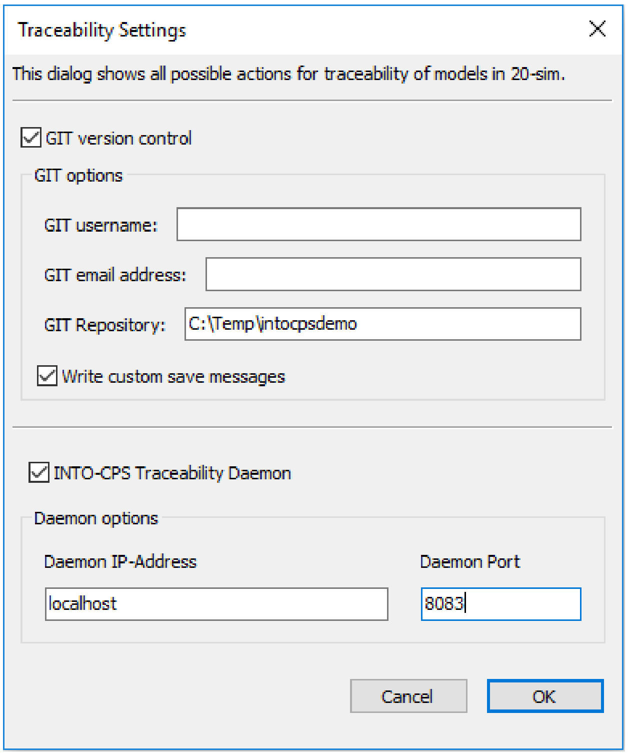
Save action respectively in the 20-sim GUI. FMU import and `modelDescription.xml` import are triggered when respectively an FMU or `modelDescription.xml` file is dragged from the Windows Explorer onto the canvas in 20-sim. See also subsubsection 5.2.4 for more information on how to import an FMU in 20-sim, and subsubsection 5.2.1 on how to import a model description XML file into 20-sim. An FMU export event is triggered when an FMU is exported from 20-sim (see subsubsection 5.5.5 on how to export an FMU from within 20-sim). To read more about what actions are performed during a trace event in 20-sim, please refer to Deliverable D4.3d [KLN+17].

8.7 RT Tester

For Windows, download the latest release bundle of RT-Tester from `https://secure.verified.de/f5x1hks4/into-cps/one-click/VSI_bundle.exe`. Alternatively, you can use the INTO-CPS download manager. RT-Tester supports tracing the following modelling activities.

- Define test model
- Define test objectives
- Run test

Prerequisites Git should be installed in the system, as well as the following Python packages: `requests`, `jsonschema`, `gitpython`. **Note**:



Traceability Settings

This dialog shows all possible actions for traceability of models in 20-sim.

☑ GIT version control

GIT options

GIT username:

GIT email address:

GIT Repository: C:\Temp\intocpsdemo

☑ Write custom save messages

☑ INTO-CPS Traceability Daemon

Daemon options

Daemon IP-Address: localhost

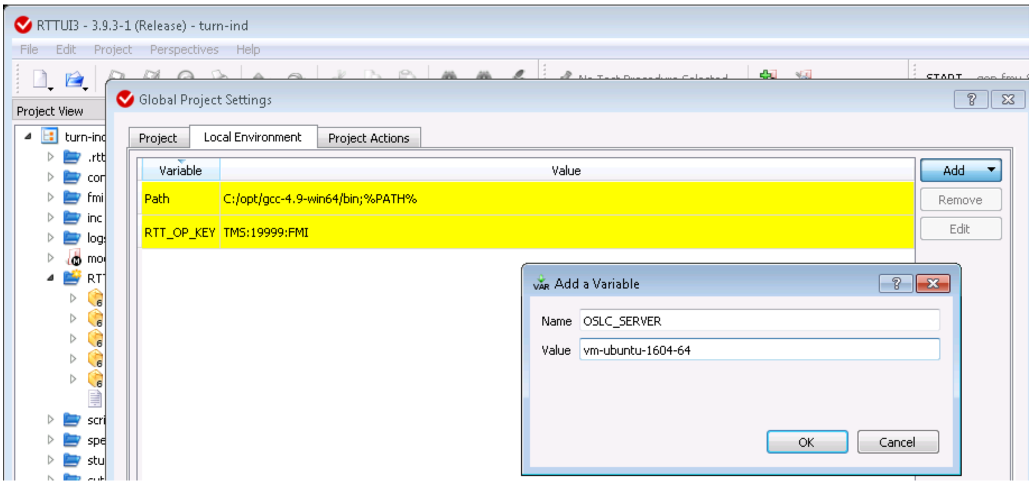
Daemon Port: 8083

Figure 162: Opening the traceability dialog in 20-sim.

The `VSI_bundle.exe` installation process this will check whether these are installed; if not, it will be attempted to install them using `pip`.

