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INtegrated TOol chain for model-based design of CPSs



INTO-CPS Tool Chain User Manual

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<http://into-cps.au.dk>

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32 Abstract

33 This deliverable is the user manual for the INTO-CPS tool chain, an update
34 of deliverable D4.2a [BLL⁺15]. It is targeted at those wishing to make use
35 of the INTO-CPS technology to design and validate cyber-physical systems.
36 As a user manual, this deliverable is concerned with those aspects of the tool
37 chain relevant to end-users, so it is necessarily high-level. Other deliverables
38 discuss finer details of individual components, including theoretical founda-
39 tions and software design decisions. Readers interested in this perspective on
40 the tool chain should consult deliverables D4.2b [PBLG16], D4.2c [BQ16],
41 D4.2d [LNH⁺16], D5.2a [PLM16], D5.2b [BLM16], D5.2c [BHPG16], D5.2d
42 [Gam16], D2.2a [ACM⁺16], D2.2b [FCC⁺16], D2.2c [CFTW16] and D2.2d
43 [CW16].

Contents

44	Contents	
45	1 Introduction	7
46	2 Overview of the INTO-CPS Tool Chain	8
47	3 Modelio and SysML for INTO-CPS	10
48	3.1 Creating a New Project	11
49	3.2 Exporting modelDescription.xml Files	14
50	4 The INTO-CPS Application	20
51	4.1 Introduction	20
52	4.2 Projects	21
53	4.3 Multi-Models	23
54	4.4 Co-simulations	28
55	4.5 Additional Features	33
56	4.6 The Co-Simulation Orchestration Engine	33
57	5 Using the Separate Modelling and Simulation Tools	36
58	5.1 Overture	36
59	5.2 20-sim	44
60	5.3 OpenModelica	53
61	6 Design Space Exploration for INTO-CPS	59
62	6.1 How to Launch a DSE	59
63	6.2 Results of a DSE	61
64	6.3 How to Edit a DSE Configuration	61
65	7 Test Automation and Model Checking	73
66	7.1 Installation of RT-Tester RTT-MBT	73
67	7.2 Test Automation	74
68	7.3 Model Checking	82
69	8 Traceability support for INTO-CPS	90
70	8.1 Overview	90
71	8.2 INTO-CPS application	90
72	8.3 Modelio	91
73	8.4 OpenModelica	91
74	8.5 20-sim	97
75	9 Code Generation for INTO-CPS	99
76	9.1 Overture	99

77	9.2	20-sim	101
78	9.3	OpenModelica	102
79	9.4	RT-Tester/RTT-MBT	102
80	10	Issue handling	102
81	10.1	Are you using the newest INTO-CPS release?	102
82	10.2	Has the issue already been reported?	103
83	10.3	Reporting a new issue	103
84	11	Conclusions	103
85	A	List of Acronyms	109
86	B	Background on the Individual Tools	111
87	B.1	Modelio	111
88	B.2	Overture	112
89	B.3	20-sim	114
90	B.4	OpenModelica	115
91	B.5	RT-Tester	116
92	C	Underlying Principles	119
93	C.1	Co-simulation	119
94	C.2	Design Space Exploration	119
95	C.3	Model-Based Test Automation	121
96	C.4	Code Generation	121

1 Introduction

This deliverable is the user manual for the INTO-CPS tool chain. The tool chain supports a model-based development and verification approach for Cyber-Physical Systems (CPSs). 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. Presently there is limited support for Linear Temporal Logic model checking of discrete models, with further model checking support being developed.

All INTO-CPS tools can be obtained from

`http://into-cps.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. The reader is therefore strongly encouraged 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 relevant parts of the Modelio SysML modelling tool.
- Section 4 explains the different features of the main user interface of the INTO-CPS tool chain, called the INTO-CPS Application.
- Section 5 describes the separate modelling and simulation tools used in elaborating and verifying the different constituent models of a multi-model.

- 132 • Design Space Exploration (DSE) for INTO-CPS multi-models is pre-
133 sented in Section 6.
- 134 • Section 7 describes model-based test automation and model checking
135 in the INTO-CPS context.
- 136 • Section 9 provides a short overview of code generation in the INTO-
137 CPS context.
- 138 • The appendices are structured as follows:
 - 139 – Appendix A lists the acronyms used throughout this deliverable.
 - 140 – Appendix B gives background information on the individual tools
141 making up the INTO-CPS tool chain.
 - 142 – Appendix C describes how the individual tools can be obtained.
 - 143 – Appendix D gives background information on the various princi-
144 ples underlying the INTO-CPS tool chain.

145 2 Overview of the INTO-CPS Tool Chain

146 The INTO-CPS tool chain consists of several special-purpose tools from a
147 number of different providers. Note that it is an open tool chain so it is
148 possible to incorporate other tools that also support the FMI standard for
149 co-simulation and we have already tested this with numerous external tools
150 (both commercial as well as open-source tools). The constituent tools are
151 dedicated to the different phases of co-simulation activities. They are dis-
152 cussed individually through the course of this manual. An overview of the
153 tool chain is shown in Figure 1. The main interface to an INTO-CPS co-
154 simulation activity is the INTO-CPS Application. This is where the user
155 can design co-simulations from scratch, assemble them using existing FMUs
156 and configure how simulations are executed. The result is a co-simulation
157 *multi-model*.

158 The design of a multi-model is carried out visually using the Modelio SysML
159 tool, in accordance with the SysML/INTO-CPS profile described in D2.2a
160 [ACM⁺16]. Here one can either design a multi-model from scratch by specify-
161 ing the characteristics and connection topology of Functional Mockup Units
162 (FMUs) yet to be developed, or import existing FMUs so that the connections
163 between them may be laid out visually. The result is a SysML multi-model of
164 the entire co-simulation, expressed in the SysML/INTO-CPS profile. In the

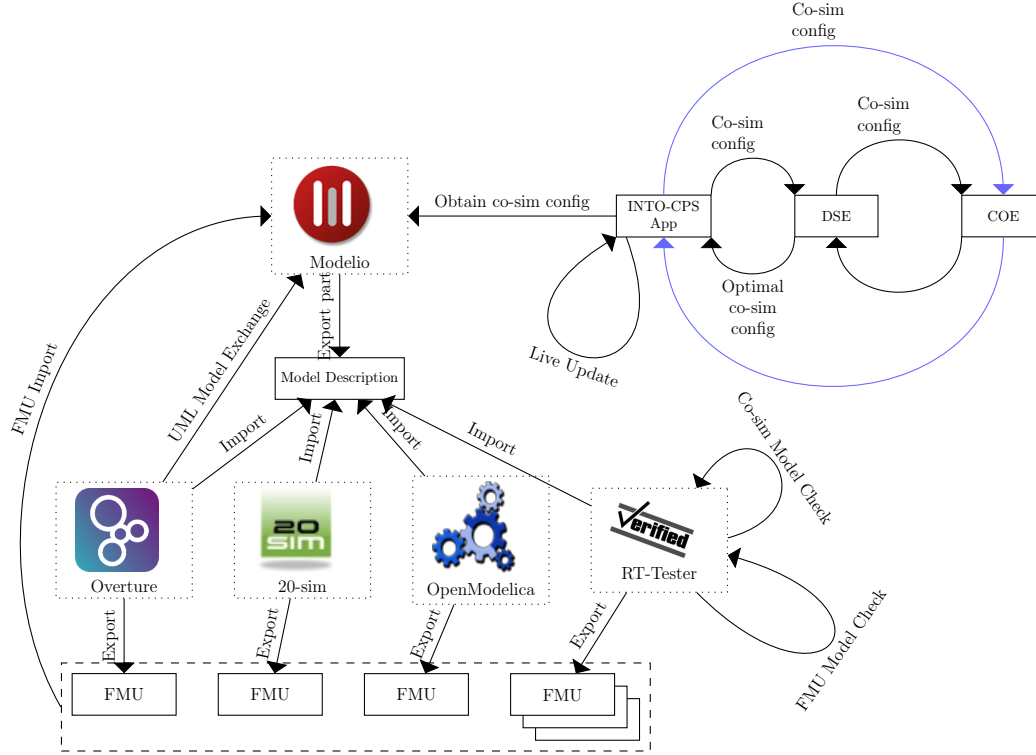


Figure 1: Overview of the structure of the INTO-CPS tool chain.

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 the 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 control 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 Design Space Exploration phase. In this mode,

182 ranges are defined for various parameters which are explored, in an intel-
 183 ligent way, by a design space exploration engine that searches for optimal
 184 parameter values based on defined optimization conditions. This engine in-
 185 teracts directly with the COE and itself controls the conditions under which
 186 the co-simulation is executed.

187 3 Modelio and SysML for INTO-CPS

188 The INTO-CPS tool chain supports a model-based approach to the develop-
 189 ment and validation of CPS. The Modelio tool and its SysML/INTO-CPS
 190 profile extension provide the diagramming starting point. This section de-
 191 scribes the Modelio extension that provides INTO-CPS-specific modelling
 192 functionality to the SysML modelling approach.

193 The INTO-CPS extension module is based on the Modelio SysML extension
 194 module, and extends it in order to fulfill INTO-CPS modelling requirements
 195 and needs. Figure 2 shows an example of a simple INTO-CPS Architecture
 Structure Diagram under Modelio. This diagram shows a *System*, named

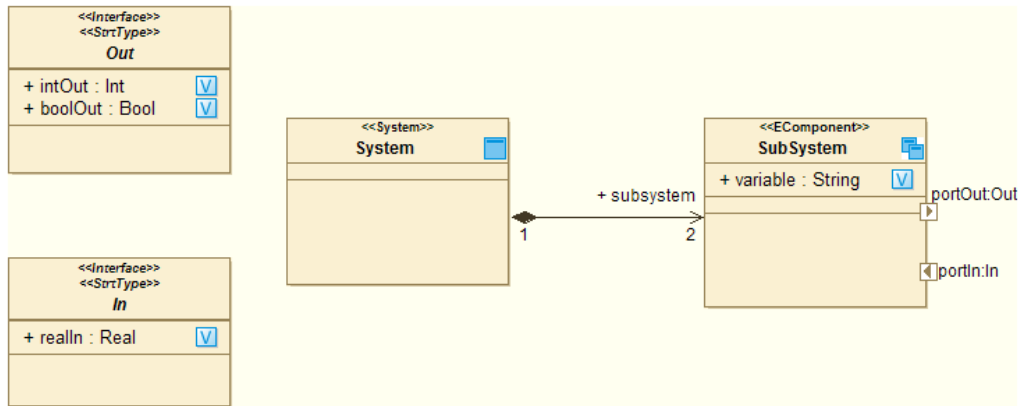


Figure 2: Example INTO-CPS multi-model.

196 “System”¹, composed of two *EComponents* of kind *Subsystem*, named “Sub-
 197 System”². These *Subsystems* have an internal *Variable* called “variable” of
 198 type *String* and expose two *FlowPorts* named “portIn” and “portOut”. The
 199 type of data going through these ports is respectively defined by types *In*
 200

¹An abstract description of an INTO-CPS multi-model.

²Abstract descriptions of INTO-CPS constituent models.

201 and *Out* of kind *StrtType*. More details on the SysML/INTO-CPS profile
 202 can be found in deliverable D2.2a [ACM⁺16].

203 Figure 3 illustrates the main graphical interface after Modelio and the INTO-CPS extension have been installed. Of all the panes, the following three are

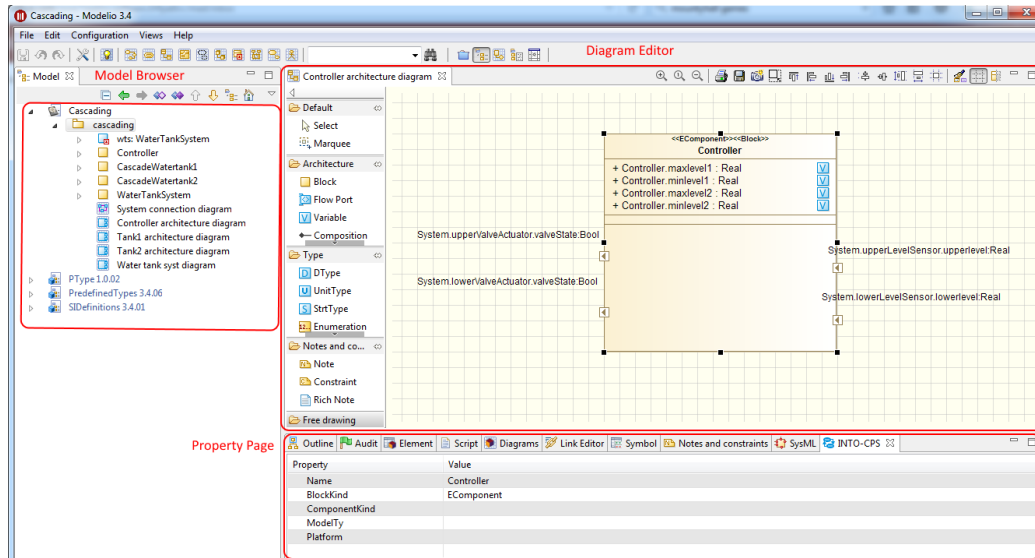


Figure 3: Modelio for INTO-CPS.

204
 205 most useful in the INTO-CPS context.

- 206 1. The Modelio model browser, which lists all the elements of your model
- 207 in tree form.
- 208 2. The diagram editor, which allows you to create INTO-CPS design ar-
- 209 chitectures and connection diagrams.
- 210 3. The INTO-CPS property page, in which values for properties of INTO-
- 211 CPS subsystems are specified.

212 3.1 Creating a New Project

213 In the INTO-CPS Modelling workflow described in Deliverable D3.2a [FGPP16],
 214 the first step will be to create, as depicted in Figure 4, a Modelio project:

- 215 1. Launch Modelio.
- 216 2. Click on *File* → *Create a project....*

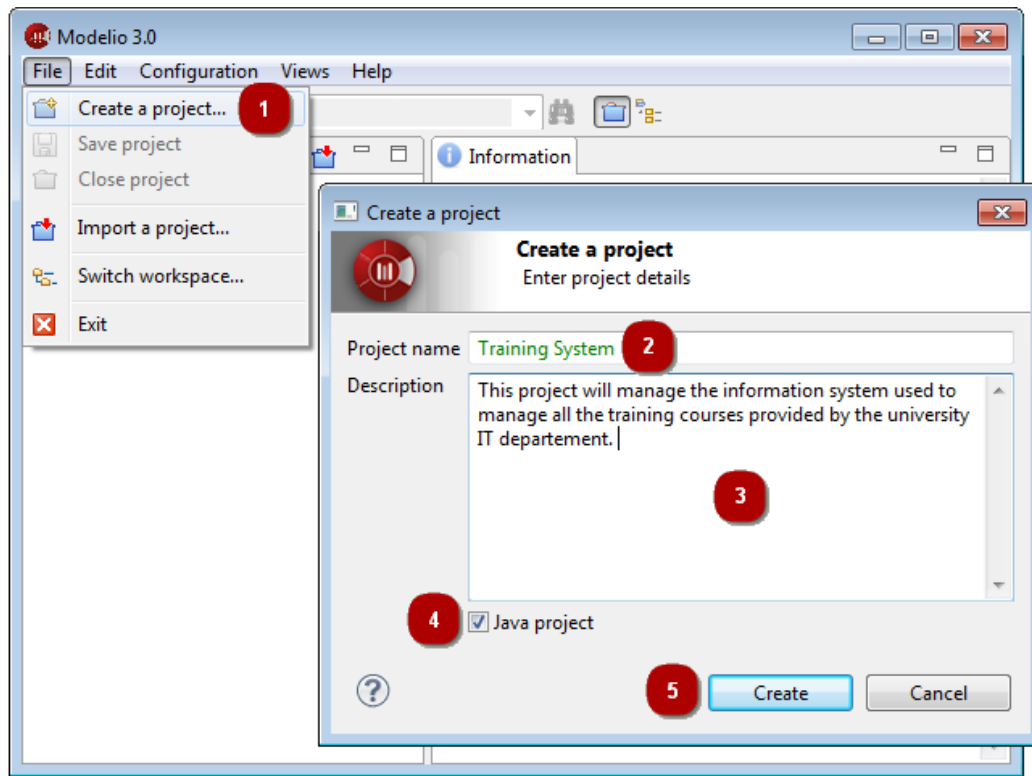


Figure 4: Creating a new Modelio project.

- 217 3. Enter the name of the project.
- 218 4. Enter the description of the project.
- 219 5. If it is envisaged that the project will be connected to a Java develop-
- 220 ment workflow in the future (unrelated to INTO-CPS), you can choose
- 221 to include the Java Designer module by selecting *Java Project*, other-
- 222 wise de-select this option.
- 223 6. Click on *Create* to create and open the project.

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

227 <http://into-cps.github.io>

228 If both modules have been correctly installed, you should be able to create,
 229 under any package, an INTO-CPS Architecture Structure Diagram in order
 230 to model the first subsystem of your multi-model. For that, in the Mode-

lio model browser, right click on a *Package* element then in the *INTO-CPS* entry, choose *Architecture Structure Diagram* as shown in Figure 5. Figure 6 represents an example of an Architecture Structure Diagram. Besides

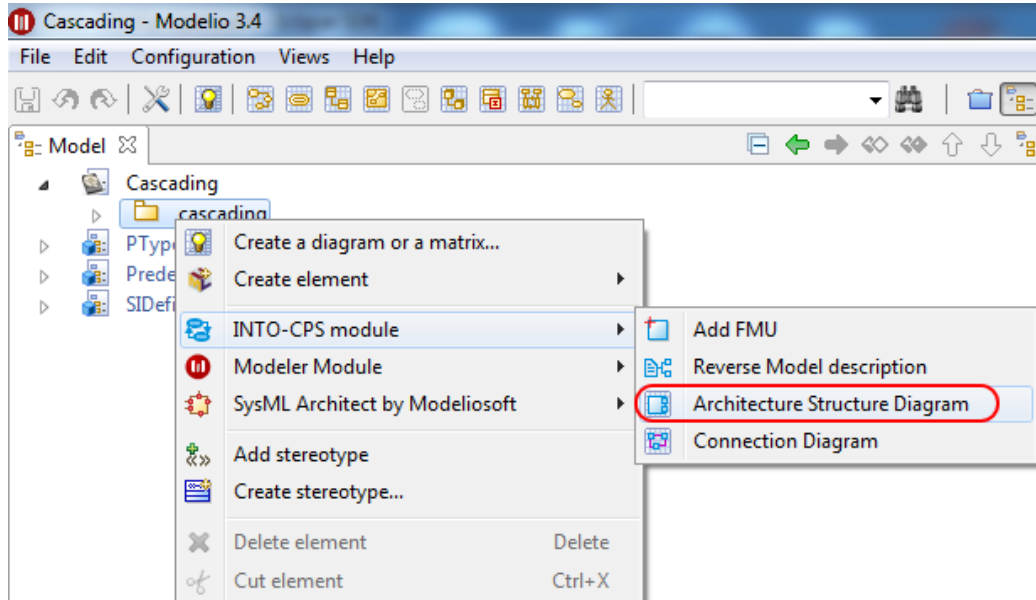


Figure 5: Creating an Architecture Structure diagram.

creating an Architecture Structure Diagram from scratch, the INTO-CPS extension allows the user to create it 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 7.
2. Select the desired `modelDescription.xml` file in your installation and click on *Import* (Figure 8).

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 9. 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 Diagram. To create an INTO-CPS Connection diagram, as for an INTO-CPS Architecture Structure Diagram, right click on a *Package* element, then

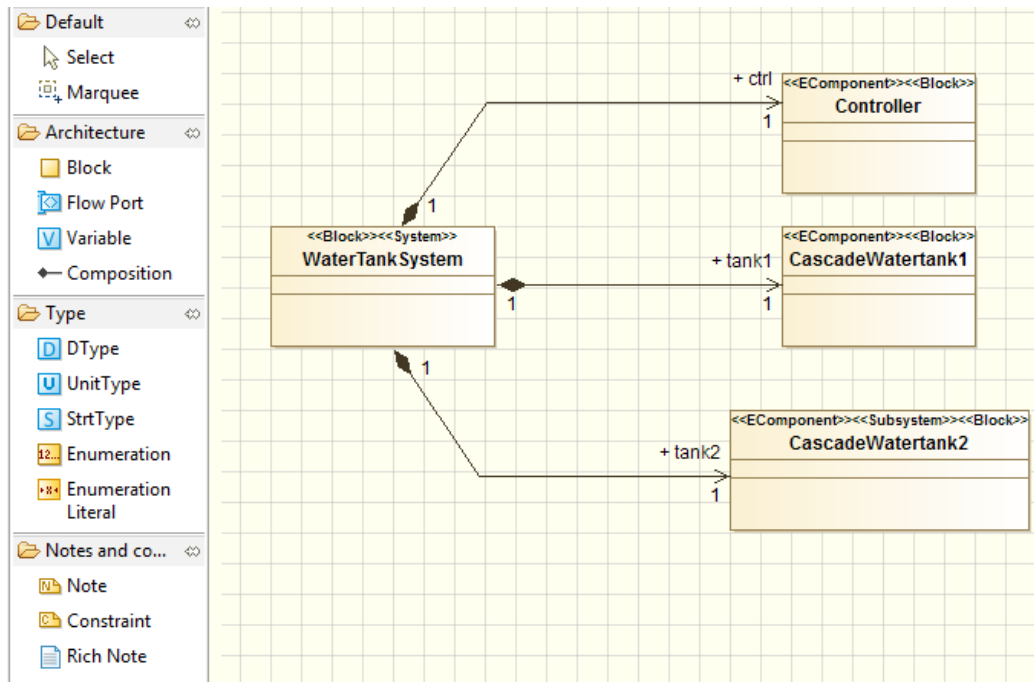


Figure 6: Example Architecture Structure diagram.

251 in the *INTO-CPS* entry choose *Connection Diagram*, as shown in Figure 10.
 252 Figure 11 shows the result of creating such a diagram. Once you have created
 253 all desired block instances and their ports by using the dedicated command in
 254 the Connection Diagram palette, you will be able to model their connections
 255 by using the connector creation command (Figure 12). At this point your
 256 blocks have been defined and the connections have been set. The next step
 257 is to simulate your multi-model using the app. For that you must first gener-
 258 erate a configuration file from your Connection diagram. Select the desired
 259 Connection diagram, right click on it and in the *INTO-CPS* entry choose
 260 *Generate configuration*, as shown in Figure 13. In the final step, choose a
 261 relevant name and click on *Generate*.

262 3.2 Exporting `modelDescription.xml` Files

263 The SysML Connection diagram defines the components of the system and
 264 their connections. The internals of these block instances are created in
 265 the various modeling tools and exported as FMUs. The modeling tools
 266 Overture, 20-sim and OpenModelica support importing the interface def-
 267 inition (ports) of the blocks in the Connection diagram by importing a

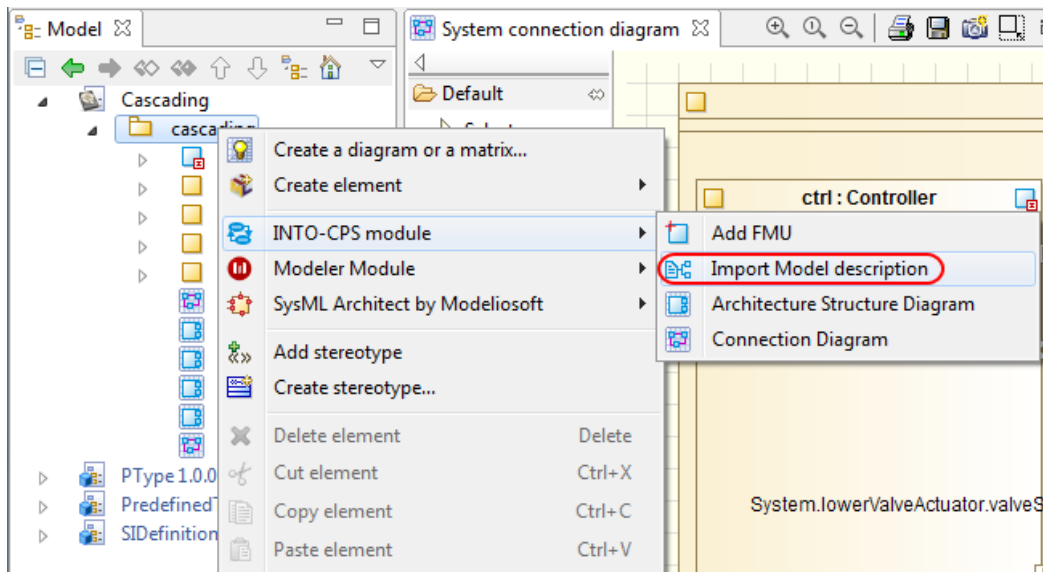


Figure 7: Importing an existing model description.

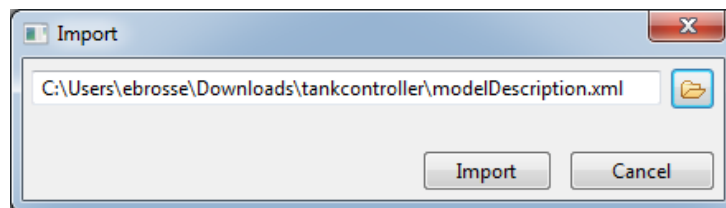


Figure 8: Model description selection.

268 modelDescription.xml file containing the block name and its interface
 269 definition.

