Functional Mock-up Interface for Model Exchange and Co-Simulation

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This document defines the Functional Mock-up Interface (FMI), version 2.0. FMI is a tool independent standard to support both model exchange and co-simulation of dynamic models using a combination of xml-files and C-code (either compiled in DLL/shared libraries or in source code). The first version, FMI 1.0, was published in 2010. The FMI development was initiated by Daimler AG with the goal to improve the exchange of simulation models between suppliers and OEMs. As of today, development of the standard continues through the participation of 16 companies and research institutes. FMI 1.0 is supported by over 45 tools and is used by automotive and non-automotive organizations throughout Europe, Asia and North America.

On the Downloads page (https://www.fmi-standard.org/downloads), this specification, as well as supporting C-header and xml schema files, and an FMI compliance checker is provided. In addition, sample models (exported from different tools in FMI format) are provided to assist tool vendors to ensure compatibility with other tools, as well as a test suite to check whether connected FMUs are appropriately handled by a tool.

Contact the FMI development group at contact@fmi-standard.org.

History / Road Map

Version	Date	Remarks
1.0	2010-01-26	First version of FMI for Model Exchange
1.0	2010-10-12	First version of FMI for Co-Simulation
2.0	2014-07-25	Second version of FMI for Model Exchange and Co-Simulation

Please, report issues that you find with this specification to the public FMI issue tracking system: https://trac.fmi-standard.org

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Abstract

This document defines the Functional Mock-up Interface (FMI), version 2.0 to (a) exchange dynamic models between tools and (b) define tool coupling for dynamic system simulation environments.

FMI for Model Exchange (chapter 3)
The intention is that a modeling environment can generate C code of a dynamic system model that can be utilized by other modeling and simulation environments. Models are described by differential, algebraic and discrete equations with time-, state- and step-events. If the C code describes a continuous system, then this system is solved with the integrators of the environment where it is used. The models to be treated by this interface can be large for usage in offline or online simulation, or can be used in embedded control systems on micro-processors.

FMI for Co-Simulation (chapter 4)
The intention is to provide an interface standard for coupling of simulation tools in a co-simulation environment. The data exchange between subsystems is restricted to discrete communication points. In the time between two communication points, the subsystems are solved independently from each other by their individual solver. Master algorithms control the data exchange between subsystems and the synchronization of all simulation solvers (slaves). Both, rather simple master algorithms, as well as more sophisticated ones are supported. Note, that the master algorithm itself is *not* part of the FMI standard.

FMI Common Concepts (chapter 2)
The two interface standards have many parts in common. In particular, it is possible to utilize several instances of a model and/or a co-simulation tool and to connect them together. The interfaces are independent of the target environment because no header files are used that depend on the target environment (with exception of the data types of the target platform). This allows generating one dynamic link library that can be utilized in any environment on the same platform. A model, a co-simulation slave or the coupling part of a tool, is distributed in one zip file called FMU (Functional Mock-up Unit) that contains several files:

(1) An XML file contains the definition of all exposed variables in the FMU and other static information. It is then possible to run the FMU on a target system without this information, in other words with no unnecessary overhead.

(2) All needed model equations or the access to co-simulation tools are provided with a small set of easy to use C functions. A new caching technique allows a more efficient evaluation of the model equations than in other approaches. These C functions can either be provided in source and/or binary form. Binary forms for different platforms can be included in the same FMU zip file.

(3) The model equations or the co-simuation tool can be either provided directly in the FMU, or the FMU contains only a generic communication module that communicates with an external tool that evaluates or simulates the model. In the XML file information about the capabilities of the FMU are present, for example to characterize the ability of a co-simulation slave to support advanced master algorithms such as the usage of variable communication step sizes, higher order signal extrapolation, or others.

(4) Further data can be included in the FMU zip file, especially a model icon (bitmap file), documentation files, maps and tables needed by the FMU, and/or all object libraries or dynamic link libraries that are utilized.

A growing set of tools supports FMI. The actual list of tools is available at:

https://www.fmi-standard.org/tools

About FMI 2.0

This version 2.0 is a major enhancement compared to FMI 1.0, where the FMI 1.0 Model Exchange and Co-Simulation standards have been merged, and many improvements have been incorporated, often due to practical experience when using the FMI 1.0 standards. New features are usually optional (need neither be supported by the tool that exports an FMU, nor by the tool that imports an FMU). Details are provided in appendix A.3.1. The appendix of the FMI 1.0 specification has been mostly moved in an extended and improved form to a companion document

"FunctionalMockupInterface-ImplementationHints.pdf"

where practical information for the implementation of the FMI standard is provided.

Conventions used in this Document

- Non-normative text is given in square brackets in italic font: [*especially examples are defined in this style.*].
- Arrays appear in two forms:
  - In the end-user/logical view, one- and two-dimensional arrays are used. Here the convention of linear algebra, the control community and the most important tools in this area is utilized, in other words the first element along one dimension starts at index one. In all these cases, the starting index is also explicitly mentioned at the respective definition of the array. Example: In the modelDescription.xml file, the set of exposed variables is defined as ordered sets where the first element is referenced with index one (these indices are, for example, used to define the sparseness structure of partial derivative matrices).
  - In the implementation view, one-dimensional C-arrays are used. In order to access an array element the C-convention is used. For example, the first element of input argument `x` for function `setContinuousStates(..)` is `x[0]`.

FMI 2.0 Implementation Help

If you plan to export or import models in FMI 2.0 format, you may find the following tools/models helpful for your development (available from https://fmi-standard.org/downloads):

- **FMU Compliance Checker**
  Free software to check whether an FMI model is compliant to the FMI standard.
- **FMUs from other tools**
  In order to test the import of FMI models from other vendors in your tool, a set of test FMUs are provided.
- **Library to test connected FMUs**
  Free Modelica library to test difficult cases of connected FMI models.
- **FMU Software Development Kit**
  Free software development kit by QTronic to demonstrate basic use of FMI.
- **FMI Library**
  Free software package by Modelon that enables integration of FMI models in applications.

Contents

1. Overview

The FMI (Functional Mock-up Interface) defines an interface to be implemented by an executable called FMU (Functional Mock-up Unit). The FMI functions are used (called) by a simulation environment to create one or more instances of the FMU and to simulate them, typically together with other models. An FMU may either have its own solvers (FMI for Co-Simulation, chapter 4) or require the simulation environment to perform numerical integration (FMI for Model Exchange, chapter 3). The goal of this interface is that the calling of an FMU in a simulation environment is reasonably simple. No provisions are provided in this document how to generate an FMU from a modeling environment. Hints for implementation can be found in the companion document "FunctionalMockupInterface-ImplementationHints.pdf".

The FMI for Model Exchange interface defines an interface to the model of a dynamic system described by differential, algebraic and discrete-time equations and to provide an interface to evaluate these equations as needed in different simulation environments, as well as in embedded control systems, with explicit or implicit integrators and fixed or variable step-size. The interface is designed to allow the description of large models.

The FMI for Co-Simulation interface is designed both for the coupling of simulation tools (simulator coupling, tool coupling), and coupling with subsystem models, which have been exported by their simulators together with its solvers as runnable code. The goal is to compute the solution of time dependent coupled systems consisting of subsystems that are continuous in time (model components that are described by differential-algebraic equations) or time-discrete (model components that are described by difference equations, for example discrete controllers). In a block representation of the coupled system, the subsystems are represented by blocks with (internal) state variables $\mathbf{x}(t)$ that are connected to other subsystems (blocks) of the coupled problem by subsystem inputs $\mathbf{u}(t)$ and subsystem outputs $\mathbf{y}(t)$.

In case of tool coupling, the modular structure of coupled problems is exploited in all stages of the simulation process beginning with the separate model setup and pre-processing for the individual subsystems in different simulation tools. During time integration, the simulation is again performed independently for all subsystems restricting the data exchange between subsystems to discrete *communication points*. Finally, also the visualization and post-processing of simulation data is done individually for each subsystem in its own native simulation tool.

The two interfaces have large parts in common. These parts are defined in chapter 2. In particular:

- FMI Application Programming Interface (C)
  All needed equations or tool coupling computations are evaluated by calling standardized "C" functions. "C" is used, because it is the most portable programming language today and is the only programming language that can be utilized in all embedded control systems.

- FMI Description Schema (XML)
  The schema defines the structure and content of an XML file generated by a modeling environment. This XML file contains the definition of all variables of the FMU in a standardized way. It is then possible to run the C code in an embedded system without the overhead of the variable definition (the alternative would be to store this information in the C code and access it via function calls, but this is neither practical for embedded systems nor for large models). Furthermore, the variable definition is a complex data structure and tools should be free how to represent this data structure in their programs. The selected approach allows a tool to store and access the variable definitions (without any memory or efficiency overhead of standardized access functions) in the programming language of the simulation environment, such as C++, C#, Java, or Python. Note, there are many free and commercial libraries in different programming languages to read XML files into an appropriate data structure, see for example http://en.wikipedia.org/wiki/XML#Parsers, and especially

the efficient open source parser SAX (http://sax.sourceforge.net/, http://en.wikipedia.org/wiki/Simple_API_for_XML).

An FMU (in other words a model without integrators, a runnable model with integrators, or a tool coupling interface) is distributed in one zip file. The zip file contains (more details are given in section 2.3):

- The FMI Description File (in XML format).
- The C sources of the FMU, including the needed run-time libraries used in the model, and/or binaries for one or several target machines, such as Windows dynamic link libraries (.dll) or Linux shared object libraries (.so). The latter solution is especially used if the FMU provider wants to hide the source code to secure the contained know-how or to allow a fully automatic import of the FMU in another simulation environment. An FMU may contain physical parameters or geometrical dimensions, which should not be open. On the other hand, some functionality requires source code.
- Additional FMU data (like tables, maps) in FMU specific file formats.

A schematic view of an FMU is shown in the next figure:

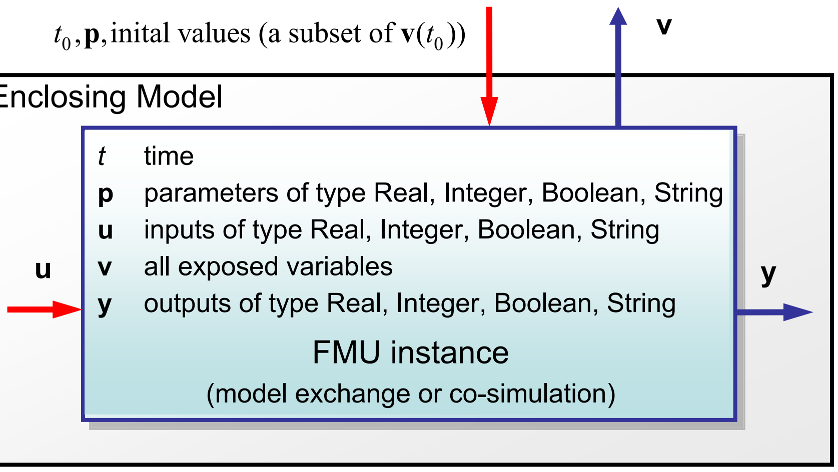
t_0, $\mathbf{p}$, inital values (a subset of $\mathbf{v}(t_0)$)
v
Enclosing Model
t time
p parameters of type Real, Integer, Boolean, String
u inputs of type Real, Integer, Boolean, String
v all exposed variables
y outputs of type Real, Integer, Boolean, String
u
y
FMU instance
(model exchange or co-simulation)

Figure 1: Data flow between the environment and an FMU. For details, see chapters 3 and 4.
Blue arrows: Information provided by the FMU.
Red arrows: Information provided to the FMU.

Publications for FMI are available from https://www.fmi-standard.org/literature, especially *Blochwitz et.al. 2011 and 2012*.

1.1 Properties and Guiding Ideas

In this section, properties are listed and some principles are defined that guided the low-level design of the FMI. This shall increase self consistency of the interface functions. The listed issues are sorted, starting from high-level properties to low-level implementation issues.

Expressivity: The FMI provides the necessary features that Modelica®, Simulink® and SIMPACK® models[1] can be transformed to an FMU.

Stability: FMI is expected to be supported by many simulation tools world wide. Implementing such support is a major investment for tool vendors. Stability and backwards compatibility of the FMI has therefore high priority. To support this, the FMI defines 'capability flags' that will be used by

[1] Modelica is a registered trademark of the Modelica Association, Simulink is a registered trademark of the MathWorks Inc., SIMPACK is a registered trademark of SIMPACK AG.

future versions of the FMI to extend and improve the FMI in a backwards compatible way, whenever feasible.

Implementation: FMUs can be written manually or can be generated automatically from a modeling environment. Existing manually coded models can be transformed manually to a model according to the FMI standard.

Processor independence: It is possible to distribute an FMU without knowing the target processor. This allows to run an FMU on a PC, a Hardware-in-the-Loop simulation platform or as part of the controller software of an ECU, e. g. as part of an AUTOSAR SWC. Keeping the FMU independent of the target processor increases the usability of the FMU and is even required by the AUTOSAR software component model. Implementation: using a textual FMU (distribute the C source of the FMU).

Simulator independence: It is possible to compile, link and distribute an FMU without knowing the target simulator. Reason: The standard would be much less attractive otherwise, unnecessarily restricting the later use of an FMU at compile time and forcing users to maintain simulator specific variants of an FMU. Implementation: using a binary FMU. When generating a binary FMU, e. g. a Windows dynamic link library (.dll) or a Linux shared object library (.so), the target operating system and eventually the target processor must be known. However, no run-time libraries, source files or header files of the target simulator are needed to generate the binary FMU. As a result, the binary FMU can be executed by any simulator running on the target platform (provided the necessary licenses are available, if required from the model or from the used run-time libraries).

Small run-time overhead: Communication between an FMU and a target simulator through the FMI does not introduce significant run time overhead. This is achieved by a new caching technique (to avoid computing the same variables several times) and by exchanging vectors instead of scalar quantities.

Small footprint: A compiled FMU (the executable) is small. Reason: An FMU may run on an ECU (Electronic Control Unit, for example a micro processor), and ECUs have strong memory limitations. This is achieved by storing signal attributes (names, units, etc.) and all other static information not needed for model evaluation in a separate text file (= Model Description File) that is not needed on the micro processor where the executable might run.

Hide data structure: The FMI for Model Exchange does not prescribe a data structure (a C struct) to represent a model. Reason: the FMI standard shall not unnecessarily restrict or prescribe a certain implementation of FMUs or simulators (whoever holds the model data), to ease implementation by different tool vendors.

Support many and nested FMUs: A simulator may run many FMUs in a single simulation run and/or multiple instances of one FMU. The inputs and outputs of these FMUs can be connected with direct feed through. Moreover, an FMU may contain nested FMUs.

Numerical Robustness: The FMI standard allows that problems which are numerically critical (for example time and state events, multiple sample rates, stiff problems) can be treated in a robust way.

Hide cache: A typical FMU will cache computed results for later reuse. To simplify usage and to reduce error possibilities by a simulator, the caching mechanism is hidden from the usage of the FMU. Reason: First, the FMI should not force an FMU to implement a certain caching policy. Second, this helps to keep the FMI simple. Implementation: The FMI provides explicit methods (called by the FMU environment) for setting properties that invalidate cached data. An FMU that chooses to implement a cache may maintain a set of 'dirty' flags, hidden from the simulator. A get method,

e. g. to a state, will then either trigger a computation, or return cached data, depending on the value of these flags.

Support numerical solvers: A typical target simulator will use numerical solvers. These solvers require vectors for states, derivatives and zero-crossing functions. The FMU directly fills the values of such vectors provided by the solvers. Reason: minimize execution time. The exposure of these vectors conflicts somewhat with the 'hide data structure' requirement, but the efficiency gain justifies this.

Explicit signature: The intended operations, argument types and return values are made explicit in the signature. For example an operator (such as 'compute_derivatives') is not passed as an int argument but a special function is called for this. The 'const' prefix is used for any pointer that should not be changed, including 'const char*' instead of 'char*'. Reason: the correct use of the FMI can be checked at compile time and allows calling of the C code in a C++ environment (which is much stricter on 'const' as C is). This will help to develop FMUs that use the FMI in the intended way.

Few functions: The FMI consists of a few, 'orthogonal' functions, avoiding redundant functions that could be defined in terms of others. Reason: This leads to a compact, easy to use, and hence attractive API with a compact documentation.

Error handling: All FMI methods use a common set of methods to communicate errors.

Allocator must free: All memory (and other resources) allocated by the FMU are freed (released) by the FMU. Likewise, resources allocated by the simulator are released by the simulator. Reason: this helps to prevent memory leaks and runtime errors due to incompatible runtime environments for different components.

Immutable strings: All strings passed as arguments or returned are read-only and must not be modified by the receiver. Reason: This eases the reuse of strings.

Named list elements: All lists defined in the `fmiModelDescription.xsd` XML schema file have a String attribute `name` to a list element. This attribute must be unique with respect to all other `name` attributes of the *same* list.

Use C: The FMI is encoded using C, not C++. Reason: Avoid problems with compiler and linker dependent behavior. Run FMU on embedded target.

This version of the functional mock-up interface does <u>not</u> have the following desirable properties. They might be added in a future version:

- The FMI for Model Exchange is for ordinary differential equations in state space form (ODE). It is not for a general differential-algebraic equation system. However, algebraic equation systems inside the FMU are supported (for example the FMU can report to the environment to re-run the current step with a smaller step size since a solution could not be found for an algebraic equation system).
- Special features as might be useful for multi-body system programs, like SIMPACK, are not included.
- The interface is for simulation and for embedded systems. Properties that might be additionally needed for trajectory optimization, for example derivatives of the model with respect to parameters during continuous integration, are not included.
- No explicit definition of the variable hierarchy in the XML file.
- The number of states and number of event indicators are fixed for an FMU and cannot be changed.