Configuration of remote OSLC server. If the traceability daemon runs on the same system as your RT-Tester, then you have nothing to configure. The actions will already be identified and traced. If the daemon is running somewhere else, you can configure this by setting the environment variable `OSLC_SERVER`. For example, you can do this from the RTTUI3 as indicated in Figure 163:

1. In the menu bar, select *Project* →*Project Settings*
2. Go to the *Local Environment* tab
3. Click *Add* →*Add a New Variable*
4. Set *Name* to `OSLC_SERVER` and *Value* to the host IP or URL
5. Click *OK* to close the *Add Variable* dialog



Variable	Value
Path	C:/opt/gcc-4.9-win64/bin;%PATH%
RTT_OP_KEY	TMS:19999:FMI

Name OSLC_SERVER

Value vm-ubuntu-1604-64

Figure 163: Configure variable `OSLC_SERVER` in RTTUI3.

6. Click *Save* to close the *Global Project Settings* dialog

8.8 Retrieving Traceability Information

The following traces can be queried from within the INTO-CPS Application:

- FMUs and the related requirements
- Users and related activities and artifacts
- Simulation results and the files that were used to produce a certain result
- Requirements and related test cases

To get an overview in the Application, right-click on the *Traceability* entry in the project browser and select *Trace Objects*. A page will appear as shown in Figure 164.

Requirements related to FMUs In the first tab of the traceability page (*FMUs*) of the INTO-CPS Application (see Figure 164), all the FMUs in the traceability database are listed. The FMUs are traced once they are exported from the modelling tool. To each FMU, the related requirements can then be traced, to give the user a quick and easy overview of which requirements

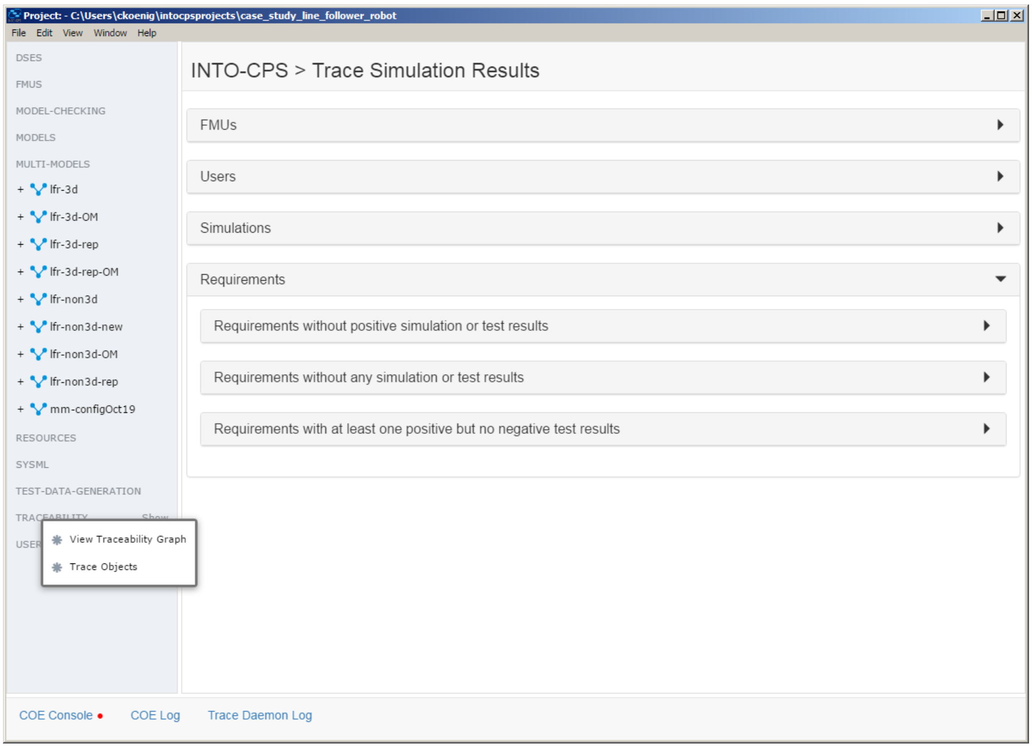


Figure 164: Overview of the different queries as they are implemented in the INTO-CPS Application.

are generally linked to a certain FMU, originating from requirements linking in Modelio.

Activities and artifacts related to users The second tab (*Users*) lists all the users that have performed traceability-related actions, as identified by their e-mail address. For each user, artifacts (*e.g.* simulation results, configuration files, `modelDescription.xml` files *etc.*) and activities (*e.g.* exporting an FMU, importing a `modelDescription.xml` file, running a simulation *etc.*) can be found, along with the time stamp. This allows evaluating which user created which file, to understand responsibilities in a complex project.

Files used to create a simulation result The third tab (*Simulations*) lists all the simulation results that were created by the INTO-CPS Application. For each result, the files and the version of the INTO-CPS Application used to create the result can be found. This allows understanding the simulation result and can give confidence, since they can be reconstructed.