270 Follow these steps to export a modelDescription.xml file from Mode-
 271 lio:

- 272 1. In Modelio, right-click on the model block in the tree.
- 273 2. Select *INTO-CPS* → *Generate Model Description* (see Figure 14).
- 274 3. Choose a file name containing the text “modelDescription.xml” and
 275 click *Export* (see Figure 15).

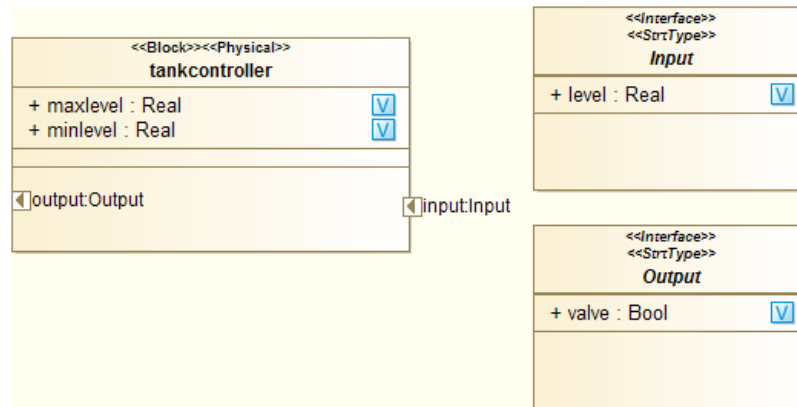


Figure 9: Result of model description import.

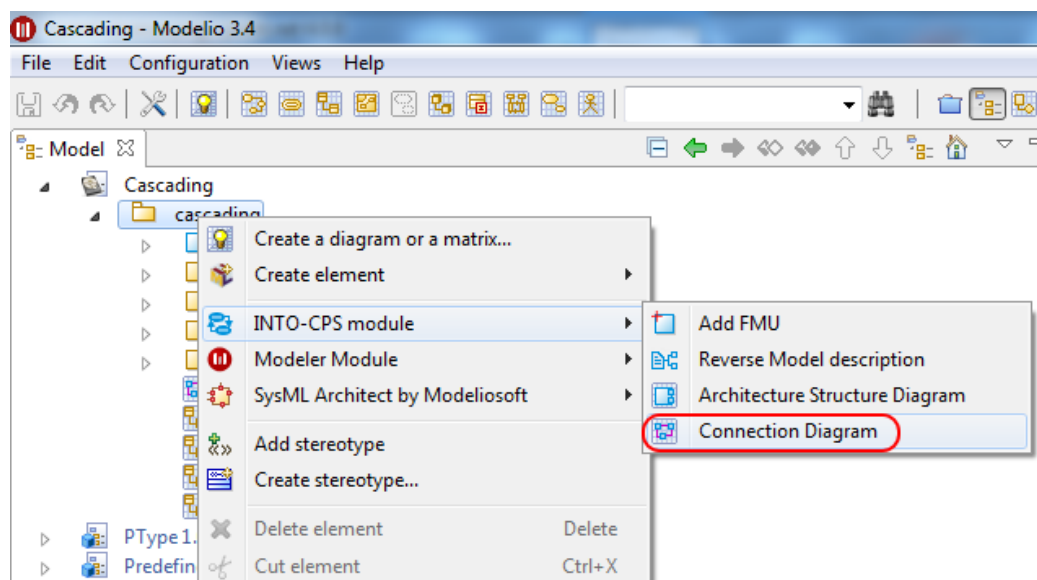


Figure 10: Creating a Connection diagram.

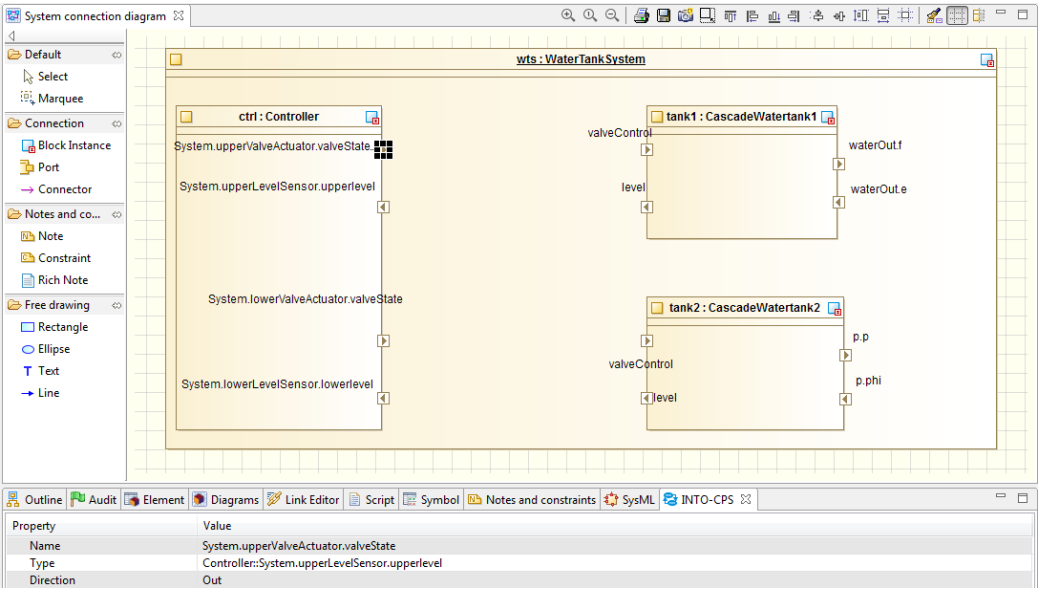


Figure 11: Unpopulated Connection diagram.

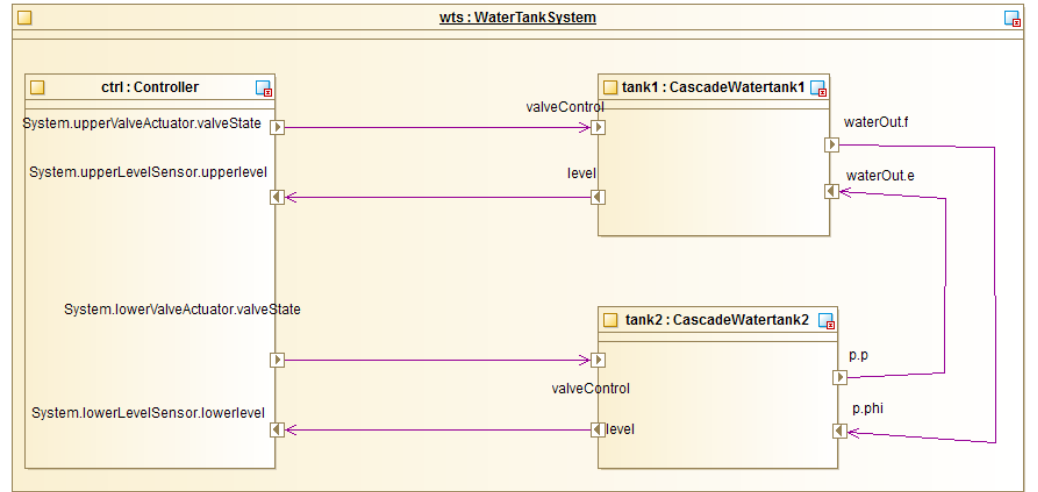


Figure 12: Populated Connection diagram.

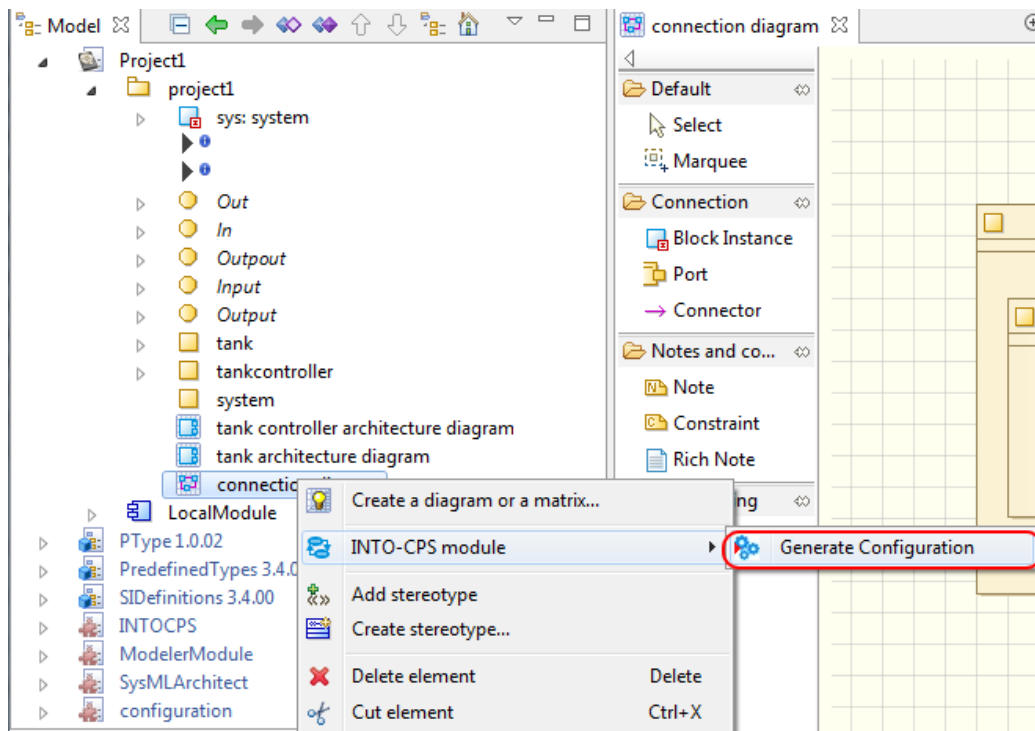


Figure 13: Generating a configuration file.

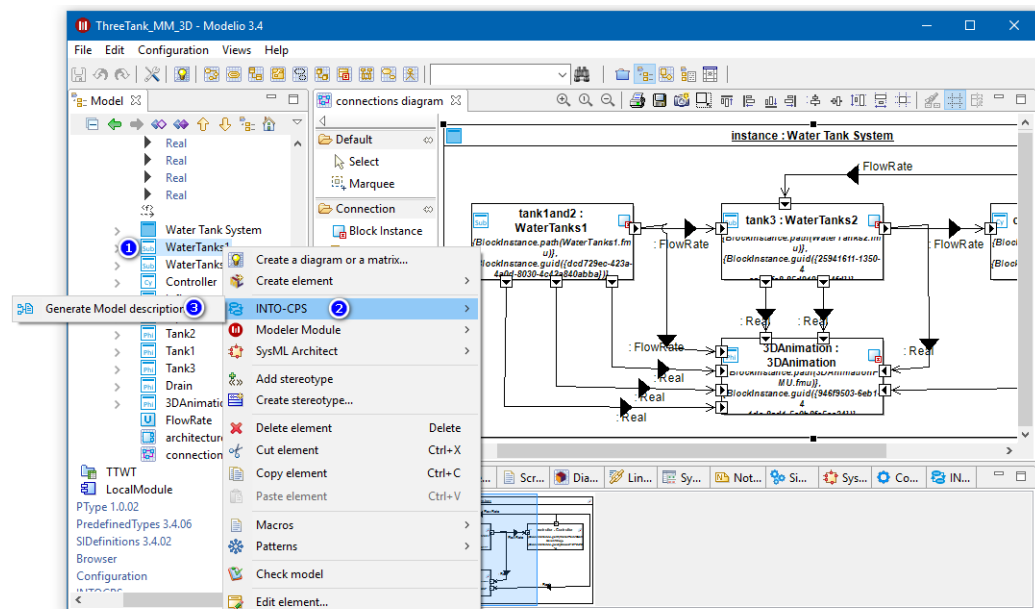


Figure 14: Exporting a modelDescription.xml file.

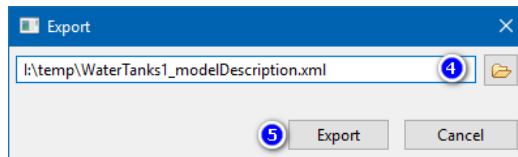


Figure 15: Naming the model description file.

276 4 The INTO-CPS Application

277 This section describes the INTO-CPS Application (here referred to as *the*
278 *app*), the primary gateway to the INTO-CPS tool chain. Section 4.1 gives
279 an introductory overview of the app. Section 4.2 describes how the app
280 can be used to create new INTO-CPS co-simulation projects. Section 4.3
281 describes how multi-models can be assembled. Section 4.4 describes how co-
282 simulations are configured, executed and visualized. Section 4.5 lists some
283 additional useful features of the app, while Section 4.6 describes how the
284 co-simulation engine itself can be started manually, for specialist use.

285 4.1 Introduction

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

292 Releases of the app can be downloaded from:

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

294 Four variants are available:

- 295 • `-darwin-x64.zip` – MacOS version
- 296 • `-linux-x64.zip` – Linux (64 bit) version
- 297 • `-win32-ia32.zip` – Windows (32 bit) version
- 298 • `-win32-x64.zip` – Windows (64 bit) version

299 The app itself has no dependencies and requires no installation. Simply unzip
300 it and run the executable. However, certain app features require Git³ and
301 Java 8⁴ to be already installed.

³<https://git-scm.com/>

⁴[http://www.oracle.com/technetwork/java/javase/overview/
java8-2100321.html](http://www.oracle.com/technetwork/java/javase/overview/java8-2100321.html)

4.2 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 16, is:

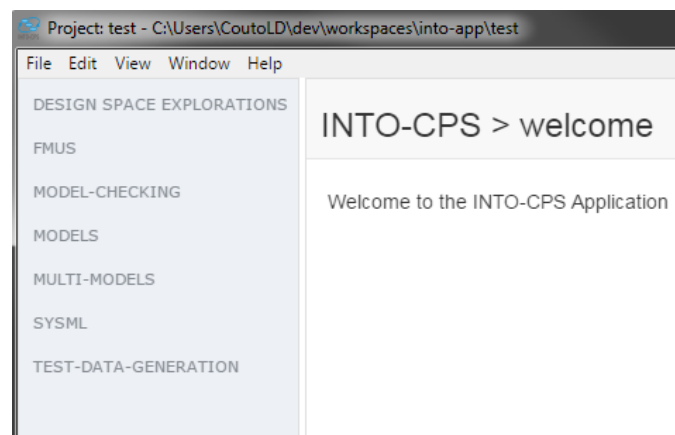


Figure 16: INTO-CPS project shown in the project browser.

Design Space Explorations 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.

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.

In order to create a new project, select *File* → *New Project*, as shown in Figure 17a. This opens the dialog shown in Figure 17b, where you must choose the project name and location – the chosen location will be the root

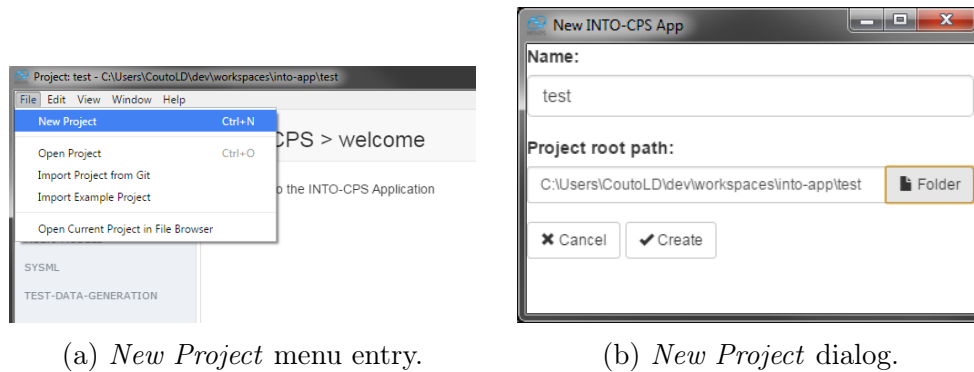


Figure 17: Creating a new INTO-CPS project.

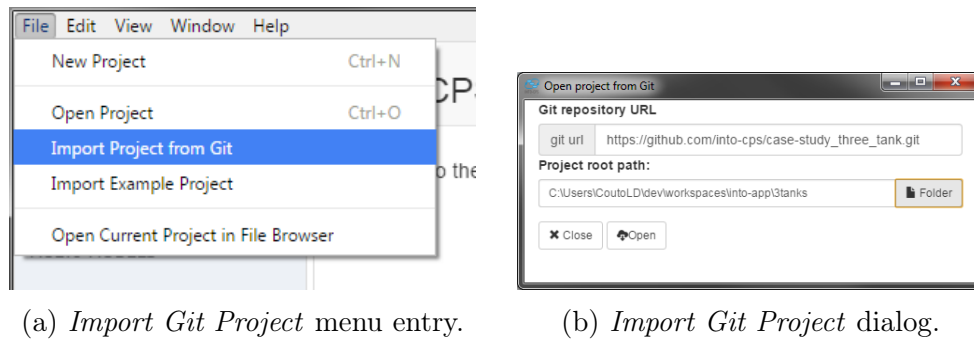


Figure 18: Importing a Git project.

of the project, so you should manually create a new folder for it. To open an existing 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 18a. This opens the dialog shown in Figure 18b, 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 D3.5 [PGP⁺16]. To import an example, select *File* → *Import Example Project*, as shown in Figure 19a. This opens the dialog box shown in Figure 19b, 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 to work. For both Git projects and examples, once you begin the import

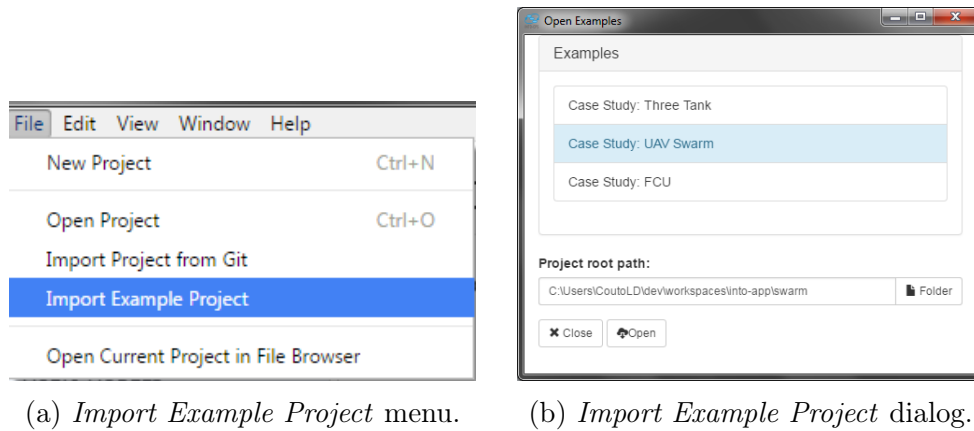


Figure 19: Importing examples.

process, a process dialog is displayed, as shown in Figure 20.

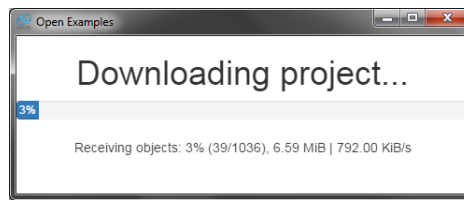


Figure 20: Progress of project imports through Git.

4.3 Multi-Models

For any given project, the app 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 21. After creation, the new multi-model is automatically opened for editing. To select an existing multi-model view for editing, double-click it. Once a multi-model is open, the multi-model view, shown in Figure 22 is displayed. The top box, *Overview*, displays an overview of the input and output variables in the FMUs, as shown in Figure 23. The bottom box, *Configuration*, enables the user to configure the multi-model. In 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 24, allows you to remove or add FMUs

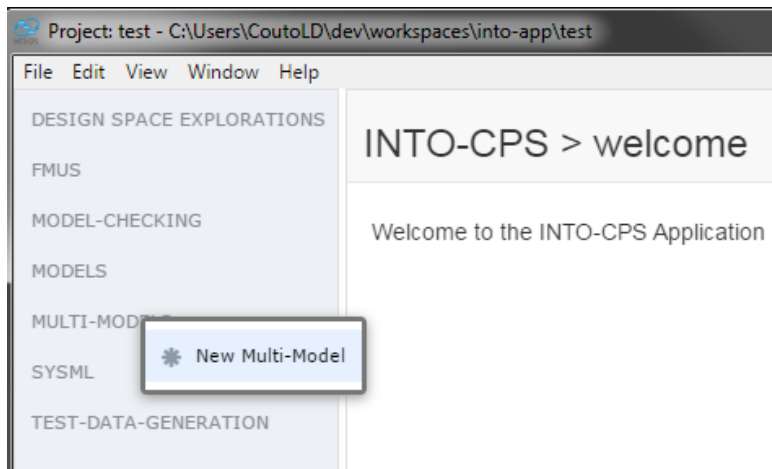


Figure 21: Creating a new multi-model.

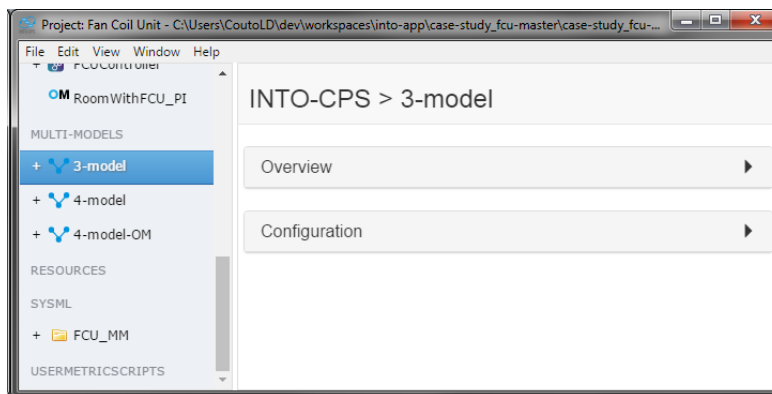


Figure 22: Main multi-model view.

354 and to associate the FMUs with their files by browsing to, or typing, the
 355 path of the FMU file. For each FMU file a marker is displayed indicating
 356 whether the FMU is supported by the app and can be used for co-simulation
 357 on the current platform. The *FMU instances* area, shown in Figure 25,
 358 allows you to create or remove FMU instances and name them. A multi-
 359 model consists of one or more interconnected instances of various FMUs.
 360 More than one instance may be created for a given FMU. As a convenient
 361 workflow shortcut, the *Connections* area, shown in Figure 26, allows you
 362 to connect output variables from an FMU instance into input variables of
 363 another:

- 364 1. Click the desired output FMU instance in the first column. The output
 365 variables for the selected FMU appear in the second column.

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 23: Multi-model overview.

Configuration			
FMUs +			
Keys	Paths		
control	FCUController_Limited.fmu	File Folder	X
	Supported		
room	RoomHeating.fmu	File Folder	X
	Supported		
env	Environment.fmu	File Folder	X
	Supported		

Figure 24: FMUs configuration.

- 366
- 367
- 368
- 369
- 370
- 371
- 372
- 373
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. The *Initial values of parameters* area, shown in Figure 27, allows you to set the



Figure 25: FMU instances configuration.

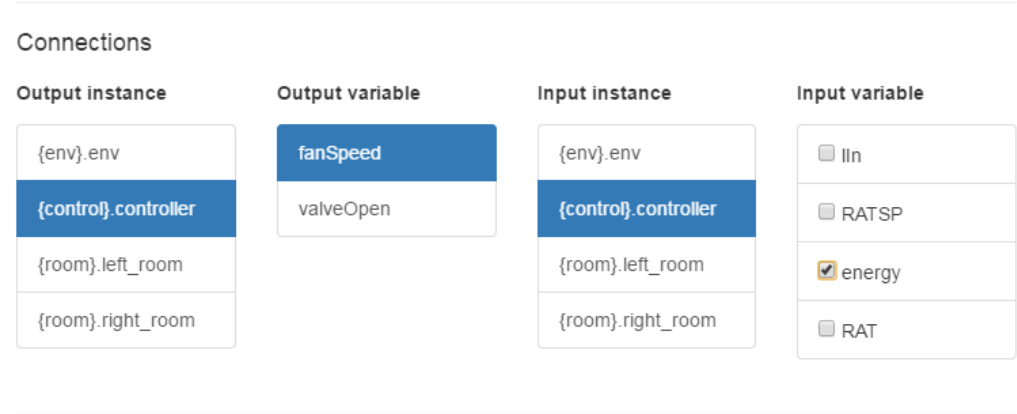



Figure 26: Connections configuration.

- 374 initial values of any parameters defined in the FMUs:
- 375 1. Click the desired FMU instance in the *Instance Column*.
- 376 2. Select the desired parameter in the *Parameters* dropdown box and click
- 377 *Add*.
- 378 3. Type the parameter value in the box that appears.
- 379 Once the multi-model configuration is complete, click the *Save* button at the
- 380 bottom of the *Configuration* box.

Initial values of parameters


Instance	Parameters
{env}.env	
{control}.controller	controllerFrequency
{room}.left_room	
{room}.right_room	

 Save

(a) Parameter selection.

Initial values of parameters

Instance	Parameters
{env}.env	
{control}.controller	Real 10 controllerFrequency
{room}.left_room	
{room}.right_room	

 Save

(b) Parameter value input.

Figure 27: Initial values of parameters configuration.

4.4 Co-simulations

With the INTO-CPS tool chain it is possible to distribute a co-simulation across several computing nodes such that FMUs need not be co-located with the COE on the same node. This capability caters to situations in which FMUs are restricted to simulation on specific platforms for reasons of legacy technology, licensing *etc.* In the current version of the tool chain this functionality is not fully integrated with the app, and requires the user to start the simulation procedure manually. This is discussed in Section 4.6 below. The remainder of this section discusses standard co-simulations on a single computing node.