1.2 Acknowledgements

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2. FMI Common Concepts for Model Exchange and Co-Simulation

In this chapter, the concepts are defined that are common for "model exchange" and for "co-simulation". In both cases, FMI defines an input/output block of a dynamic model where the distribution of the block, the platform dependent header file, several access functions, as well as the schema files are identical. The definitions that are specific to the particular case are defined in chapters 3 and 4.

Below, the term **FMU** (Functional Mock-up Unit) will be used as common term for a model in the "FMI for model exchange" format, or a co-simulation slave in the "FMI for co-simulation" format. Note, the interface supports several instances of one FMU.

2.1 FMI Application Programming Interface

This section contains the common interface definitions to execute functions of an FMU from a C program.

Note, the following general properties hold for an FMU:

- FMI functions of one instance don't need to be thread safe.
  [*For example, if the functions of one instance of an FMU are accessed from more than one thread, the multi-threaded environment that uses the FMU must guarantee that the calling sequences of functions defined in section 3.2.3 and section 4.2.4. are used. The FMU itself does not implement any services to support this.*]
- FMI functions must not change global settings which affects other processes/threads. An FMI function may change settings of the process/thread in which it is called (such as floating point control registers), provided these changes are restored before leaving the function or before a callback function is called.
  [*So functions of different FMU instances can be called safely in any order. Additionally, they can be called in parallel provided the functions are called in different process/threads. If an FMI function changes for example the floating point control word of the CPU, it must restore the previous value before return of the function. For x86 CPUs, the floating point control word is set using the fldcw instruction. This can be used to switch on additional exceptions such as "floating point division by zero". An FMU might temporarily change the floating point control word and get notified on floating point exceptions internally, but has to restore the flag and clear the floating point status word before return of the respective FMI function.*]

2.1.1 Header Files and Naming of Functions

Three header files are provided that define the interface of an FMU. In all header files the convention is used that all C function and type definitions start with the prefix "fmi2":

- "`fmi2TypesPlatform.h`"
  contains the type definitions of the input and output arguments of the functions. This header file must be used both by the FMU and by the target simulator. If the target simulator has different definitions in the header file (for example "`typedef float fmi2Real`" instead of "`typedef double fmi2Real`"), then the FMU needs to be re-compiled with the header file used by the target simulator. Note, the header file platform for which the model was compiled can be inquired in the target simulator with `fmi2GetTypesPlatform`, see section 2.1.4.
  [*Example for a definition in this header file:*
  ```
  typedef double fmi2Real;
  ```
  ]

- "fmi2FunctionTypes.h"
  contains **typedef** definitions of all function prototypes of an FMU. When dynamically loading an FMU, these definitions can be used to type-cast the function pointers to the respective function definition.
  [*Example for a definition in this header file:*
  ```
    typedef fmi2Status fmi2SetTimeTYPE(fmi2Component, fmi2Real);
  ```
  ]
- "fmi2Functions.h"
  contains the function prototypes of an FMU that can be accessed in simulation environments and that are defined in chapters 2, 3, and 4. This header file includes "fmi2TypesPlatform.h" and "fmi2FunctionTypes.h". Note, the header file version number for which the model was compiled, can be inquired in the target simulator with fmi2GetVersion, see section 2.1.4.
  [*Example for a definition in this header file*[2]*:*
  ```
    FMI2_Export fmi2SetTimeTYPE fmi2SetTime;
  ```
  ]

The goal is that both textual and binary representations of FMUs are supported and that several FMUs might be present at the same time in an executable (for example FMU A may use an FMU B). In order for this to be possible, the names of the functions in different FMUs must be different or function pointers must be used. To support the first variant macros are provided in "fmi2Functions.h" to build the actual function names by using a function prefix that depends on how the FMU is shipped. Typically, FMU functions are used as follows:

```
// FMU is shipped with C source code, or with static link library
#define  FMI2_FUNCTION_PREFIX MyModel_
#include "fmi2Functions.h"
< usage of the FMU functions >


// FMU is shipped with DLL/SharedObject
#include "fmi2Functions.h"
< usage of the FMU functions >
```

A function that is defined as "fmi2GetReal" is changed by the macros to the following function name:

- FMU is shipped with C source code, or with static link library:
  The constructed function name is "MyModel_fmi2GetReal", in other words the function name is prefixed with the model name and an "_". As FMI2_FUNCTION_PREFIX the "modelIdentifier" "attribute defined in <fmiModelDescription><ModelExchange>, or <fmiModelDescription><CoSimulation> is used, together with "_" at the end (see sections 3.3.1 and 4.3.1). A simulation environment can therefore construct the relevant function names by generating code for the actual function call. In case of a static link library, the name of the library is MyModel.lib on Windows, and libMyModel.a on Linux, in other words the "modelIdentifier" attribute is used as library name.
- FMU is shipped with DLL/SharedObject:
  The constructed function name is "fmi2GetReal", in other words it is not changed. A simulation environment will then dynamically load this library and will explicitly import the function symbols by providing the FMI function names as strings. The name of the library is MyModel.dll on Windows or MyModel.so on Linux, in other words the "modelIdentifier" attribute is used as library name.

[2] For Microsoft and Cygwin compilers, "FMI2_Export" is defined as "__declspec(dllexport)" and for Gnu-Compilers "FMI2_Export" is defined as "__attribute__((visibility("default")))" in order to export the name for dynamic loading. Otherwise it is an empty definition.

[*An FMU can be optionally shipped so that it basically contains only the communication to another tool (needsExecutionTool = true, see section 4.3.1). This is particularily common for co-simulation tasks. In FMI 1.0, the function names are always prefixed with the model name and therefore a DLL/Shared Object has to be generated for every model. FMI 2.0 improves this situation since model names are no longer used as prefix in case of DLL/Shared Objects: Therefore one DLL/Shared Object can be used for all models in case of tool coupling. If an FMU is imported into a simulation environment, this is usually performed dynamically (based on the FMU name, the corresponding FMU is loaded during execution of the simulation environment) and then it does not matter whether a model name is prefixed or not.*]

Since "`modelIdentifier`" is used as prefix of a C-function name it must fulfill the restrictions on C-function names (only letters, digits and/or underscores are allowed). [*For example if modelName = "A.B.C", then modelIdentifier might be "A_B_C"*]. Since "`modelIdentifier`" is also used as name in a file system, it must also fulfill the restrictions of the targeted operating system. Basically, this means that it should be short. For example the Windows API only supports full path-names of a file up to 260 characters (see: http://msdn.microsoft.com/en-us/library/aa365247%28VS.85%29.aspx).

2.1.2 Platform Dependent Definitions (fmi2TypesPlatform.h)

To simplify porting, no C types are used in the function interfaces, but the alias types defined in this section. All definitions in this section are provided in the header file "`fmi2TypesPlatform.h`".

#define `fmi2TypesPlatform "default"`

A definition that can be inquired with `fmi2GetTypesPlatform`. It is used to uniquely identify the header file used for compilation of a binary. [*The "default" definition below is suitable for most common platforms. It is recommended to use this "default" definition for all binary FMUs. Only for source code FMUs, a change might be useful in some cases.*]:

```
fmi2Component           : an opaque object pointer
fmi2ComponentEnvironment: an opaque object pointer
fmi2FMUstate            : an opaque object pointer
fmi2ValueReference      : value handle type
fmi2Real                : real data type
fmi2Integer             : integer data type
fmi2Boolean             : datatype to be used with fmi2True and
                          fmi2False
fmi2Char                : character data type (size of one character)
fmi2String              : pointer to a vector of fmi2Char characters
                          ('\0' terminated, UTF8 encoded)
fmi2Byte                : smallest addressable unit of the machine
                          (typically one byte)
```

typedef void* `fmi2Component;`

This is a pointer to an FMU specific data structure that contains the information needed to process the model equations or to process the co-simulation of the respective slave. This data structure is implemented by the environment that provides the FMU, in other words the calling environment does not know its content and the code to process it must be provided by the FMU generation environment and must be shipped with the FMU.

typedef void* `fmi2ComponentEnvironment;`

This is a pointer to a data structure in the simulation environment that calls the FMU. Via this pointer, data from the modelDescription.xml file [*(for example mapping of valueReferences to variable names)*] can be transferred between the simulation environment and the logger function (see section 2.1.5).

typedef void* `fmi2FMUstate;`

This is a pointer to a data structure in the FMU that saves the internal FMU state of the actual or a previous time instant. This allows to restart a simulation from a previous FMU state (see section 2.1.8)

```
typedef unsigned int fmi2ValueReference;
```

This is a handle to a (base type) variable value of the model. Handle and base type (such as `fmi2Real`) uniquely identify the **value** of a variable. Variables of the same base type that have the same handle, always have identical values, but other parts of the variable definition might be different [*(for example min/max attributes)*].

All structured entities, like records or arrays, are “flattened” into a set of scalar values of type `fmi2Real`, `fmi2Integer` etc. An `fmi2ValueReference` references one such scalar. The coding of `fmi2ValueReference` is a “secret” of the environment that generated the FMU. The interface to the equations only provides access to variables via this handle. Extracting concrete information about a variable is specific to the used environment that reads the Model Description File in which the value handles are defined.

If a function in the following sections is called with a wrong “`fmi2ValueReference`” value [*(for example setting a constant with a `fmi2SetReal(..)` function call)*], then the function has to return with an error (`fmi2Status = fmi2Error`, see section 2.1.3).

```
typedef double          fmi2Real   ; // Data type for floating point real numbers
typedef int             fmi2Integer; // Data type for signed integer numbers
typedef int             fmi2Boolean; // Data type for Boolean numbers
                                     // (only two values: fmi2False, fmi2True)
typedef char            fmi2Char;    // Data type for one character
typedef const fmi2Char* fmi2String;  // Data type for character strings
                                     // ('\0' terminated, UTF8 encoded)
typedef char            fmi2Byte;    // Data type for the smallest addressable
                                     // unit, typically one byte

#define fmi2True  1
#define fmi2False 0
```

These are the basic data types used in the interfaces of the C functions. More data types might be included in future versions of the interface. In order to keep flexibility, especially for embedded systems or for high performance computers, the exact data types or the word length of a number are not standardized. Instead, the precise definition (in other words the header file “`fmi2TypesPlatform.h`”) is provided by the environment where the FMU shall be used. In most cases, the definition above will be used. If the target environment has different definitions and the FMU is distributed in binary format, it must be newly compiled and linked with this target header file.

If an `fmi2String` variable is passed as <u>input</u> argument to a FMI function and the FMU needs to use the string later, the FMI function must copy the string before it returns and store it in the internal FMU memory, because there is no guarantee for the lifetime of the string after the function has returned.

If an `fmi2String` variable is passed as <u>output</u> argument from a FMI function and the string shall be used in the target environment, the target environment must copy the whole string (not only the pointer). The memory of this string may be deallocated by the next call to any of the FMI interface functions (the string memory might also be just a buffer, that is reused)

2.1.3 Status Returned by Functions

This section defines the “`status`” flag (an enumeration of type `fmi2Status` defined in file “`fmi2FunctionTypes.h`”) that is returned by all functions to indicate the success of the function call:

```
typedef enum { fmi2OK,
               fmi2Warning,
               fmi2Discard,
               fmi2Error,
               fmi2Fatal,
               fmi2Pending } fmi2Status;
```

Status returned by functions. The status has the following meaning

`fmi2OK` – all well

`fmi2Warning` – things are not quite right, but the computation can continue. Function "`logger`" was called in the model (see below) and it is expected that this function has shown the prepared information message to the user.

`fmi2Discard` – this return status is only possible, if explicitly defined for the corresponding function[3] (ModelExchange: `fmi2SetReal`, `fmi2SetInteger`, `fmi2SetBoolean`, `fmi2SetString`, `fmi2SetContinuousStates`, `fmi2GetReal`, `fmi2GetDerivatives`, `fmi2GetContinuousStates`, `fmi2GetEventIndicators;`
CoSimulation: `fmi2SetReal`, `fmi2SetInteger`, `fmi2SetBoolean`, `fmi2SetString`, `fmi2DoStep`, `fmiGetXXXStatus`):
For "model exchange": It is recommended to perform a smaller step size and evaluate the model equations again, for example because an iterative solver in the model did not converge or because a function is outside of its domain (for example sqrt(<negative number>)). If this is not possible, the simulation has to be terminated.
For "co-simulation": `fmi2Discard` is returned also if the slave is not able to return the required status information. The master has to decide if the simulation run can be continued.
In both cases, function "`logger`" was called in the FMU (see below) and it is expected that this function has shown the prepared information message to the user if the FMU was called in debug mode (`loggingOn` = `fmi2True`). Otherwise, "`logger`" should not show a message.

`fmi2Error` – the FMU encountered an error. The simulation cannot be continued with this FMU instance. If one of the functions returns `fmi2Error`, it can be tried to restart the simulation from a formerly stored FMU state by calling `fmi2SetFMUstate`. This can be done if the capability flag `canGetAndSetFMUstate` is true and `fmu2GetFMUstate` was called before in non-erroneous state. If not, the simulation cannot be continued and `fmi2FreeInstance` or `fmi2Reset` must be called afterwards.[4]
Further processing is possible after this call; especially other FMU instances are not affected. Function "`logger`" was called in the FMU (see below) and it is expected that this function has shown the prepared information message to the user.

`fmi2Fatal` – the model computations are irreparably corrupted for all FMU instances. [*For example, due to a run-time exception such as access violation or integer division by zero during the execution of an fmi function*]. Function "`logger`" was called in the FMU (see below) and it is expected that this function has shown the prepared information message to the user. It is not possible to call any other function for any of the FMU instances.

`fmi2Pending` – is returned only from the co-simulation interface, if the slave executes the function in an

[3] Functions `fmi2SetXXX` are usually not performing calculations but just store the passed values in internal buffers. The actual calculation is performed by `fmi2GetXXX` functions. Still `fmi2SetXXX` functions could check whether the input arguments are in their validity range. If not, these functions could return with `fmi2Discard`.

[4] Typically, `fmi2Error` return is for non-numerical reasons, like „disk full". There might be cases where the environment can fix such errors (eventually with the help oft the user), and then simulation can continue at the last consistent state defined with `fmi2SetFMUstate`.

asynchronous way. That means the slave starts to compute but returns immediately. The master has to call `fmi2GetStatus(..., fmi2DoStepStatus)` to determine, if the slave has finished the computation. Can be returned only by `fmi2DoStep` and by `fmi2GetStatus` (see section 4.2.3).

2.1.4 Inquire Platform and Version Number of Header Files

This section documents functions to inquire information about the header files used to compile its functions.

```
const char* fmi2GetTypesPlatform(void);
```

Returns the string to uniquely identify the "`fmi2TypesPlatform.h`" header file used for compilation of the functions of the FMU. The function returns a pointer to a static string specified by "`fmi2TypesPlatform`" defined in this header file. The standard header file, as documented in this specification, has `fmi2TypesPlatform` set to "`default`" (so this function usually returns "`default`").

```
const char* fmi2GetVersion(void);
```

Returns the version of the "`fmi2Functions.h`" header file which was used to compile the functions of the FMU. The function returns "`fmiVersion`" which is defined in this header file. The standard header file as documented in this specification has version "`2.0`" (so this function usually returns "`2.0`").

2.1.5 Creation, Destruction and Logging of FMU Instances

This section documents functions that deal with instantiation, destruction and logging of FMUs.

```
fmi2Component fmi2Instantiate(fmi2String  instanceName,
                              fmi2Type    fmuType,
                              fmi2String  fmuGUID,
                              fmi2String  fmuResourceLocation,
                              const fmi2CallbackFunctions* functions,
                              fmi2Boolean                  visible,
                              fmi2Boolean                  loggingOn);
```

```
typedef enum {fmi2ModelExchange,
              fmi2CoSimulation
             }fmi2Type;
```

The function returns a new instance of an FMU. If a null pointer is returned, then instantiation failed. In that case, "`functions->logger`" was called with detailed information about the reason. An FMU can be instantiated many times (provided capability flag `canBeInstantiatedOnlyOncePerProcess = false`).

This function must be called successfully, before any of the following functions can be called. For co-simulation, this function call has to perform all actions of a slave which are necessary before a simulation run starts (for example loading the model file, compilation...).

Argument `instanceName` is a unique identifier for the FMU instance. It is used to name the instance, for example in error or information messages generated by one of the `fmi2XXX` functions. It is not allowed to provide a null pointer and this string must be non-empty (in other words must have at least one character that is no white space). [*If only one FMU is simulated, as instanceName attribute `modelName` or `<ModelExchange/CoSimulation modelIdentifier=".."> ` from the XML schema `fmiModelDescription` might be used.*]

Argument `fmuType` defines the type of the FMU:

- = `fmi2ModelExchange`: FMU with initialization and events; between events simulation of continuous systems is performed with external integrators from the environment (see section 3).
- = `fmi2CoSimulation`: Black box interface for co-simulation (see section 4).

Argument `fmuGUID` is used to check that the modelDescription.xml file (see section 2.3) is compatible with the C code of the FMU. It is a vendor specific globally unique identifier of the XML file (for example it is a "fingerprint" of the relevant information stored in the XML file). It is stored in the XML file as attribute "guid" (see section 2.2.1) and has to be passed to the `fmi2Instantiate` function via argument `fmuGUID`. It must be identical to the one stored inside the `fmi2Instantiate` function. Otherwise the C code and the XML file of the FMU are not consistent to each other. This argument cannot be null.

Argument `fmuResourceLocation` is an URI according to the IETF RFC3986 syntax to indicate the location to the "`resources`" directory of the unzipped FMU archive. The following schemes must be understood by the FMU:

- Mandatory: "file" with absolute path (either including or omitting the authority component)
- Optional: "http", "https", "ftp"
- Reserved: "fmi2" for FMI for PLM.

[*Example: An FMU is unzipped in directory "C:\temp\MyFMU", then fmuResourceLocation = "file:///C:/temp/MyFMU/resources" or "file:/C:/temp/MyFMU/resources". Function fmi2Instantiate is then able to read all needed resources from this directory, for example maps or tables used by the FMU.*]

Argument `functions` provides callback functions to be used from the FMU functions to utilize resources from the environment (see type `fmi2CallbackFunctions` below).