Test cases and requirements The fourth tab (*Requirements*) is subdivided into three queries. The first, requirements without positive simulation or test results indicates those requirements that have not yet been validated. The second, requirements without any simulation or test result, shows requirements which are not yet covered by a test case, neither positive nor negative. The third, requirements with at least one positive but no negative test result shows those requirements that have had a positive test or simulation result, and can therefore be regarded as fulfilled.

9 Code Generation

The INTO-CPS tools Overture, OpenModelica and 20-sim have the ability, to varying degrees, to translate models into platform-independent C source code. Overture can moreover translate VDM models written in the executable subset of VDM++ [LLB11] (itself a subset of VDM-RT) to Java, but C is the language of interest for the INTO-CPS technology.

The purpose of translating models into source code is twofold. First, the source code can be compiled and wrapped as standalone FMUs for co-simulation, such that the source tool is not required. Second, with the aid of existing C compilers, the automatically generated source code can be compiled for specific hardware targets.

The INTO-CPS approach is to use 20-sim 4C to compile and deploy the code to hardware targets, since the tool incorporates the requisite knowledge regarding compilers, target configuration *etc.* This is usually done for control software modelled in one of the high-level modelling notations, after validation through the INTO-CPS tool chain. Deployment to target hardware is also used for SiL and HiL validation and prototyping.

For each of the modelling and simulation tools of the INTO-CPS tool chain, code generation is a standalone activity. As such, the reader should refer to the tool-specific documentation referenced in Appendix B for guidance on code generation. Deliverable D5.1d [HLG$^+$15] contains the details of how each tool approaches code generation.

The remainder of this section lists information about the code generation capabilities of each tool. Extensive guidance on how to tailor models for problem-free translation to code can be found in the tools' individual user manuals, as referenced in Appendix B. Further references are given herein.

9.1 Overture

Overture provides a code generator for VDM-RT that is geared toward resource-constrained embedded platforms. Of these, PIC32 and ATmega microcontrollers have been tested, as well as Raspberry Pi and typical Intel-based computers. A complete description of Overture's C code generator can be found in Deliverable D5.3d [BHPG17] and in the Overture User Manual, which is accessible through Overture's Help system. As a quick-start guide, this section only provides an introduction to invoking the C code generator, and an overview of the features of VDM-RT that are stable from a code generation point of view. Please note that exporting a source code FMU with Overture (Section 5.1) automatically invokes the code generator and packages the result as an FMU.

The C code generator is invoked from the context menu in the Project Explorer as shown in Figure 165. The code generator currently supports the following VDM-RT language features:

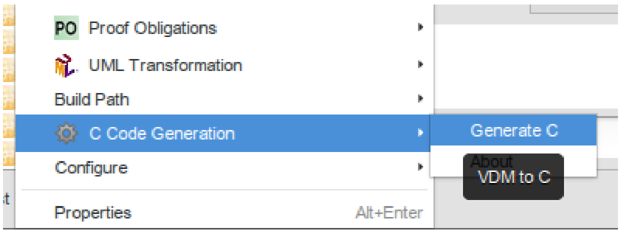


Figure 165: Invoking the code generator.

- Basic data types and operations: integers, reals, booleans, *etc.*
- The `is_` type test
- Quote types
- Token types
- `let` expressions
- Pattern matching (partial support)
- For and while loops
- `case` expressions
- Record types
- Union types
- Product types
- Aggregate types and operations: sets, sequences and maps
- Object-oriented features
- The `time` expression
- Pre-condition checks
- Quantifiers

- Distributed architectures

The following language features are not supported:

- Lambda expressions.
- Post-conditions and invariants.
- File I/O via the I/O library.

A key feature of the C code generator is the use of a garbage collector for memory management. Generating a VDM-RT model to C code via the context menu results in a `main.c` file containing a skeletal `main()` function. This function contains calls to `vdm_gc_init()` and `vdm_gc_shutdown()`, the garbage collector initialization and shutdown functions. The collector proper can not be invoked automatically, so calls to the essential function `vdm_gc()` must be inserted manually in the main code, for instance after each repetition of a cyclic task. The source code FMU exporter, on the other hand, can handle automatic invocation of the garbage collector, so no manual intervention is required. Please note that it is generally unsafe to insert calls to `vdm_gc()` in the generated code. The following is a typical `main()` function:

```c
#include <Vdm.h>

extern void periodic_task();
extern void other_init();
extern void other_shutdown();

extern int keep_going;

int main()
{
      vdm_gc_init();
      other_init();

      while(keep_going != 0)
      {
            periodic_task();
            vdm_gc();
      }

      vdm_gc_shutdown();
      other_shutdown();

      return 0;
}
```

9.2 20-sim

20-sim supports ANSI-C and C++ code generation through the use of external and user-modifiable code-generation templates. Only a subset of the supported 20-sim modelling language elements can be exported as ANSI-C or C++ code. The exact supported features depend on the chosen template and its purpose and are discussed in Section 5.2.