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 28. After creation, the new configuration automatically opens for editing. To select an existing co-simulation configuration, double-click it. Once a

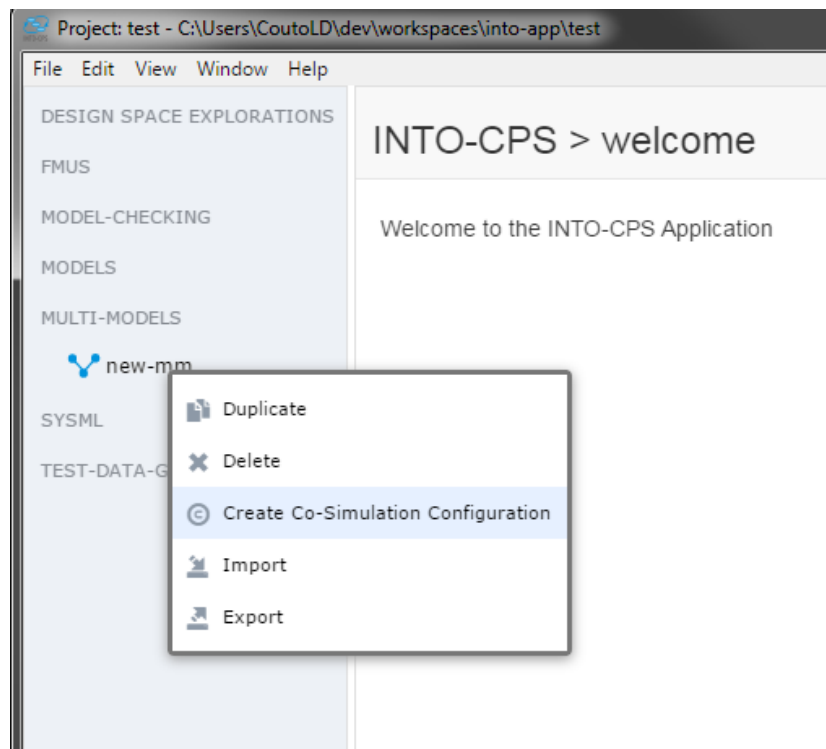


Figure 28: Creating a co-simulation configuration.

configuration is open, the co-simulation configuration, shown in Figure 29, is

397 displayed. The top box, *Configuration*, lets you configure the co-simulation.
 The bottom box, *Simulation*, lets you execute the co-simulation. In order to

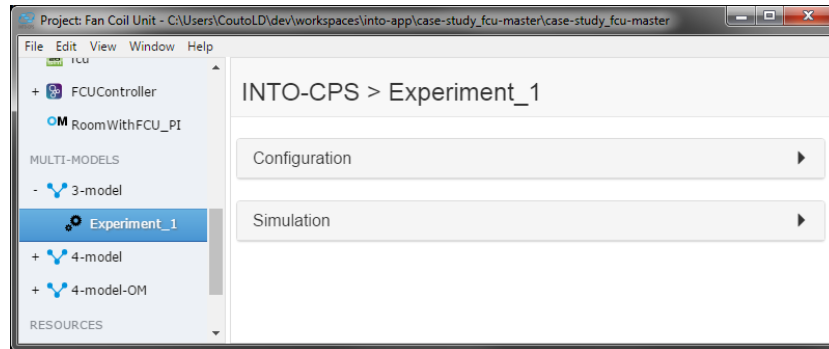


Figure 29: Main co-simulation configuration view.

398
 399 configure a co-simulation, the configuration must first be unlocked for editing
 400 by clicking the *Edit* button at the bottom of the *Configuration* box. There
 401 are three things to configure for a co-simulation, discussed next.

402 The top area, shown in Figure 30, allows you to select the start and end
 time for the co-simulation as well as the master algorithm to be used. For

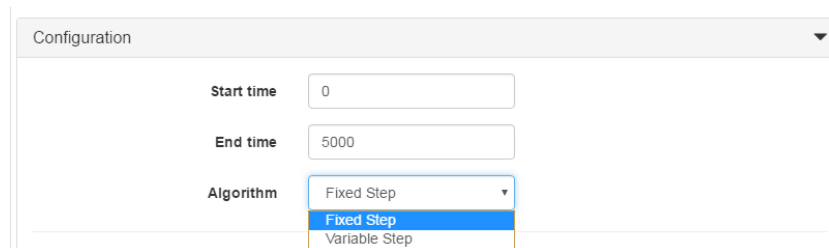


Figure 30: Start/End time and master algorithm configuration.

403
 404 every algorithm, there are configuration parameters that can be set. These
 405 are displayed below the top area, as shown in Figure 31. These parameters
 406 differ with the master algorithm chosen. The *Livestream Configuration* area,
 407 shown in Figure 32, allows you to select which variables to live stream and
 408 plot during the co-simulation. Every instance in the multi-model is displayed
 409 and the output variables are shown for each instance. Check the box for each
 410 variable that you wish to live stream. Once the co-simulation configuration is
 411 complete, click the *Save* button at the bottom of the *Configuration* box.

412 The *Simulation* box, shown in Figure 33, allows you to launch a co-simulation.
 413 To run a co-simulation, the COE must be online. The area at the top of the

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

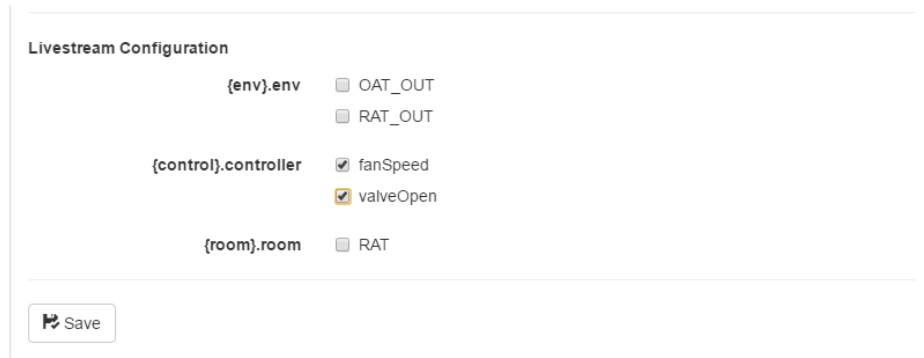
▼

+ Add

(b) Variable step size.

Figure 31: Master algorithm configuration.

414 *Simulation* box displays the status of the COE. If the COE is offline, you
 415 may click the *Launch* button to start it. Once a co-simulation is in progress,
 416 any variables chosen for live streaming are plotted in real time in the simula-
 417 tion box, as shown in Figure 34. A progress bar is also displayed. When the
 418 simulation is complete, the live stream plot can be explored or exported as
 419 a PNG image. In addition, an `outputs.csv` file is created containing the
 420 values of every FMU output variable at every point in time in the simula-
 421 tion. This file can be double-clicked and it will open with the default system
 422 program for CSV files. It can also be imported into programs such as R,
 423 MATLAB or Excel for more complex analysis. Furthermore, it is possible
 424 to add a Post-processing script that receives the csv file name and the total
 425 simulation time as arguments. It is also possible to configure the amount of
 426 logging performed by the Co-Simulation Orchestration Engine.



The Livestream Configuration window displays a list of variables and their corresponding checkboxes. The variables are grouped by component: {env}.env, {control}.controller, and {room}.room. The checkboxes are as follows:

Component	Variable	Checked
{env}.env	OAT_OUT	<input type="checkbox"/>
	RAT_OUT	<input type="checkbox"/>
{control}.controller	fanSpeed	<input checked="" type="checkbox"/>
	valveOpen	<input checked="" type="checkbox"/>
{room}.room	RAT	<input type="checkbox"/>

A Save button is located at the bottom left of the window.

Figure 32: Livestream configuration.

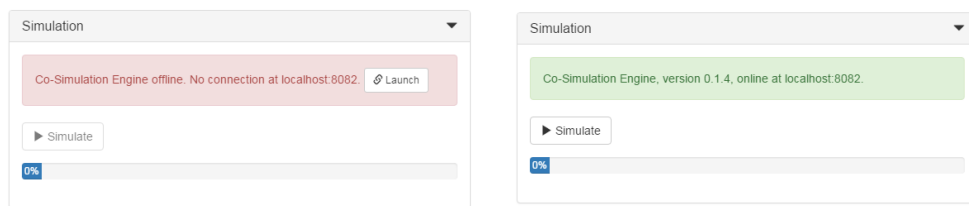


Figure 33: Launching a co-simulation.

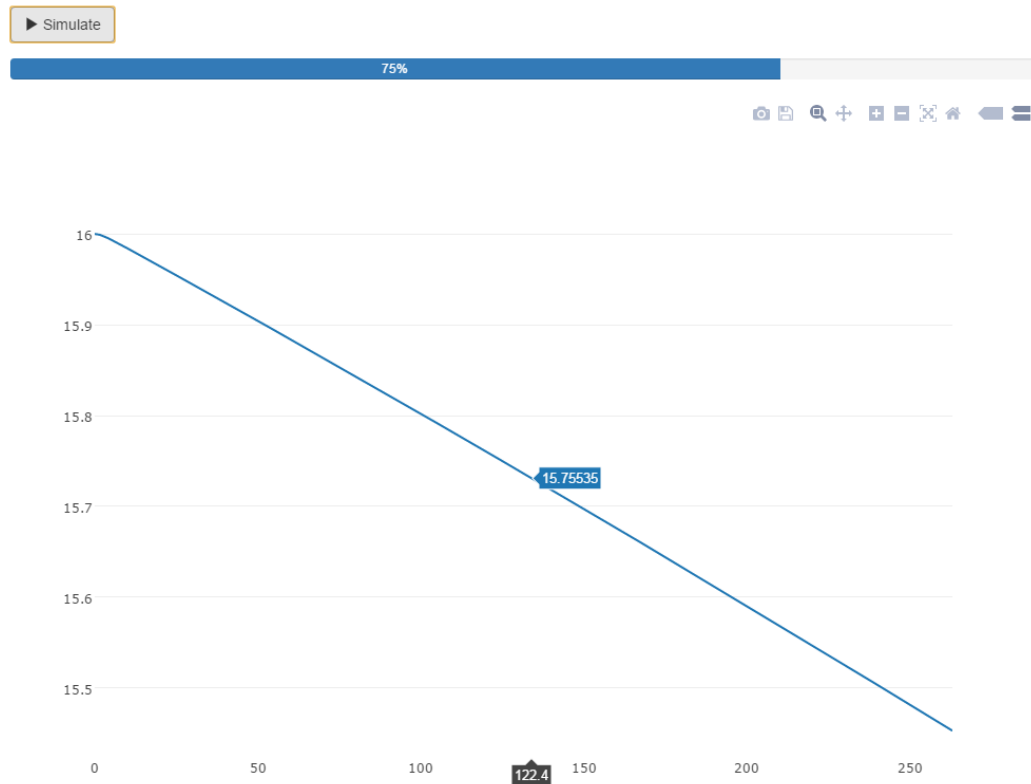


Figure 34: Live stream variable plot.

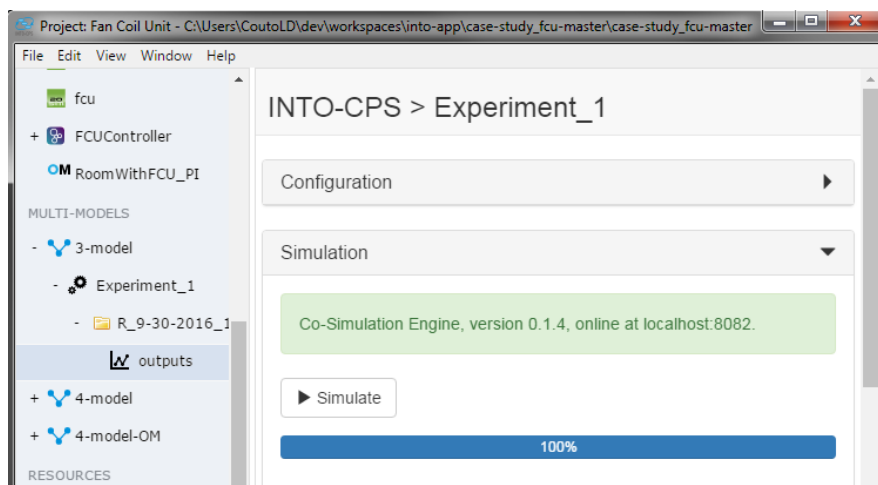


Figure 35: Co-simulation results file.

4.5 Additional Features

The app has several secondary features, most of them accessible through the *Window* menu, as shown in Figure 36. They are briefly explained below.

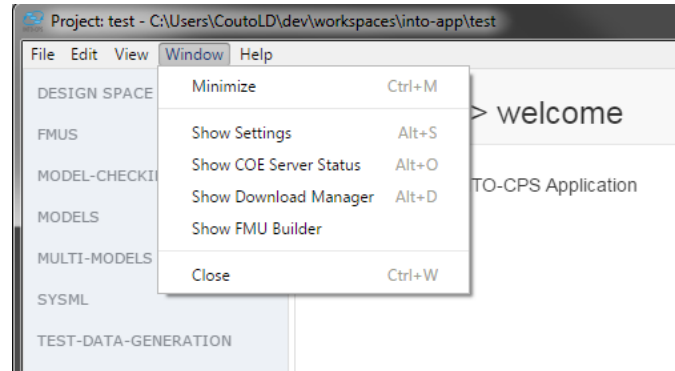


Figure 36: Additional features.

Show Settings displays a settings page where various default paths can be set. Development mode can also be enabled from this page, but this feature is primarily meant to be used by app developers for testing.

Show COE Server Status displays a page where you can launch and stop the COE as well as observe its log.

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.

4.6 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

448 port 8080. It can be started from the app, but it may be started manually at
449 the command prompt for testing and specialist purposes by executing:

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

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

455 The COE is controlled using simple HTTP requests. These are documented
456 in the API manual, which can be obtained from the COE's own web page by
457 navigating to `http://localhost:8082`. Port 8082 should be changed to
458 that specified when the COE is started.

459 Following the protocol detailed in the API document, a co-simulation session
460 can be controlled manually from the command prompt using, for example,
461 the `curl` utility, as demonstrated in the following example.

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

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

464 This command will return a `sessionId` that is used in the following com-
465 mands.

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

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

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

```
473     curl -H "Content-Type: application/json"  
474     --data @coeconf.json  
475     http://localhost:8082/simulate/sessionID
```

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

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

479 The session can now be terminated:

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

481 The app fundamentally controls the COE in this way.

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

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

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

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

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

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

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

501 The second difference is the way in which the location of the remote FMUs
502 is specified. For a standard co-simulation, the "fmus" clause of the co-
503 simulation configuration file (`coeconf.json`, in our example) contains el-
504 ements of the form

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

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

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

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

510 This configuration file is only generated when a co-simulation is executed. It
511 is therefore possible to assemble a "dummy" co-simulation that is similar to
512 the desired distributed version, but with a local FMU topology. Since it is
513 likely that the remote FMUs are not supported on the COE platform itself,

514 it is necessary here to construct “dummy” FMUs with the same interface.
515 If this local co-simulation is then executed briefly, a COE configuration file
516 will be emitted that can be easily modified as described above. The app
517 will name this file `config.json` and emit it to the `Multi-models` folder
518 under each co-simulation run. This modified configuration can then be used
519 to execute the distributed co-simulation.

520 5 Using the Separate Modelling and Simula- 521 tion Tools

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

526 5.1 Overture

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

535 5.1.1 Installing the FMI import/export plugin for Overture

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

- 538 1. Open Overture.
- 539 2. Select *Help -> Install New Software*.
- 540 3. Click *Add...*
- 541 4. In the *Name:* field write *Overture FMU*.

- 542 5. In the *Location:* field there are two options:
- 543 **INTO-CPS Application:** Download the *Overture FMU Import / Ex-*
 544 *porter - Overture FMI Support* using the Download Manager men-
 545 tioned in Section 4.5. Locate the file using the *Archive...* button
 546 next to the *Location:* field.
- 547 **Update site:** Enter the following URL in the *Location:* field:
 548 *http://overture.au.dk/into-cps/vdm-tool-wrapper/master/latest.*
- 549 6. Check the box next to *Overture FMI Integration* as shown in Figure
 550 37.
- 551 7. Click *Next* or *Finish* to accept and install.

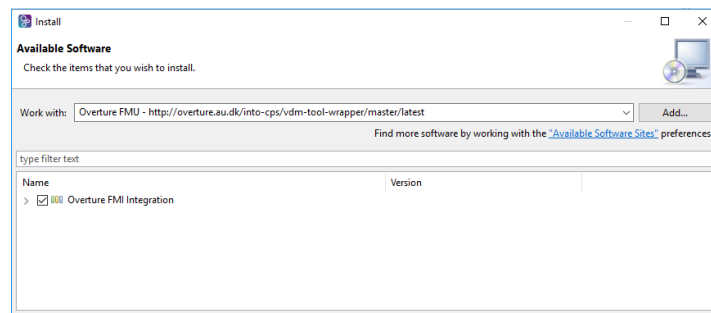


Figure 37: Installing Overture FMI Integration

552 5.1.2 Import of `modelDescription.xml` File

553 A `modelDescription.xml` file is easily imported into an existing, typ-
 554 ically blank, VDM-RT project from the project explorer context menu as
 555 shown in Figure 38. This results in the project being populated with the
 556 classes necessary for FMU export:

- 557 • A VDM-RT system class named “System” containing the system def-
 558 inition. The corresponding “System” class for the water tank controller
 559 FMU is shown in Listing 39.
- 560 • A standard VDM-RT class named “World”. This class is conventional
 561 and only provides an entry point into the model. The corresponding
 562 “World” class for the water tank controller FMU is shown in Listing 40.
- 563 • A standard VDM-RT class named “HardwareInterface”. This class con-
 564 tains the definition of the input and output ports of the FMU. Its struc-

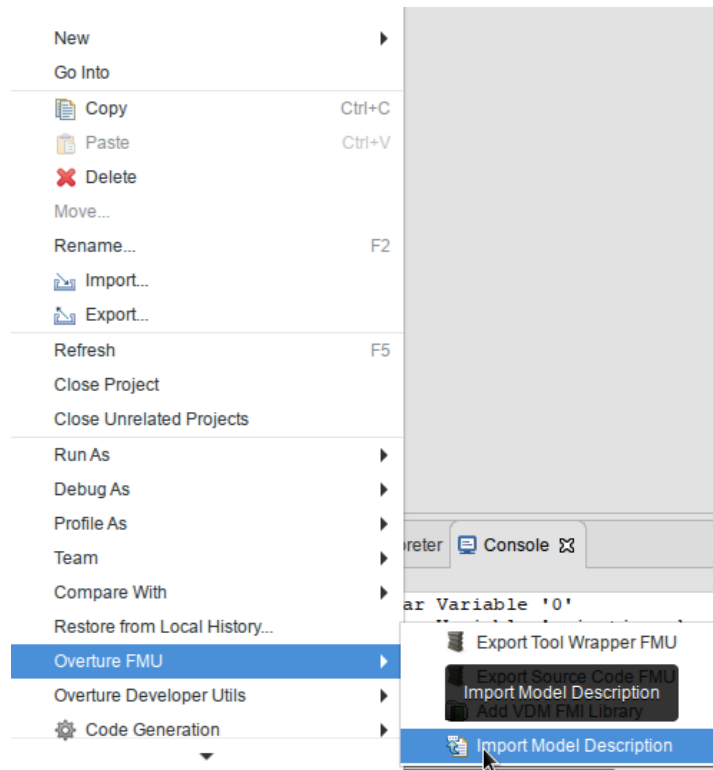


Figure 38: Importing a modelDescription.xml file.

ture is enforced, and a self-documenting annotation scheme⁵ is used such that the “HardwareInterface” class may be hand-written. The corresponding “HardwareInterface” class for the water tank controller FMU is shown in Listing 41.

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

⁵The annotation scheme is documented on the INTO-CPS website into-cps.github.io under “Constituent Model Development → Overture → FMU Import/Export”.

```
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 39: “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 40: “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 41: “HardwareInterface” class for water tank controller.

571 The port structure used in the “HardwareInterface” class is a simple inheri-
572 tance structure, with a top-level generic “Port”, subclassed by ports for spe-
573 cific values: booleans, reals, integers and strings. The hierarchy is shown in
574 Listing 42. When a model is developed without the benefit of an existing
575 `modelDescription.xml` file, this library file can be added to the project
576 from the project context menu, also under the category “Overture FMU”.
577

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

580 5.1.3 Tool-Wrapper FMU Export

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

586 A tool-wrapper FMU is easily exported from the project context menu as
587 shown in Figure 43. The FMU will be placed in the generated folder.
588

```
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 42: Excerpt of “Fmi.vdmrt” library file defining FMI interface port hierarchy.

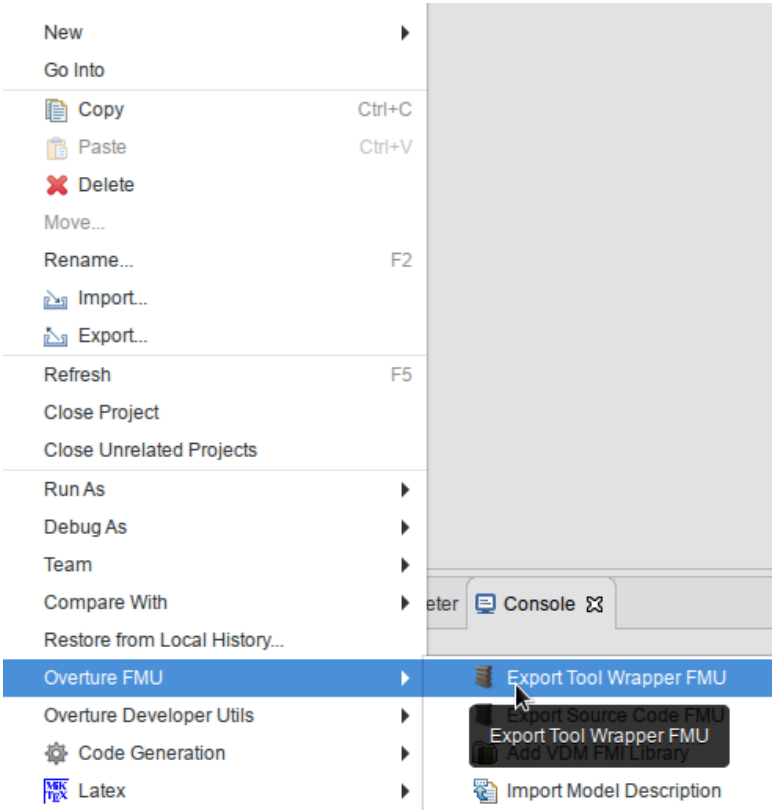


Figure 43: Exporting a tool-wrapper FMU.

589 5.1.4 Standalone FMU Export

590 In contrast to tool-wrapper FMUs, models exported as standalone FMUs
591 do not require Overture in order to simulate. Instead, they are first passed
592 through Overture's C code generator such that a standalone implementation
593 of the model is first obtained. Once compiled, this executable model then
594 replaces the combination of VDM interpreter and model, and the FMU ex-
595 ecutes natively on the co-simulation platform. Currently Mac OS, Windows
596 and Linux are supported, with embedded platform support for SiL and HiL
597 simulation under development.

598 The export process consists of two steps. First, a source code FMU is ob-
599 tained from Overture as shown in Figure 44. Second, the INTO-CPS Appli-
600 cation must be used to upload the resulting FMU to the FMU compilation
601 server using the built-in facility described in Section 4.5. This is accessed by
602 navigating to *Window* → *Show FMU Builder*.

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

605 5.2 20-sim

606 This section explains the FMI and INTO-CPS related features of 20-sim⁶.
607 We focus on the import of `modelDescription.xml` files, standalone and
608 tool-wrapper FMU export (FMU slave), 3D visualization of FMU operation
609 and an experimental FMU import (FMU master) feature. The complete
610 20-sim tool documentation can be found in the 20-sim Reference Manual
611 [KGD16].

612 5.2.1 Import of `modelDescription.xml` File

613 In Modelio it is possible to export the desired interface for a new FMU
614 from a multi-model as a `modelDescription.xml` file (see Section 3.2.
615 20-sim can automatically generate an empty 20-sim submodel⁷ from this
616 `modelDescription.xml` file with this desired FMU interface. To use

⁶Note 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.

⁷Please 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.