Argument `visible = fmi2False` defines that the interaction with the user should be reduced to a minimum (no application window, no plotting, no animation, etc.), in other words the FMU is executed in batch mode. If `visible = fmi2True`, the FMU is executed in interactive mode and the FMU might require to explicitly acknowledge start of simulation / instantiation / initialization (acknowledgment is non-blocking).

If `loggingOn=fmi2True`, debug logging is enabled. If `loggingOn=fmi2False`, debug logging is disabled. [*The FMU enable/disables* `LogCategories` *which are useful for debugging according to this argument. Which* `LogCategories` *the FMU sets is unspecified.*]

```
typedef struct {
     void  (*logger)(fmi2ComponentEnvironment componentEnvironment,
                     fmi2String instanceName,
                     fmi2Status status,
                     fmi2String category,
                     fmi2String message, ...);
     void* (*allocateMemory)(size_t nobj, size_t size);
     void  (*freeMemory)     (void* obj);
     void  (*stepFinished)   (fmi2ComponentEnvironment componentEnvironment,
                              fmi2Status status);
     fmi2ComponentEnvironment componentEnvironment;
} fmi2CallbackFunctions;
```

The struct contains pointers to functions provided by the environment to be used by the FMU. It is not allowed to change these functions between `fmi2Instantiate(..)` and `fmi2Terminate(..)` calls. Additionally, a pointer to the environment is provided (componentEnvironment) that needs to be passed to the "logger" function, in order that the

logger function can utilize data from the environment, such as mapping a `valueReference` to a string. In the unlikely case that `fmi2Component` is also needed in the logger, it has to be passed via argument `componentEnvironment`. Argument `componentEnvironment` may be a null pointer.
The `componentEnvironment` pointer is also passed to the `stepFinished(..)` function in order that the environment can provide an efficient way to identify the slave that called `stepFinished(..)`.

In the default `fmi2FunctionTypes.h` file, `typedef`s for the function definitions are present to simplify the usage. This is non-normative. The functions have the following meaning:

Function **logger**:
Pointer to a function that is called in the FMU, usually if a `fmi2XXX` function does not behave as desired. If "`logger`" is called with "`status = fmi2OK`", then the message is a pure information message. "`instanceName`" is the instance name of the model that calls this function. "`category`" is the category of the message. The meaning of "`category`" is defined by the modeling environment that generated the FMU. Depending on this modeling environment, none, some or all allowed values of "`category`" for this FMU are defined in the `modelDescription.xml` file via element "`<fmiModelDescription><LogCategories>`", see section 2.2.4. Only messages are provided by function `logger` that have a category according to a call to `fmi2SetDebugLogging` (see below). Argument "`message`" is provided in the same way and with the same format control as in function "`printf`" from the C standard library. [*Typically, this function prints the message and stores it optionally in a log file.*]
All string-valued arguments passed by the FMU to the logger may be deallocated by the FMU directly after function `logger` returns. The environment must therefore create copies of these strings if it needs to access these strings later.
The logger function will append a line break to each message when writing messages after each other to a terminal or a file (the messages may also be shown in other ways, for example as separate text-boxes in a GUI). The caller may include line-breaks (using "\n") within the message, but should avoid trailing line breaks.
Variables are referenced in a message with "#<Type><ValueReference>#" where <Type> is "r" for `fmi2Real`, "i" for `fmi2Integer`, "b" for `fmi2Boolean` and "s" for `fmi2String`. If character "#"shall be included in the message, it has to be prefixed with "#", so "#" is an escape character. [*Example:*

A message of the form
"`#r1365# must be larger than zero (used in IO channel ##4)`"
might be changed by the `logger` *function to*
"`body.m must be larger than zero (used in IO channel #4)`"
if "`body.m`" *is the name of the* `fmi2Real` *variable with* `fmi2ValueReference = 1365`.]

Function **allocateMemory**:
Pointer to a function that is called in the FMU if memory needs to be allocated. If attribute "`canNotUseMemoryManagementFunctions = true`" in `<fmiModelDescription><ModelExchange / CoSimulation>`, then function `allocateMemory` is not used in the FMU and a void pointer can be provided. If this attribute has a value of "`false`" (which is the default), the FMU must not use `malloc`, `calloc` or other memory allocation functions. One reason is that these functions might not be available for embedded systems on the target machine. Another reason is that the environment may have optimized or specialized memory allocation functions. `allocateMemory` returns a

pointer to space for a vector of `nobj` objects, each of size "`size`" or `NULL`, if the request cannot be satisfied. The space is initialized to zero bytes [*(a simple implementation is to use `calloc` from the C standard library)*].

Function **freeMemory**:
Pointer to a function that must be called in the FMU if memory is freed that has been allocated with `allocateMemory`. If a null pointer is provided as input argument `obj`, the function shall perform no action [*(a simple implementation is to use `free` from the C standard library; in ANSI C89 and C99, the null pointer handling is identical as defined here)*]. If attribute "`canNotUseMemoryManagementFunctions = true`" in `<fmiModelDescription><ModelExchange / CoSimulation>`, then function `freeMemory` is not used in the FMU and a null pointer can be provided.

Function **stepFinished**:
Optional call back function to signal if the computation of a communication step of a co-simulation slave is finished. A null pointer can be provided. In this case the master must use `fmiGetStatus(..)` to query the status of `fmi2DoStep`. If a pointer to a function is provided, it must be called by the FMU after a completed communication step.

```
void fmi2FreeInstance(fmi2Component c);
```

Disposes the given instance, unloads the loaded model, and frees all the allocated memory and other resources that have been allocated by the functions of the FMU interface. If a null pointer is provided for "`c`", the function call is ignored (does not have an effect).

```
fmi2Status fmi2SetDebugLogging(fmi2Component c, fmi2Boolean loggingOn,
                               size_t nCategories,
                               const fmi2String categories[]);
```

If `loggingOn=fmi2True`, debug logging is enabled, otherwise it is switched off.
If `loggingOn=fmi2True` and `nCategories > 0`, then only debug messages according to the `categories` argument shall be printed via the logger function. Vector `categories` has `nCategories` elements. The allowed values of "`category`" are defined by the modeling environment that generated the FMU. Depending on the generating modeling environment, none, some or all allowed values for "`categories`" for this FMU are defined in the `modelDescription.xml` file via element "`fmiModelDescription.LogCategories`", see section 2.2.4.

2.1.6 Initialization, Termination, and Resetting an FMU

This section documents functions that deal with initialization, termination, and resetting of an FMU.

```
fmi2Status fmi2SetupExperiment(fmi2Component c,
                               fmi2Boolean   toleranceDefined,
                               fmi2Real      tolerance,
                               fmi2Real      startTime,
                               fmi2Boolean   stopTimeDefined,
                               fmi2Real      stopTime);
```

Informs the FMU to setup the experiment. This function can be called after `fmi2Instantiate` and before `fmi2EnterInitializationMode` is called. Arguments `toleranceDefined` and `tolerance` depend on the FMU type:

fmuType = fmi2ModelExchange:

If "`toleranceDefined = fmi2True`" then the model is called with a numerical integration scheme where the step size is controlled by using "`tolerance`" for error estimation (usually as relative tolerance). In such a case, all numerical algorithms used inside the model (for example to solve non-linear algebraic equations) should also operate with an error estimation of an appropriate smaller relative tolerance.

fmuType = fmi2CoSimulation:
If "`toleranceDefined = fmi2True`" then the communication interval of the slave is controlled by error estimation. In case the slave utilizes a numerical integrator with variable step size and error estimation, it is suggested to use "`tolerance`" for the error estimation of the internal integrator (usually as relative tolerance).
An FMU for Co-Simulation might ignore this argument.

The arguments `startTime` and `stopTime` can be used to check whether the model is valid within the given boundaries or to allocate memory which is necessary for storing results. Argument `startTime` is the fixed initial value of the independent variable[5] [*if the independent variable is "`time`", `startTime` is the starting time of initializaton*]. If `stopTimeDefined = fmi2True`, then `stopTime` is the defined final value of the independent variable [*if the independent variable is "`time`", `stopTime` is the stop time of the simulation*] and if the environment tries to compute past `stopTime` the FMU has to return `fmi2Status = fmi2Error`. If `stopTimeDefined = fmi2False`, then no final value of the independent variable is defined and argument `stopTime` is meaningless.

```
fmi2Status fmi2EnterInitializationMode(fmi2Component c);
```
Informs the FMU to enter Initialization Mode. Before calling this function, all variables with attribute `<ScalarVariable initial = "exact"` or `"approx">` can be set with the "`fmi2SetXXX`" functions (the `ScalarVariable` attributes are defined in the Model Description File, see section 2.2.7). Setting other variables is not allowed. Furthermore, `fmi2SetupExperiment` must be called at least once before calling `fmi2EnterInitializationMode`, in order that `startTime` is defined.

```
fmi2Status fmi2ExitInitializationMode(fmi2Component c);
```
Informs the FMU to exit Initialization Mode.
For `fmuType = fmi2ModelExchange`, this function switches off all initialization equations and the FMU enters implicitely Event Mode, that is all continuous-time and active discrete-time equations are available.

```
fmi2Status fmi2Terminate(fmi2Component c);
```
Informs the FMU that the simulation run is terminated. After calling this function, the final values of all variables can be inquired with the `fmi2GetXXX(..)` functions. It is not allowed to call this function after one of the functions returned with a status flag of `fmi2Error` or `fmi2Fatal`.

```
fmi2Status fmi2Reset(fmi2Component c);
```
Is called by the environment to reset the FMU after a simulation run. The FMU goes into the same state as if `fmi2Instantiate` would have been called. All variables have their default values. Before starting a new run, `fmi2SetupExperiment` and `fmi2EnterInitializationMode` have to be called.

[5] The variable that is defined with `causality = "independent"` in the `fmiModelDescription.xml` file.

2.1.7 Getting and Setting Variable Values

All variable values of an FMU are identified with a variable handle called "value reference". The handle is defined in the `modelDescription.xml` file (as attribute "`valueReference`" in element "`ScalarVariable`"). Element "`valueReference`" might not be unique for all variables. If two or more variables of the same base data type (such as `fmi2Real`) have the same `valueReference`, then they have identical values but other parts of the variable definition might be different [*(for example min/max attributes)*].

The actual values of the variables that are defined in the `modelDescription.xml` file can be inquired after calling `fmi2EnterInitializationMode` with the following functions:

```
fmi2Status fmi2GetReal   (fmi2Component c, const fmi2ValueReference vr[],
                          size_t nvr, fmi2Real value[]);
fmi2Status fmi2GetInteger(fmi2Component c, const fmi2ValueReference vr[],
                          size_t nvr, fmi2Integer value[]);
fmi2Status fmi2GetBoolean(fmi2Component c, const fmi2ValueReference vr[],
                          size_t nvr, fmi2Boolean value[]);
fmi2Status fmi2GetString (fmi2Component c, const fmi2ValueReference vr[],
                          size_t nvr, fmi2String value[]);
```

Get actual values of variables by providing their variable references. [*These functions are especially used to get the actual values of output variables if a model is connected with other models. Since state derivatives are also ScalarVariables, it is possible to get the value of a state derivative. This is useful when connecting FMUs together. Furthermore, the actual value of every variable defined in the modelDescription.xml file can be determined at the actually defined time instant (see section 2.2.7).*]

- Argument "`vr`" is a vector of "`nvr`" value handles that define the variables that shall be inquired.
- Argument "`value`" is a vector with the actual values of these variables.
- The strings returned by `fmi2GetString` must be copied in the target environment, because the allocated memory for these strings might be deallocated by the next call to any of the fmi2 interface functions or it might be an internal string buffer that is reused.
- Note for ModelExchange: `fmi2Status = fmi2Discard` is possible for `fmi2GetReal` only, but not for `fmi2GetInteger`, `fmi2GetBoolean`, `fmi2GetString`, because these are discrete-time variables and their values can only change at an event instant where `fmi2Discard` does not make sense.

It is also possible to <u>set</u> the values of <u>certain</u> variables at particular instants in time using the following functions:

```
fmi2Status fmi2SetReal   (fmi2Component c, const fmi2ValueReference vr[],
                          size_t nvr, const fmi2Real value[]);
fmi2Status fmi2SetInteger(fmi2Component c, const fmi2ValueReference vr[],
                          size_t nvr, const fmi2Integer value[]);
fmi2Status fmi2SetBoolean(fmi2Component c, const fmi2ValueReference vr[],
                          size_t nvr, const fmi2Boolean value[]);
fmi2Status fmi2SetString (fmi2Component c, const fmi2ValueReference vr[],
                          size_t nvr, const fmi2String value[]);
```

Set parameters, inputs, start values and re-initialize caching of variables that depend on these variables (see section 2.2.7 for the exact rules on which type of variables `fmi2SetXXX` can be called, as well as section 3.2.3 in case of ModelExchange and section 4.2.4 in case of CoSimulation).

- Argument "`vr`" is a vector of "`nvr`" value handles that define the variables that shall be set.
- Argument "`value`" is a vector with the actual values of these variables.
- All strings passed as arguments to `fmi2SetString` must be copied inside this function, because there is no guarantee of the lifetime of strings, when this function returns.
- Note: `fmi2Status = fmi2Discard` is possible for the `fmi2SetXXX` functions.

For co-simulation FMUs, additional functions are defined in section 4.2.1 to set and inquire derivatives of variables with respect to time in order to allow interpolation.

2.1.8 Getting and Setting the Complete FMU State

The FMU has an internal state consisting of all values that are needed to continue a simulation. This internal state consists especially of the values of the continuous-time states, iteration variables, parameter values, input values, delay buffers, file identifiers and FMU internal status information. With the functions of this section, the internal FMU state can be copied and the pointer to this copy is returned to the environment. The FMU state copy can be set as actual FMU state, in order to continue the simulation from it.

[*Examples, for using this feature:*

For variable step-size control of co-simulation master algorithms (get the FMU state for every accepted communication step; if the follow-up step is not accepted, restart co-simulation from this FMU state).

For nonlinear Kalman filters (get the FMU state just before initialization; in every sample period, set new continuous states from the Kalman filter algorithm based on measured values; integrate to the next sample instant and inquire the predicted continuous states that are used in the Kalman filter algorithm as basis to set new continuous states).

For nonlinear model predictive control (get the FMU state just before initialization; in every sample period, set new continuous states from an observer, initialize and get the FMU state after initialization. From this state, perform many simulations that are restarted after the initialization with new input signals proposed by the optimizer).]

Furthermore, the FMU state can be serialized and copied in a byte vector: [*This can be, for example used to perform an expensive steady-state initialization, copy the received FMU state in a byte vector and store this vector on file. Whenever needed, the byte vector can be loaded from file, can be deserialized and the simulation is restarted from this FMU state, in other words from the steady-state initialization.*]

```
fmi2Status fmi2GetFMUstate (fmi2Component c, fmi2FMUstate* FMUstate);
fmi2Status fmi2SetFMUstate (fmi2Component c, fmi2FMUstate  FMUstate);
fmi2Status fmi2FreeFMUstate(fmi2Component c, fmi2FMUstate* FMUstate);
```

`fmi2GetFMUstate` makes a copy of the internal FMU state and returns a pointer to this copy (`FMUstate`). If on entry `*FMUstate == NULL`, a new allocation is required. If `*FMUstate != NULL`, then `*FMUstate` points to a previously returned `FMUstate` that has not been modified since. In particular, `fmi2FreeFMUstate` had not been called with this `FMUstate` as an argument. [*Function `fmi2GetFMUstate` typically reuses the memory of this `FMUstate` in this case and returns the same pointer to it, but with the actual `FMUstate`.*]

`fmi2SetFMUstate` copies the content of the previously copied `FMUstate` back and uses it as actual new FMU state. The `FMUstate` copy does still exist.

`fmi2FreeFMUstate` frees all memory and other resources allocated with the `fmi2GetFMUstate` call for this `FMUstate`. The input argument to this function is the `FMUstate` to be freed. If a null pointer is provided, the call is ignored. The function returns a null pointer in argument `FMUstate`.

These functions are only supported by the FMU, if the optional capability flag `<fmiModelDescription> <ModelExchange / CoSimulation canGetAndSetFMUstate` in `= "true">` in the XML file is explicitly set to `true` (see sections 3.3.1 and 4.3.1).

```
fmi2Status fmi2SerializedFMUstateSize(fmi2Component c, fmi2FMUstate FMUstate,
                                      size_t *size);
fmi2Status fmi2SerializeFMUstate     (fmi2Component c, fmi2FMUstate FMUstate,
                                      fmi2Byte serializedState[], size_t size);
fmi2Status fmi2DeSerializeFMUstate   (fmi2Component c,
                                      const fmi2Byte serializedState[],
                                      size_t size, fmi2FMUstate* FMUstate);
```

`fmi2SerializedFMUstateSize` returns the `size` of the byte vector, in order that `FMUstate` can be stored in it. With this information, the environment has to allocate an `fmi2Byte` vector of the required length `size`.

`fmi2SerializeFMUstate` serializes the data which is referenced by pointer `FMUstate` and copies this data in to the byte vector `serializedState` of length `size`, that must be provided by the environment.

`fmi2DeSerializeFMUstate` deserializes the byte vector `serializedState` of length `size`, constructs a copy of the FMU state and returns `FMUstate`, the pointer to this copy. [*The simulation is restarted at this state, when calling fmi2SetFMUState with FMUstate.*]

These functions are only supported by the FMU, if the optional capability flags `canGetAndSetFMUstate` and `canSerializeFMUstate` in `<fmiModelDescription><ModelExchange / CoSimulation>` in the XML file are explicitly set to `true` (see sections 3.3.1 and 4.3.1).