The main purpose of the 20-sim code generator is to export control systems. Therefore the focus in on running code on limited embedded targets (*e.g.* Arduino) with no operating system, or as a real-time task on a real-time operating system. The code generated by 20-sim does not contain any target-related or operating system specific code. The exported code is generated such that it can be embedded in an external software project. To run 20-sim generated code on a target, you can use 20-sim 4C. This is a tool that extends the 20-sim generated code with target code based on target templates [Con17].

9.3 OpenModelica

OpenModelica supports code generation from Modelica to source code targeting both ANSI-C and C++. From the generated source code, co-simulation and model-exchange FMUs can be built. The only supported solver in the generated co-simulation FMUs is forward Euler. Additional solvers will be supported in the future.

9.4 RT-Tester/RTT-MBT

When generating test FMUs from SysML discrete-event state-chart specifications using RTTester/RTT-MBT, the user should be aware of the following sources of errors:

- Livelock resulting from a transition cycle in the state-chart specification in which all transition guards are true simultaneously. This can be checked separately using a livelock checker.
- Race conditions arising from parallel state-charts assigning different values to the same variable. Model execution in this case will deadlock.
- State-charts specifying a replacement SUT must be deterministic.

10 Issue handling

Should you experience an issue while using one or more of the INTO-CPS tools, please take the time to report the issue to the INTO-CPS project team, so we can help you resolve it as soon as possible.

Before you go any further with your current issue, please check that the INTO-CPS version you are using is the newest. The version number is part of the file name of the INTO-CPS Application. To find the list of released INTO-CPS Applications, and to see what the current version of INTO-CPS is, please visit

`https://github.com/into-cps-association/intocps-ui/releases/`

If your issue is not listed on the *Issues* tab, please report it there.

11 Conclusions

The tool chain supports model-based design and validation of CPSs, with an emphasis on multi-model co-simulation.

Several independent simulation tools are orchestrated by a custom co-simulation orchestration engine, which implements both fixed and variable step size co-simulation semantics. A multi-model thus co-simulated can be further verified through automated model-based testing and bounded model checking.

The tool chain benefits from a cohesive management interface, the INTO-CPS Application, the main gateway to modelling and validation with the INTO-CPS technology. Following the manual should give a new user of the INTO-CPS tool chain an understanding of all the elements of the INTO-CPS vision for co-simulation. This manual is accompanied by tutorial material and guidance on the main INTO-CPS tool chain website at

`http://into-cps-association.github.io`

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A List of Acronyms

20-sim	Software package for modelling and simulation of dynamic systems
API	Application Programming Interface
AST	Abstract Syntax Tree
AU	Aarhus University
BCS	Basic Control States
CLE	ClearSy
CLP	Controllab Products B.V.
COE	Co-simulation Orchestration Engine
CORBA	Common Object Request Broker Architecture
CPS	Cyber-Physical Systems
CT	Continuous-Time
DE	Discrete Event
DESTECS	Design Support and Tooling for Embedded Control Software
DSE	Design Space Exploration
FMI	Functional Mockup Interface
FMI-Co	Functional Mockup Interface – for Co-simulation
FMI-ME	Functional Mockup Interface – Model Exchange
FMU	Functional Mockup Unit
HiL	Hardware-in-the-Loop
HMI	Human Machine Interface
HW	Hardware
ICT	Information Communication Technology
IDE	Integrated Design Environment
LTL	Linear Temporal Logic
M&S	Modelling and Simulation
MARTE	Modeling and Analysis of Real-Time and Embedded Systems
MBD	Model-based Design
MBT	Model-based Testing
MC/DC	Modified Decision/Condition Coverage
MDE	Model Driven Engineering
MiL	Model-in-the-Loop
MIWG	Model Interchange Working Group
OMG	Object Management Group
OS	Operating System
PID	Proportional Integral Derivative
PROV-N	The Provenance Notation
RPC	Remote Procedure Call
RTT	Real-Time Tester

SiL	Software-in-the Loop
SMT	Satisfiability Modulo Theories
ST	Softeam
SUT	System Under Test
SVN	Subversion
SysML	Systems Modelling Language
TA	Test Automation
TE	Test Environment
TR	TRansitions
TRL	Technology Readiness Level
TWT	TWT GmbH Science & Innovation
UML	Unified Modelling Language
UNEW	University of Newcastle upon Tyne
UTP	Unifying Theories of Programming
UTRC	United Technologies Research Center
UY	University of York
VDM	Vienna Development Method
VSI	Verified Systems International
WP	Work Package
XML	Extensible Markup Language

B Background on the Individual Tools

This appendix provides background information on each of the independent tools of the INTO-CPS tool chain.