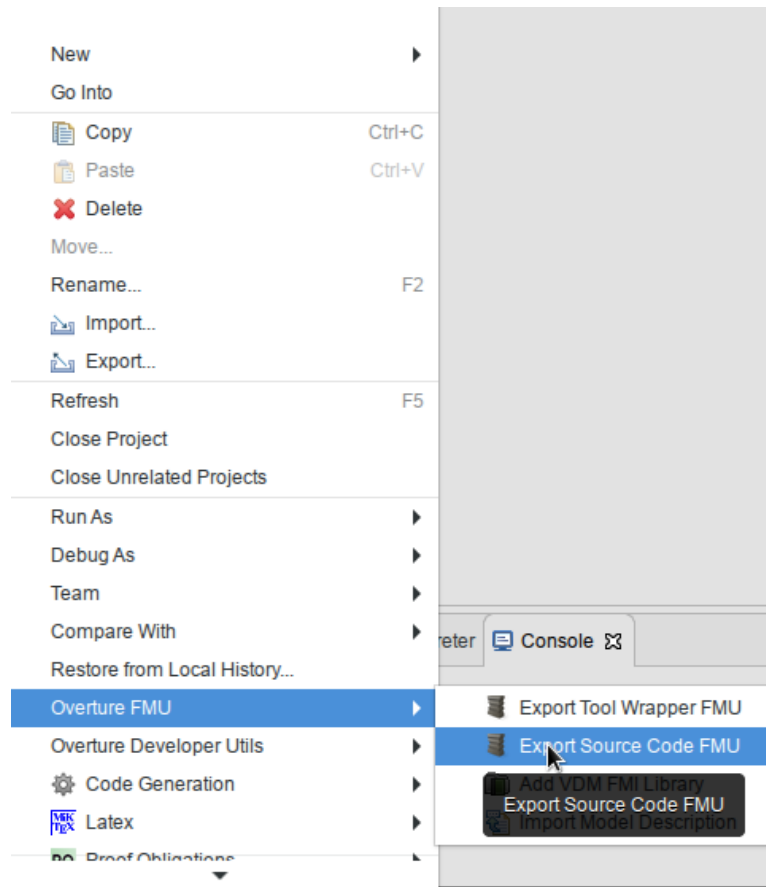


Figure 44: Exporting a standalone FMU.

617 the `modelDescription.xml` import, you will need to use the “4.6.2-
 618 intocps” version of 20-sim⁸, since this feature is still under development. A
 619 `modelDescription.xml` file can be imported into 20-sim by using Win-
 620 dows Explorer to drag the `modelDescription.xml` file onto your 20-sim
 621 model (see Figure 45). This creates a new empty submodel with a blue icon
 622 that has the same inputs and outputs as defined in the `modelDescription`
 623 `.xml` file.

624 5.2.2 Tool-wrapper FMU Export

625 A tool-wrapper FMU is a communication FMU that opens the original model
 626 in the modelling tool and takes care of remotely executing the co-simulation

⁸You can download the INTO-CPS version of 20-sim using the Download Manager in the INTO-CPS Application.

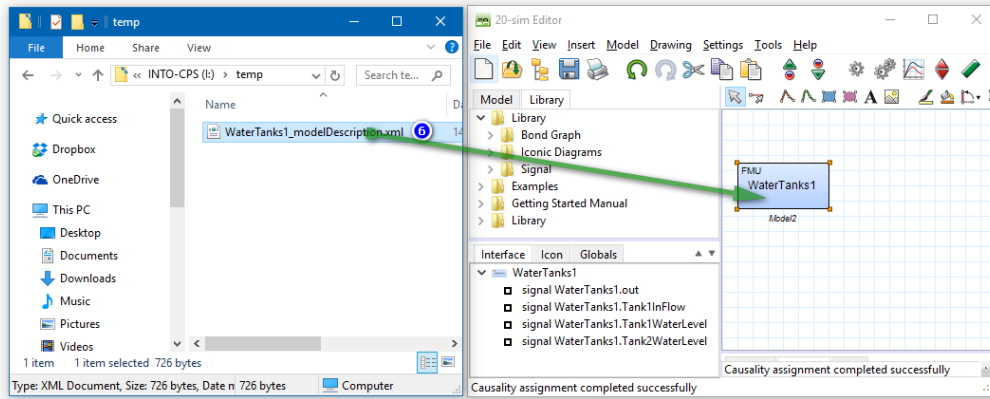


Figure 45: Import a ModelDescription in 20-sim.

steps inside the modelling using some tool-supported communication mechanism. 20-sim supports co-simulation using the XML-RPC-based DEST ECS 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.

653 This requires at least the “4.6.3-intocps” version of 20-sim⁹. This version of
654 20-sim comes with a Python script that generates a tool-wrapper FMU for
655 the loaded model.

656 To generate the tool-wrapper FMU:

- 657 1. Make sure that the tool-wrapper prepared 20-sim model is saved at
658 a writable location. The tool-wrapper FMU will be generated in the
659 same folder as the model.
- 660 2. Open the prepared 20-sim model in 20-sim.
- 661 3. Run the BATCH script:
662 *C:\Program Files (x86)\20-sim 4.6\addons\FMI\
663 ToolwrapperFMUExport\generate.bat*
664 Note that the (x86) is only for 64-bit versions of Windows.
- 665 4. You can find the generated tool-wrapper finu as *<modelname>.fmu* in
666 the same folder as your model.

667 5.2.3 Standalone FMU Export

668 Starting with 20-sim version 4.6, the tool has a built-in option to generate
669 standalone co-simulation FMUs for both FMI 1.0 and 2.0 (note that version
670 2.0 must be used here).

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

674 Next, follow these steps (see also Figure 46):

- 675 1. In the Simulator window, choose from the menu: *Tools*.
- 676 2. Select *Real Time Toolbox*.
- 677 3. Click *C-Code Generation*.
- 678 4. Select the *FMU 2.0 export for 20-sim submodel* target.
- 679 5. Select the submodel to export as an FMU.
- 680 6. Click OK to generate the FMU. This will pop-up a blue window.

⁹You can download the INTO-CPS version of 20-sim using the Download Manager in the INTO-CPS Application.

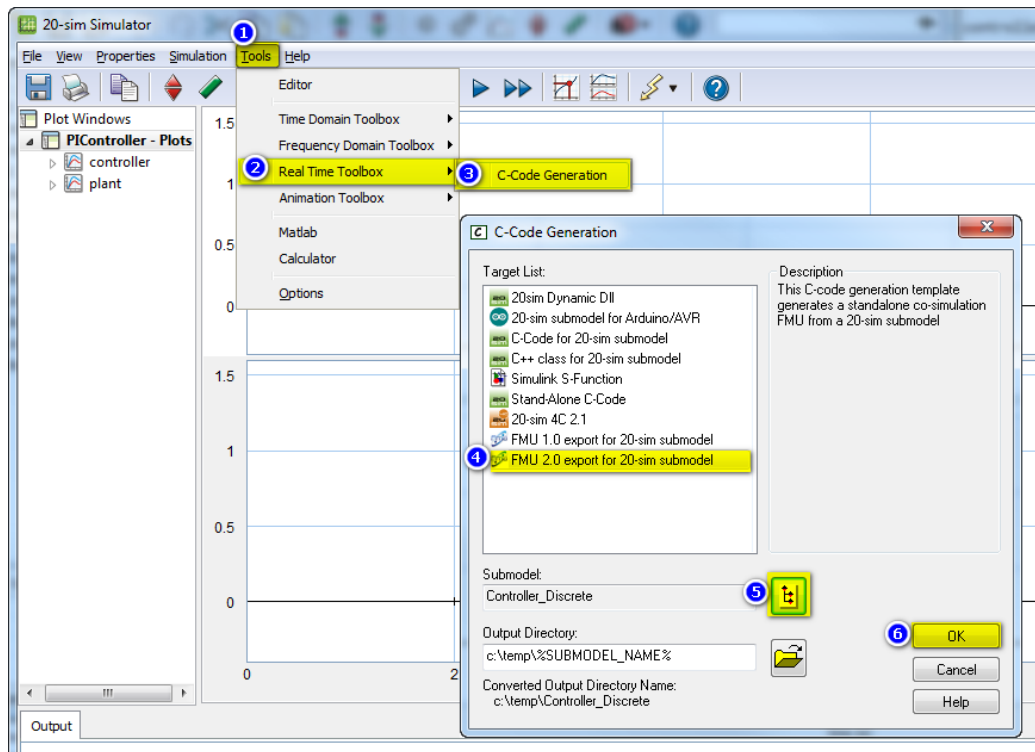


Figure 46: Export an FMU from 20-sim.

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

699 supported) for code generation, are:

- 700 • **Hybrid models:** Models that contain both discrete- and continuous-
701 time sections cannot be generated at once. However, it is possible to
702 export the continuous and discrete blocks separate.
- 703 • **File I/O:** The 20-sim “Table2D” block is supported; the “datafromfile”
704 block is not yet supported.
- 705 • **External code:** Calls to external code are not supported. Examples
706 are: `DLL()`, `DLLDynamic()` and the MATLAB functions.
- 707 • **Variable delays:** The `tdelay()` function is not supported due to
708 the requirement for dynamic memory allocation.
- 709 • **Event functions:** `timeevent()`, `frequencyevent()` statements
710 are ignored in the generated code.
- 711 • **Fixed-step integration methods:** *Euler*, *Runge-Kutta 2* and *Runge-*
712 *Kutta 4* are supported.
- 713 • **Implicit models:** Models that contain unsolved algebraic loops are
714 not supported.
- 715 • **Variable-step integration methods:** *Vode-Adams* and *Modified Back-*
716 *ward Differential Formula* (MeBDF) are available on GitHub (see below
717 for the link).

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

723 <https://github.com/controllab/fmi-export-20sim>

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

728 5.2.4 3D Animation FMU

729 It is possible to visualize a 20-sim simulation as a live 3D animation. This 20-
730 sim 3D animation can be exported as a 3D animation FMU that can be used

731 for visualization purposes in a FMI co-simulation experiment. An example
732 of a 3D animation FMU in action is shown in Figure 47.

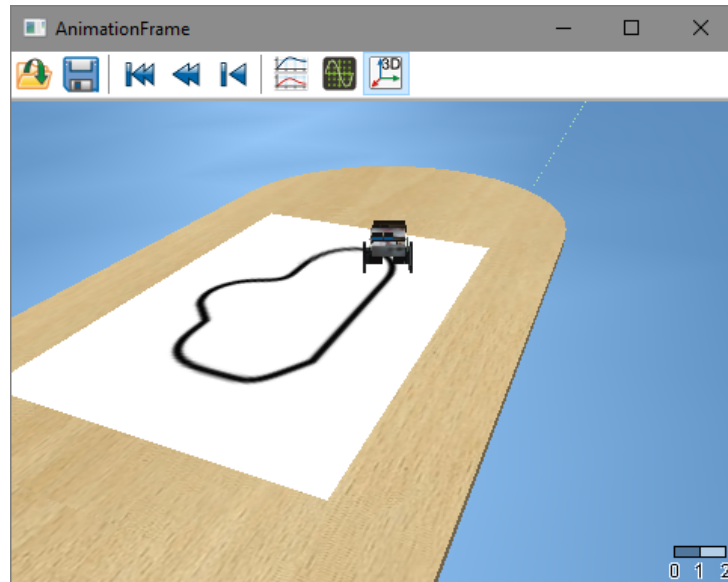


Figure 47: 3D animation FMU

733 To create a 3D animation FMU, you will need to create a 3D animation in
734 20-sim that reacts to some signals first (identical to the creation of standard
735 3D animation in 20-sim):

- 736 1. Open your 20-sim model.
- 737 2. Open the simulator and add a new 3D animation window using *View*
738 *→ New 3D animation window*.
- 739 3. Create a new 3D animation scene by following the instructions from
740 the Animation toolbox section in the 20-sim Getting Started manual
741 [KG16].
- 742 4. For elements that should move or change color based on external sig-
743 nals, create one equation submodel in 20-sim with all required input
744 signals for the animation.
- 745 5. Connect the 3D animation object to the signals from this animation
746 submodel.

747 The next step is to export the 3D animation as standalone scenery:

- 748 1. Go to the 3D animation plot in your 20-sim model.

- 749 2. Right-click in the 3D animation plot and select *Plot properties*.
- 750 3. Choose *File* → *Save scene*.
- 751 4. Select *Yes* to save the whole scenery.
- 752 5. Save the scenery under the name `scenery.scn`.

753 The 3D animation FMU uses the just exported `scenery.scn` file. Since
754 the 3D animation is only a view of the simulation results, the FMU only has
755 a list of inputs. To generate a `modelDescription.xml` file with the right
756 FMU interface, a Python script must be executed which collects the list of
757 external signals referred to by the exported scenery. This Python script and
758 other required resources can be found in the following Controllab GitHub
759 repository:

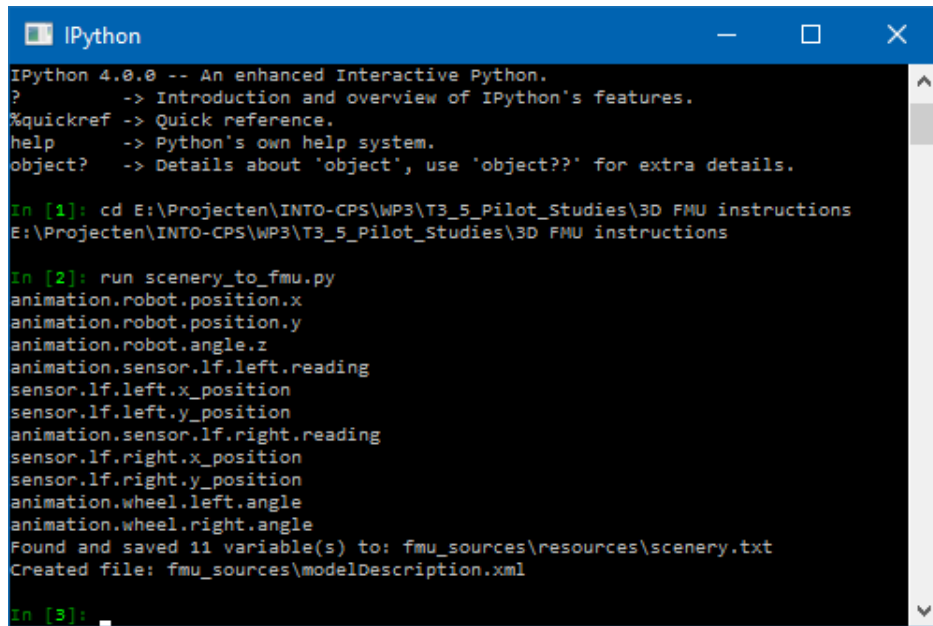
760 `https://github.com/controllab/fmi-3D-animation`

761 To generate the FMU `modelDescription.xml` file, do the following:

- 762 1. Copy the generated `scenery.scn` in the `fmu_sources\resources`
763 folder under *3D FMU instructions*.
- 764 2. Update `FMU_GUID` in the `scenery_to_fmu.py` Python script with
765 a new GUID for your 3D Animation FMU.
- 766 3. Execute the `scenery_to_fmu.py` Python script, *e.g.* using the Python
767 installation that comes with 20-sim 4.6:
 - 768 • Start *IPython* found under *20-sim 4.6* in the Windows Start Menu.
 - 769 • `cd <my 3D FMU instructions path>`
 - 770 • `run scenery_to_fmu.py`
771 This parses the `scenery.scn` file for objects that point to vari-
772 ables/parameters (references). The variables/parameters are trans-
773 lated to FMU inputs and FMU parameters. The 3D scenery does
774 not contain any information that indicates whether the referred
775 name is a variable or a parameter. As a workaround, all names
776 that start with *parameter.* are marked as as FMU parameters
777 (`causality = parameter`), while all others are generated as inputs
778 (`variability = continuous`). This script also generates a `scenery.`
779 `txt` file with the list of found references. This file is read by the
780 3D animation DLL to couple the FMU interface to the 3D scenery
781 objects. The output resembles that shown in Figure 48.

- 782 4. Create the actual FMU:

- 783 • Copy all needed textures to the `fmu_sources\resources` folder.
- 784 • Zip the `fmu_sources` folder.
- 785 • Rename the Zip file, *e.g.* `3DAnimationFMU.fmu`.



```

IPython 4.0.0 -- An enhanced Interactive Python.
?      -> Introduction and overview of IPython's features.
%quickref -> Quick reference.
help    -> Python's own help system.
object? -> Details about 'object', use 'object??' for extra details.

In [1]: cd E:\Projecten\INTO-CPS\WP3\T3_5_Pilot_Studies\3D FMU instructions
E:\Projecten\INTO-CPS\WP3\T3_5_Pilot_Studies\3D FMU instructions

In [2]: run scenery_to_fmu.py
animation.robot.position.x
animation.robot.position.y
animation.robot.angle.z
animation.sensor.lf.left.reading
sensor.lf.left.x_position
sensor.lf.left.y_position
animation.sensor.lf.right.reading
sensor.lf.right.x_position
sensor.lf.right.y_position
animation.wheel.left.angle
animation.wheel.right.angle
Found and saved 11 variable(s) to: fmu_sources\resources\scenery.txt
Created file: fmu_sources\modelDescription.xml

In [3]:

```

Figure 48: Generating `modelDescription.txt` file from 3D scenery.

786 5.2.5 FMI 2.0 Import

787 The “4.6.2-intocps” version of 20-sim has an experimental option to import
 788 an FMU directly in 20-sim for co-simulation within 20-sim itself. This is
 789 useful for quickly testing exported FMUs without the need to set-up a full
 790 co-simulation experiment in the app. Presently only FMI 2.0 co-simulation
 791 FMUs can be imported.

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

- 795 1. Copy/move the FMU to the same folder as your model. This is not
 796 required but recommended to prevent embedding hardcoded paths in
 797 your model.
- 798 2. Using Windows Explorer, drag the FMU file on your 20-sim model (see
 799 Figure 49).

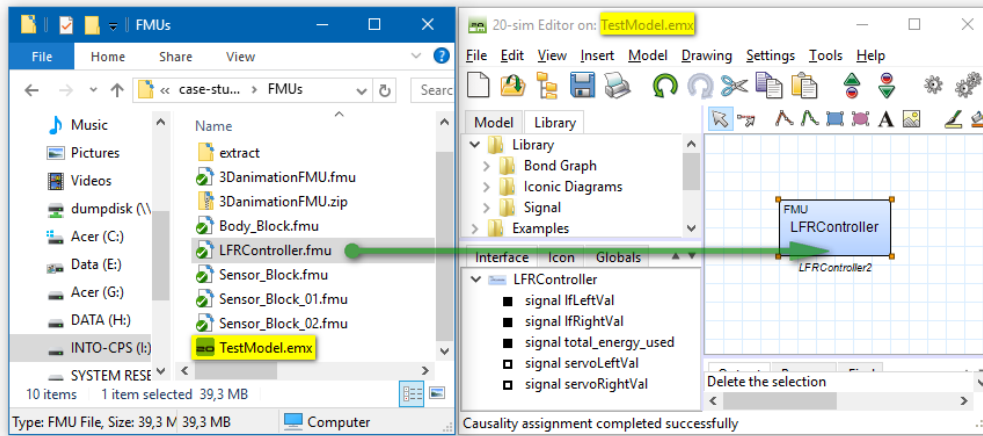


Figure 49: Importing an FMU in 20-sim.

800 This creates a new submodel with a blue icon that acts as an FMU wrap-
 801 per. FMU inputs and outputs are translated into 20-sim submodel input
 802 and output signals. FMU parameters (scalar variables with causality “pa-
 803 rameter”) are also available in 20-sim. This means that you can alter the
 804 default values of these FMU parameters in 20-sim. The altered FMU param-
 805 eters are transferred to the FMU during the initialization mode phase of the
 806 FMU.

807 5.3 OpenModelica

808 This section explains the FMI and INTO-CPS related features of Open-
 809 Modelica. The focus is on import of `modelDescription.xml` files, and
 810 standalone and tool-wrapper FMU export.

811 5.3.1 Import of `modelDescription.xml` File

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

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

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

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

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

```
822 // start script.mos
823 // import the FMU modelDescription.xml
824 importFMUModelDescription("path/to/modelDescription.xml");
825 getErrorString();
826 // end script.mos
827
828
```

829 The MOS script can be executed from command line via:

```
830 // on Linux and Mac OS
831 > path/to/omc script.mos
832 // on Windows
833 > %OPENMODELICAHOME%\bin\omc script.mos
834
835
```

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

```
838
839 model Modelica_Blocks_Math_Gain_cs_FMU "Output the product
840   of a gain value with the input signal"
841   Modelica.Blocks.Interfaces.RealInput u "Input signal
842   connector" annotation (Placement (transformation (extent
843     ={{-120, 60}, {-100, 80}})));
844   Modelica.Blocks.Interfaces.RealOutput y "Output signal
845   connector" annotation (Placement (transformation (extent
846     ={{100, 60}, {120, 80}})));
847 end Modelica_Blocks_Math_Gain_cs_FMU; "
848
```

849 This functionality will ultimately be integrated in the OMEdit (the Open-
 850 Modelica Connection Editor) graphical user interface.

851 5.3.2 FMU Export

852 Currently all FMUs exported from OpenModelica are standalone. There are
 853 two ways to export an FMU:

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

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

```
859 // load Modelica library
860 loadModel(Modelica); getErrorString();
861
862 // load other libraries if needed
863 // loadModel(OtherLibrary); getErrorString();
864
865 // generate the FMU: PathTo.MyModel.fmu
866 translateModelFMU(PathTo.MyModel, "2.0", "cs");
867 getErrorString();
868
```

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

```
871 // on Linux and Mac OS
872 > path/to/omc generateFMU.mos
873 // on Windows
874 > %OPENMODELICAHOME%\bin\omc generateFMU.mos
875
876
```

877 **FMU export from OMEdit** One can also use OMEdit (the OpenMod-
878 elica Connection Editor) to export an FMU as detailed in the figures be-
879 low.

- 880 • Open OMEdit (see Figure 50).
- 881 • Load the model in OMEdit (see Figure 51).
- 882 • Open the model in OMEdit (see Figure 52).
- 883 • Use the menu to export the FMU (see Figure 53).
- 884 • The FMU is now generated (see Figure 54).

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

886

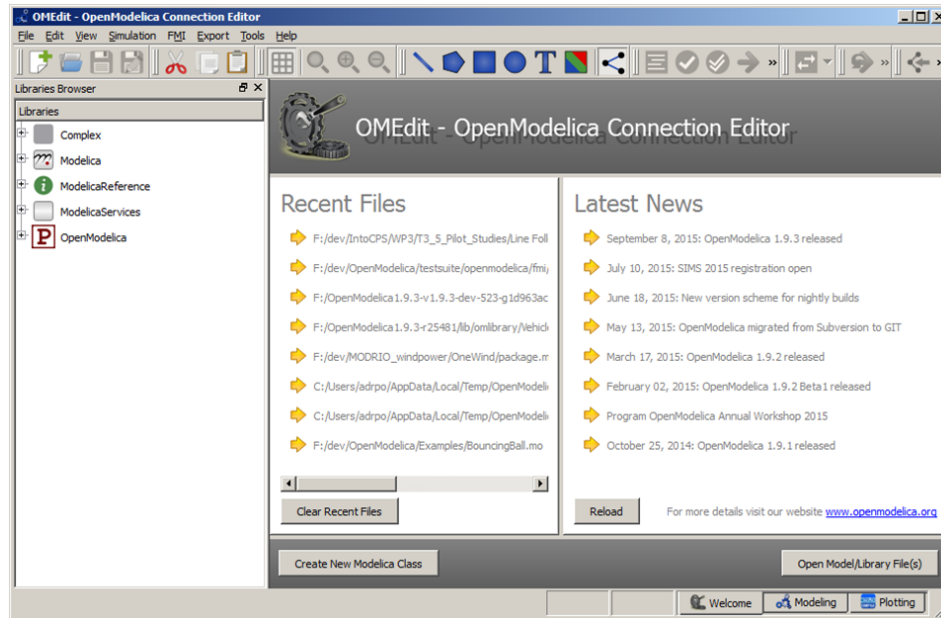


Figure 50: Opening OMEdit.

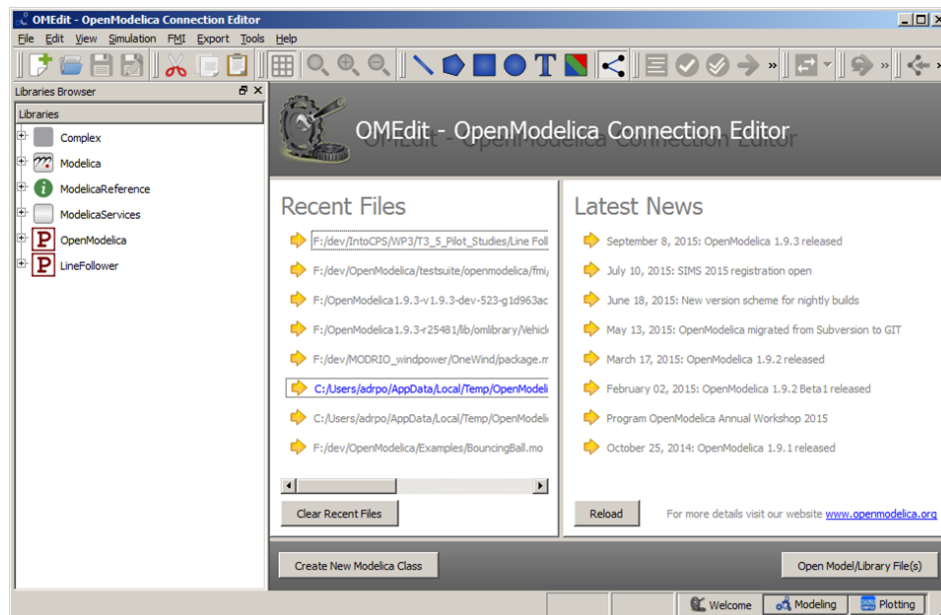


Figure 51: Loading the Modelica model in OMEdit.