2.1.9 Getting Partial Derivatives

It is optionally possible to provide evaluation of partial derivatives for an FMU. For Model Exchange, this means computing the partial derivatives at a particular time instant. For Co-Simulation, this means to compute the partial derivatives at a particular communication point. One function is provided to compute directional derivatives. This function can be used to construct the desired partial derivative matrices.

```
fmi2Status fmi2GetDirectionalDerivative(fmi2Component c,
                    const fmi2ValueReference vUnknown_ref[], size_t nUnknown,
                    const fmi2ValueReference vKnown_ref[]  , size_t nKnown,
                    const fmi2Real dvKnown[],
                          fmi2Real dvUnknown[])
```

This function computes the directional derivatives of an FMU. An FMU has different Modes and in every Mode an FMU might be described by different equations and different unknowns. The precise definitions are given in the mathematical descriptions of Model Exchange (section 3.1) and Co-Simulation (section 4.1). In every Mode, the general form of the FMU equations are:

$$\mathbf{v}_{unknown} = \mathbf{h}(\mathbf{v}_{known}, \mathbf{v}_{rest})$$

where

- $\mathbf{v}_{unknown}$ is the vector of unknown Real variables computed in the actual Mode:
  - *Initialization Mode*: The exposed unknowns listed under `<ModelStructure><InitialUnknowns>` that have type Real.
  - *Continuous-Time Mode* (ModelExchange): The continuous-time outputs and state derivatives (= the variables listed under `<ModelStructure><Outputs>` with type Real and `variability = "continuous"` and the variables listed as state derivatives under `<ModelStructure><Derivatives>`).

- *Event Mode (ModelExchange):* The same variables as in the *Continuous-Time Mode* and additionally variables under `<ModelStructure><Outputs>` with type Real and `variability = "discrete"`.
- *Step Mode (CoSimulation):* The variables listed under `<ModelStructure><Outputs>` with type Real and `variability = "continuous"` or `"discrete"`. If `<ModelStructure><Derivatives>` is present, also the variables listed here as state derivatives.

- $\mathbf{v}_{known}$ is the vector of Real input variables of function **h** that changes its value in the actual Mode. Details are described in the description of element `dependencies` on page 61 [*for example continuous-time inputs in Continuous-Time Mode. If a variable with `causality` = "`independent`" is explicitely defined under `ScalarVariables`, a directional derivative with respect to this variable can be computed. If such a variable is not defined, the directional derivative with respect to the independent variable cannot be calculated*].
- $\mathbf{v}_{rest}$ is the set of input variables of function **h** that either changes its value in the actual Mode but are non-Real variables, or do not change their values in this Mode, but change their values in other Modes [*for example discrete-time inputs in Continuous-Time Mode*].

If the capability attribute "`providesDirectionalDerivative`" is `true`, `fmi2GetDirectionalDerivative` computes a linear combination of the partial derivatives of **h** with respect to the selected input variables $\mathbf{v}_{known}$:

$$\Delta\mathbf{v}_{unkown} = \frac{\partial\mathbf{h}}{\partial\mathbf{v}_{known}}\mathbf{v}_{known}$$

Accordingly, it computes the directional derivative vector $\Delta\mathbf{v}_{unknown}$ (`dvUnknown`) from the seed vector $\Delta\mathbf{v}_{known}$(`dvKnown`).

[*The variable relationships are different in different modes. For example, during Continuous-Time Mode, a continuous-time output y does not depend on discrete-time inputs (because they are held constant between events). However, at Event Mode, y depends on discrete-time inputs.*]

The function may compute the directional derivatives by numerical differentiation taking into account the sparseness of the equation system, or (preferred) by analytic derivatives.

Example:
Assume an FMU has the output equations

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} g_1(x, u_1, u_3, u_4) \\ g_2(x, u_1) \end{bmatrix}$$

and this FMU is connected, so that y_1, u_1, u_3 *appear in an algebraic loop. Then the nonlinear solver needs a Jacobian and this Jacobian can be computed (without numerical differentiation) provided the partial derivative of* y_1 *with respect to* u_1 *and* u_3 *is available. Depending on the environment where the FMUs are connected, these derivatives can be provided*

(a) with one wrapper function around function fmi2GetDirectionalDerivative to compute the directional derivatives with respect to these two variables (in other words $v_{unknown} = y_1$, $v_{known} = \{u_1, u_3\}$*) and then the environment calls this wrapper function with* $\Delta v_{known} = \{1{,}0\}$ *to compute the partial derivative with respect to* u_1 *and* $\Delta v_{known} = \{0{,}1\}$ *to compute the partial derivative with respect to* u_3*, or*

(b) with two direct function calls of fmi2GetDirectionalDerivative (in other words $v_{unknown} = y_1,\ v_{known} = u_1,\ \Delta v_{known} = 1$*; and* $v_{unknown} = y_1,\ v_{known} = u_3,\ \Delta v_{known} = 1$*).*

Note, a direct implementation of this function with analytic derivatives provides:

(a) The directional derivative for all input variables;

so in the above example: $\Delta y_1 = \frac{\partial g_1}{\partial x} \cdot \Delta x + \frac{\partial g_1}{\partial u_1} \cdot \Delta u_1 + \frac{\partial g_1}{\partial u_3} \cdot \Delta u_3 + \frac{\partial g_1}{\partial u_4} \cdot \Delta u_4$

(b) *Initializes all seed-values to zero;*
so in the above example: $\Delta x = \Delta u_1 = \Delta u_3 = \Delta u_4 = 0$

(c) *Computes the directional derivative with the seed-values provided in the function arguments; so in the above example:* $\Delta v_{unknown} = \Delta y_1 \; (\Delta x = 0, \Delta u_1 = 1, \Delta u_3 = 1, \Delta u_4 = 0)$

]

[*Note, function fmi2GetDirectionalDerivative can be utilized for the following purposes:*

- *Numerical integrators of stiff methods need matrix* $\frac{\partial \mathbf{f}}{\partial \mathbf{x}}$.
- *If the FMU is connected with other FMUs, the partial derivatives of the state derivatives and outputs with respect to the continuous states and the inputs are needed in order to compute the Jacobian for the system of the connected FMUs.*
- *If the FMU shall be linearized, the same derivatives as in the previous item are needed.*
- *If the FMU is used as the model for an extended Kalman filter,* $\frac{\partial \mathbf{f}}{\partial \mathbf{x}}$ and $\frac{\partial \mathbf{g}}{\partial \mathbf{x}}$ are needed.

If a dense matrix shall be computed, the columns of the matrix can be easily constructed by successive calls of fmi2GetDirectionalDerivative. For example, constructing the system Jacobian $\mathbf{A} = \frac{\partial \mathbf{f}}{\partial \mathbf{x}}$ *as dense matrix can be performed in the following way (in pseudo-code notation):*

```
m = M_fmi2Instantiate("m", ...)  // "m" is the instance name
                                // "M_" is the MODEL_IDENTIFIER
// from XML file
nx      = ...   // number of states
x_ref [..] = ...    // vector of value references of cont.-time states
xd_ref[..] = ...    // vector of value references of state derivatives
...
// If required at this step, compute the Jacobian as dense matrix
   // Set time, states and inputs
   M_fmi2SetTime(m, time)
   M_fmi2SetContinuousStates(m, x, nx)
   M_fmi2SetReal/Integer/Boolean/String(m, ...)

   // Construct the Jacobian elements J[:,:] columnwise
   for i in 1:nx loop
      M_fmi2GetDirectionalDerivative(m, x_ref[i], 1, xd_ref, nx, 1.0, ci);
      J[:,i] = ci;    // ci is an auxiliary vector of nx elements
                      // (it holds the i-th column of the Jacobian)
   end for;
```

If the sparsity of a matrix shall be taken into account, then the matrix can be constructed in the following way:

1. *The incidence information of the matrix (whether an element is zero or not zero) is extracted from the xml file from element <ModelStructure>.*
2. *A so called graph coloring algorithm is employed to determine the columns of the matrix that can be computed by one call of fmi2GetDirectionalDerivative. Efficient graph coloring algorithms are freely available, such as library ColPack (http://www.cscapes.org/coloringpage/) written in C/C++ (LGPL),*

or the routines by Coleman, Garbow, Moré: "Software for estimating sparse Jacobian matrices", ACM Transactions on Mathematical Software - TOMS , vol. 10, no. 3, pp. 346-347, 1984. See e.g. http://www.netlib.org/toms/618.

3. *For the columns determined in (2), one call to fmi2DirectionalDerivative is made. After each such call, the elements of the resulting directional derivative vector are copied into their correct locations of the partial derivative matrix.*

More details and implementational notes are available from (Akesson et.al. 2012).

]

2.2 FMI Description Schema

All static information related to an FMU is stored in the text file `modelDescription.xml` in XML format. Especially, the FMU variables and their attributes such as name, unit, default initial value etc. are stored in this file. The structure of this XML file is defined with the schema file "`fmiModelDescription.xsd`". This schema file utilizes the following helper schema files:

```
fmi2Annotation.xsd
fmi2AttributeGroups.xsd
fmi2ScalarVariable.xsd
fmi2Type.xsd
fmi2VariableDependency.xsd
fmi2Unit.xsd
```

In this section these schema files are discussed. The normative definition are the above mentioned schema files[6]. Below, optional elements are marked with a "dashed" box. The required data types (like: xs:normalizedString) are defined in the XML-schema standard: http://www.w3.org/TR/XMLschema-2/. The types used in the fmi2 schema files are:

XML	Description (http://www.w3.org/TR/XMLschema-2/)	*Mapping to C*
xs:double	IEEE double-precision 64-bit floating point type [*In order to not loose precision, a number of this type should be stored on an XML file with at least **16** significant digits; for example 2/3 should be stored as* `0.6666666666666667`]	double
xs:int	Integer number with maximum value 2147483647 and minimum value -2147483648 (32 bit Integer)	int
xs:unsignedInt	Integer number with maximum value 4294967295 and minimum value 0 (unsigned 32 bit Integer)	unsigned int
xs:boolean	Boolean number. Legal literals: false, true, 0, 1	char
xs:string	Any number of characters	char*
xs:normalizedString	String without carriage return, line feed, and tab characters	char*
xs:dateTime	Date, time and time zone (for details see the link above). Example: 2002-10-23T12:00:00Z (noon on October 23, 2002, Greenwich Mean Time)	tool specific

The first line of an XML file, such as `modelDescription.xml`, must contain the encoding scheme of the XML file. It is required that the encoding scheme is always UTF-8:

[6] Note, the screenshots of this section have been generated from the schema files with the tool "Altova XMLSpy" (www.altova.com). With the enterprise edition of XMLSpy it is possible to automatically generate C++, C# and Java code that reads an XML file of fmiModelDescription.xsd. An efficient open source XML parser is SAX (http://sax.sourceforge.net/, http://en.wikipedia.org/wiki/Simple_API_for_XML). All data from the XML file is only defined via "attributes" and not via "elements". Therefore, only an "attribute" handler needs to be defined for a SAX parser.

```
<?xml version="1.0" encoding="UTF-8"?>
```

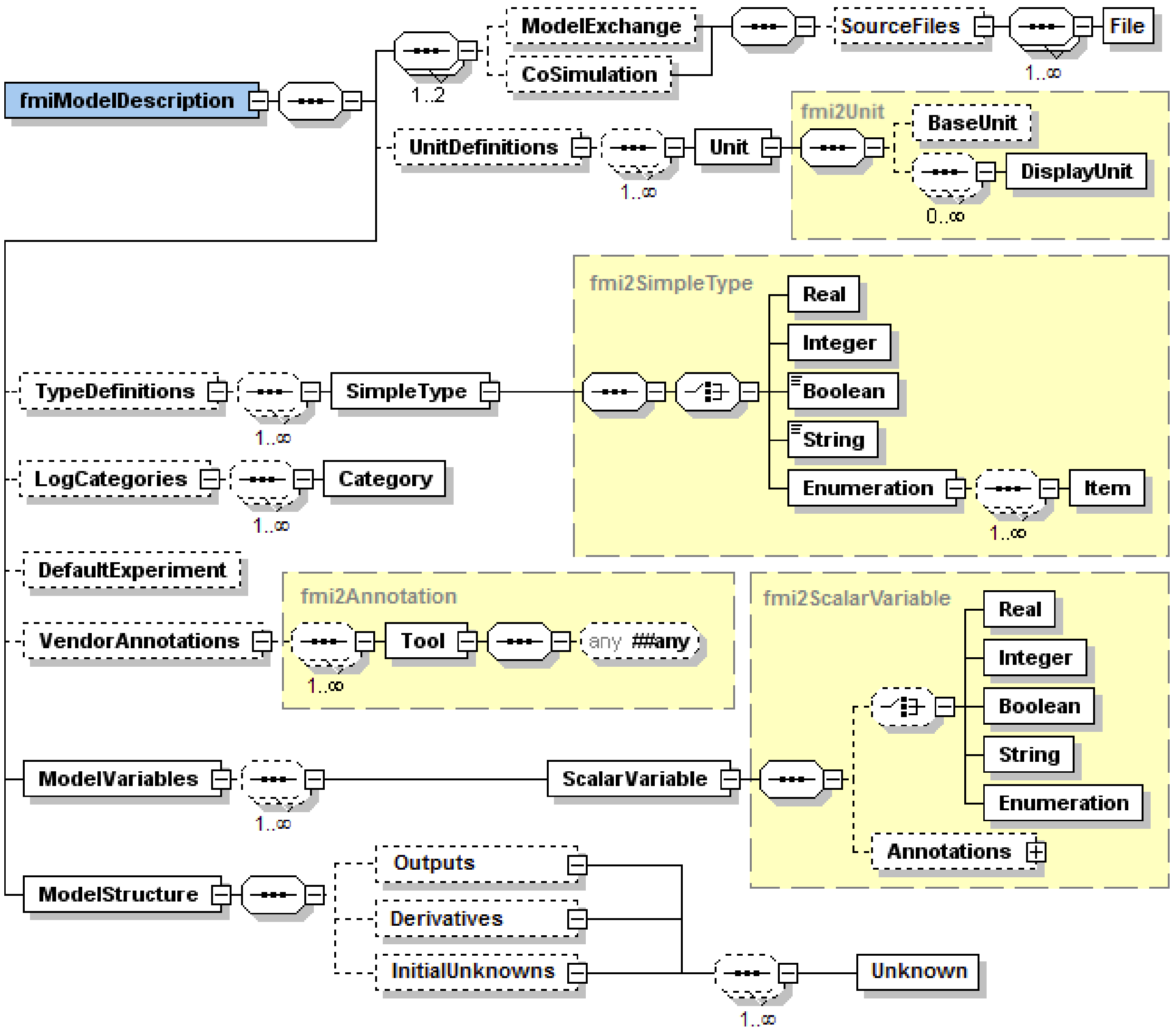
The FMI schema files (*.xsd) are also stored in “UTF-8”.
[*Note, the definition of an encoding scheme is a prerequisite, in order for the XML file to contain letters outside of the 7 bit ANSI ASCII character set, such as German umlauts, or Asian characters. Furthermore, note the FMI calling interface requires that strings are encoded in UTF-8. Since the *.xml files are also required to be encoded in UTF-8, string variables need not to be transformed when reading from the xml-files in to C string variables.*].

The special values NAN, +INF, -INF for variables values are not allowed in the FMI xml files.

Note, child information items, such as “elements” in a “sequence” are **ordered lists** according to document order, whereas attribute information items are **unordered sets** (see http://www.w3.org/TR/XML-infoset/#infoitem.element). The FMI schema is based on ordered lists in a sequence and therefore parsing must preserve this order. [*For example the information stored in* `ModelVariables.Derivatives` *is only correct if this property is fulfilled*].