B.1 Modelio

Modelio is a comprehensive MDE [Fav05] workbench tool which supports the UML2.x standard. Modelio adds modern Eclipse-based graphical environment to the solid modelling and generation know-how obtained with the earlier Softeam MDE workbench, Objecteering, which has been on the market since 1991. Modelio provides a central repository for the local model, which allows various languages (UML profiles) to be combined in the same model, abstraction layers to be managed and traceability between different model elements to be established. Modelio makes use of extension modules, enabling the customization of this MDE environment for different purposes and stakeholders. The XMI module allows models to be exchanged between different UML modelling tools. Modelio supports the most popular XMI UML2 flavors, namely EMF UML2 and OMG UML 2.3. Modelio is one of the leaders in the OMG Model Interchange Working Group (MIWG), due to continuous work on XMI exchange improvements.

Among the extension modules, some are dedicated to IT system architects. For system engineering, SysML or MARTE modules can be used. They provide dedicated modelling support for dealing with general, software and hardware aspects of embedded or cyber physical systems. In addition, several utility modules are available, such as the Document Publisher which provides comprehensive support for the generation of different types of document.

Modelio is highly extendable and can be used as a platform for building new MDE features. The tool enables users to build UML2 Profiles, and to combine them with a rich graphical interface for dedicated diagrams, model element property editors and action command controls. Users can use several extension mechanisms: light Python scripts or a rich Java API, both of which provide access to Modelio‘s model repository and graphical interface.

B.2 Overture

The Overture platform [LBF+10] is an Eclipse-based integrated development environment (IDE) for the development and validation of system specifications in three dialects of the specification language of the Vienna Development Method. Overture is distributed with a suite of examples and step-by-step tutorials which demonstrate the features of the three dialects. A user manual for the platform itself is also provided [LLJ+13], which is accessible through Overture's help system. Although certain features of Overture are relevant only to the development of software systems, VDM itself can be used for the specification and validation of any system with distinct states, known as *discrete-event systems*, such as physical plants, protocols, controllers (both mechanical and software) *etc.*, and Overture can be used to aid in validation activities in each case.

Overture supports the following activities:

- The definition and elaboration of syntactically correct specifications in any of the three dialects, via automatic syntax and type validation.
- The inspection and assay of automatically generated proof obligations which ensure correctness in those aspects of specification validation which can not be automated.
- Direct interaction with a specification via an execution engine which can be used on those elements of the specification written in an executable subset of the language.
- Automated testing of specifications via a custom test suite definition language and execution engine.
- Visualization of test coverage information gathered from automated testing.
- Visualization of timing behaviours for specifications incorporating timing information.
- Translation to/from UML system representations.
- For specifications written in the special executable subset of the language, obtaining Java implementations of the specified system automatically.

For more information and tutorials, please refer to the documentation distributed with Overture.

The following is a brief introduction to the features of the three dialects of the VDM specification language.

VDM-SL This is the foundation of the other two dialects. It supports the development of monolithic state-based specifications with state transition operations. Central to a VDM-SL specification is a definition of the state of the system under development. The meaning of the system and how it operates is conveyed by means of changes to the state. The nature of the changes is captured by state-modifying operations. These may make use of auxiliary functions which do not modify state. The language has the usual provisions for arithmetic, new dependent types, invariants, pre- and post-conditions *etc*. Examples can be found in the VDM-SL tutorials distributed with Overture.

VDM++ The VDM++ dialect supports a specification style inspired by object-oriented programming. In this specification paradigm, a system is understood as being composed of entities which encapsulate both state and behaviour, and which interact with each other. Entities are defined via templates known as *classes*. A complete system is defined by specifying *instances* of the various classes. The instances are independent of each other, and they may or may not interact with other instances. As in object-oriented programming, the ability of one component to act directly on any other is specified in the corresponding class as a state element. Interaction is naturally carried out via precisely defined interfaces. Usually a single class is defined which represents the entire system, and it has one instance, but this is only a convention. This class may have additional state elements of its own. Whereas a system in VDM-SL has a central state which is modified throughout the lifetime of the system, the state of a VDM++ system is distributed among all of its components. Examples can be found in the VDM++ tutorials distributed with Overture.

VDM-RT VDM-RT is a small extension to VDM++ which adds two primary features:

- The ability to define how the specified system is envisioned to be allocated on a distributed execution platform, together with the communication topology.
- The ability to specify the timing behaviours of individual components, as well as whether certain behaviours are meant to be cyclical.

Finer details can be specified, such as execution synchronization and mutual exclusion on shared resources. A VDM-RT specification has the same structure as a VDM++ specification, only the conventional system class of VDM++ is mandatory in VDM-RT. Examples can be found in the VDM-RT tutorials distributed with Overture.