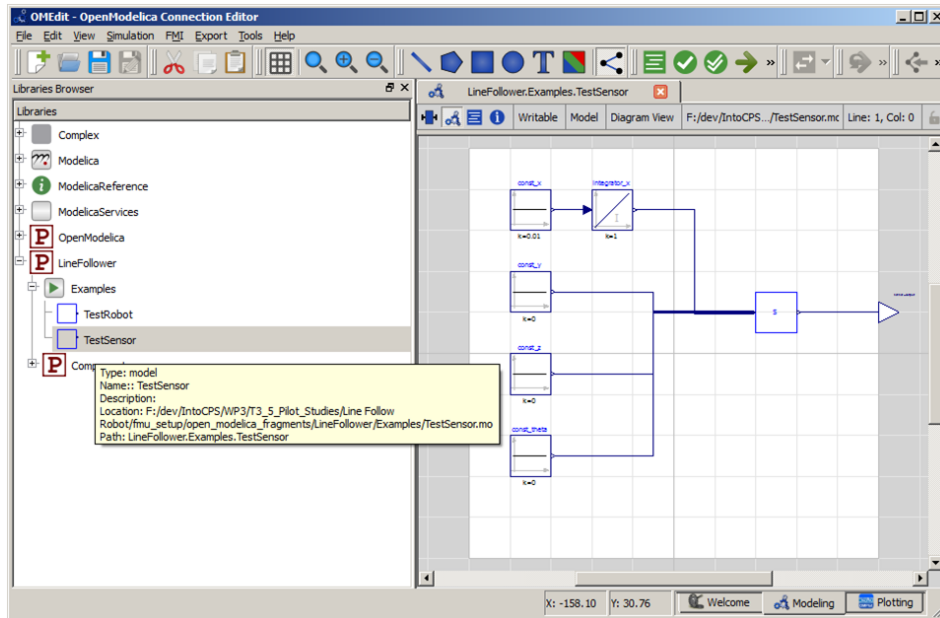


Figure 52: Opening the Modelica model in OMEdit.

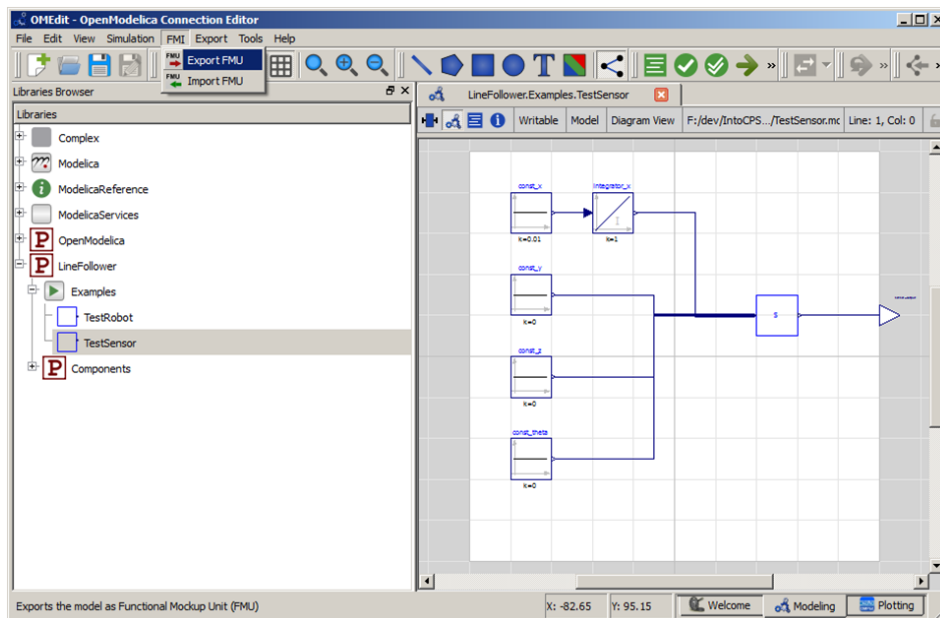


Figure 53: Exporting the FMU.

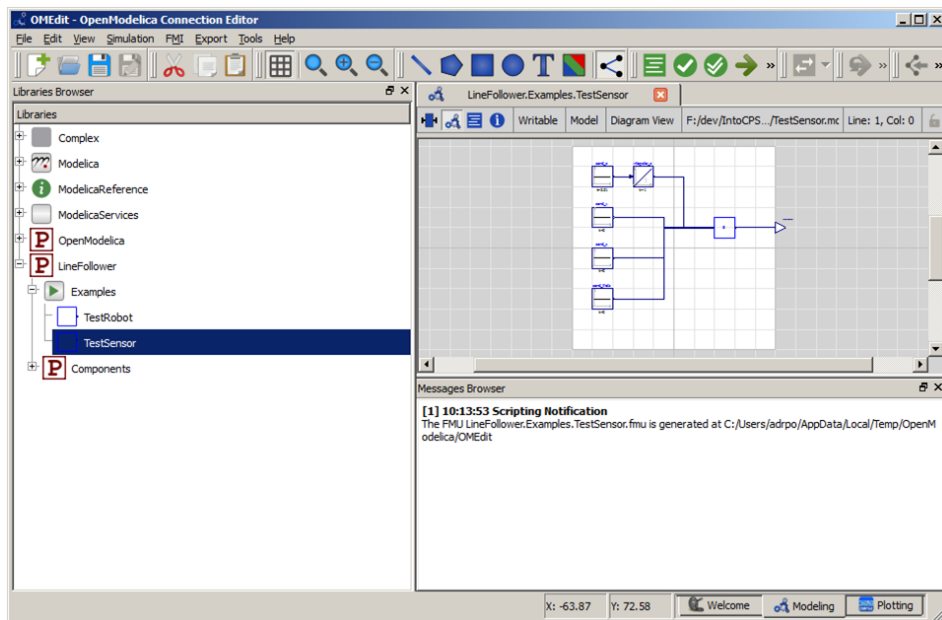


Figure 54: Final step of FMU export.

887 6 Design Space Exploration for INTO-CPS

888 This section provides a description of tool support for design space exploration (DSE) developed as part of the INTO-CPS project. Presently the
889 INTO-CPS Application does not provide support for automated creation of
890 the configuration files required to define a DSE experiment. Therefore, this
891 section is split into three parts. Section 6.1 describes how the INTO-CPS
892 Application can be used to launch a DSE using an existing configuration
893 file and Section 6.2 describes how the results from DSE are generated and
894 stored. Section 6.3 describes the structure of the DSE configuration file, giving
895 enough detail for the user to be able to edit one for their purposes.
896

897 6.1 How to Launch a DSE

898 To launch a DSE we need to provide the INTO-CPS Application with the
899 path to two files. The first is the DSE configuration, defining the parameters
900 of the design space, how it should be searched, measured and the results compared.
901 The second is the multi-model configuration, defining the base model
902 that will be used for the search. A DSE configuration is selected by double
903 clicking on one of the configurations listed in the *Design Space Explorations*
904 section of the INTO-CPS Application project explorer; these configurations
905 are identified with the (🔍) icon. If the COE is not already running, the
906 DSE page is shown with a red “*Co-simulation engine not running*” status,
907 as shown in Figure 55.

908 If this is the case, click on the *Launch* button to start the COE. This results
909 in a green co-simulation engine status (see Figure 56). With the DSE
910 configuration selected and the COE running, the next step is to select the
911 multi-model to use. One can be selected from the *Co-simulation Configuration*
912 drop-down box, as shown in Figure 57. Pressing the *Simulate* button
913 starts the DSE background process.

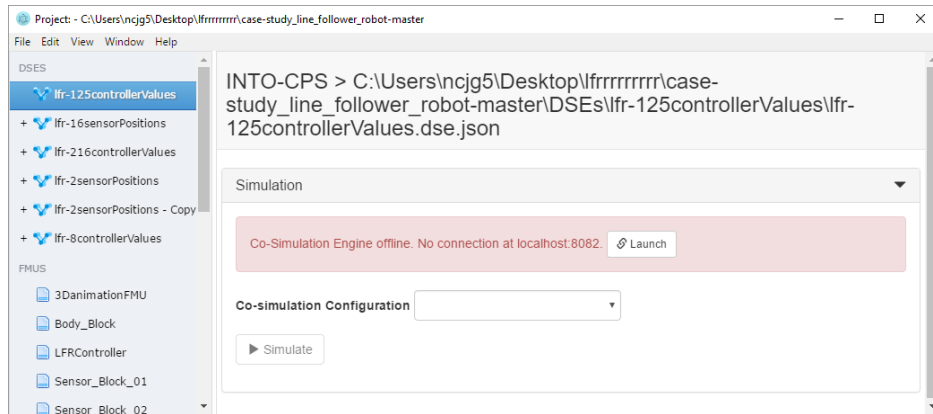


Figure 55: Status when COE is not running.

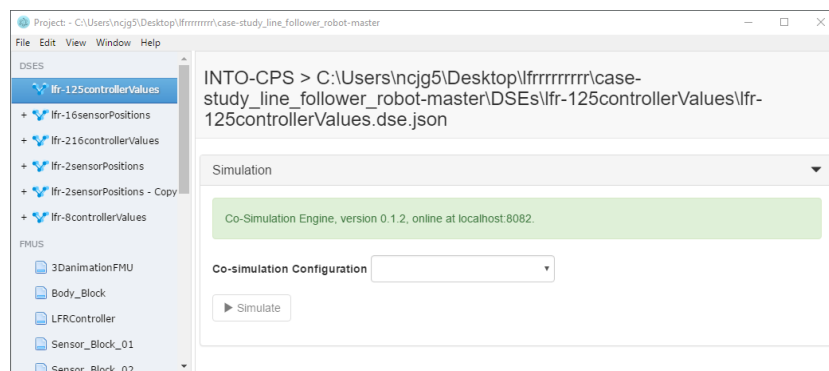


Figure 56: Status when COE is running.

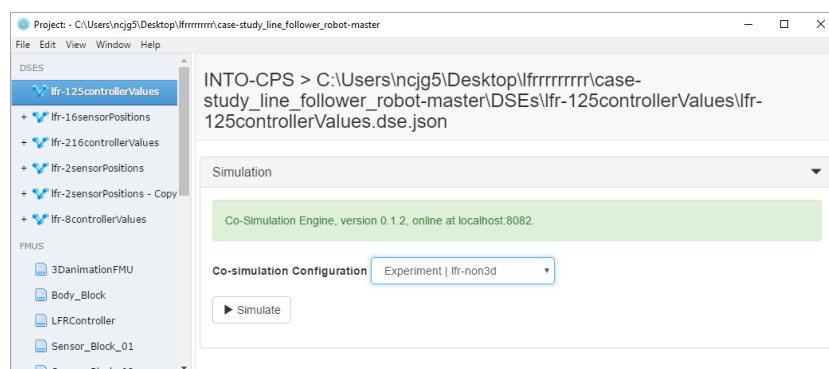



Figure 57: Selecting a multi-model.

6.2 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 58. 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, and double clicking on it opens the results page in the default browser.

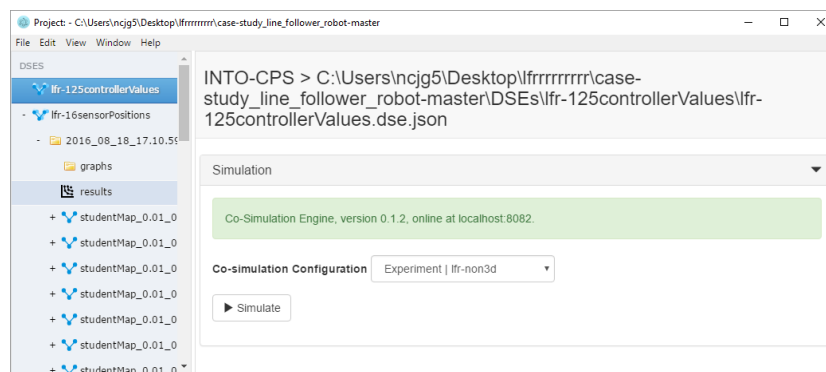


Figure 58: Icon shown when DSE results are ready.

The results, shown in Figure 59, 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.

6.3 How to Edit a DSE Configuration

Editing of a DSE configuration is currently a manual process and so guidance regarding each section of the configuration is presented in this section.

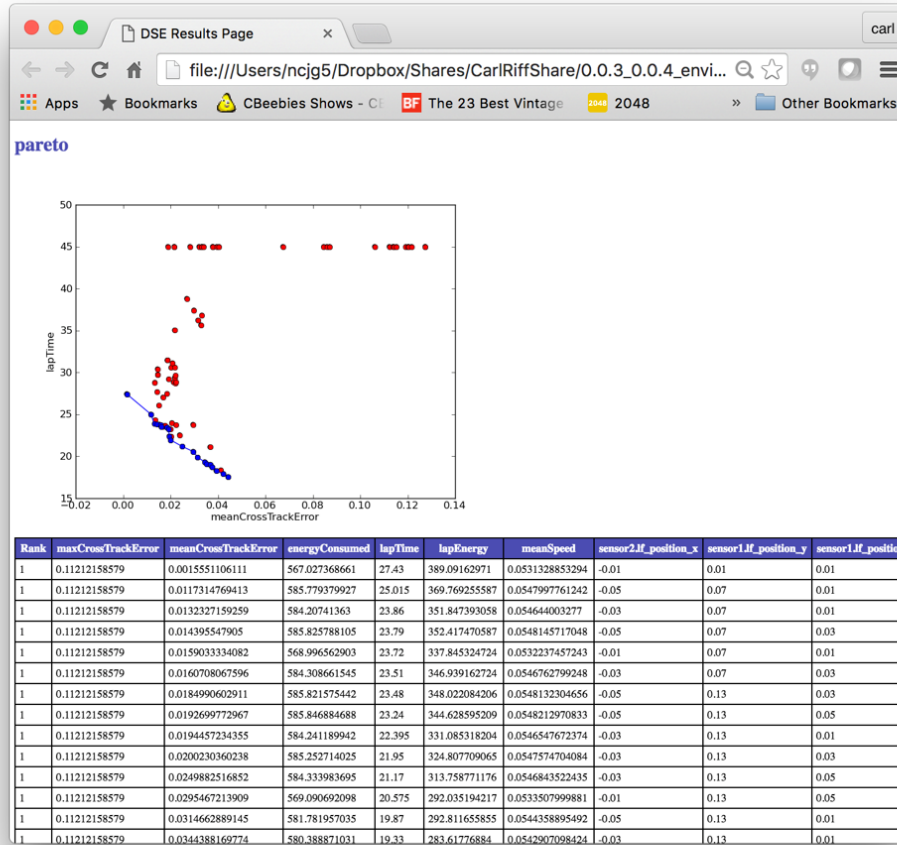


Figure 59: A page of DSE results.

6.3.1 File Creation

The suggested 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 60 (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`.

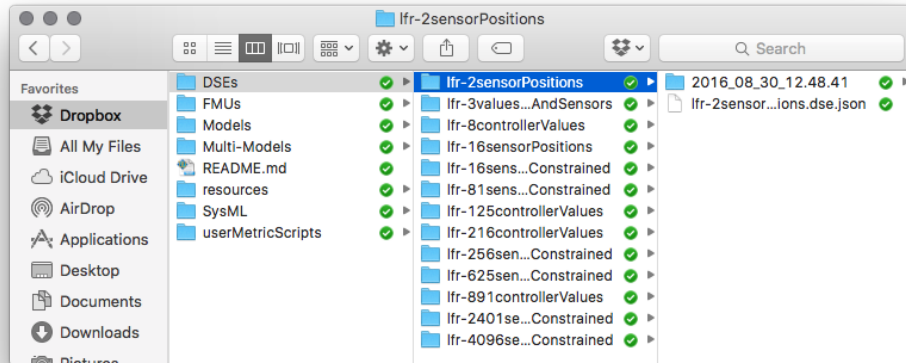


Figure 60: Location of DSE configurations.

943 6.3.2 Parameters

944 The parameters section is used to define a list of values for each parameter
 945 to be explored. Figure 61 shows the definition of four parameters, each with
 946 two values. If a parameter is included in the DSE configuration file, then it
 947 must have at least one value defined. The order of the values in the list is
 948 not important. If a parameter that is to be explored is not in the list, its ID
 949 may be found in the three ways listed below.

- 950 1. If the parameter is listed in the multi-model configuration, then copy
 951 it from there.
- 952 2. If the parameter is not in the multi-model parameters list then its name
 953 may be found by examining the model description file in the associated
 954 FMU. In this case it will be necessary to prepend the parameter ID
 955 with the ID for the FMU and the instance ID of the FMU, for example
 956 in “{sensor1FMU}.sensor1.lf_position_x”.
 - 957 • the ID of the FMU is {sensor1FMU}.
 - 958 • the instance ID of the FMU in the multi-model is sensor1.
 - 959 • the parameter ID is lf_position_x.
- 960 3. The IDs for each parameter may also be found on the Architecture
 961 Structure Diagram in the SysML models of the system. The full name
 962 for use in the multi-model may then be constructed as above.

```

"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 61: Example parameter definitions.

963 6.3.3 Parameter Constraints

964 It may be the case that not all combinations of the parameter values defined
 965 in the previous section are valid. So, it is necessary to be able to define
 966 constraints over the design parameters such that no time is wasted simulating
 967 invalid designs. For example, in the line follower robot we define ranges for
 968 the x and y co-ordinates of the left and right sensors separately, and running
 969 all combinations of these leads to asymmetric designs that do not have the
 970 same turning behaviour on left and right turns. To prevent this we can define
 971 boolean expressions based upon the design parameters and evaluate these
 972 before a simulation is launched. Figure 62 shows two constraints defined for
 973 the line follower DSE experiment that ensure only symmetrical designs are
 974 allowed. The first constraint ensures the y co-ordinates of both sensors are
 975 the same, while the second constraint ensures that the x co-ordinate of the
 976 left sensor is the same, but negated as the x co-ordinate of the right sensor.
 977 Note that the names used when defining such constraints have the same
 978 FMU_ID.instance_ID.parameter_ID format as used when defining a
 979 parameter range (see Section 6.3.2)

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

```

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

```

Figure 62: Example parameter constraints.

981

982 6.3.4 Scenario List

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

991 Changing a scenario may involve changing one or more different parts of
992 the multi-model and its analysis, such as the specific FMUs used, parame-
993 ters passed to an FMU, the multi-model the DSE is based upon, along with
994 any data files used by the objective scripts (Section 6.3.6) to evaluate perfor-
995 mance. This feature is currently under development and so only the objective
996 data file selection is implemented presently.

997 6.3.5 Objective Definitions: Internal

998 There are two means for defining the objectives used to assess the perfor-
999 mance of a simulated model. The first of these, described here, is using the
1000 internal functions included in the DSE scripts. This is a set of simple func-
1001 tions that can be applied to any of the values recorded by the COE during
1002 simulation. The current set of internal functions is:

1003 **max** Returns the maximum value of a variable during a simulation.

1004 **min** Returns the minimum value of a variable during a simulation.

1005 **mean** Returns the mean value of a variable during a simulation (*n.b.*, a fixed
1006 simulation step size is currently assumed.)

1007 Defining an internal objective requires three pieces of information:

1008 **name** This is the name that the objective value will be stored under in the
1009 objectives file.

1010 **type** This selects the function to be applied. The key `objectiveType` is
1011 used in the DSE configuration file.

1012 **variable** This defines the variable to which the function is to be applied.
1013 The key `columnID` is used to denote this parameter in the DSE con-
1014 figuration file.

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

Figure 63: Definition of an internal objective.

1015 Figure 63 shows the definition of an objective named `energyConsumed`,
1016 which records the maximum value of the variable
1017 `{bodyFMU}.body.total_energy_used`. This objective is recorded and
1018 may be used later, primarily for the purpose of ranking designs, but it could
1019 also be used for any other analysis required.

1020 6.3.6 Objective Definitions: External Scripts

1021 The second form of objective definition makes use of user-defined Python
1022 scripts to allow bespoke analysis of simulation results to be launched auto-
1023 matically and results recorded using the common format. The definition has
1024 two parts: the construction of the Python script to perform the analysis and
1025 the definition of the script's required parameters in the DSE configuration
1026 file, these two steps are described below.

1027 **Construction of the Script** The outline functionality of an analysis script
1028 is that, at the appropriate times, a DSE script calls it, passing four or more
1029 arguments. The script uses these arguments to locate a raw simulation results
1030 file (`results.csv`), processes those results and then writes the objective
1031 values into an objectives file (`objectives.json`) for that simulation.

1032 The first three arguments sent to the script are common to all scripts. These
1033 are listed below.

1034 **argv 1** The absolute path to the folder containing the `results.csv` re-
1035 sults file. This is also the path where the script finds the
1036 `objectives.json` file.

1037 **argv 2** The name of the objective. This is the key against which the script
1038 should save its results in the objectives file.

1039 **argv 3** The name of the scenario.

1040 With this information the script can find the raw simulation data and also
1041 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 64. 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.

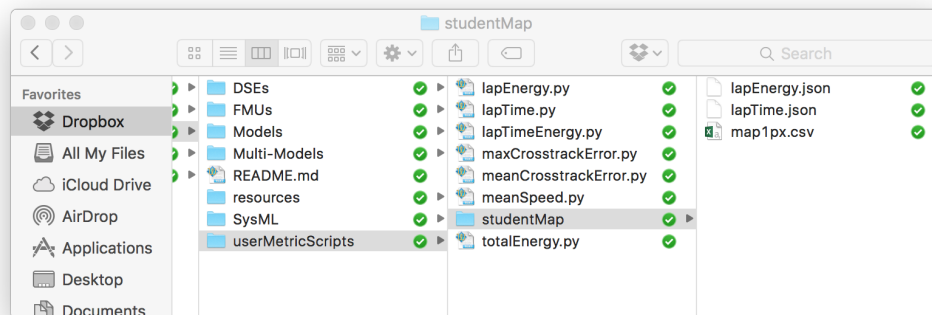


Figure 64: External analysis script data files for the “studentMap” scenario.

Figure 65 shows an example of an external analysis script. In this case it computes the cumulative deviation of the water level from some target level. 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 cal-

```

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)

```

Common
SectionScript
Specific
Section

Figure 65: External analysis script to calculate cumulative deviation in the water tank example

1067 culate the value of the objective and finally write the objective value into
 1068 objectives.json.

1069 In the 'Script Specific Section' of Figure 65 we see the example of the script
 1070 calculating the cumulative deviation of the water level from a target level in
 1071 the water tank model. It starts by reading a further two arguments passed
 1072 when the script is launched and initializes the variables. The script then it-
 1073 erates through all rows of data in results.csv to calculate the cumulative
 1074 deviation which is then written to the objectives.json file in the final
 1075 line.

```

    "externalScripts": {
      "lapTime": {
        "scriptId": "lapTime.py",
        "scriptParameters": {
          "1": "time",
          "2": "{bodyFMU}.body.robot_x",
          "3": "{bodyFMU}.body.robot_y",
          "4": "studentMap"
        }
      },
      "meanCrossTrackError": {
        "scriptId": "meanCrossTrackError.py",
        "scriptParameters": {
          "1": "{bodyFMU}.body.robot_x",
          "2": "{bodyFMU}.body.robot_y"
        }
      }
    }
  },

```

Figure 66: Definition of the external analysis functions for the line follower robot.

1076 **Definition of External Analysis in DSE Configuration** With the
 1077 analysis scripts constructed, the next step is to define their use in the DSE
 1078 configuration file. The definition essentially contains three parts: a name for
 1079 the objective, the file name of the script and a list arguments to pass. The
 1080 name given to the objective allows it to be referenced in the objectives con-
 1081 straints and ranking sections of the DSE configuration. The file name tells
 1082 the DSE scripts which script to launch and the arguments define additional
 1083 data (over the standard three arguments described earlier) that the script
 1084 needs, such as the names of data it needs or constant values.

1085 In Figure 67 we find the definition of the external analysis used in the three
 1086 tank water tank example. There are two analysis defined, the first is named
 1087 'cumulativeDeviation' and the second is 'vCount'. In each there are two
 1088 parameters defined, the 'scriptId' contains the file name of the script file to
 1089 run in each case, while the 'scriptParameters' parameter contains the list of

1090 additional arguments each needs.

```

"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 67: Definition of the external analysis functions for the three water tank model.

1091 The purpose of both internal and external analysis functions is to populate
 1092 the `objectives.json` file with values that characterize the performance
 1093 of the designs being explored. Figure 68 shows an example objectives file
 1094 generated during a DSE of the three water tank example. There is an instance
 1095 of the objectives file created for each simulation in DSE, its primary use being
 1096 to inform the ranking of designs, but it may be used for any other analysis a
 user wishes to define.

```

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

```

Figure 68: Contents of `objectives.json` file for a single simulation of the three tank water tank

1097

1098 6.3.7 Ranking

1099 The final part of a DSE configuration file concerns the placing of designs in a
 1100 partial order according to their performance. The DSE currently supports a
 1101 Pareto method of ranking, as was shown earlier in Figure 59. The purpose of
 1102 the ranking section of the configuration is to define the pair of objectives that
 1103 will be used to rank the designs, and whether to maximize or minimize each.
 1104 Figure 69 shows an example of a ranking definition from the line following
 1105 robot example. Here the user has specified that the lap time and mean

1106 cross track error objectives will be used to rank. The use of '-' after each
1107 indicates that the aim is to minimize both, whereas a '+' indicates the desire
to maximize.

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

Figure 69: Defining parameters and their preferred directions for ranking.