2.2.1 Definition of an FMU (fmiModelDescription)

This is the root-level schema file and contains the following definition (the figure below contains all elements in the schema file. Data is defined by attributes to these elements):



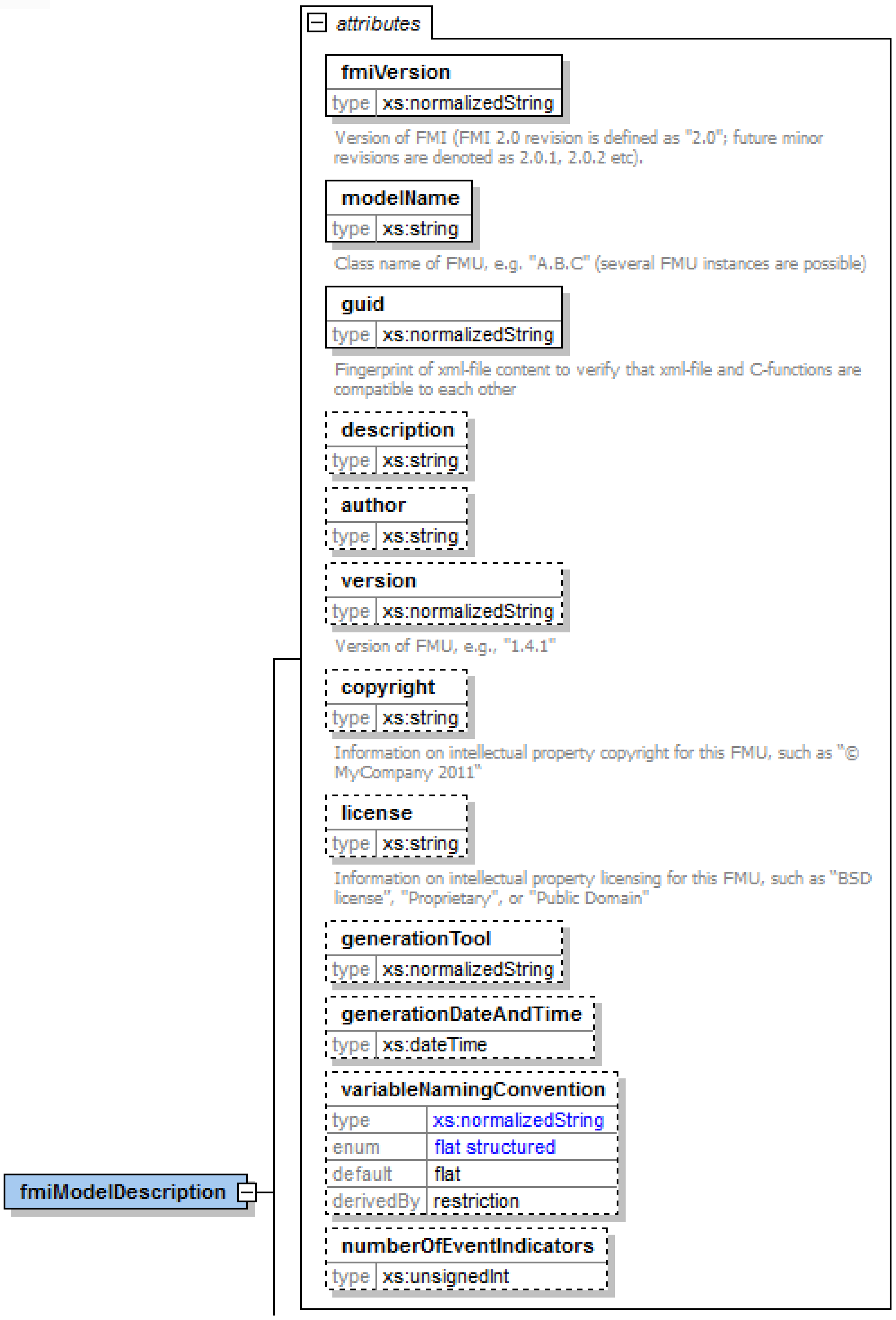
On the top level, the schema consists of the following elements (see figure above[7]):

Element-Name	*Description*
`ModelExchange`	If present, the FMU is based on "FMI for Model Exchange" [*(in other words the FMU includes the model or the communication to a tool that provides the model, and the environment provides the simulation engine)*].
`CoSimulation`	If present, the FMU is based on "FMI for Co-Simulation" [*(in other words the FMU includes the model <u>and</u> the simulation engine, or a communication to a tool that provides the model and the simulation engine, and the environment provides the master algorithm to run coupled FMU co-simulation slaves together)*].
`UnitDefinitions`	A global list of unit and display unit definitions [*for example to convert display units into the units used in the model equations*]. These definitions are used in the XML element "`ModelVariables`".
`TypeDefinitions`	A global list of type definitions that are utilized in "`ModelVariables`".
`LogCategories`	A global list of log categories that can be set to define the log information that is supported from the FMU.
`DefaultExperiment`	Providing default settings for the integrator, such as stop time and relative tolerance.
`VendorAnnotations`	Additional data that a vendor might want to store and that other vendors might ignore.
`ModelVariables`	The central FMU data structure defining all variables of the FMU that are visible/accessible via the FMU functions.
`ModelStructure`	Defines the structure of the model. Especially, the ordered lists of outputs, continuous-time states and initial unknowns (the unknowns during Initialization Mode) are defined here. Furthermore, the dependency of the unkowns from the knowns can be optionally defined. [*This information can be, for example used to compute efficiently a sparse Jacobian for simulation or to utilize the input/output dependency in order to detect that in some cases there are actually no algebraic loops when connecting FMUs together*].

At least one element of `ModelExchange` or `CoSimulation` must be present to identify the type of the FMU. If both elements are defined, different types of models are included in the FMU. The details of these elements are defined in section 3.3.1 and section 4.3.1.

The XML attributes of `fmiModelDescription` are:

[7] Note, elements `<ModelVariables>` and `<ModelStructure>` are mandatory, whereas `<UnitDefinitions>`, `<TypeDefinitions>`, `<LogCategories>`, `<DefaultExperiment>`, `<VendorAnnotation>` are optional. If an optional element is present and defines a list (such as `<UnitDefinitions>`) , the list must have at least one element (such as `<Unit>`).


attributes
fmiVersion
type xs:normalizedString
Version of FMI (FMI 2.0 revision is defined as "2.0"; future minor revisions are denoted as 2.0.1, 2.0.2 etc).
modelName
type xs:string
Class name of FMU, e.g. "A.B.C" (several FMU instances are possible)
guid
type xs:normalizedString
Fingerprint of xml-file content to verify that xml-file and C-functions are compatible to each other
description
type xs:string
author
type xs:string
version
type xs:normalizedString
Version of FMU, e.g., "1.4.1"
copyright
type xs:string
Information on intellectual property copyright for this FMU, such as "© MyCompany 2011"
license
type xs:string
Information on intellectual property licensing for this FMU, such as "BSD license", "Proprietary", or "Public Domain"
generationTool
type xs:normalizedString
generationDateAndTime
type xs:dateTime
variableNamingConvention
type xs:normalizedString
enum flat structured
default flat
derivedBy restriction
numberOfEventIndicators
type xs:unsignedInt
fmiModelDescription

Attribute-Name	*Description*
`fmiVersion`	Version of “FMI for Model Exchange or Co-Simulation” that was used to generate the XML file. The value for this version is “2.0”. Future minor revisions are denoted as “2.0.1”, “2.0.2”, …
`modelName`	The name of the model as used in the modeling environment that generated the XML file, such as “Modelica.Mechanics.Rotational.Examples.CoupledClutches”.
`guid`	The “Globally Unique IDentifier” is a string that is used to check that the XML file is compatible with the C functions of the FMU. Typically when

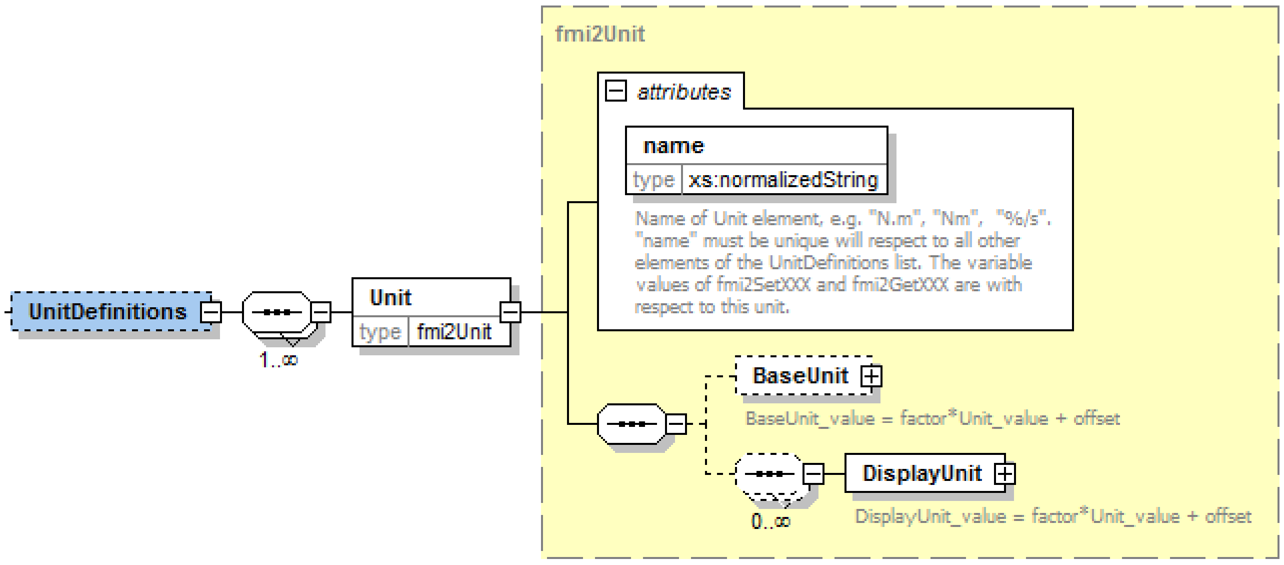
	generating the XML file, a fingerprint of the "relevant" information is stored as guid and in the generated C-function.
`description`	Optional string with a brief description of the model.
`author`	Optional string with the name and organization of the model author.
`version`	Optional version of the model, for example "1.0".
`copyright`	Optional information on the intellectual property copyright for this FMU. [*Example: copyright = "© My Company 2011"*].
`license`	Optional information on the intellectual property licensing for this FMU. [*Example: license = "BSD license <license text or link to license>"*].
`generationTool`	Optional name of the tool that generated the XML file.
`generationDateAndTime`	Optional date and time when the XML file was generated. The format is a subset of "xs:dateTime" and should be: "YYYY-MM-DDThh:mm:ssZ" (with one "T" between date and time; "Z" characterizes the Zulu time zone, in other words Greenwich meantime). [*Example:* `"2009-12-08T14:33:22Z"`].
`variableNamingConvention`	Defines whether the variable names in "`ModelVariables / ScalarVariable / name`" and in "`TypeDefinitions / Type / name`" follow a particular convention. For the details, see section 2.2.9. Currently standardized are: • "`flat`": A list of strings (the default). • "`structured`": Hierarchical names with "." as hierarchy separator, and with array elements and derivative characterization.
`numberOfEventIndicators`	The (fixed) number of event indicators for an FMU based on FMI for Model Exchange. For Co-Simulation, this value is ignored.

[The *attribute "numberOfContinuousStates" available in FMI 1.0 has been removed for FMI 2.0, since this information can be deduced from the remaining data in the XML file]*

2.2.2 Definition of Units (UnitDefinitions)

[*In this section the units of the variables are (optionally) defined. Unit support is important for technical systems since otherwise it is very easy for errors to occur. Unit handling is a difficult topic and there seems to be no method available that is really satisfactory for all applications such as unit check, unit conversion, unit propagation or dimensional analysis. In FMI a pragmatic approach is used that takes into account that every software system supporting units has potentially its own specific technique to describe and utilize units. The approach used here is slightly different to FMI 1.0 to reduce the need for standardized string representations.*]

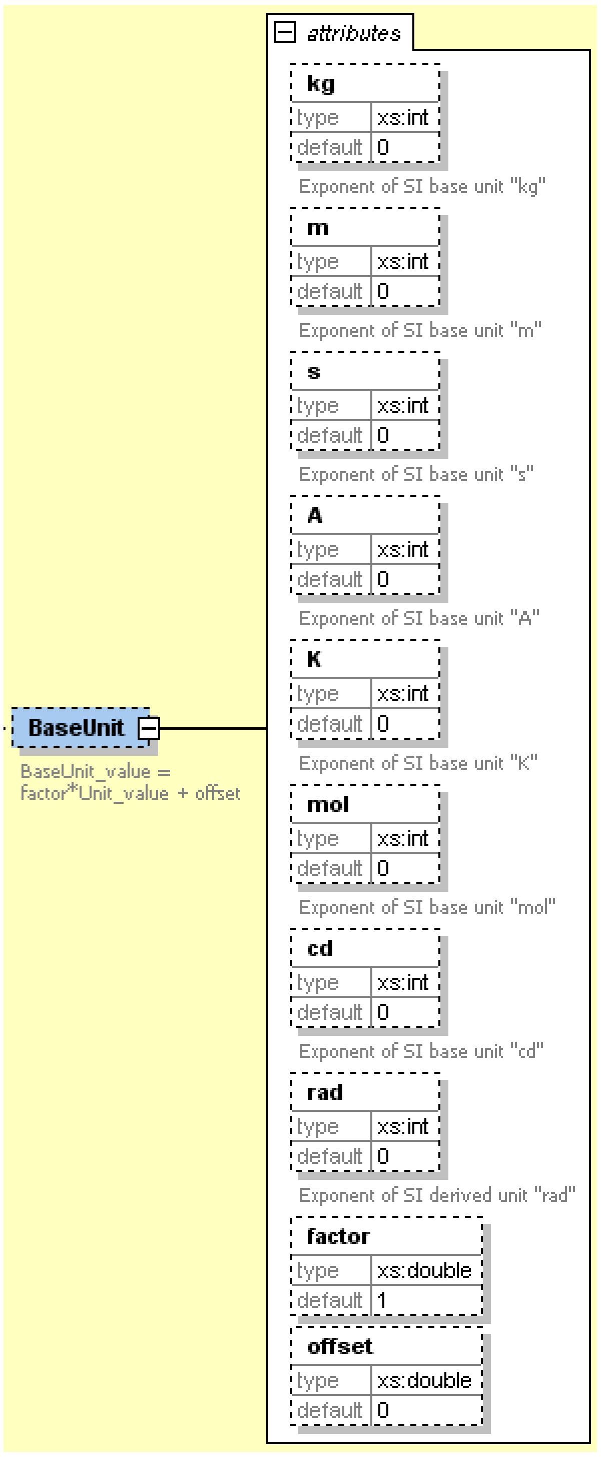
Element "**`UnitDefinitions`**" of `fmiModelDescription` is defined as:


fmi2Unit
attributes
name
type xs:normalizedString
Name of Unit element, e.g. "N.m", "Nm", "%/s". "name" must be unique will respect to all other elements of the UnitDefinitions list. The variable values of fmi2SetXXX and fmi2GetXXX are with respect to this unit.
UnitDefinitions
1..∞
Unit
type fmi2Unit
BaseUnit
BaseUnit_value = factor*Unit_value + offset
DisplayUnit
0..∞
DisplayUnit_value = factor*Unit_value + offset

It consists of zero or more `Unit` definitions[8]. A `Unit` is defined by its `name` attribute such as "N.m" or "N*m" or "Nm", which must be unique with respect to all other defined elements of the `UnitDefinitions` list. If a variable is associated with a `Unit`, then the value of the variable has to be provided with the `fmi2SetXXX` functions or is returned by the `fmi2GetXXX` functions with respect to this `Unit`. [*The purpose of the name is to uniquely identify a unit and, for example use it to display the unit in menus or in plots. Since there is no standard to represent units in strings, and there are different ways how this is performed in different tools, no specific string representation of the unit is required.*]

Optionally, a value given in unit `Unit` can be converted to a value with respect to unit `BaseUnit` utilizing the conversion `factor` and `offset` attributes:

[8] If no units are defined, element `<UnitDefinitions>` must not be present. If 1 or more units are defined, this element must be present.


attributes
kg
type xs:int
default 0
Exponent of SI base unit "kg"
m
type xs:int
default 0
Exponent of SI base unit "m"
s
type xs:int
default 0
Exponent of SI base unit "s"
A
type xs:int
default 0
Exponent of SI base unit "A"
K
type xs:int
default 0
Exponent of SI base unit "K"
mol
type xs:int
default 0
Exponent of SI base unit "mol"
cd
type xs:int
default 0
Exponent of SI base unit "cd"
rad
type xs:int
default 0
Exponent of SI derived unit "rad"
factor
type xs:double
default 1
offset
type xs:double
default 0
BaseUnit
BaseUnit_value = factor*Unit_value + offset

Besides `factor` and `offset`, the `BaseUnit` definition consists of the exponents of the 7 SI base units “kg”, “m”, “s”, “A”, “K”, “mol”, “cd”, and of the exponent of the SI derived unit “rad”. [*Depending on the analysis/operation carried out, the SI derived unit “rad” is or is not utilized, see discussion below. The additional “rad” base unit helps to handle the often occurring quantities in technical systems that depend on an angle.*]

A value with respect to `Unit` (abbreviated as “Unit_value”) is converted with respect to `BaseUnit` (abbreviated as “BaseUnit_value”) by the equation:

BaseUnit_value = `factor`*Unit_value + `offset`

[*For example if p_{bar} is a pressure value in Unit "bar" and p_{Pa} is the pressure value in BaseUnit, then*

$$p_{Pa} = 10^5\, p_{bar}$$

and therefore `factor = 1.0e5` *and* `offset = 0.0`.

In the following table several unit examples are given (note, if in column "`exponents`*" the definition "kgm^2/s^2"is present, then the attributes of* `BaseUnit` *are: "*`kg=1, m=2, s=-2`*"):*

Quantity	**`Unit.name`** `(examples)`	**`Unit.BaseUnit`**		
		`exponents`	**`factor`**	**`offset`**
Torque	`"N.m"`	$kg \cdot m^2/s^2$	`1.0`	`0.0`
Energy	`"J"`	$kg \cdot m^2/s^2$	`1.0`	`0.0`
Pressure	`"bar"`	$\frac{kg}{m \cdot s^2}$	`1.0e5`	`0.0`
Angle	`"deg"`	`rad`	`0.01745329251994330` `(= pi/180)`	`0.0`
Angular velocity	`"rad/s"`	`rad/s`	`1.0`	`0.0`
Angular velocity	`"rpm"`	`rad/s`	`0.1047197551196598` `(=2*pi/60)`	`0.0`
Frequency	`"Hz"`	`rad/s`	`6.283185307179586` `(= 2*pi)`	`0.0`
Temperature	`"°F"`	`K`	`0.5555555555555556` `(= 5/9)`	`255.3722222222222` `(= 273.15-32*5/9)`
Per cent by length	`"%/m"`	`1/m`	`0.01`	`0.0`
Parts per million	`"ppm"`	`1`	`1.0e-6`	`0.0`
Length	`"km"`	`m`	`1000`	`0.0`
Length	`"yd"`	`m`	`0.9144`	`0.0`

Note, "Hz" is typically used as `Unit.name` *for a frequency quantity, but it can also be used as* `DisplayUnit` *for an angular velocity quantity (since "*`revolution/s`*").*

The `BaseUnit` *definitions can be utilized for different purposes (the following application examples are optional and a tool may also completely ignore the* `Unit` *definitions):*

Signal connection check:

When two signals v1 and v2 are connected together, and on at least one of the signals no `BaseUnit` *element is defined, then the connection equation "v2 = v1" holds (if v1 is an output of an FMU and v2 is an input of another FMU, with* `fmi2GetXXX` *the value of v1 is inquired and used as value for v2 by calling* `fmi2SetXXX`*).*

When two signals v1 and v2 are connected together, and for both of them `BaseUnit` *elements are defined, then they must have identical exponents of their* `BaseUnit`*. If* `factor` *and* `offset` *are also identical, again the connection equation "v2 = v1" holds. If* `factor` *and* `offset` *are not identical, the tool may either trigger an error or, if supported, perform a conversion, in other words use the connection equation (in this case the* `relativeQuantity` *of the* `TypeDefinition`*, see below, has to be taken into account in order to determine whether* `offset` *shall or shall not be utilized, since absolute or relative quantities):*

```
factor(v1)*v1 + offset(v1) = factor(v2)*v2 + offset(v2)
```

As a result, wrong connections can be detected (for example connecting a force with an angle signal would trigger an error) and conversions between, say, US and SI units can be either automatically performed or, if not supported, an error is triggered as well. Note, this approach is not satisfactory for variables belonging to different quantities that have, however, the same `BaseUnit`, such as quantities "Energy" and "Torque", or "AngularVelocity" and "Frequency". To handle such cases quantity definitions have to be taken into account (see TypeDefinitions) and quantity names need to be standardized.