B.3 20-sim

20-sim [Con13, Bro97] is a commercial modelling and simulation software package for mechatronic systems. With 20-sim, models can be created graphically, similar to drawing an engineering scheme. With these models, the behaviour of dynamic systems can be analyzed and control systems can be designed. 20-sim models can be exported as C-code to be run on hardware for rapid prototyping and HiL-simulation. 20-sim includes tools that allow an engineer to create models quickly and intuitively. Models can be created using equations, block diagrams, physical components and bond graphs [KR68]. Various tools give support during the model building and simulation. Other toolboxes help to analyze models, build control systems and improve system performance. Figure 166 shows 20-sim with a model of a controlled hexapod. The mechanism is generated with the 3D Mechanics Toolbox and connected with standard actuator and sensor models from the mechanics library. The hexapod is controlled by PID controllers which are tuned in the

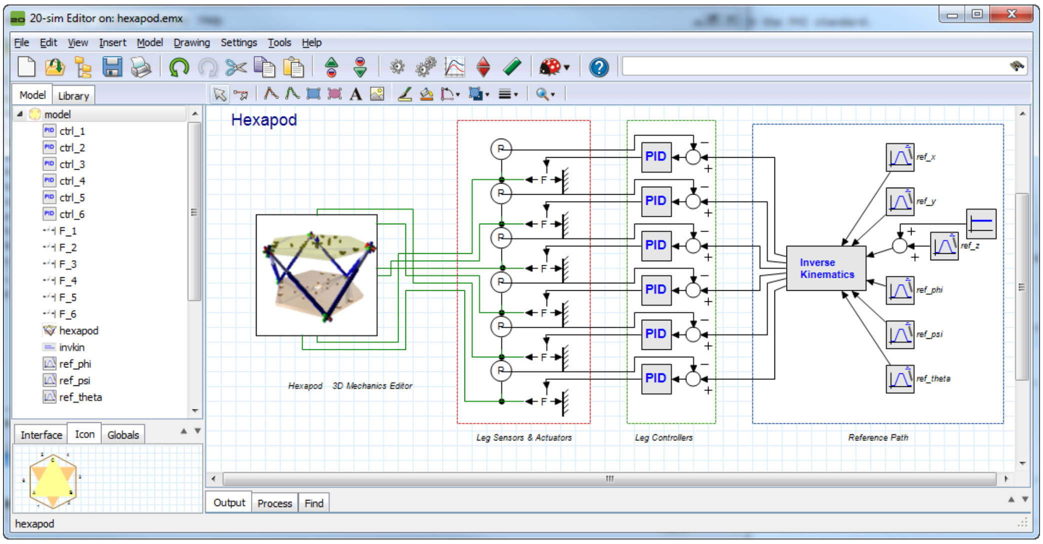

Figure 166: Example of a hexapod model in 20-sim.

frequency domain. Everything that is required to build and simulate this model and generate the controller code for the real system is included inside the package.

The 20-sim Getting Started manual [KG16] contains examples and step-by-step tutorials that demonstrate the features of 20-sim. More information on 20-sim can be found at `http://www.20sim.com` and in the user manual at `http://www.20sim.com/webhelp` [KGD16]. The integration of 20-sim into the INTO-CPS tool-chain is realized via the FMI standard.

B.4 OpenModelica

OpenModelica [Fri04] is an open-source Modelica-based modelling and simulation environment. Modelica [FE98] is an object-oriented, equation based language to conveniently model complex physical systems containing, e.g., mechanical, electrical, electronic, hydraulic, thermal, control, electric power or process-oriented subcomponents. The Modelica language (and OpenModelica) supports continuous, discrete and hybrid time simulations. OpenModelica already compiles Modelica models into FMU, C or C++ code for simulation. Several integration solvers, both fixed and variable step size, are available in OpenModelica: euler, rungekutta, dassl (default), radau5, radau3, radau1.

OpenModelica can be interfaced to other tools in several ways as described in the OpenModelica user's manual [Ope]:

- via command line invocation of the omc compiler
- via C API calls to the omc compiler dynamic library
- via the CORBA interface
- via OMPython interface [GFR$^+$12]

OpenModelica has its own scripting language, Modelica script (mos files), which can be used to perform actions via the compiler API, such as loading, compilation, simulation of models or plotting of results. OpenModelica supports Windows, Linux and Mac Os X.

The integration of OpenModelica into the INTO-CPS tool chain is realized via compliance with the FMI standard, and is described in Deliverable D4.3b [PBL$^+$17].

B.5 RT-Tester

The RT-Tester [Ver15a] is a test automation tool for automatic test generation, test execution and real-time test evaluation. Key features include a strong C/C++-based test script language, high performance multi-threading, and hard real-time capability. The tool has been successfully applied in avionics, rail automation, and automotive test projects. In the INTO-CPS tool chain, RT-Tester is responsible for model-based testing, as well as for model checking. This section gives some background information on the tool from these two perspectives.

B.5.1 Model-based Testing

The RT-Tester Model Based Test Case and Test Data Generator (RTT-MBT) [Ver15b] supports model-based testing (MBT), that is, automated generation of test cases, test data, and test procedures from UML/SysML models. A number of common modelling tools can be used as front-ends for this. The most important technical challenge in model-based test automation is the extraction of test cases from test models. RTT-MBT combines an SMT solver with a technique akin to bounded model checking so as to extract finite paths through the test model according to some predefined criterion. This criterion can, for instance, be MC/DC coverage, or it can be requirements coverage (if the requirements are specified as temporal logic formulae within the model). A further aspect is that the environment can be modelled within the test model. For example, the test model may contain a constraint such that a certain input to the system-under-test remains in a predefined range. This aspect becomes important once test automation is lifted from single test models to multi-model cyber-physical systems. The derived test procedures use the RT-Tester Core as a back-end, allowing the system under test to be provided on real hardware, software only, or even just simulation to aid test model development.