1108

1109 Combining all these sections results in a complete DSE configuration, as
1110 shown in Figure 70.

```

{
  "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 70: A complete DSE configuration for the line follower robot example.

1111 7 Test Automation and Model Checking

1112 Test Automation and Model Checking for INTO-CPS is provided by the RT-
1113 Tester RTT-MBT tool. This section first describes installation and configu-
1114 ration of RT-Tester MBT in Section 7.1. It then describes test automation
1115 in Section 7.2 and model checking in Section 7.3. Note, that these features
1116 are explained in more detail in the deliverables D5.2a [PLM16] and D5.2b
1117 [BLM16], respectively.

1118 7.1 Installation of RT-Tester RTT-MBT

1119 In order to use RTT-MBT, a number of software packages must be installed.
1120 These software packages have been bundled into two installers:

- 1121 • **VSI tools dependencies bundle:**

1122 This bundle is required on the Windows platform and installs the fol-
1123 lowing third party software:

- 1124 – Python 2.7.
- 1125 – GCC 4.9 compiler suite, used to compile FMUs.

- 1126 • **VSI tools – VSI Test Tool Chain:**

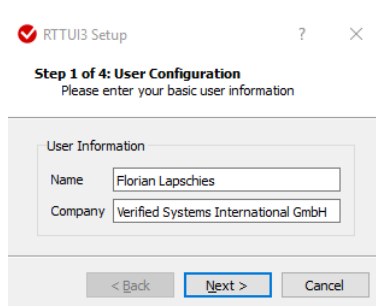
- 1127 – RT-Tester 6.0, a stripped version of the RT-Tester core test system
1128 that contains the necessary functionality for INTO-CPS.
- 1129 – RT-Tester MBT 9.0, the model-based testing extension of RT-
1130 Tester.
- 1131 – RTTUI 3.9, the RT-Tester graphical user interface.
- 1132 – Utility scripts to run RTT-MBT.
- 1133 – Examples for trying out RTT-MBT.

1134 These bundles can be downloaded via the download manager of the INTO-
1135 CPS Application.

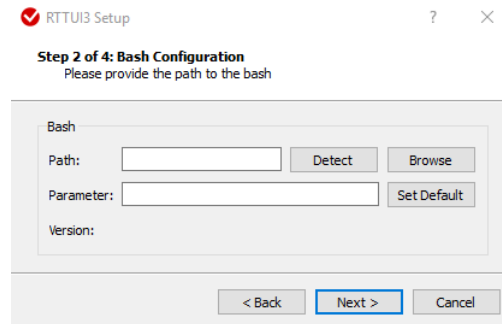
1136 7.1.1 Setup of the RT-Tester User Interface

1137 When the RT-Tester User Interface (RTTUI) is first started, a few configu-
1138 ration settings must be made.

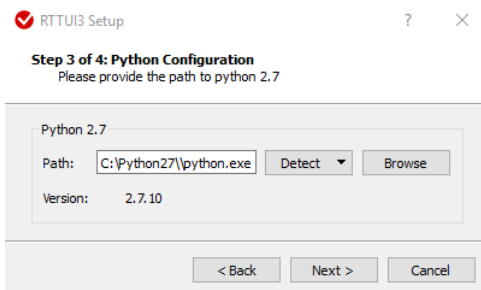
- User name and company name (Figure 71a).
- Location of Bash shell (Figure 71b): You can safely skip this step by clicking *Next*.
- Path to Python 2.7 executable (Figure 71c): Click *Detect* and then *Installation Path* for auto-detection, or *Browse* to select manually.
- Location of RT-Tester (Figure 71d): 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 properly detected.



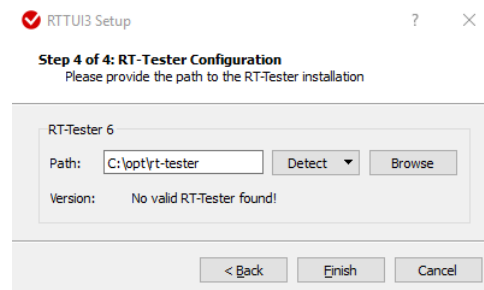
(a) Configuring user.



(b) Configuring Bash.



(c) Configuring Python.



(d) Configuring RT-Tester.

Figure 71: 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.

- 1152 • Compiling test driver FMUs.
- 1153 • Setting up test runs.
- 1154 • Running tests.
- 1155 • Evaluating test results.

1156 These activities can be performed either solely using the RT-Tester graphical
1157 user interface, or using a combination of the INTO-CPS Application and the
1158 RT-Tester GUI. In this section we focus on describing the latter, since it
1159 supports the complete set of features necessary for test automation. The
1160 INTO-CPS Application currently only exposes a subset of these. A more
1161 comprehensive description of the test automation workflow can be found in
1162 deliverable D5.2a [PLM16].

1163 In the INTO-CPS Application test automation functionality can be found
1164 below the main activity *Test-Data-Generation* in the project browser. Before
1165 using most of the test automation utilities, the license management process
1166 has to be started. To this, end right-click on *Test-Data-Generation* and select
Start RT-Tester License Dongle (see Figure 72).

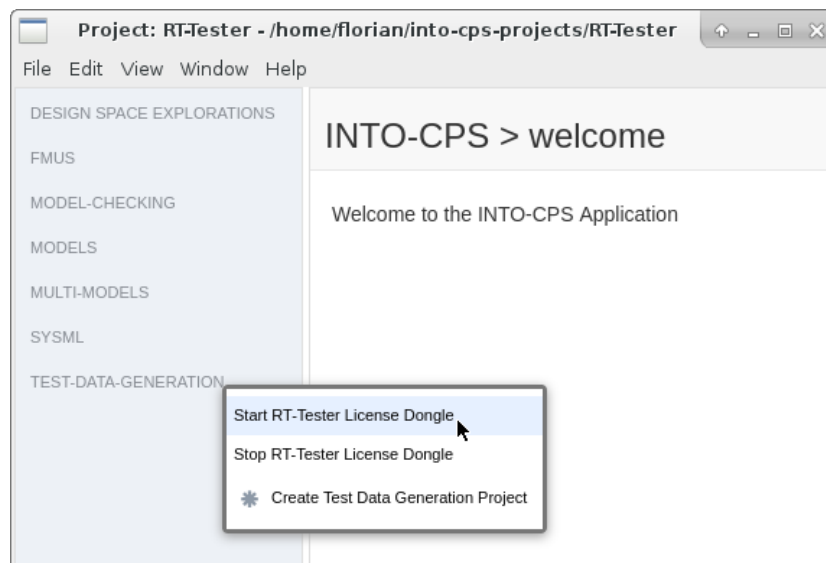


Figure 72: Starting the license management process.

1167
1168 After developing the behavioural model in Modelio and exporting it to an
1169 XMI file, test automation projects can be created from the INTO-CPS Ap-
1170 plication. Such a project is then added as a sub-project within a containing
1171 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 73).
2. Specify a name for the project, select the XMI file containing the test model and press *Create*, as shown in Figure 74.

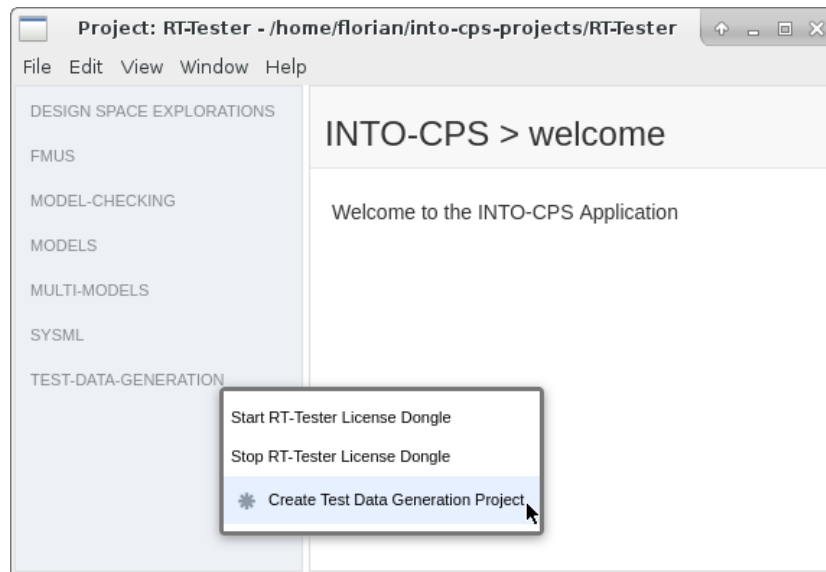


Figure 73: Creating a test automation project.

The newly created sub-project and its directory hierarchy is displayed in the project browser. Some directories and files of the RT-Tester project that are not of great importance to the INTO-CPS workflow are hidden from the 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

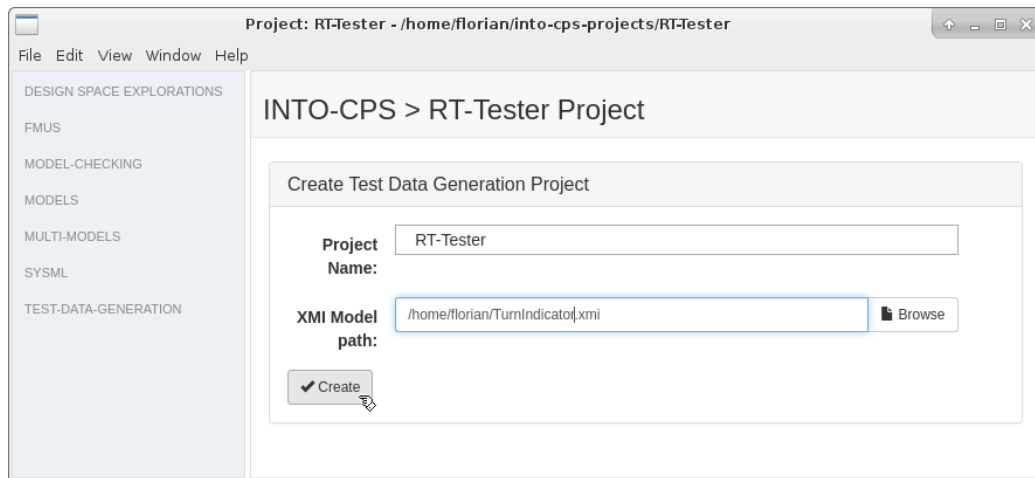


Figure 74: Test automation project specifics.

goals can also be specified by selecting structural elements from a tree representation of the test model and then choosing a coverage metric 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 75), 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 76). 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.

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 77).

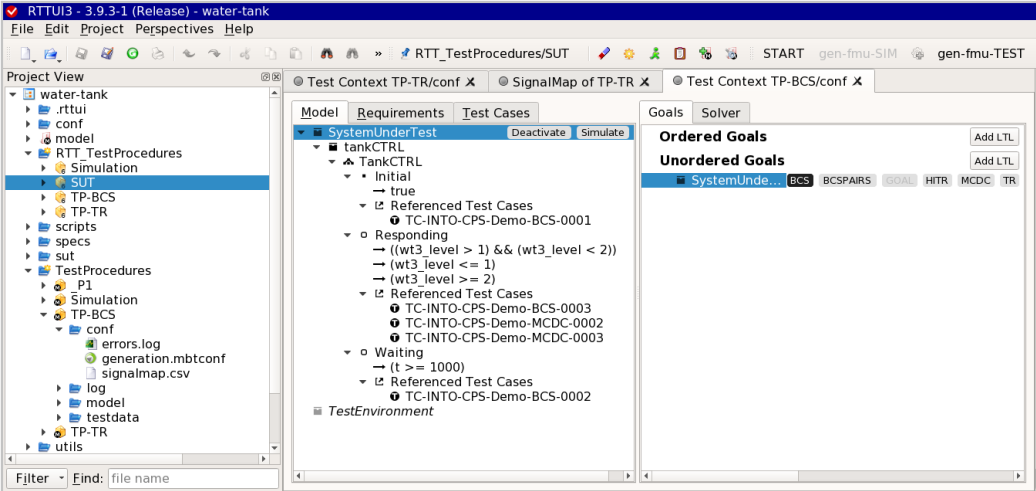


Figure 75: Configuring a test goal.

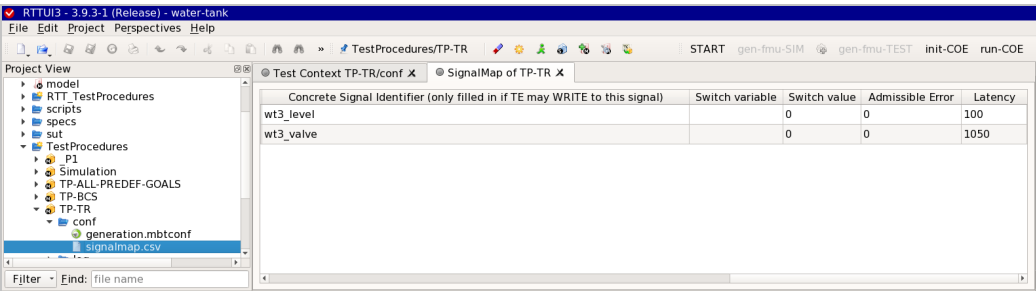


Figure 76: Configuring signals.

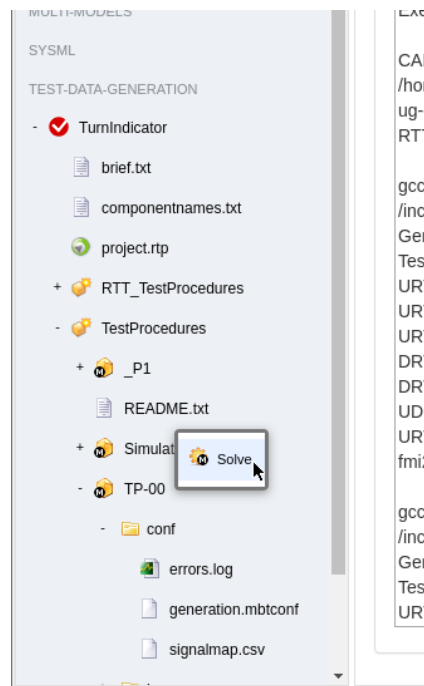


Figure 77: Generating a concrete test procedure.

1208 A solver component then computes the necessary timed inputs to realize the
 1209 test objectives. A concrete test procedure is generated that feeds a system
 1210 under test with these inputs and observes its outputs against expected results
 1211 derived from the test model. This test procedure will be placed in `RTT_
 1212 TestProcedures` and has the same name as the symbolic test procedure.
 Figure 78 shows how test generation progresses.

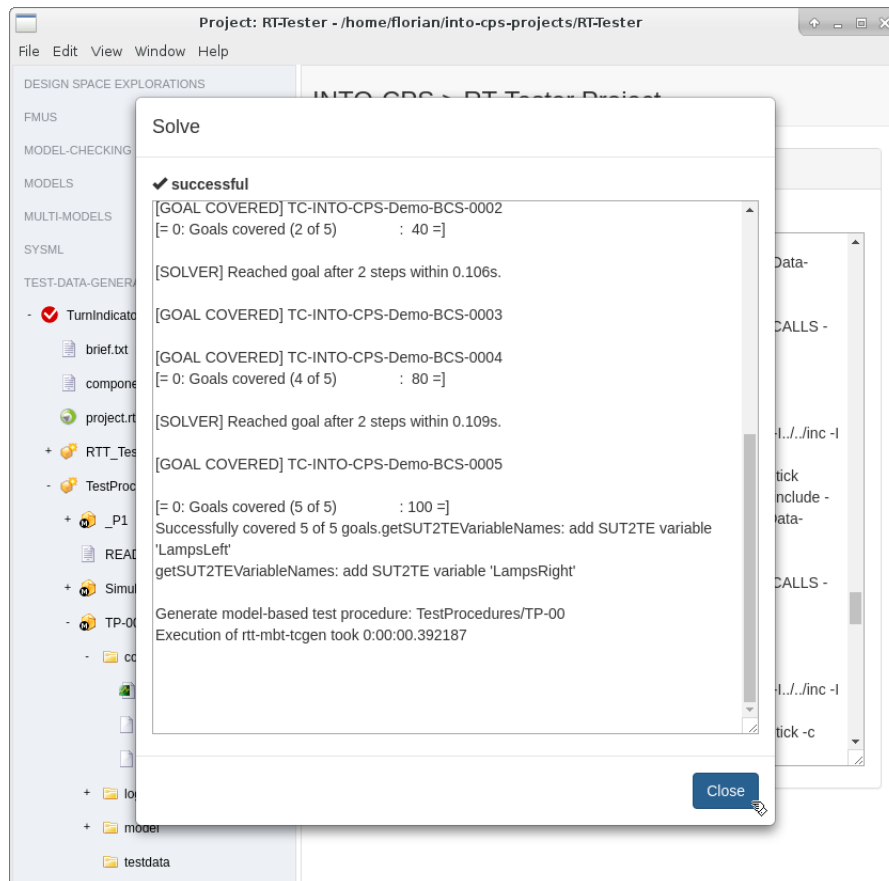


Figure 78: Test data generation progress.

1213

1214 A generated test procedure can be cast into an FMU, which can then be
 1215 run in a co-simulation against the system under test. To this end, right
 1216 click on the concrete test procedure and select *Generate Test FMU* (see
 1217 Figure 79). In cases where a real and perhaps physical system under test is
 1218 not available, a simulation of the system under test can be generated from
 1219 the behavioural model. To generate such an FMU, right-click on *Simulation*
 1220 and select *Generate Simulation FMU* as depicted in Figure 80.

1221 In order to run a test, right-click on the test procedure and select *Run Test*

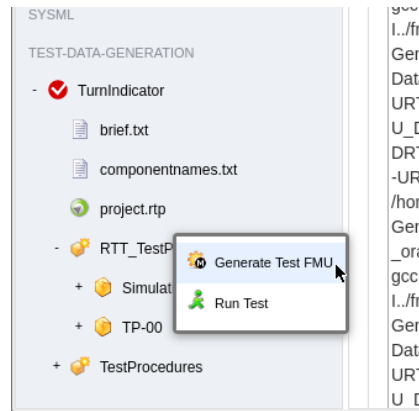