*This approach allows a general treatment of units, without being forced to standardize the grammar and allowed values for units (for example in FMI 1.0, a unit could be defined as "N.m" in one FMU and as "N*m" in another FMU and a tool would have to reject a connection, since the units are not identical, In FMI 2.0 the connection would be accepted, provided both elements have the same BaseUnit definition).*

Dimensional analysis of equations:

In order to check the validity of equations in a modeling language, the defined units can be used for dimensional analysis, by using the `BaseUnit` definition of the respective unit. For this purpose, the `BaseUnit` "rad" has to be treated as "1". Example:

$J*\alpha = \tau \rightarrow [kg.m^2]*[rad/s^2] = [kg.m^2/s^2])$. // o.k. ("rad" is treated as "1")
$J*\alpha = f \rightarrow [kg.m^2]*[rad/s^2] = [kg.m/s^2])$. // error, since dimensions do not agree

Unit propagation:

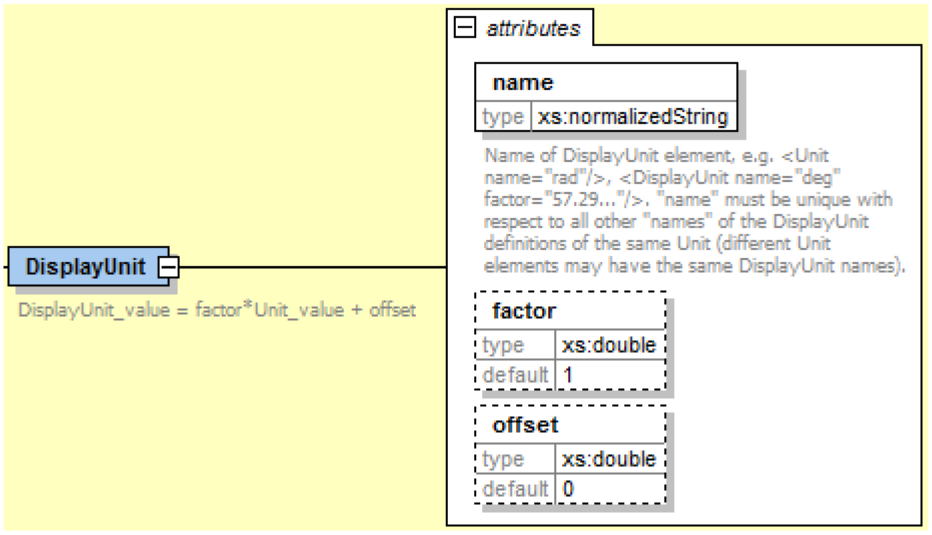
If unit definitions are missing for signals, they might be deduced from the equations where the signals are used. If no unit computation is needed, "rad" is propagated. If a unit computation is needed and one of the involved units has "rad" as a `BaseUnit`, then unit propagation is not possible. Examples:

- *a = b + c, and `Unit` of c is provided, but not `Unit` of a and b:*
  The `Unit` definition of c (in other words `Unit.name`, `BaseUnit`, `DisplayUnit`) is also used for a and b. For example if BaseUnit(c) = "rad/s", then BaseUnit(a) = BaseUnit(b) = "rad/s".

- *a = b*c, and `Unit` of a and of c is provided, but not `Unit` of b:*
  If "rad" is either part of the BaseUnit of "a" and/or of "c", then the BaseUnit of b cannot be deduced (otherwise it can be deduced). Example: If BaseUnit(a)="$kg.m/s^2$" and BaseUnit(c)="m/s^2", then the BaseUnit(b) can be deduced to be "kg". In such a case `Unit.name` of b cannot be deduced from the `Unit.name` of a and c, and a tool would typically construct the `Unit.name` of b from the deduced `BaseUnit`.

]

Additionally to the unit definition, optionally a set of display units can be defined that can be utilized for input/output of a value:


attributes
name
type xs:normalizedString
Name of DisplayUnit element, e.g. <Unit name="rad"/>, <DisplayUnit name="deg" factor="57.29..."/>. "name" must be unique with respect to all other "names" of the DisplayUnit definitions of the same Unit (different Unit elements may have the same DisplayUnit names).
DisplayUnit
DisplayUnit_value = factor*Unit_value + offset
factor
type xs:double
default 1
offset
type xs:double
default 0

A `DisplayUnit` is defined by `name`, `factor` and `offset`. The attribute `name` must be unique with respect to all other `name`s of the `DisplayUnit` definitions of the same `Unit` [(different `Unit` elements may have the same `DisplayUnit` `name`s)]. A value with respect to Unit (abbreviated as “Unit_value”) is converted with respect to DisplayUnit (abbreviated as “DisplayUnit_value”) by the equation:

DisplayUnit_value `=` `factor*`Unit_value `+` `offset`

[*“offset” is, for example needed for temperature units.*]

[*For example if T_K is the temperature value of Unit.name (in “K”) and T_F is the temperature value of DisplayUnit (in “°F”), then*

$$T_F = (9/5) * (T_K - 273.15) + 32$$

and therefore `factor = 1.8 (=9/5)` and `offset = -459.67 (= 32 - 273.15*9/5).`

Both the `DisplayUnit.name` definitions as well as the `Unit.name` definitions are used in the ScalarVariable elements. Example for a definition:

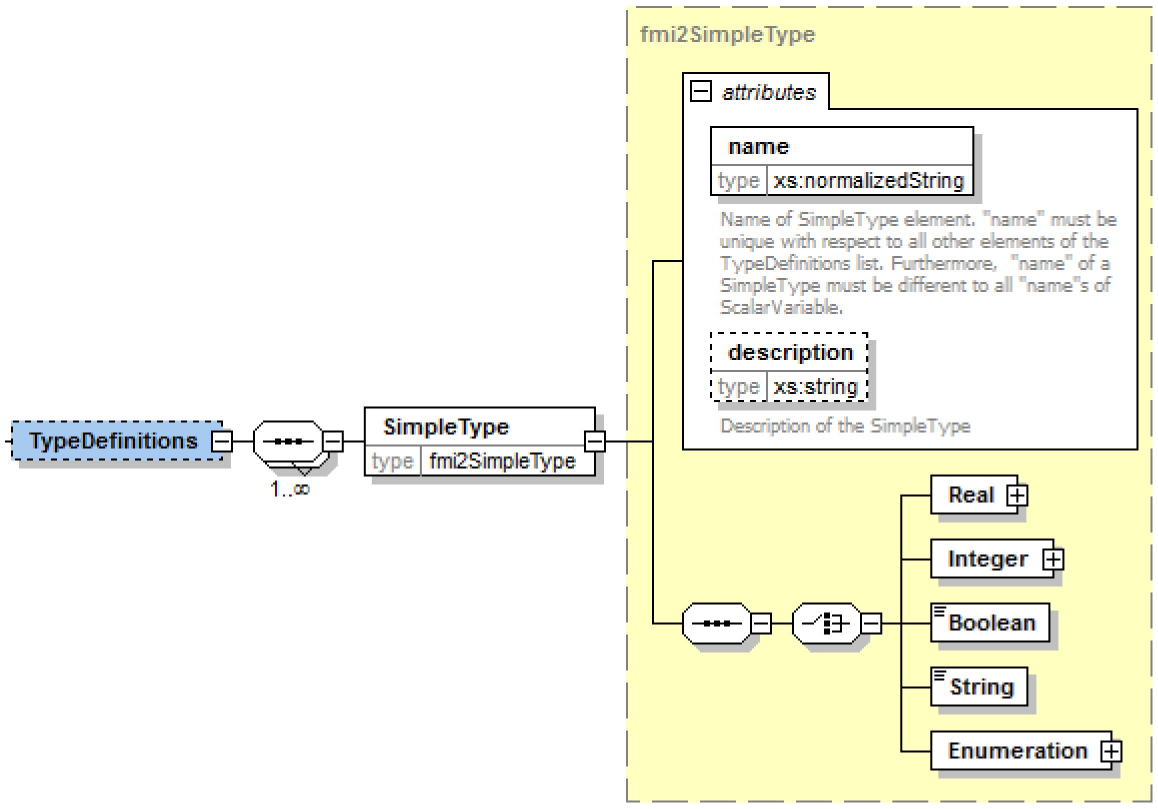
```
<Unit name="rad/s">
   <BaseUnit s="-1" rad="1"/>
   <DisplayUnit name="deg/s" factor= "57.29577951308232"/>
   <DisplayUnit name="rev/min" factor= "9.549296585513721"/>
</Unit>

<Unit name="bar">
   <BaseUnit kg="1", m="-1", s="-2", factor="1.0e5", offset="0"/>
</Unit>

<Unit name="Re">
   <BaseUnit/>     // unit = "1"
                   //(dimensionless, all exponents of BaseUnit are zero)
</Unit>

<Unit name="Euro/PersonYear"/>  // no mapping to BaseUnit defined
```

]

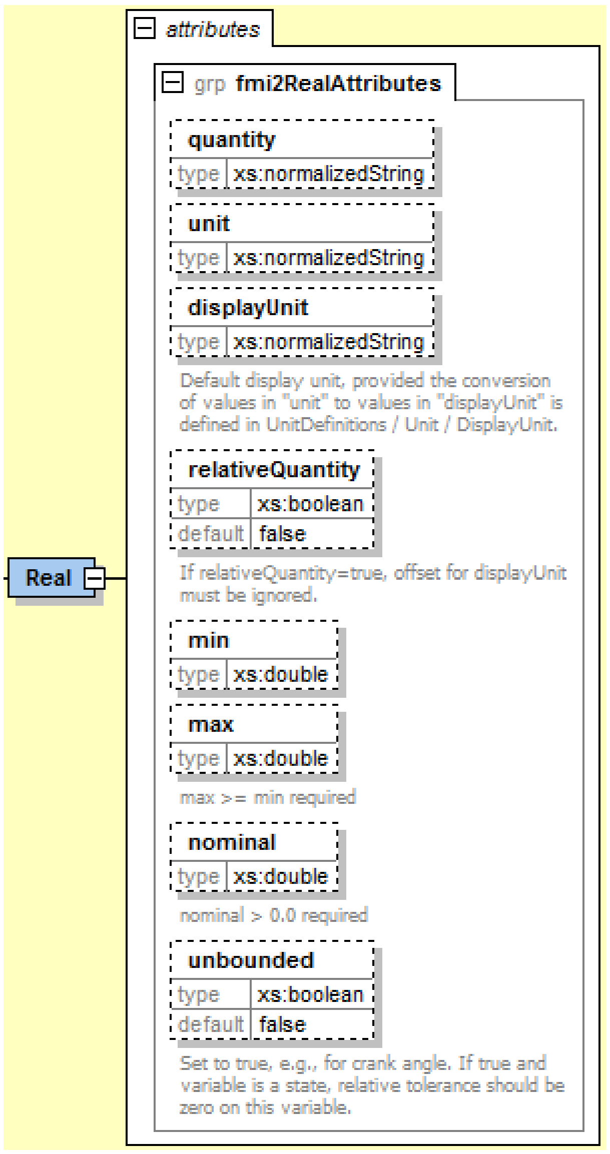
The schema definition is present in a separate file “`fmi2Unit.xsd`”.

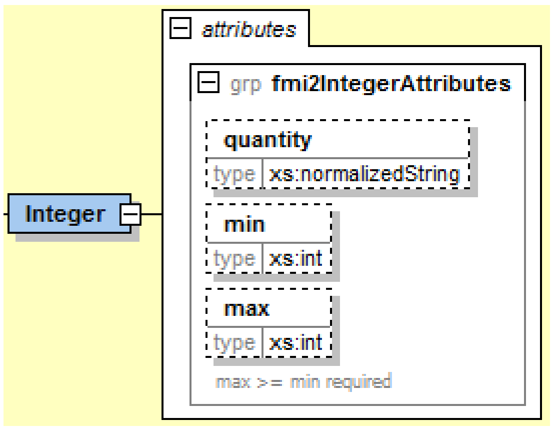
2.2.3 Definition of Types (TypeDefinitions)

Element "**`TypeDefinitions`**" of `fmiModelDescription` is defined as:

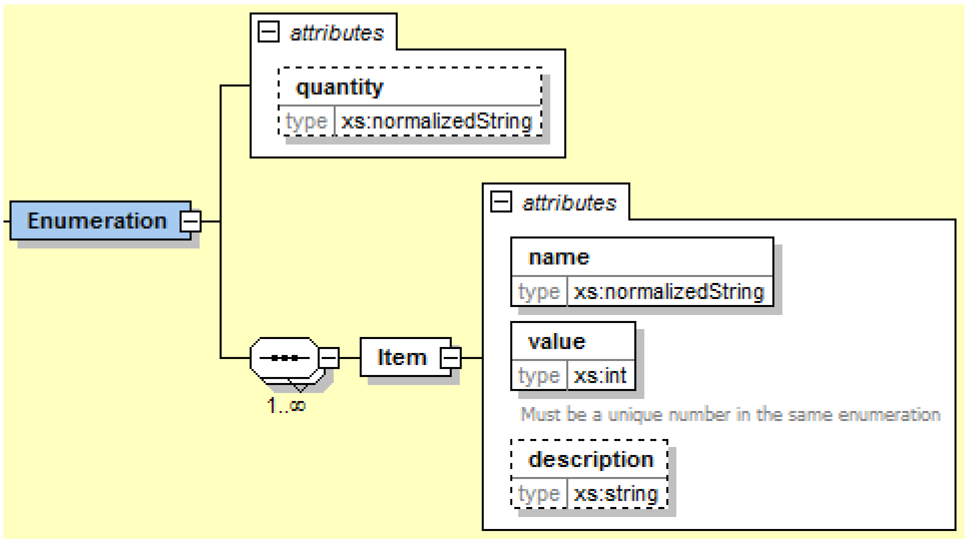

fmi2SimpleType
attributes
name
type xs:normalizedString
Name of SimpleType element. "name" must be unique with respect to all other elements of the TypeDefinitions list. Furthermore, "name" of a SimpleType must be different to all "name"s of ScalarVariable.
description
type xs:string
Description of the SimpleType
TypeDefinitions
1..∞
SimpleType
type fmi2SimpleType
Real
Integer
Boolean
String
Enumeration

This element consists of a set of "`SimpleType`" definitions according to schema "`fmi2SimpleType`" in file "`fmi2Type.xsd`". One "`SimpleType`" has a type "`name`" and "`description`" as attributes. Attribute "`name`" must be unique with respect to all other elements of the `TypeDefinitions` list. Furthermore, "`name`" of a "`SimpleType`" must be different to all "`name`" attributes of ScalarVariables [*if the same names would be used, then this would nearly always give problems when importing the FMU in an environment such as Modelica, where a type name cannot be used as instance name*].Additionally, one of the elements `Real`, `Integer`, `Boolean`, `String`, or `Enumeration` must be present. They have the following definitions:


attributes
grp fmi2RealAttributes
quantity
type xs:normalizedString
unit
type xs:normalizedString
displayUnit
type xs:normalizedString
Default display unit, provided the conversion of values in "unit" to values in "displayUnit" is defined in UnitDefinitions / Unit / DisplayUnit.
relativeQuantity
type xs:boolean
default false
If relativeQuantity=true, offset for displayUnit must be ignored.
min
type xs:double
max
type xs:double
max >= min required
nominal
type xs:double
nominal > 0.0 required
unbounded
type xs:boolean
default false
Set to true, e.g., for crank angle. If true and variable is a state, relative tolerance should be zero on this variable.
Real



[The attributes of "Real" and "Integer" are collected in the attribute groups "fmi2RealAttributes" and "fmi2IntegerAttributes" in file "fmi2AttributeGroups.xsd", since these attributes are reused in the ScalarVariable element definitions below.]



These definitions are used as default values in element ScalarVariables[*, in order that, say, the definition of a "Torque" type does not have to be repeated over and over again*]. The attributes and elements have the following meaning:

Name	*Description*
quantity	Physical quantity of the variable, for example "Angle", or "Energy". The quantity names are not standardized.
unit	Unit of the variable defined with UnitDefinitions.Unit.name that is used for the model equations *[, for example "N.m": in this case a Unit.name = "N.m" must be present under UnitDefinitions*].
displayUnit	Default display unit. The conversion to the "unit" is defined with the element "<fmiModelDescription><UnitDefinitions>". If the corresponding "displayUnit" is not defined under <UnitDefinitions> <Unit> <DisplayUnit>, then displayUnit is ignored. It is an error if displayUnit is defined in element Real, but unit is not, or unit is not defined under <UnitDefinitions><Unit>.
relativeQuantity	If this attribute is true, then the "offset" of "displayUnit" must be ignored (for example 10 degree Celsius = 10 Kelvin if "relativeQuantity = true" and not 283,15 Kelvin).
min	Minimum value of variable (variable Value ≥ min). If not defined, the minimum is the largest negative number that can be represented on the machine. The min definition is an information from the FMU to the environment defining the region in which the FMU is designed to operate, see also comment after this table.
max	Maximum value of variable (variableValue ≤ max). If not defined, the maximum is the largest positive number that can be represented on the machine. The max definition is an information from the FMU to the environment defining the region in which the FMU is designed to operate, see also comment after this table.
nominal	Nominal value of variable. If not defined and no other information about the nominal value is available, then nominal = 1 is assumed. [*The nominal value of a variable can be, for example used to determine the absolute tolerance for this variable as needed by numerical algorithms:* *absoluteTolerance* = nominal*tolerance**0.01* *where* tolerance *is, e.g., the relative tolerance defined in <DefaultExperiment>, see section 2.2.5.*]
unbounded	If true, indicates that the variable gets during time integration much larger than its nominal value nominal. [*Typical examples are the monotonically increasing rotation angles of crank shafts and the longitudinal position of a vehicle along the track in long distance simulations. This information can, for example, be used to increase numerical stability and accuracy by setting the corresponding bound for the relative error to zero (relative tolerance = 0.0), if the corresponding variable or an alias of it is a continuous state variable.*]
Item	Items of an enumeration as a sequence of "name" and "value" pairs. The values can be any integer number, but must be unique within the same enumeration (in order that the mapping between "name" and "value" is bijective). An Enumeration element must have at least one Item.