Further, RTT-MBT includes requirement tracing from test models down to test executions and allows for powerful status reporting in large scale testing projects.

B.5.2 Model Checking of Timed State Charts

RTT-MBT applies model checking to behavioural models that are specified as timed state charts in UML and SysML, respectively. From these models, a transition relation is extracted and represented as an SMT formula in bit-vector theory [KS08], which is then checked against LTL formulae [Pnu77] using the algorithm of Biere *et al.* [BHJ+06]. The standard setting of RTT-MBT is to apply model checking to a single test model, which consists of the system specification and an environment.

- A component called *TestModel* that is annotated with stereotype *TE*.
- A component called *SystemUnderTest* that is annotated with stereotype *SUT*.

RTT-MBT uses the stereotypes to infer the role of each component. The interaction between these two parts is implemented via input and output interfaces that specify the accessibility of variables using UML stereotypes.

- A variable that is annotated with stereotype *SUT2TE* is written by the system model and readable by the environment.
- A variable that is annotated with stereotype *TE2SUT* is written by the environment and read by the system model as an input.

A simple example is depicted in Figure 167, which shows a simple composite structure diagram in Modelio for a turn indication system. The purpose of the system is to control the lamps of a turn indication system in a car. Further details are given in [Ver13]. The test model consists of the two aforementioned components and two interfaces:

- **Interface1** is annotated with stereotype *TE2SUT* and contains three variables `voltage`, `TurnIndLvr` and `EmerSwitch`. These variables are controlled by the environment and fed to the system under test as inputs.
- **Interface2** is annotated with stereotype *SUT2TE* and contains two variables `LampsLeft` and `LampsRight`. These variables are controlled by the system under test and can be read by the environment.

Observe that the two variables `LampsLeft` and `LampsRight` have type `int`, but should only hold values `0` or `1` to indicate states *on* or *off*. A straightforward system property that could be verified would thus be that `LampsLeft` and `LampsRight` indeed are only assigned `0` or `1`, which could be expressed by the following LTL specification:

$$\mathbf{G}(0 \leq \texttt{LampsLeft} \leq 1 \land 0 \leq \texttt{LampsRight} \leq 1)$$

A thorough introduction with more details is given in the RTT-MBT user manual [Ver13].

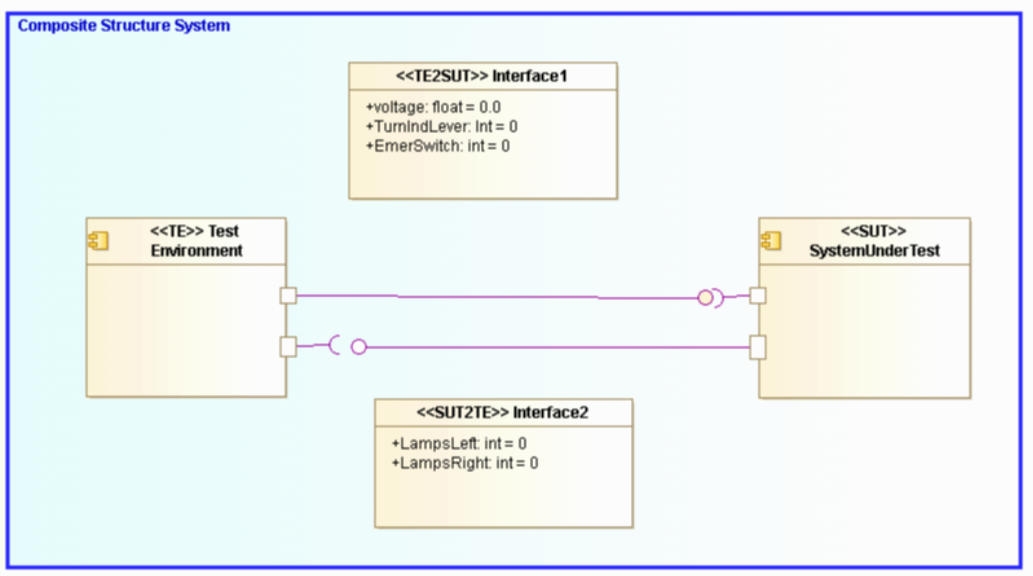

Figure 167: Simple model that highlights interfaces between the environment and the system-under-test.

C Underlying Principles

The INTO-CPS tool chain facilitates the design and validation of CPSs through its implementation of results from a number of underlying principles. These principles are co-simulation, design space exploration, model-based test automation and code generation. This appendix provides an introduction to these concepts.