Figure 79: Generating a test FMU.

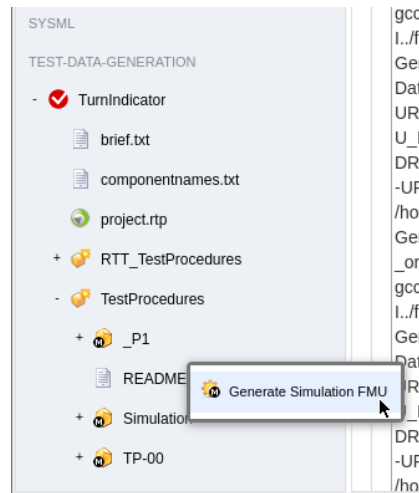


Figure 80: Generating a simulation FMU.

1222 (see Figure 81). Then specify the FMU of the system under test. If the sys-
 1223 tem under test is to be replaced by a simulation, press on the corresponding
 1224 *Simulation* button. The duration of the test is derived during test data gen-
 1225 eration and does not need to be manually specified. However, an appropriate
 1226 step size must be set. Finally, after making sure the COE is running, press
 1227 *Run* to start the test (see Figure 82).

1228 Every test execution yields as its result an evaluation of test cases, *i.e.*, each is
 1229 associated with a verdict of PASS, FAIL, or INCONCLUSIVE.¹⁰ The details
 1230 are found in the test log files below the folder `testdata`. See the RT-Tester

¹⁰The 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.

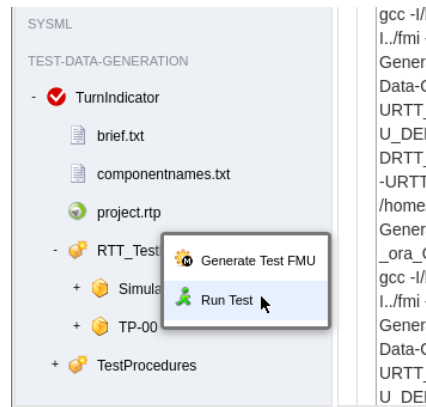


Figure 81: Running a test.

1231 user manual [Ver15a] for details.

1232 The file `testcase_tags.txt` gives a condensed record of test case, ver-
 1233 dict, and point in a `*.log` file where a corresponding PASS, FAIL, or—
 1234 in case of INCONCLUSIVE—test case occurrence without assertion can
 1235 be found. The project-wide test-case verdict summary as well the require-
 1236 ment verdict summary can be found in the folder `RTT_TestProcedures/`
 1237 `verification`. More details on the evaluation of test runs can be found
 1238 in deliverable D5.2a [PLM16].

1239 7.3 Model Checking

1240 This section describes how to use the INTO-CPS Application as a front-
 1241 end to the LTL model checker of RT-Tester RTT-MBT. More details on the
 1242 algorithms used and the syntax of LTL formulas can be found in deliverable
 1243 D5.2b [BLM16].

1244 Once an INTO-CPS project has been created (see Section 4.2), model check-
 1245 ing functionality can be found under the top-level activity *Model Checking* in
 1246 the project browser. Before getting started, the RT-Tester license manage-
 1247 ment process must be launched. To this end, right-click on *Model Checking*
 1248 and select *Start RT-Tester License Dongle* (see Figure 83). Model checking
 1249 projects are presented as sub-projects of INTO-CPS Application projects. In
 1250 order to add a new project,

- 1251 1. Right-click on the top-level activity *Model Checking* in the project
 1252 browser and select *Create Model Checking Project* (see Figure 84).

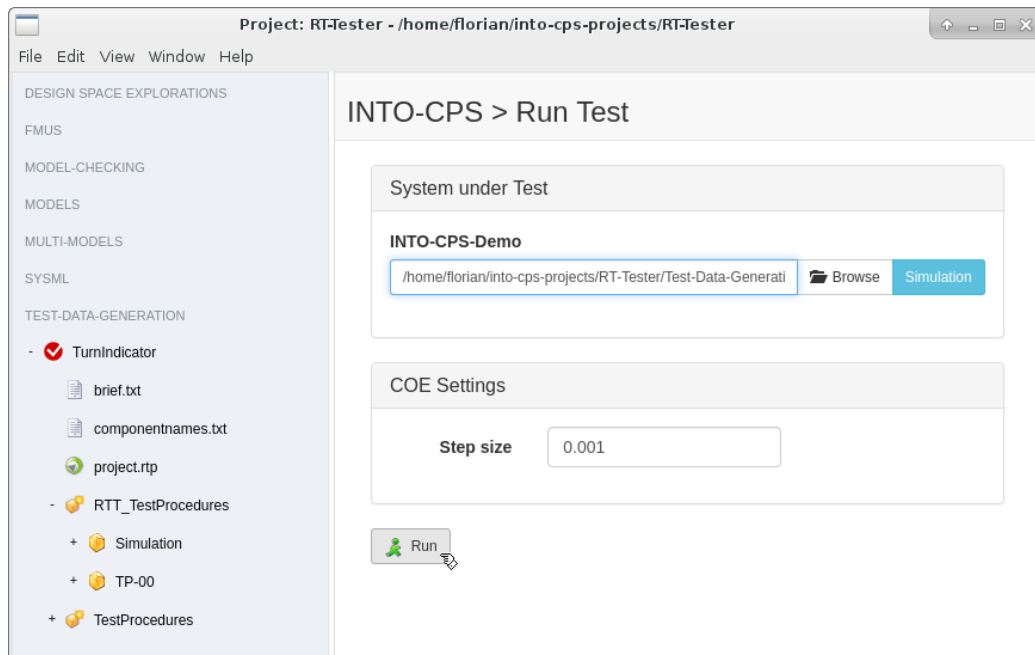


Figure 82: Configuring a test.

- 1253 2. Provide a project name and the model that has been exported to XMI
1254 from Modelio.

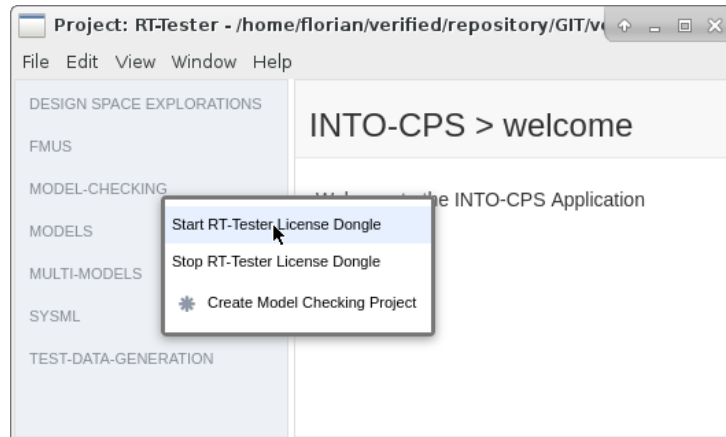


Figure 83: Starting the RT-Tester license dongle.

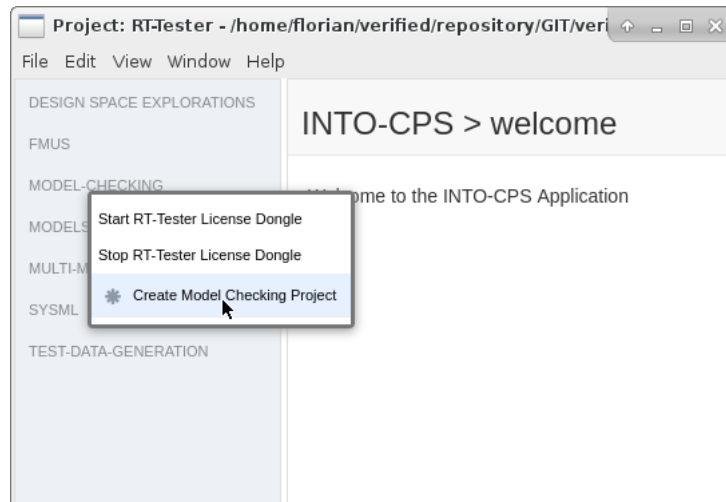


Figure 84: Creating a model checking project.

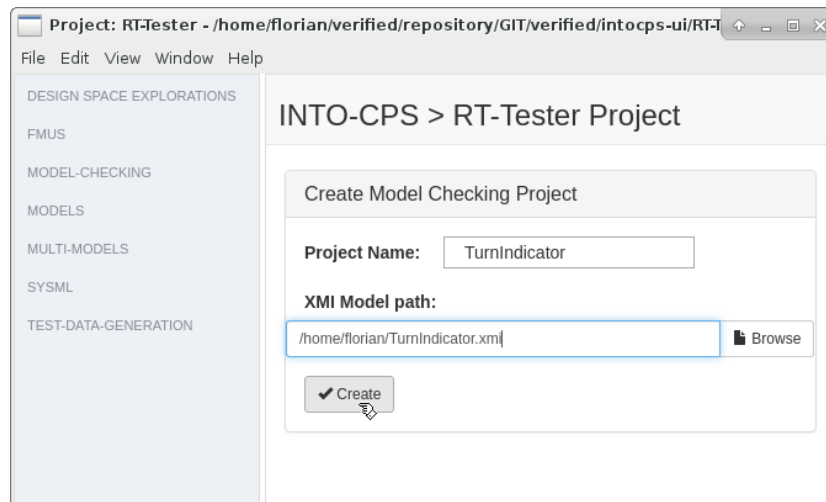


Figure 85: Specifying the model checking project.

1255 After pressing *Create*, a new node representing the model checking project is
 1256 added to the project browser.

1257 The next step is to add LTL queries to the project:

- 1258 1. Right click on the project and select *Add LTL Query* (see Figure 86).
- 1259 2. Enter a name for the new query (see Figure 87).
- 1260 3. To edit the LTL query, double click on the corresponding node in the
 1261 project browser (see Figure 88). The LTL formula can then be edited in
 1262 a text field. Note that the editor supports auto-completion for variable
 1263 names and LTL operators (see Figure 89).
- 1264 4. Provide the upper bound for the bounded model checking query.

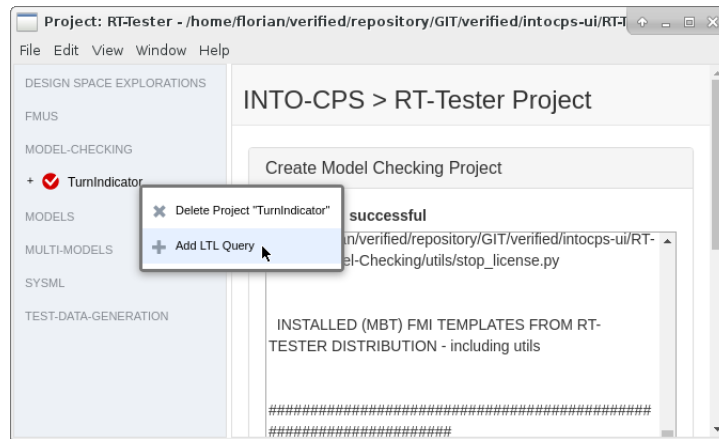


Figure 86: Adding an LTL formula.

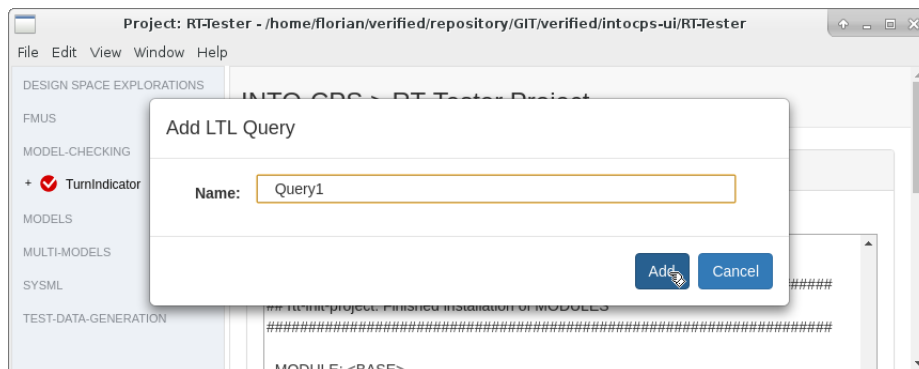


Figure 87: Naming the new LTL formula.

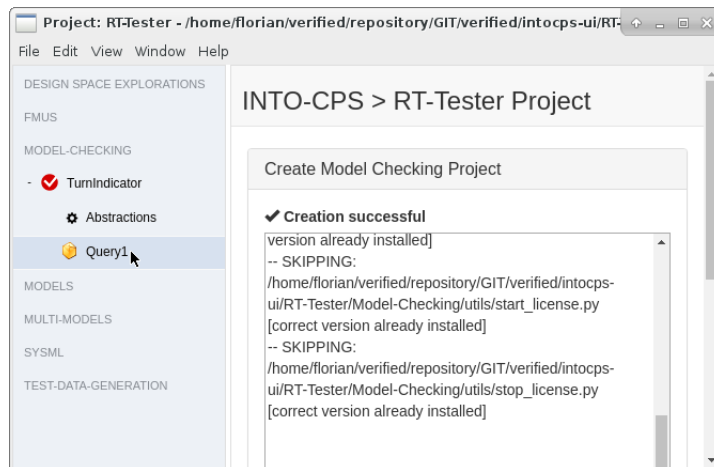


Figure 88: Opening the LTL formula editor.

1265 To check the query, press *Save & Check*. A window opens and is filled with
 1266 the output of the model checking tool. The tool either reports that the query
 1267 holds within the specified number of steps — as depicted in Figure 90 — or
 1268 it prints a counterexample to demonstrate that the property does not hold.

1269

1270 It is possible to configure abstractions¹¹ for a particular model checking
 1271 project. To do so, double-click on the corresponding *Abstractions* node below
 1272 that project in the project browser. It is then possible to choose an abstrac-
 1273 tion method for each output variable of an environment component along
 1274 with making the associated setting. In Figure 91 the interval abstraction has
 1275 been selected for the output variable `voltage`. This abstraction has further
 1276 been configured to restrict the variable's value within the interval `[10, 12]`.
 1277 After pressing *Save*, this abstraction is applied to all model checking queries
 1278 in the current model checking project.

¹¹Information on abstractions and their associated configuration items can be found in deliverable D5.2b [BLM16].

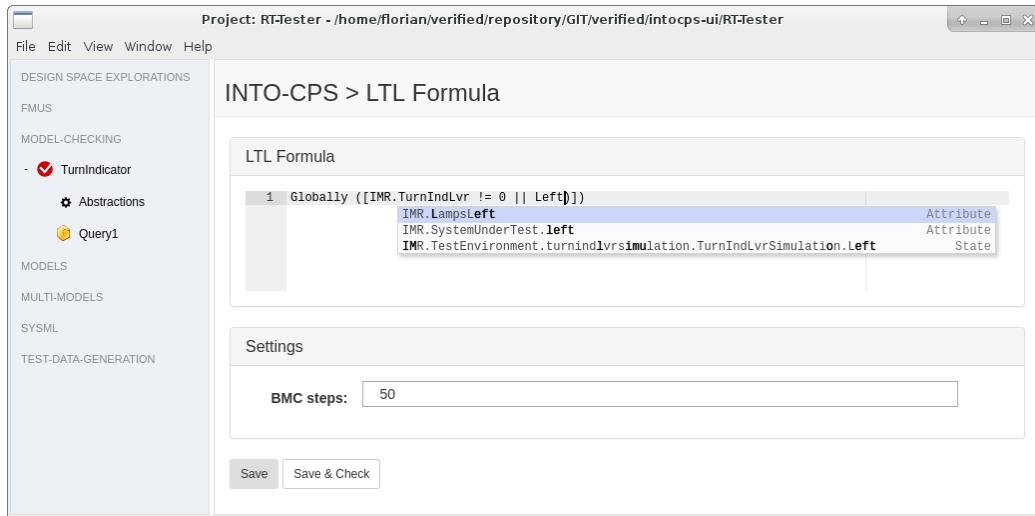


Figure 89: LTL formula editor.

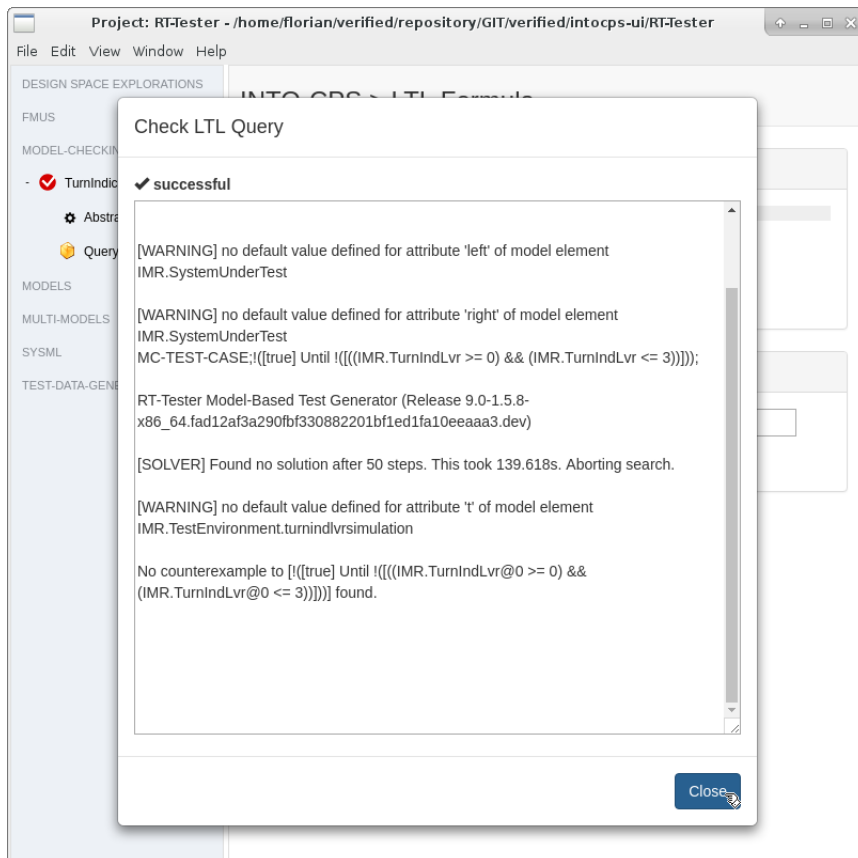


Figure 90: Model checking result.

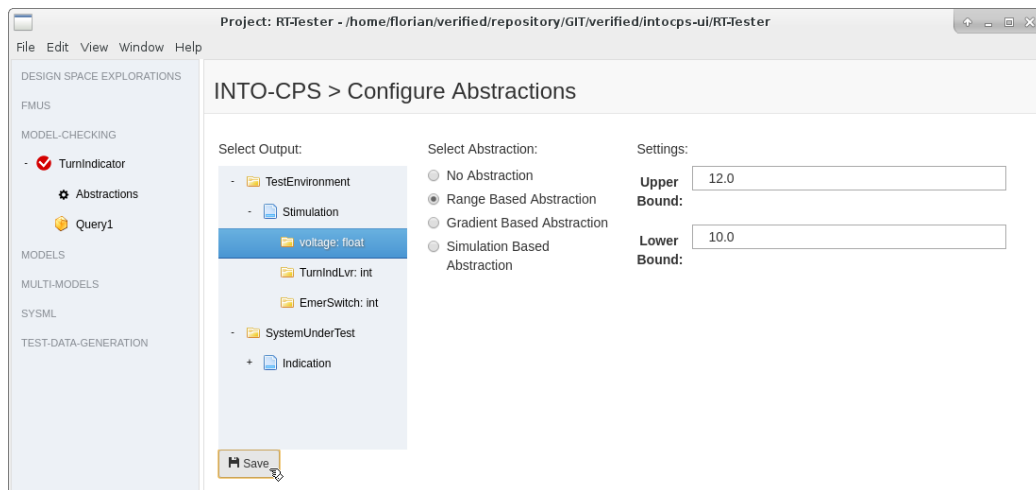


Figure 91: Configuring abstractions.

8 Traceability support for INTO-CPS

This section provides a description of tool support for traceability developed as part of the INTO-CPS project.

8.1 Overview

Traceability support is divided into two steps: sending data from the tools to the traceability database, and retrieving information from the database. Currently, only the first part is available in prototypes in the different tools. This is documented below.

8.2 INTO-CPS application

The traceability daemon is now (since INTO-CPS App 2.1.19 RC) integrated in the App and it starts with the App. Only Neo4J has to be downloaded. To do so, one can use the download-manager of the INTO-CPS App. When downloaded, Neo4J needs to be extracted by hand into the folder `<user>/into-cps-projects/install` (the archive file is located at `<user>/into-cps-projects/install_downloads` after download). Note that Neo4J is a singleton, so make sure all other instances of Neo4J are down before starting the App.

Traceability 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 App. 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:

```
username = intoCPSApp
password = KLHJiK8k2378HKsg823jKKLJ89sjklJHBNf8j8JH7FxE
```

To view the raw data from the database, right-click on the “traceability” entry in the project browser (in the App) and select “view traceability graph” (see figure 92). Select the database symbol, and click in “relationship types” on “Trace”. This shows you the graph database. By default, the view is limited

1309 to 25 entries. To change this, edit the line `MATCH p=()-[r:Trace]->()`
1310 `RETURN p LIMIT 25` and set the limit to a different value.

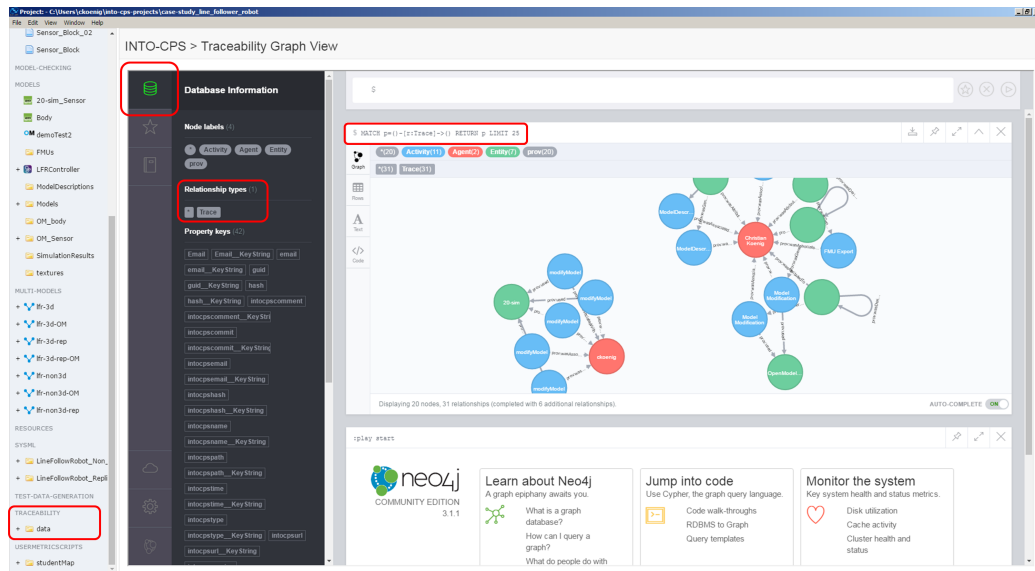


Figure 92: Current view of the traceability in the app

1311 **8.3 Modelio**

1312 The Modelio module can be downloaded here: [https://www.dropbox.](https://www.dropbox.com/s/bad36t9f8x4n0gl/INTOCPS_1.1.03.jmdac?dl=0)
1313 [com/s/bad36t9f8x4n0gl/INTOCPS_1.1.03.jmdac?dl=0](https://www.dropbox.com/s/bad36t9f8x4n0gl/INTOCPS_1.1.03.jmdac?dl=0). Modelio
1314 supports traceability for the following modelling activities:

- 1315 • Model creation
- 1316 • Model modification

1317 Steps:

1318 Go to *Configuration > Modules...* Select *INTO-CPS* and set the parameters.
1319 To commit a change, right click on any element and use the *INTO-CPS >*
1320 *Commit* command.

1321 8.4 OpenModelica

1322 The latest nightly builds of OpenModelica support traceability:

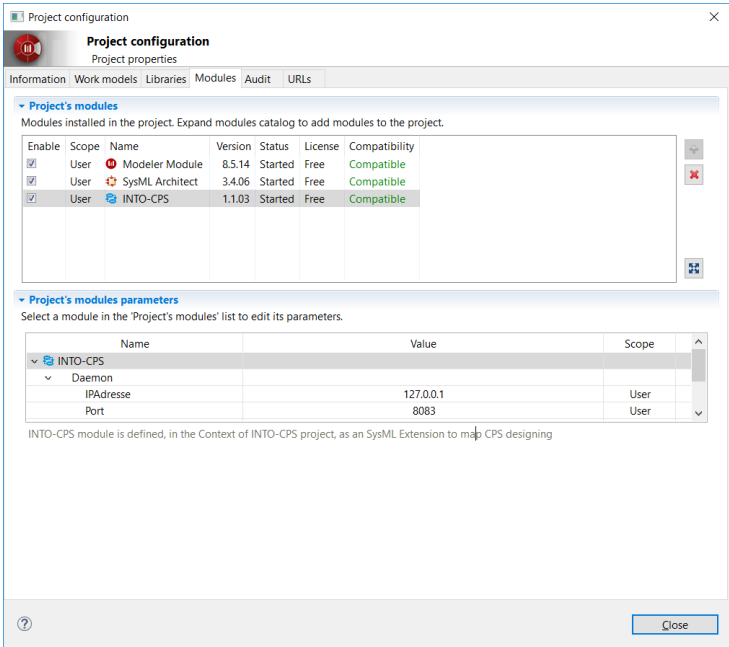


Figure 93: Configuration of traceability features in Modelio

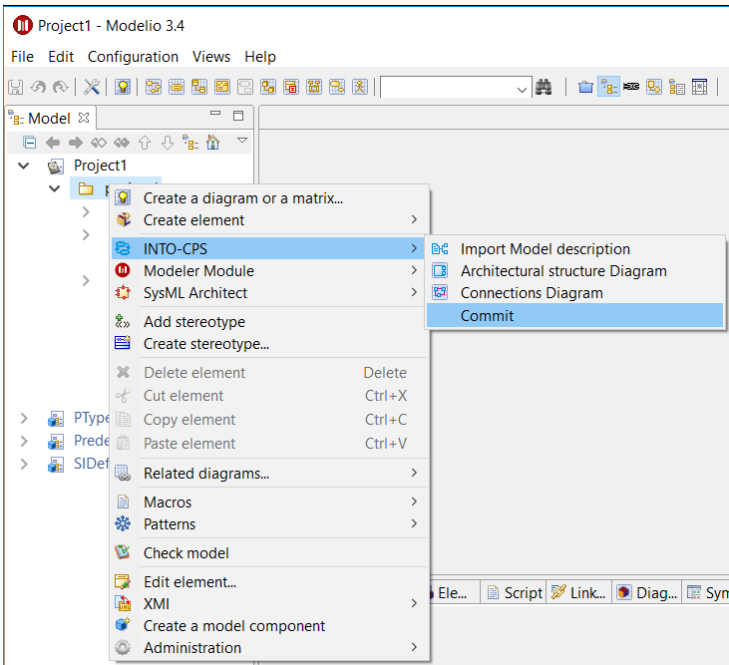


Figure 94: Commit the traceability information in Modelio

1323 Win32: `https://build.openmodelica.org/omc/builds/windows/`
 1324 `nightly-builds/32bit/OpenModelica-latest.exe` Win64: `https://build.openmodelica.org/omc/builds/windows/nightly-builds/`
 1325 `64bit/OpenModelica-latest.exe`
 1326

1327 OpenModelica supports tracing the following modeling activities:

- 1328 • Model creation
- 1329 • Model modification
- 1330 • FMU export
- 1331 • Model description XML import

1332 As a prerequisite for traceability support, Git should be installed in the
 1333 system.

1334 To configure the traceability support, go to *Tools > Options > Traceability*,
 1335 select the traceability checkbox and set all the fields, the traceability daemon
 1336 IP-Address and Port (see Figure 95). By default, the port is 8083.

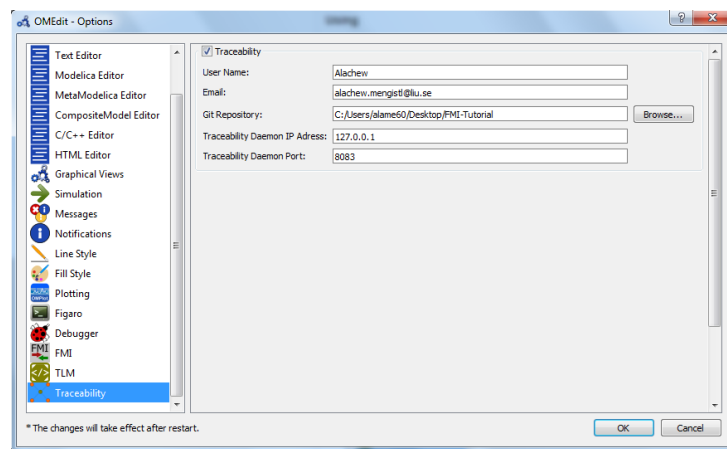


Figure 95: Configure the traceability settings in OpenModelica

1337 Then, go to *Tools > Options > General* and set the working directory to
 1338 which you would like to export the FMU (see Figure 96).

1339 Create a Modelica model via *File > New Modelica Class* or load a model via
 1340 *File > Open Model/LibraryFile(s)*, see Figure 97.

1341 After modification of the model/class, click the *File > Save* button, press
 1342 Ctrl + s or click the Save button from the menu bar shown below in the

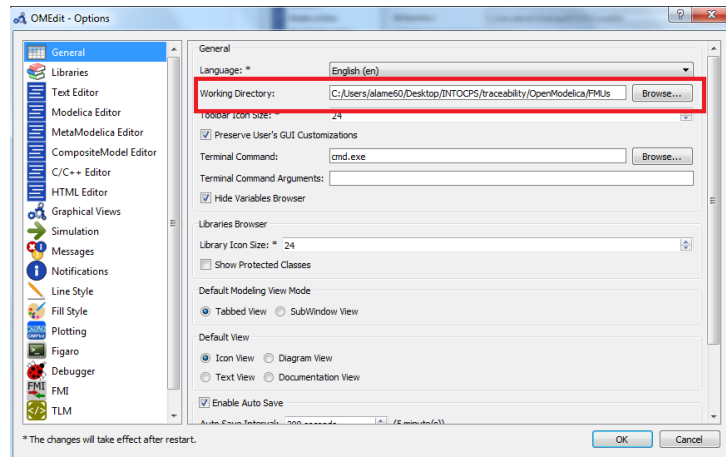


Figure 96: Set the FMU export directory in OpenModelica

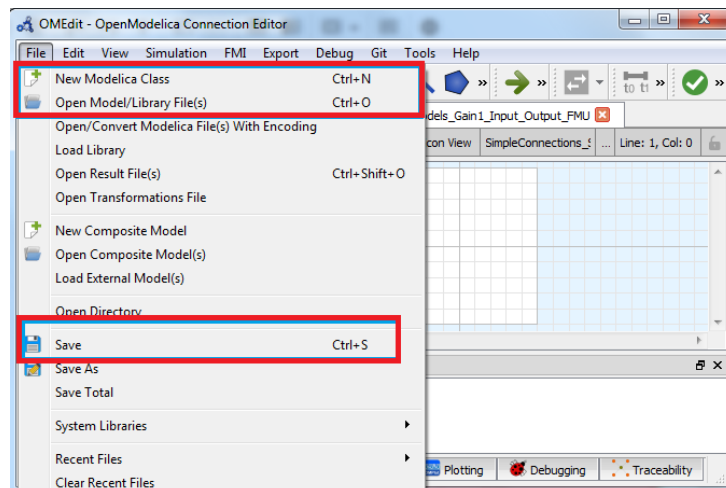


Figure 97: Create or open a Class in OpenModelica

1343 Figure 98. A dialog as shown below in Figure 99 will appear to enter the
1344 commit description.

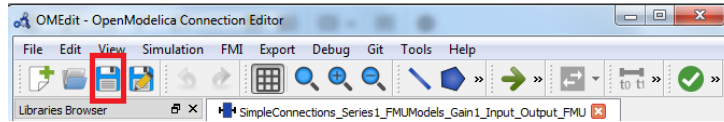


Figure 98: Save a model in OpenModelica

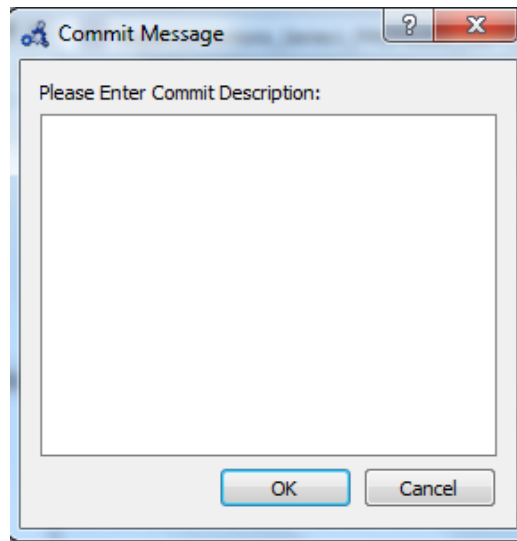


Figure 99: The commit message in OpenModelica

1345 To trace the export of an FMU, load the Modelica model or create a new
1346 model, then go to *FMI > Export FMU* (see Figure 100). OpenModelica gen-
1347 erates the FMU, commits and send the traceability information to daemon
1348 automatically.

1349 To import a `modelDescription.xml` file, go to *FMI > Import FMU*
1350 *Model Description*. A dialog as shown in Figure 101 will appear. Select the
1351 `modelDescription.xml` file and the output directory then press *OK*. The
1352 Modelica model with SysML block inputs and outputs will be generated and
1353 automatically loaded (see the left part of Figure 101). To send the traceability
1354 information, double click on the model then go to *Git > Traceability > Push*
1355 *Traceability Information*.

1356 To visualize the traceability graph, click on the Traceability perspective but-
1357 ton shown below.

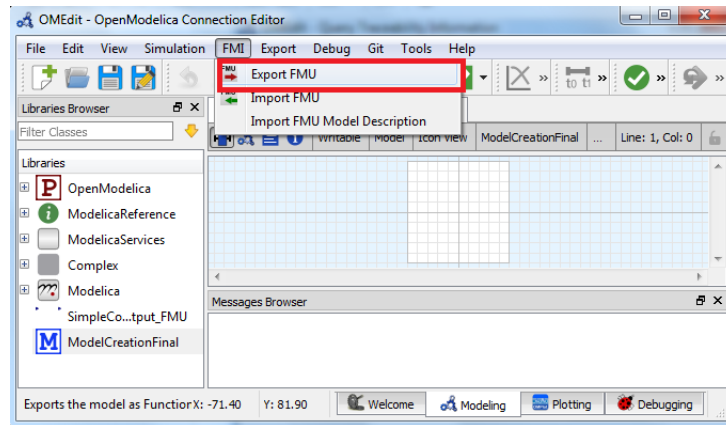


Figure 100: FMU export in OpenModelica

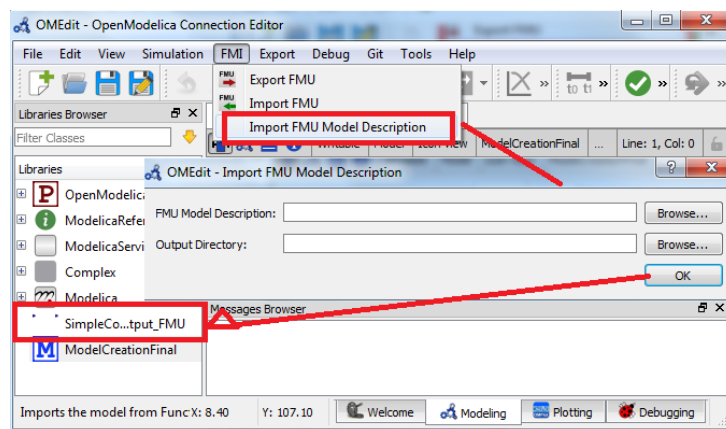


Figure 101: FMI model description import in OpenModelica

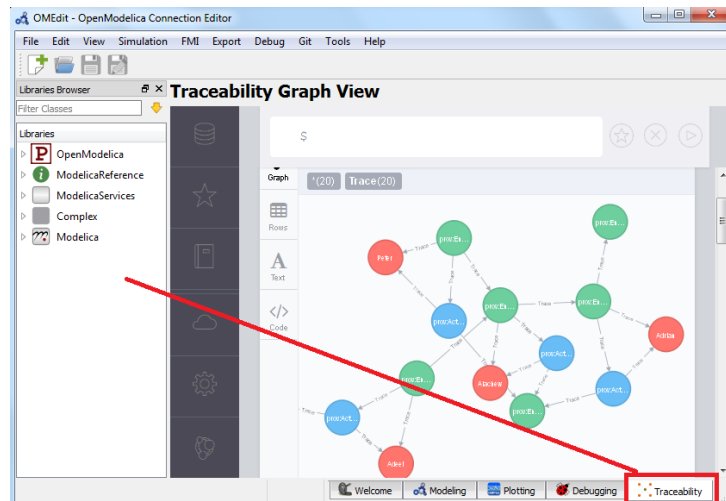


Figure 102: View traceability data in OpenModelica

8.5 20-sim

Use any version of 20-sim 4.6.3-intocps or higher. The one in the download manager for version 2.1.19 RC is not sufficient. The first suitable release bundle is 0.0.12.

The download can be found here:

<https://www.dropbox.com/s/lgr461ddb97kl8h/20-sim-4.6.3.7711-intocps-win32.exe?dl=1>.

During installation, make sure you keep the Python option enabled. This is necessary, even if you already have another Python installation on your PC. This Python version will only overwrite Python versions you installed earlier with 20-sim, it will not install other Python versions.

Currently, the actions “create model” and “modify model” are supported by 20-sim

In 20-sim, go to *Tools > Version Control Toolbox > Traceability*. First enable “GIT version control” and insert a GIT repository, which can be an existing GIT repository or a folder in the local file system. The model will be committed to this repository on a “save” (modify) or “save as” (create) action. If the model does not reside in the GIT repository, it will also be copied to the GIT repository on a “save” or “save as” action.

You can leave the “Write custom save messages” option unchecked, as it is not currently fully functional.

1379 If you would like to send data to the traceability daemon as well, then you
1380 can enable “INTO-CPS Traceability Daemon”. Below, you can then enter the
1381 IP-address and Port of the daemon. If you run the INTO-CPS application
1382 and traceability daemon locally, the IP-address is *localhost* and the port is
1383 8083 by default.

1384 Now, pressing “save” or “save as” in any form, will (copy and) commit your
1385 model to the GIT repository, and then send the action you just performed
1386 to the traceability daemon.

9 Code Generation for INTO-CPS

Of all 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. It describes what the user can expect currently from each tool's code generator, in the hopes that this will be helpful in eliminating stumbling blocks for new users trying to quickly get started with the INTO-CPS tool chain. 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.

9.1 Overture

A complete description of Overture's C code generator can be found in the Overture User Manual, 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

1421 currently considered stable from a code generation point of view. Please note
 1422 that exporting a source code FMU with Overture (Section 5.1) automatically
 1423 invokes the code generator and packages the result as an FMU.

1424 The C code generator is invoked from the context menu in the Project Explorer as shown in Figure 103. The code generator currently supports the

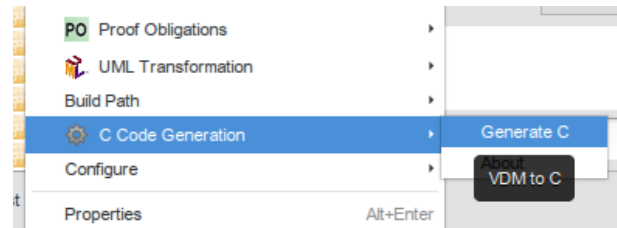


Figure 103: Invoking the code generator.

1425 following VDM-RT language constructs:
 1426

- 1427 • Basic data types and operations: integers, reals, booleans, *etc.*
- 1428 • The `is_` type test for basic types.
- 1429 • Quote types.
- 1430 • `let` expressions.
- 1431 • Pattern matching.
- 1432 • For and while loops.
- 1433 • case expressions.
- 1434 • Record types.
- 1435 • Products.
- 1436 • Aggregate types and operations: sets, sequences, maps (to a limited
 1437 extent).
- 1438 • Object-oriented features: classes and class field access, inheritance,
 1439 method overloading and overriding, the `self` keyword, subclass re-
 1440 sponsibility, *is not yet specified*, multiple constructors, and
 1441 constructor calls within constructors.
- 1442 • The `time` expression.

1443 The following language features are not yet supported:

- 1444 • Lambda expressions.

- 1445 • Pre-conditions, post-conditions and invariants.
- 1446 • Quantifiers.
- 1447 • Type queries on class instances.
- 1448 • File I/O via the I/O library.

1449 Most importantly, the development of Overture's C code generator is now be-
1450 ing geared toward resource-constrained embedded platforms. Improvements
1451 are currently being made to enable deployment of the generated code on PIC
1452 and ATmega microcontrollers.

1453 A key feature of this development is the use of a garbage collector for memory
1454 management. Generating a VDM-RT model to C code via the context menu
1455 results in a `main.c` file containing a skeletal `main()` function. This function
1456 contains calls to `vdm_gc_init()` and `vdm_gc_shutdown()`, the garbage
1457 collector initialization and shutdown functions. The collector proper can not
1458 be invoked automatically, so calls to the essential function `vdm_gc()` must
1459 be inserted manually in the main code, for instance after each repetition of a
1460 cyclic task. The source code FMU exporter, on the other hand, can handle
1461 automatic invocation of the garbage collector, so no manual intervention is
1462 required. Please note that it is generally unsafe to insert calls to `vdm_gc()`
1463 in the generated code.

1464 9.2 20-sim

1465 20-sim supports ANSI-C and C++ code generation through the usage of
1466 external and user-modifiable code-generation templates. Currently only a
1467 subset of the supported 20-sim modelling language elements can be exported
1468 as ANSI-C or C++ code. The exact supported features depend on the
1469 chosen template and its purpose and are discussed in Section 5.2.

1470 The main purpose of the 20-sim code generator is to export control systems.
1471 Therefore the focus is on running code on bare-bone targets (*e.g.* Arduino)
1472 or as a real-time task on a real-time operating system.

1473 The code generated by 20-sim does not contain any target-related or operat-
1474 ing system specific code. The exported code is generated such that it can be
1475 embedded in an external software project. For running 20-sim generated code
1476 on a target, you can use 20-sim 4C. This is a tool that extends the 20-sim
1477 generated code with target code based on target templates [Con16].

1478 9.3 OpenModelica

1479 OpenModelica supports code generation from Modelica to source-code tar-
1480 geting both ANSI-C and C++. From the generated source code, co-simulation
1481 and model-exchange FMUs can be built. Currently, the only supported solver
1482 in the generated co-simulation FMUs is forward Euler. Work to support ad-
1483 ditional solvers is underway. The ability to deploy the generated code to
1484 specific hardware targets will be supported via 20-sim 4C.

1485 9.4 RT-Tester/RTT-MBT

1486 When generating test FMUs from SysML discrete-event state-chart specifi-
1487 cations using RTTester/RTT-MBT, the user should be aware of the following
1488 sources of errors:

- 1489 • Livelock resulting from a transition cycle in the state-chart specification
1490 in which all transition guards are true simultaneously. This can be
1491 checked separately using a livelock checker.
- 1492 • Race conditions arising from parallel state-charts assigning different
1493 values to the same variable. Model execution in this case will deadlock.
- 1494 • State-charts specifying a replacement SUT must be deterministic.

1495 10 Issue handling

1496 Should you experience an issue while using one or more of the INTO-CPS
1497 tools, please take the time to report the issue to the INTO-CPS project team,
1498 so we can help you resolve it as soon as possible.

1499 The following three small sub-sections will guide you through the three simple
1500 steps of issue handling and reporting.

1501 10.1 Are you using the newest INTO-CPS release?

1502 Before you go any further with your current issue, please check that the
1503 INTO-CPS version you are using is the newest. The version number is part
1504 of the file name of the ZIP-bundle of the release. To find the list of released

1505 INTO-CPS bundle versions, and to see what the current version of INTO-
1506 CPS is, please visit

1507 <https://github.com/into-cps/intocps-ui/releases/>

1508 **10.2 Has the issue already been reported?**

1509 To make it easy for you to check whether the issue you are experiencing is
1510 an already known one, we have created a list of all currently known issues
1511 across all the INTO-CPS tools, with links directly to the online issue report
1512 page of the relevant tool supplier. Have a quick look at the list, and if your
1513 issue is already known, we recommend you follow the link and read more
1514 about the specifics of the issue. Perhaps someone has found a work-around
1515 or perhaps you have new information to add that might help the developers
1516 solve the issue faster.

1517 For the list of currently known issues, please visit

1518 <http://into-cps.github.io/weekly-issue/index.html>

1519 Note that some of the issue tracker sites might require you to register before
1520 you can view or submit issues. Registration is free.

1521 **10.3 Reporting a new issue**

1522 If you have followed the steps in the two previous sections and are now
1523 certain that you have spotted a new issue relating to a specific INTO-CPS
1524 tool, please visit the issue tracker site for that tool and report it. To ease
1525 this process we have listed direct links for each tool to their relevant online
1526 issue reporting page. To see the list of issue tracker links please visit

1527 <http://into-cps.github.io/report-an-issue.html>

1528 **11 Conclusions**

1529 This deliverable is the user manual for the INTO-CPS tool chain after the
1530 second year of the project. The tool chain supports model-based design and
1531 validation of CPSs, with an emphasis on multi-model co-simulation.

1532 Several independent simulation tools are orchestrated by a custom co-simu-
1533 lation orchestration engine, which implements both fixed and variable step
1534 size co-simulation semantics. A multi-model thus co-simulated can be fur-
1535 ther verified through automated model-based testing and bounded model
1536 checking.

1537 The tool chain benefits from a cohesive management interface, the INTO-
1538 CPS Application, the main gateway to modelling and validation with the
1539 INTO-CPS technology. Following the manual should give a new user of the
1540 INTO-CPS tool chain an understanding of all the elements of the INTO-CPS
1541 vision for co-simulation. This manual is accompanied by tutorial material
1542 and guidance on the main INTO-CPS tool chain website,

1543 `http://into-cps.github.io`

1544 Features that have not yet been fully developed or integrated with the INTO-
1545 CPS Application are currently being addressed and are targeted for the final
1546 year of the INTO-CPS project.

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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	Softteam
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.

1747 The following is a brief introduction to the features of the three dialects of
1748 the VDM specification language.

1749 **VDM-SL** This is the foundation of the other two dialects. It supports the
1750 development of monolithic state-based specifications with state transition
1751 operations. Central to a VDM-SL specification is a definition of the state
1752 of the system under development. The meaning of the system and how it
1753 operates is conveyed by means of changes to the state. The nature of the
1754 changes is captured by state-modifying operations. These may make use of
1755 auxiliary functions which do not modify state. The language has the usual
1756 provisions for arithmetic, new dependent types, invariants, pre- and post-
1757 conditions *etc.* Examples can be found in the VDM-SL tutorials distributed
1758 with Overture.

1759 **VDM++** The VDM++ dialect supports a specification style inspired by
1760 object-oriented programming. In this specification paradigm, a system is
1761 understood as being composed of entities which encapsulate both state and
1762 behaviour, and which interact with each other. Entities are defined via tem-
1763 plates known as *classes*. A complete system is defined by specifying *instances*
1764 of the various classes. The instances are independent of each other, and they
1765 may or may not interact with other instances. As in object-oriented program-
1766 ming, the ability of one component to act directly on any other is specified
1767 in the corresponding class as a state element. Interaction is naturally carried
1768 out via precisely defined interfaces. Usually a single class is defined which
1769 represents the entire system, and it has one instance, but this is only a con-
1770 vention. This class may have additional state elements of its own. Whereas a
1771 system in VDM-SL has a central state which is modified throughout the life-
1772 time of the system, the state of a VDM++ system is distributed among all of
1773 its components. Examples can be found in the VDM++ tutorials distributed
1774 with Overture.

1775 **VDM-RT** VDM-RT is a small extension to VDM++ which adds two pri-
1776 mary features:

- 1777 • The ability to define how the specified system is envisioned to be allo-
1778 cated on a distributed execution platform, together with the commu-
1779 nication topology.
- 1780 • The ability to specify the timing behaviours of individual components,
1781 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 104 shows 20-sim with a model of a controlled

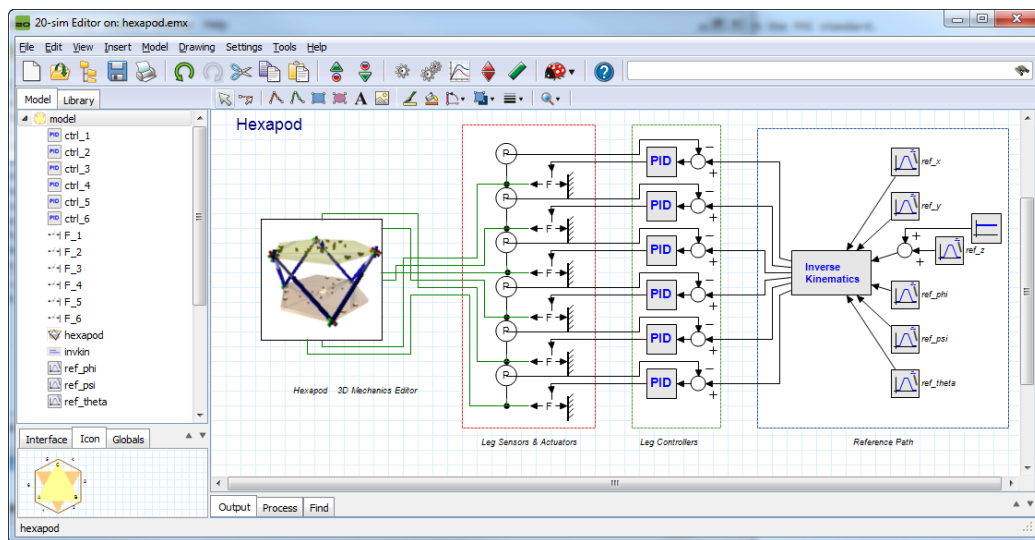


Figure 104: Example of a hexapod model in 20-sim.

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

1802 frequency domain. Everything that is required to build and simulate this
1803 model and generate the controller code for the real system is included inside
1804 the package.

1805 The 20-sim Getting Started manual [KG16] contains examples and step-by-
1806 step tutorials that demonstrate the features of 20-sim. More information on
1807 20-sim can be found at <http://www.20sim.com> and in the user manual
1808 at <http://www.20sim.com/webhelp> [KGD16]. The integration of 20-
1809 sim into the INTO-CPS tool-chain is realized via the FMI standard.

1810 B.4 OpenModelica

1811 OpenModelica [Fri04] is an open-source Modelica-based modelling and sim-
1812 ulation environment. Modelica [FE98] is an object-oriented, equation based
1813 language to conveniently model complex physical systems containing, e.g.,
1814 mechanical, electrical, electronic, hydraulic, thermal, control, electric power
1815 or process-oriented subcomponents. The Modelica language (and OpenMod-
1816 elica) supports continuous, discrete and hybrid time simulations. OpenMod-
1817 elica already compiles Modelica models into FMU, C or C++ code for simula-
1818 tion. Several integration solvers, both fixed and variable step size, are avail-
1819 able in OpenModelica: euler, rungekutta, dassl (default), radau5, radau3,
1820 radau1.

1821 OpenModelica can be interfaced to other tools in several ways as described
1822 in the OpenModelica user's manual [Ope]:

- 1823 • via command line invocation of the omc compiler
- 1824 • via C API calls to the omc compiler dynamic library
- 1825 • via the CORBA interface
- 1826 • via OMPython interface [GFR⁺12]

1827 OpenModelica has its own scripting language, Modelica script (mos files),
1828 which can be used to perform actions via the compiler API, such as load-
1829 ing, compilation, simulation of models or plotting of results. OpenModelica
1830 supports Windows, Linux and Mac Os X.

1831 The integration of OpenModelica into the INTO-CPS tool chain is realized
1832 via compliance with the FMI standard, and is described in deliverable D4.1b
1833 [PBLG15].

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 105, 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:

$$\mathbf{G}(0 \leq \text{LampsLeft} \leq 1 \wedge 0 \leq \text{LampsRight} \leq 1)$$

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

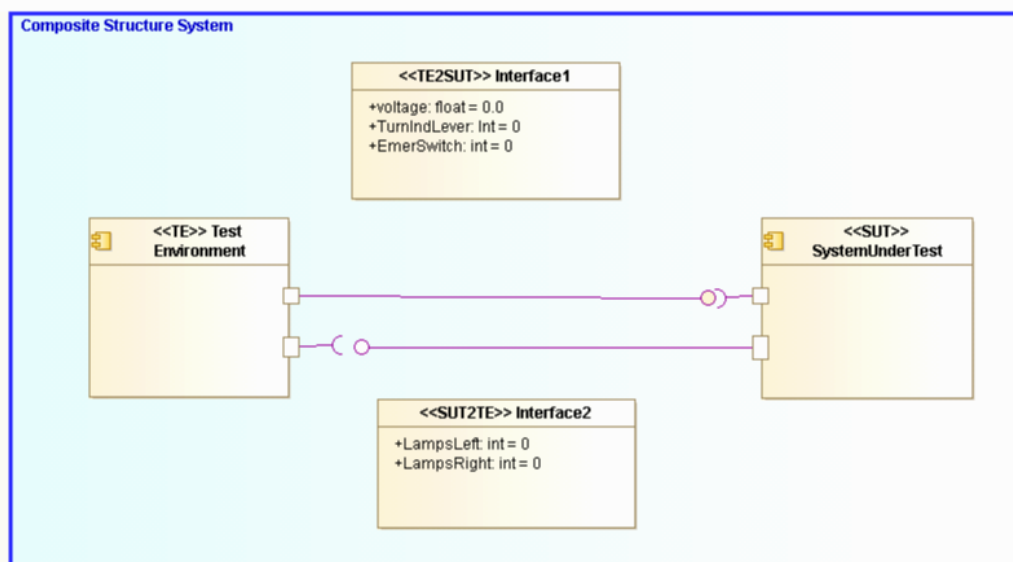


Figure 105: Simple model that highlights interfaces between the environment and the system-under-test.

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

1930 final product. The activity of investigating and gathering data about the
1931 merits of the different choices available is termed Design Space Exploration.
1932 Some of the choices the designer will face could be described as being the
1933 selection of parameters for specific components of the design, such as the
1934 exact position of a sensor, the diameter of wheels or the parameters affecting
1935 a control algorithm. Such parameters are variable to some degree and the
1936 selection of their value will affect the values of objectives by which a design
1937 will be measured. In these cases it is desirable to explore the different values
1938 each parameter may take and also different combinations of these parameter
1939 values if there are more than one parameter, to find a set of designs that best
1940 meets its objectives. However, since the size of the design space is the prod-
1941 uct of the number of parameters and the number of values each may adopt,
1942 it is often impractical to consider performing simulations of all parameter
1943 combinations or to manually assess each design.

1944 The purpose of an automated DSE tool is to help manage the exploration
1945 of the design space, and it separates this problem into three distinct parts:
1946 the search algorithm, obtaining objective values and ranking the designs
1947 according to those objectives. The simplest of all search algorithms is the
1948 exhaustive search, and this algorithm will methodically move through each
1949 design, performing a simulation using each and every one. This is termed
1950 an open loop method, as the simulation results are not considered by the
1951 algorithm at all. Other algorithms, such as a genetic search, where an initial
1952 set of randomly generated individuals are bred to produce increasingly good
1953 results, are closed loop methods. This means that the choice of next design
1954 to be simulated is driven by the results of previous simulations.

1955 Once a simulation has been performed, there are two steps required to close
1956 the loop. The first is to analyze the raw results output by the simulation to
1957 determine the value for each of the objectives by which the simulations are
1958 to be judged. Such objective values could simply be the maximum power
1959 consumed by a component or the total distance traveled by an object, but
1960 they could also be more complex measures, such as the proportion of time
1961 a device was operating in the correct mode given some conditions. As well
1962 as numerical objectives, there can also be constraints on the system that
1963 are either passed or failed. Such constraints could be numeric, such as the
1964 maximum power that a substation must never exceed, or they could be based
1965 on temporal logic to check that undesirable events do not occur, such as all
1966 the lights at a road junction not being green at the same time.

1967 The final step in a closed loop is to rank the designs according to how well
1968 each performs. The ranking may be trivial, such as in a search for a design

1969 that minimizes the total amount of energy used, or it may be more complex
1970 if there are multiple objectives to optimize and trade off. Such ranking
1971 functions can take the form of an equation that returns a score for each
1972 design, where the designs with the highest/lowest scores are considered the
1973 best. Alternatively, if the relationship between the desired objectives is not
1974 well understood, then a Pareto approach can be taken to ranking, where
1975 designs are allocated to ranks of designs that are indistinguishable from each
1976 other, in that each represents an optimum, but there exist different tradeoffs
1977 between the objective values.

1978 C.3 Model-Based Test Automation

1979 The core fragment of test automation activities is a model of the desired
1980 system behaviour, which can be expressed in SysML. This test model in-
1981 duces a transition relation, which describes a collection of execution paths
1982 through the system, where a path is considered a sequence of timed data
1983 vectors (containing internal data, inputs and outputs). The purpose of a test
1984 automation tool is to extract a subset of these paths from the test model
1985 and turn these paths into test cases, respectively test procedures. The test
1986 procedures then compare the behaviour of the actual system-under-test to
1987 the path, and produce warnings once discrepancies are observed.

1988 C.4 Code Generation

1989 Code generation refers to the translation of a modelling language to a com-
1990 mon programming language. Code generation is commonly employed in con-
1991 trol engineering, where a controller is modelled and validated using a tool
1992 such as 20-sim, and finally translated into source code to be compiled for
1993 some embedded execution platform, which is its final destination.

1994 The relationship that must be maintained between the source model and
1995 translated program must be one of refinement, in the sense that the trans-
1996 lated program must not do anything that is not captured by the original
1997 model. This must be considered when translating models written in high-
1998 level specification languages, such as VDM. The purpose of such languages
1999 is to allow the specification of several equivalent implementations. When
2000 a model written in such a language is translated to code, one such imple-
2001 mentation is essentially chosen. In the process, any non-determinism in the
2002 specification, the specification technique that allows a choice of implemen-

2003 tations, must be resolved. Usually this choice is made very simple by re-
2004 stricting the modelling language to an executable subset, such that no such
2005 non-determinism is allowed in the model. This restricts the choice of imple-
2006 mentations to very few, often one, which is the one into which the model is
2007 translated via code generation.