[A*ttributes „min" and „max" can be set for variables of type Real, Integer or Enumeration. The question is how fmi2SetReal, fmi2SetInteger, fmi2GetReal, fmi2GetInteger shall utilize this definition. There are several conflicting requirements:*
Avoiding forbidden regions (e.g. if „u" is an input and „sqrt(u)" is computed in the FMU, min=0 on „u" shall guarantee that only values of „u" in the allowed regions are provided).
Numerical algorithms (ODE-solver, optimizers. nonlinear solvers) do not guarantee constraints. If a variable is outside of the bounds, the solver tries to bring it back into the bounds. As a consequence, calling fmi2GetReal during an iteration of such a solver might return values that are not in the defined min/max region. After the iteration is finalized, it is only guaranteed that a value is within its bounds upto a certain numerical precision.
In debug mode checks on min/max should be performed. For maximum performance on a real-time system the checks might not be performed.
The approach in FMI is therefore that min/max definitions are an information from the FMU to the environment defining the region in which the FMU is designed to operate. The environment is free to utilize this information (typically, in debug mode of the environment the min/max is checked in the cases as stated above). In any case, it is expected that the FMU handles variables appropriately where the region definition is critical. For example, dividing by an input (so the input should not be in a small range of zero) or taking the square root of an input (so the input should not be negative) may either result in fmi2Error, or the FMU is able to handle this situation in other ways.

If the FMU is generated so that min/max shall be checked whenever meaningful (e.g. for debug purposes) then the following strategy should be used:

If `fmi2SetReal` *or* `fmi2SetInteger` *is called violating the min/max attribute settings of the corresponding variable, the following actions are performed:*

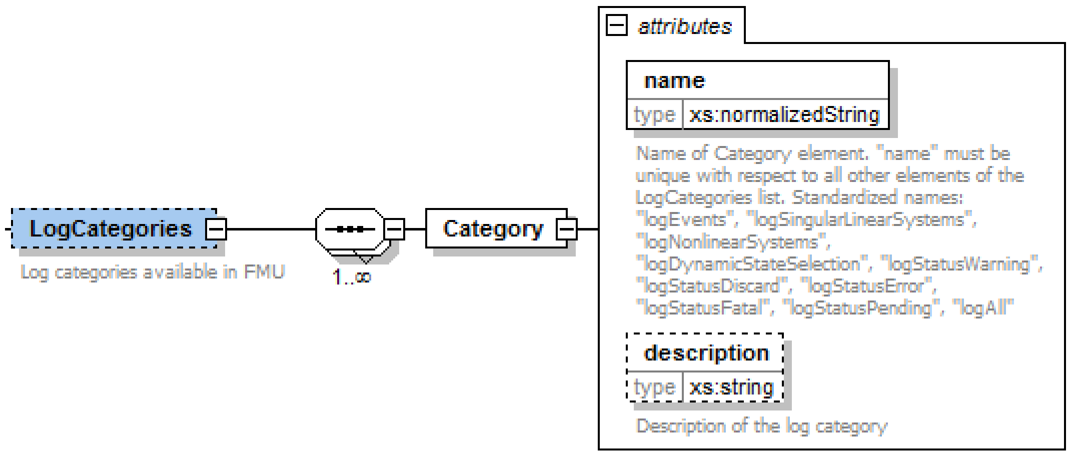
- *On a fixed or tunable parameter* `fmi2Status` = `fmi2Discard` *is returned.*
- *On an input, the FMU decides what to return (If no computation is possible, it could return* `fmi2Status` = `fmi2Discard`*, in other situations it may return* `fmi2Warning` *or* `fmi2Error`*, or* `fmi2OK`*, if it is uncritical).*

If an FMU defines min/max values for Integer and Enumerations (local and output variables), then the expected behavior of the FMU is that `fmi2GetInteger` *returns values in the defined range.*

If an FMU defines min/max values for Reals, then the expected behavior of the FMU is that `fmi2GetReal` *returns values at the solution (accepted steps of the integrators) in the defined range with a certain uncertainty related to the tolerances of the numerical algorithms.*
]

2.2.4 Definition of Log Categories (LogCategories)

Element “**`LogCategories`**” of “`fmiModelDescription` is defined as:


LogCategories
Log categories available in FMU
1..∞
Category
attributes
name
type xs:normalizedString
Name of Category element. "name" must be unique with respect to all other elements of the LogCategories list. Standardized names: "logEvents", "logSingularLinearSystems", "logNonlinearSystems", "logDynamicStateSelection", "logStatusWarning", "logStatusDiscard", "logStatusError", "logStatusFatal", "logStatusPending", "logAll"
description
type xs:string
Description of the log category

LogCategories defines an unordered set of category strings that can be utilized to define the log output via function “`logger`”, see section 2.1.5. A tool is free to use any normalizedString for a category value. The “`name`” attribute of “`Category`” must be unique with respect to all other elements of the `LogCategories` list.

There are the following standardized names for “`Category`” and these names should be used if a tool supports the corresponding log category. If a tool supports one of these log categories and wants to expose it, then an element Category with this name should be added to LogCategories [*To be clear: only the Category names listed under LogCategories in the xml-file are known to the environment in which the FMU is called.*]

Category name	*Description*
`logEvents`	Log all events (during initialization and simulation).
`logSingularLinearSystems`	Log the solution of linear systems of equations if the solution is singular (and the tool picked one solution of the infinitely many solutions).
`logNonlinearSystems`	Log the solution of nonlinear systems of equations.
`logDynamicStateSelection`	Log the dynamic selection of states.
`logStatusWarning`	Log messages when returning fmi2Warning status from any function.
`logStatusDiscard`	Log messages when returning fmi2Discard status from any function.
`logStatusError`	Log messages when returning fmi2Error status from any function.
`logStatusFatal`	Log messages when returning fmi2Fatal status from any function.
`logStatusPending`	Log messages when returning fmi2Pending status from any function.
`logAll`	Log all messages.

The optional attribute `description` shall contain a description of the respective log category. [*Typically, this string can be shown by a tool if more details for a log category shall be presented.*]

[*This approach to define LogCategories has the following advantages:*

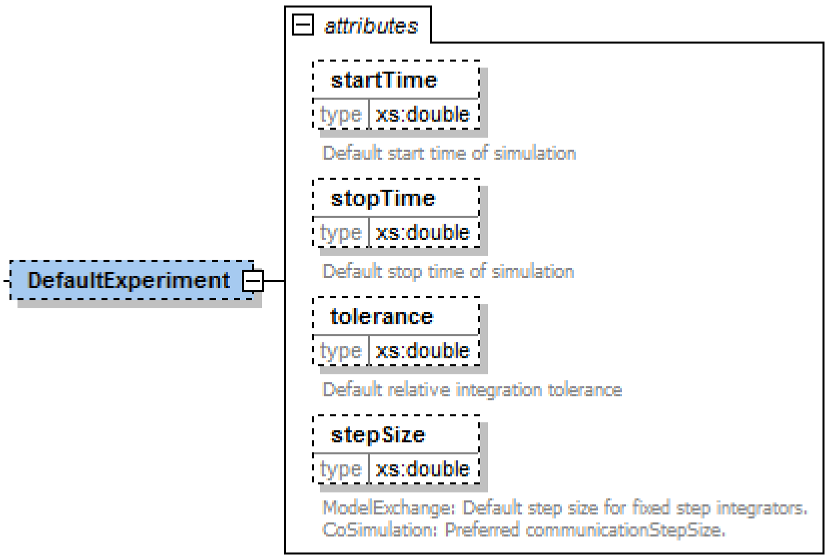
1. *A simulation environment can present the possible log categories in a menu and the user can select the desired one (in the FMI 1.0 approach, there was no easy way for a user to figure out from a given FMU what log categories could be provided). Note, since element* `<LogCategories>` *is optional, an FMU does not need to expose its log categories.*

2. *The log output is drastically reduced, because via* `fmi2SetDebugLogging` *exactly the categories are set that shall be logged and therefore the FMU only has to print the messages with the corresponding categories to the* `logger` *function. In FMI 1.0 it was necessary to provide all log output of the FMU to the* `logger` *and then a filter in the* `logger` *could select what to show to the end-user. The approach introduced in FMI 2.0 is therefore much more efficient.*

]

2.2.5 Definition of a Default Experiment (DefaultExperiment)

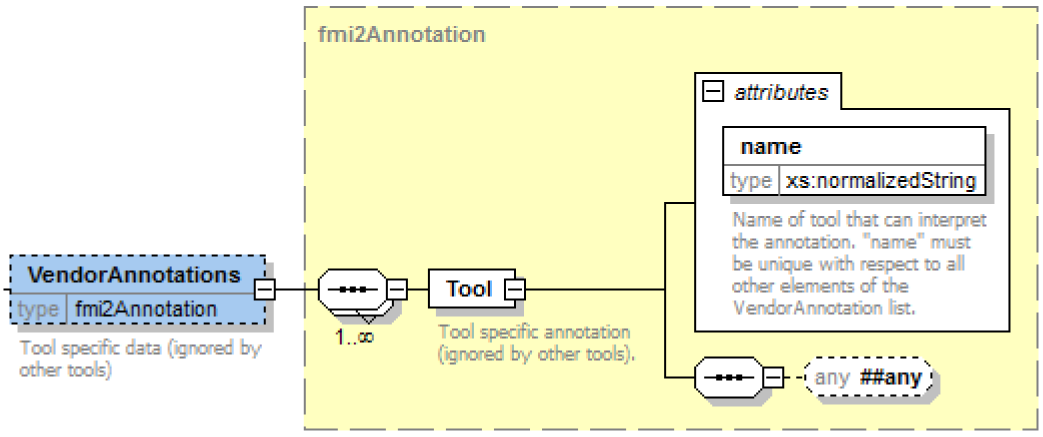
Element "**`DefaultExperiment`**" of `fmiModelDescription` is defined as:


attributes
startTime
type xs:double
Default start time of simulation
stopTime
type xs:double
Default stop time of simulation
tolerance
type xs:double
Default relative integration tolerance
stepSize
type xs:double
ModelExchange: Default step size for fixed step integrators.
CoSimulation: Preferred communicationStepSize.
DefaultExperiment

`DefaultExperiment` consists of the optional default start time, stop time, relative tolerance, and step size for the first simulation run. A tool may ignore this information. However, it is convenient for a user that `startTime`, `stopTime`, `tolerance` and `stepSize` have already a meaningful default value for the model at hand. Furthermore, for CoSimulation the `stepSize` defines the `preferred communicationStepSize`.

2.2.6 Definition of Vendor Annotations (VendorAnnotations)

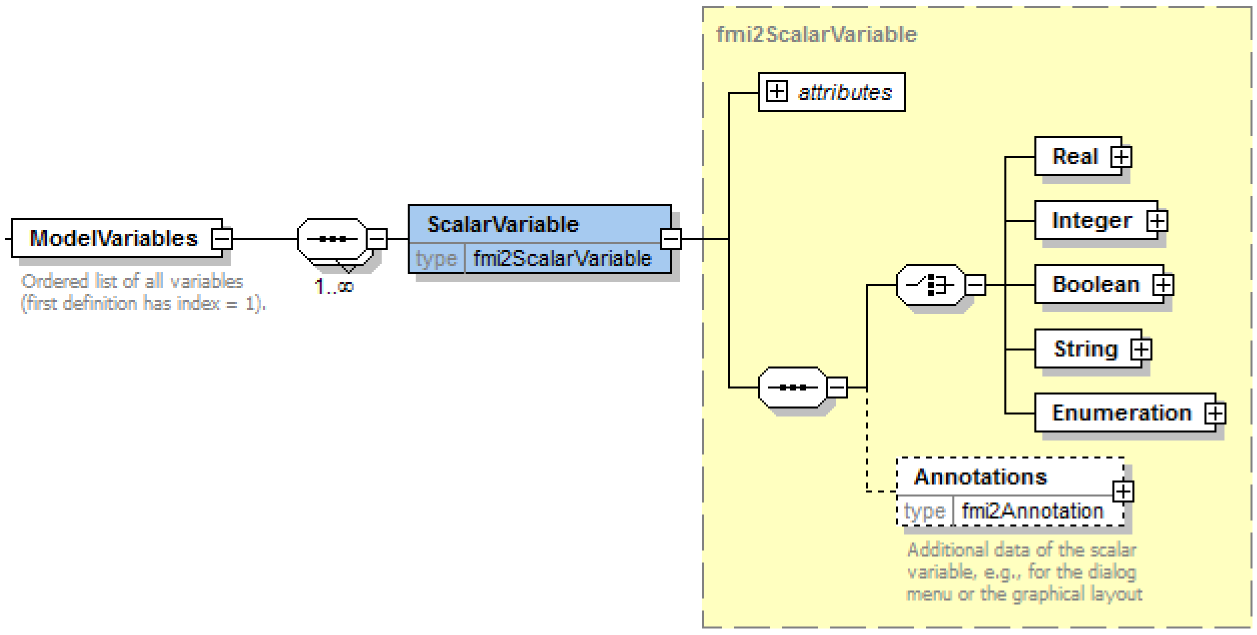
Element "**`VendorAnnotations`**" of `fmiModelDescription` is defined as:


fmi2Annotation
attributes
name
type xs:normalizedString
Name of tool that can interpret the annotation. "name" must be unique with respect to all other elements of the VendorAnnotation list.
VendorAnnotations
type fmi2Annotation
Tool specific data (ignored by other tools)
1..∞
Tool
Tool specific annotation (ignored by other tools).
any ##any

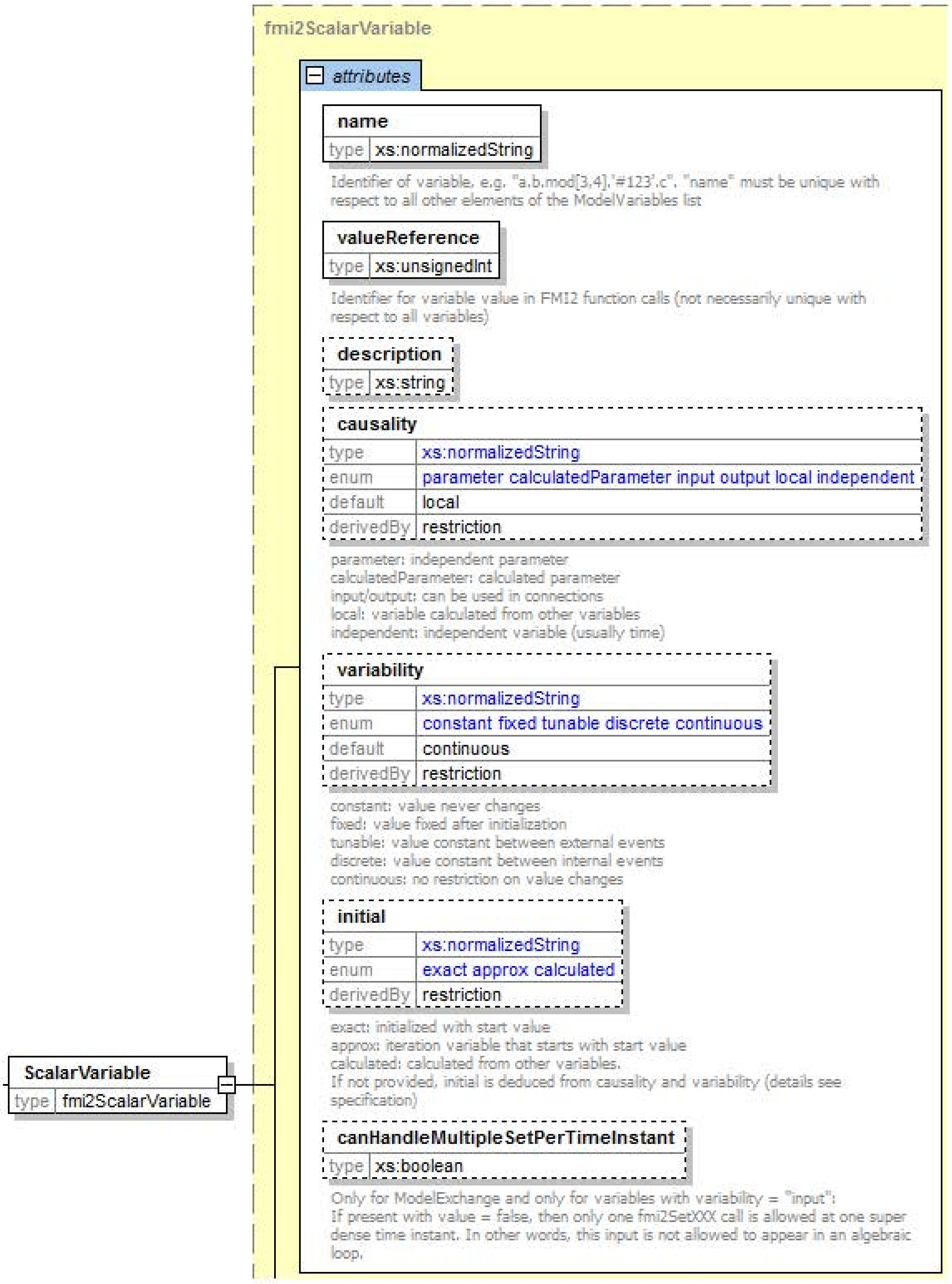
VendorAnnotations consist of an ordered set of annotations that are identified by the name of the tool that can interpret the "`any`" element. The "`any`" element can be an arbitrary XML data structure defined by the tool. Attribute “`name`” must be unique with respect to all other elements of the `VendorAnnotation` list.