C.1 Co-simulation

Co-simulation refers to the simultaneous simulation of individual models which together make up a larger system of interest, for the purpose of obtaining a simulation of the larger system. A co-simulation is performed by a co-simulation orchestration engine. This engine is responsible for initializing the individual simulations as needed; for selecting correct time step sizes such that each constituent model can be simulated successfully for that duration, thus preventing time drift between the constituent simulations; for asking each individual simulation to perform a simulation step; and for synchronizing information between models as needed after each step. The result of one such round of simulations is a single simulation step for the complete multi-model of the system of interest.

As an example, consider a very abstract model of a nuclear power plant. This consists of a nuclear reactor core, a controller for the reactor, a water and steam distribution system, a steam-driven turbine and a standard electrical generator. All these individual components can be modelled separately and simulated, but when composed into a model of a nuclear power plant, the outputs of some become the inputs of others. In a co-simulation, outputs are matched to inputs and each component is simulated one step at a time in such a way that when each model has performed its simulation step, the overall result is a simulation step of the complete power plant model. Once the correct information is exchanged between the constituent models, the process repeats.

C.2 Design Space Exploration

During the process of developing a CPS, either starting from a completely blank canvas or constructing a new system from models of existing components, the architects will encounter many design decisions that shape the final product. The activity of investigating and gathering data about the merits of the different choices available is termed Design Space Exploration. Some of the choices the designer will face could be described as being the selection of parameters for specific components of the design, such as the exact position of a sensor, the diameter of wheels or the parameters affecting a control algorithm. Such parameters are variable to some degree and the selection of their value will affect the values of objectives by which a design will be measured. In these cases it is desirable to explore the different values each parameter may take and also different combinations of these parameter values if there are more than one parameter, to find a set of designs that best meets its objectives. However, since the size of the design space is the product of the number of parameters and the number of values each may adopt, it is often impractical to consider performing simulations of all parameter combinations or to manually assess each design.

The purpose of an automated DSE tool is to help manage the exploration of the design space, and it separates this problem into three distinct parts: the search algorithm, obtaining objective values and ranking the designs according to those objectives. The simplest of all search algorithms is the exhaustive search, and this algorithm will methodically move through each design, performing a simulation using each and every one. This is termed an open loop method, as the simulation results are not considered by the algorithm at all. Other algorithms, such as a genetic search, where an initial set of randomly generated individuals are bred to produce increasingly good results, are closed loop methods. This means that the choice of next design to be simulated is driven by the results of previous simulations.

Once a simulation has been performed, there are two steps required to close the loop. The first is to analyze the raw results output by the simulation to determine the value for each of the objectives by which the simulations are to be judged. Such objective values could simply be the maximum power consumed by a component or the total distance traveled by an object, but they could also be more complex measures, such as the proportion of time a device was operating in the correct mode given some conditions. As well as numerical objectives, there can also be constraints on the system that are either passed or failed. Such constraints could be numeric, such as the maximum power that a substation must never exceed, or they could be based on temporal logic to check that undesirable events do not occur, such as all the lights at a road junction not being green at the same time.

The final step in a closed loop is to rank the designs according to how well each performs. The ranking may be trivial, such as in a search for a design that minimizes the total amount of energy used, or it may be more complex if there are multiple objectives to optimize and trade off. Such ranking functions can take the form of an equation that returns a score for each design, where the designs with the highest/lowest scores are considered the best. Alternatively, if the relationship between the desired objectives is not well understood, then a Pareto approach can be taken to ranking, where designs are allocated to ranks of designs that are indistinguishable from each other, in that each represents an optimum, but there exist different tradeoffs between the objective values.

C.3 Model-Based Test Automation

The core fragment of test automation activities is a model of the desired system behaviour, which can be expressed in SysML. This test model induces a transition relation, which describes a collection of execution paths through the system, where a path is considered a sequence of timed data vectors (containing internal data, inputs and outputs). The purpose of a test automation tool is to extract a subset of these paths from the test model and turn these paths into test cases, respectively test procedures. The test procedures then compare the behaviour of the actual system-under-test to the path, and produce warnings once discrepancies are observed.

C.4 Code Generation

Code generation refers to the translation of a modelling language to a common programming language. Code generation is commonly employed in control engineering, where a controller is modelled and validated using a tool such as 20-sim, and finally translated into source code to be compiled for some embedded execution platform, which is its final destination.

The relationship that must be maintained between the source model and translated program must be one of refinement, in the sense that the translated program must not do anything that is not captured by the original model. This must be considered when translating models written in high-level specification languages, such as VDM. The purpose of such languages is to allow the specification of several equivalent implementations. When a model written in such a language is translated to code, one such implementation is essentially chosen. In the process, any non-determinism in the specification, the specification technique that allows a choice of implementations, must be resolved. Usually this choice is made very simple by restricting the modelling language to an executable subset, such that no such non-determinism is allowed in the model. This restricts the choice of implementations to very few, often one, which is the one into which the model is translated via code generation.