2.2.7 Definition of Model Variables (ModelVariables)

The “**`ModelVariables`**” element of `fmiModelDescription` is the central part of the model description. It provides the static information of all exposed variables and is defined as:


fmi2ScalarVariable
attributes
Real
Integer
Boolean
String
Enumeration
ModelVariables
Ordered list of all variables (first definition has index = 1).
1..∞
ScalarVariable
type fmi2ScalarVariable
Annotations
type fmi2Annotation
Additional data of the scalar variable, e.g., for the dialog menu or the graphical layout

The “`ModelVariables`” element consists of an ordered set of “`ScalarVariable`” elements (see figure above). The first element has `index = 1`, the second `index=2`, etc. This `ScalarVariable index` is used in element `ModelStructure` to uniquely and efficiently refer to `ScalarVariable` definitions. A “`ScalarVariable`” represents a variable of primitive type, like a real or integer variable. For simplicity, only scalar variables are supported in the schema file in this version and structured entities (like arrays or records) have to be mapped to scalars. The schema definition is present in a separate file “`fmi2ScalarVariable.xsd`”. The attributes of “`ScalarVariable`” are:



Identifier of variable, e.g. "a.b.mod[3,4].'#123'.c". "name" must be unique with respect to all other elements of the ModelVariables list

Identifier for variable value in FMI2 function calls (not necessarily unique with respect to all variables)

parameter: independent parameter
calculatedParameter: calculated parameter
input/output: can be used in connections
local: variable calculated from other variables
independent: independent variable (usually time)

constant: value never changes
fixed: value fixed after initialization
tunable: value constant between external events
discrete: value constant between internal events
continuous: no restriction on value changes

exact: initialized with start value
approx: iteration variable that starts with start value
calculated: calculated from other variables.
If not provided, initial is deduced from causality and variability (details see specification)

Only for ModelExchange and only for variables with variability = "input":
If present with value = false, then only one fmi2SetXXX call is allowed at one super dense time instant. In other words, this input is not allowed to appear in an algebraic loop.

Attribute-Name	*Description*
`name`	The full, <u>unique name</u> of the variable. Every variable is uniquely identified within an FMU instance by this name or by its `ScalarVariable index` (the element position in the ModelVariables list; the first list element has `index=1`).
`valueReference`	A handle of the variable to efficiently identify the variable <u>value</u> in the model interface. This handle is a secret of the tool that generated the C functions. It is not required to be unique. The only guarantee is that `valueReference` is sufficient to identify the

	respective variable value in the call of the C functions. This implies that it is unique for a particular base data type (`Real, Integer/Enumeration, Boolean, String`) with exception of variables that have identical values (such variables are also called "alias" variables). This attribute is "required".
`description`	An optional description string describing the meaning of the variable.
`causality`	Enumeration that defines the causality of the variable. Allowed values of this enumeration: • `"parameter"`: Independent parameter (a data value that is constant during the simulation and is provided by the environment and cannot be used in connections). `variability` must be `"fixed"` or `"tunable"`. `initial` must be `exact` or not present (meaning `exact`). • `"calculatedParameter"`: A data value that is constant during the simulation and is computed during initialization or when tunable parameters change. `variability` must be `"fixed"` or `"tunable"`. `initial` must be `"approx", "calculated"` or not present (meaning `calculated`). • `"input"`: The variable value can be provided from another model or slave. It is not allowed to define `initial`. • `"output"`: The variable value can be used by another model or slave. The algebraic relationship to the inputs is defined via the `dependencies` attribute of `<fmiModelDescription><ModelStructure><Outputs><Unknown>`. • `"local"`: Local variable that is calculated from other variables or is a continuous-time state (see section 2.2.8). It is not allowed to use the variable value in another model or slave. • `"independent"`: The independent variable (usually "time"). All variables are a function of this independent variable. `variability` must be `"continuous"`. At most one `ScalarVariable` of an FMU can be defined as `"independent"`. If no variable is defined as `"independent"`, it is implicitely present with name = `"time"` and unit = `"s"`. If one variable is defined as `"independent"`, it must be defined as `"Real"` without a `"start"` attribute. It is not allowed to call function `fmi2SetReal` on an `"independent"` variable. Instead, its value is initialized with `fmi2SetupExperiment` and after initialization set by `fmi2SetTime` for ModelExchange and by arguments `currentCommunicationPoint` and `communicationStepSize` of `fmi2DoStep` for CoSimulation. [*The actual value can be inquired with `fmi2GetReal`.*] The default of `causality` is "`local`". A continuous-time state must have `causality = "local"` or `"output"`, see also section 2.2.8. [*`causality = "calculatedParameter"` and `causality = "local"` with `variability = "fixed"` or `"tunable"` are similar. The difference is that a `calculatedParameter` can be used in another model or slave, whereas a `local` variable cannot. For example, when importing an FMU in a Modelica environment, a `"calculatedParameter"` should be imported in a* `public` *section as* `final parameter`*, whereas a `"local"` variable should be imported in a* `protected` *section of the model.*]
`variability`	Enumeration that defines the time dependency of the variable, in other words it defines the time instants when a variable can change its value. [*The purpose of this attribute is*

	to define when a result value needs to be inquired and to be stored. For example discrete variables change their values only at event instants (ModelExchange) or at a communication point (CoSimulation) and it is therefore only necessary to inquire them with fmi2GetXXX and store them at event times]. Allowed values of this enumeration: • `"constant"`: The value of the variable never changes. • `"fixed"`: The value of the variable is fixed after initialization, in other words after `fmi2ExitInitializationMode` was called the variable value does not change anymore. • `"tunable"`: The value of the variable is constant between *external events* (ModelExchange) and between *Communication Points* (CoSimulation) due to changing variables with `causality = "parameter"` or `"input"` and `variability = "tunable"`. Whenever a `parameter` or `input` signal with `variability = "tunable"` changes, then an event is triggered externally (ModelExchange) or the change is performed at the next *Communication Point* (CoSimulation) and the variables with `variability = "tunable"` and causality = `"calculatedParameter" or "output"` must be newly computed. • `"discrete"`: ModelExchange: The value of the variable is constant between *external* and *internal events* (= time, state, step events defined implicitly in the FMU). CoSimulation: By convention, the variable is from a "real" sampled data system and its value is only changed at Communication Points (also inside the slave). • `"continuous"`: Only a variable of type = "`Real`" can be "`continuous`". ModelExchange: No restrictions on value changes. CoSimulation: By convention, the variable is from a differential The default is "`continuous`". [*Note, the information about continuous states is defined with element* `fmiModelDescription.ModelStructure.Derivatives`]
`initial`	Enumeration that defines how the variable is initialized. It is not allowed to provide a value for `initial` if `causality` = `"input"` or `"independent"`: • = "`exact`": The variable is initialized with the `start` value (provided under `Real`, `Integer`, `Boolean`, `String` or `Enumeration`). • = "`approx`": The variable is an iteration variable of an algebraic loop and the iteration at initialization starts with the `start` value. • = "`calculated`": The variable is calculated from other variables during initialization. It is not allowed to provide a "`start`" value. If `initial` is not present, it is defined by the table below based on `causality` and `variability`. If `initial` = `exact` or `approx`, or `causality = "input"` a `start` value must be provided. If `initial` = `calculated`, or causality = `"independent"` it is not allowed to provide a `start` value. [*The environment decides when to use the start value of a variable with* `causality` = `"input"`. *Examples: (a) automatic tests of FMUs are performed, and the FMU is tested by providing the* `start` *value as constant input. (b) For a ModelExchange FMU, the FMU might be part of an algebraic loop. If the input variable is iteration variable of this algebraic loop, then initialization starts with its* `start` *value.*]. If `fmiSetXXX` is not called on a variable with `causality` = `"input"` then the FMU must use the `start` value as value of this input.
`canHandleMultipleSetPerTimeInstant`	

	Only for ModelExchange (if only CoSimulation FMU, this attribute must not be present. If both ModelExchange and CoSimulation FMU, this attribute is ignored for CoSimulation): Only for variables with `variability = "input"`: If present with value = false then only one fmi2SetXXX call is allowed at one super dense time instant (model evaluation) on this variable. That is, this input is not allowed to appear in a (real) algebraic loop requiring multiple calls of `fmi2SetXXX` on this variable [*, for example due to a Newton iteration*]. [*This flag must be set by FMUs where (internal) discrete-time states are directly updated when assigned (xd := f(xd) instead of xd = f(previous(xd)), and at least one output depends on this input and on discrete states.* *It is strongly recommended that such an FMU checks the fulfillment of the requirement by itself during run-time, because an environment might not be able to check it: Usually, there is a generic mechanism to import an FMU in an environment, but the mechanism to connect FMUs together is unrelated to the import mechanism. For example, there is no mechanism in the Modelica language to formulate a connection restrictions for C-functions (the FMU) called in a Modelica model.*]

fmi2SetXXX can be called on any variable with `variability` ≠ "`constant`" **before initialization** (before calling `fmi2EnterInitializationMode`) if

- `initial` = "`exact`" or "`approx`" [*in order to set the corresponding* `start` *value*].

fmi2SetXXX can be called on any variable with `variability` ≠ "`constant`" **during initialization** (after calling `fmi2EnterInitializationMode` and before `fmi2ExitInitializationMode` is called) if

- `initial` = "`exact`" [*in order to set the corresponding* `start` *value*], or if
- `causality` = "`input`" [*in order to provide new values for inputs*]

fmi2SetXXX can be called on any variable **for ModelExchange at an event instant** (after calling `fmi2EnterEventMode` and before `fmi2ExitEventMode` is called), and **for Co-Simulation at every communication point**, if

- `causality` = "`parameter`" and `variability` = "`tunable`" [*in order to change the value of the tunable parameter at an event instant or at a communication point*], or if
- `causality` = "`input`" [*in order to provide new values for inputs*]

fmi2SetXXX can be called on any variable for **ModelExchange in Continuous-Time Mode** if

- `causality` = "`input`" and `variability` = "`continuous`"
  [*in order to provide new values for inputs during continuous integration*]

If `initial` is not present, its value is defined by the following tables based on the values of `causality` and `variability`:

			causality					
			parameter	**calculated parameter**	**input**	**output**	**local**	**independent**
variability	data	**constant**	--	--	--	(A)	(A)	--
		fixed	(A)	(B)	--	--	(B)	--
		tunable	(A)	(B)	--	--	(B)	--
	signals	**discrete**	--	--	(D)	(C)	(C)	--
		continuous	--	--	(D)	(C)	(C)	(E)

with

	initial	
	default	**possible values**
(A)	`exact`	`exact`
(B)	`calculated`	`approx`, `calculated`
(C)	`calculated`	`exact`, `approx`, `calculated`
(D)	`---`	`---`
(E)	`---`	`---`

[*Note: (1) If* `causality = "independent"`*, it is neither allowed to define a value for* `initial` *nor a value for* `start`*. (2) If* `causality = "input"`*, it is not allowed to define a value for* `initial` *and a value for* `start` *must be defined. (3) If (C) and* `initial = "exact"`*, then the variable is explicitely defined by its start value in Initialization Mode (so directly after calling* `fmi2ExitInitializationMode`*, the value of the variable is either the start value stored in element* `<ScalarVariable><XXX start=YYY/>`*, or the value provided by* `fmiSetXXX`*, if this function was called on this variable).*]

The following combinations of `variability/causality` settings are allowed:

			causality					
			parameter	**calculated Parameter**	**input**	**output**	**local**	**independent**
variability	data	**constant**	-- (a)	-- (a)	-- (a)	(7)	(10)	-- (c)
		fixed	(1)	(3)	-- (d)	-- (e)	(11)	-- (c)
		tunable	(2)	(4)	-- (d)	-- (e)	(12)	-- (c)
	signals	**discrete**	-- (b)	-- (b)	(5)	(8)	(13)	-- (c)
		continuous	-- (b)	-- (b)	(6)	(9)	(14)	(15)

[*Discussion of the combinations that are <u>not allowed</u>:*

	Explanation why this combination is not allowed
(a)	*The combinations "constant / parameter", "constant / calculatedParameter" and "constant / input" do not make sense, since parameters and inputs are set from the environment, whereas a constant has always a value.*
(b)	*The combinations "discrete / parameter", "discrete / calculatedParameter", "continuous / parameter" and continuous / calculatedParameter do not make sense, since causality = "parameter" and "calculatedParameter" define variables that do not depend on time, whereas "discrete" and "continuous" define variables where the values can change during simulation.*
(c)	*For an "independent" variable only variability = continuous" makes sense.*
(d)	*A fixed or tunable "input" has exactly the same properties as a fixed or tunable parameter. For simplicity, only fixed and tunable parameters shall be defined.*
(e)	*A fixed or tunable "output" has exactly the same properties as a fixed or tunable calculatedParameter. For simplicity, only fixed and tunable calculatedParameters shall be defined.*

Discussion of the combinations that are <u>allowed</u>:

	Setting	***Example***
(1)	*fixed parameter*	*Non-tunable independent parameter*
(2)	*tunable parameter*	*Tunable independent parameter (changing such a parameter triggers*

		an external event (ModelExchange) or takes effect at the next Communication Point (CoSimulation), and tunable calculatedParameter/output/local variables might change their values).
(3)	*fixed dependent parameter*	*Non-tunable dependent parameter (variable that is computed directly or indirectly from constants or parameters).*
(4)	*tunable dependent parameter*	*Tunable dependent parameter (changing an independent parameter triggers an external event (ModelExchange) or takes effect at the next Communication Point (CoSimulation), and tunable dependent parameters and tunable local variables might change their values).*
(5)	*discrete input*	*Discrete input variable from another model.*
(6)	*continuous input*	*Continuous input variable from another model.*
(7)	*constant output*	*Variable where the value never changes and that can be used in another model,*
(8)	*discrete output*	*Discrete variable that is computed in the FMU. Can be used in another model.*
(9)	*continuous output*	*Continuous variable that is computed in the FMU and can be used in another model.*
(10)	*constant local*	*Variable where the value never changes. Cannot be used in another model.*
(11)	*fixed local*	*Local variable that depends on fixed parameters only and is computed in the FMU. Cannot be used in another model. After initialization, the value of this local variable cannot change.*
(12)	*tunable local*	*Local variable that depends on tunable parameters only and is computed in the FMU. Cannot be used in another model. The value of this local variable can only change during initialization and at event instants, provided a tunable parameter was changed.*
(13)	*discrete local*	*Discrete variable that is computed in the FMU and cannot be used in another model.*
(14)	*continuous local*	*Continuous variable that is computed in the FMU and cannot be used in another model.*
(15)	*continuous independent*	*All variables are a function of the continuous-time variable marked as "independent". Usually, this is "time".*

How to treat tunable variables:

A parameter p is a variable that does not change its value during simulation, in other words dp/dt = 0. If the parameter "p" is changing, then Dirac impulses are introduced since dp/dt of a discontinuous constant variable "p" is a Dirac impulse. Even if this Dirac impulse would be modeled correctly by the modeling environment, it would introduce unwanted "vibrations". Furthermore, in many cases the model equations are derived under the assumption of a constant value (like mass or capacity), and the model equations would be different if "p" would be time varying.

FMI for Model Exchange:
Therefore, "tuning a parameter" during simulation does not mean to "change the parameter online" during simulation. Instead, this is a short hand notation for:

1. *Stop the simulation at an event instant*
   (usually, a step event, in other words after a successful integration step).
2. *Change the values of the tunable parameters.*
3. *Compute all parameters that depend on the tunable parameters.*

4. *Newly start the simulation using as initial values the current values of all previous variables and the new values of the parameters.*

Basically this means that a new simulation run is started from the previous FMU state with changed parameter values. With this interpretation, changing parameters online is "clean", as long as these changes appear at an event instant.

FMI for Co-Simulation:
Changing of tunable parameters is allowed before an `fmi2DoStep` call (so whenever an input can be set with `fmi2SetXXX`) and before `fmi2ExitInitializationMode` is called (so before and during Initialization Mode). The FMU internally carries out event handling if necessary.
]

Variables of the same base type (like `fmi2Real`) that have identical `valueReference` definitions are called "alias" variables. The main purpose of "alias" variables is to enhance efficiency. If two variables `a` and `b` are alias variables, then this is only allowed if the behavior of the FMU would be exactly the same, as if `a` and `b` would not be treated as alias variables (that is, would have different `valueReferences`). This requirement leads naturally to the following restrictions:

1. Variables `a` and `b` that can both be set with `fmi2SetXXX`, or variable `a` that can be set with `fmiSetXXX` and variable `b` that is defined with `causality = "independent"`, cannot be alias variables [*since these variables are "independent" variables and alias means that there is a constraint equation between variables (= the values are the same), and then the variables are no longer "independent".*
   For example if variables `a` and `b` have `causality = "parameter"`, then the value references of `a` and `b` must be different. However, if variable `a` has `causality = "parameter"` and `b` has `causality = "calculatedParameter"` and `b := a`, then `a` and `b` can have the same value reference.].

2. At most one variable of the same alias set of variables with `variability` ≠ "`constant`" can have a `start` attribute. [*since "`start`" variables are independent initial values.*]

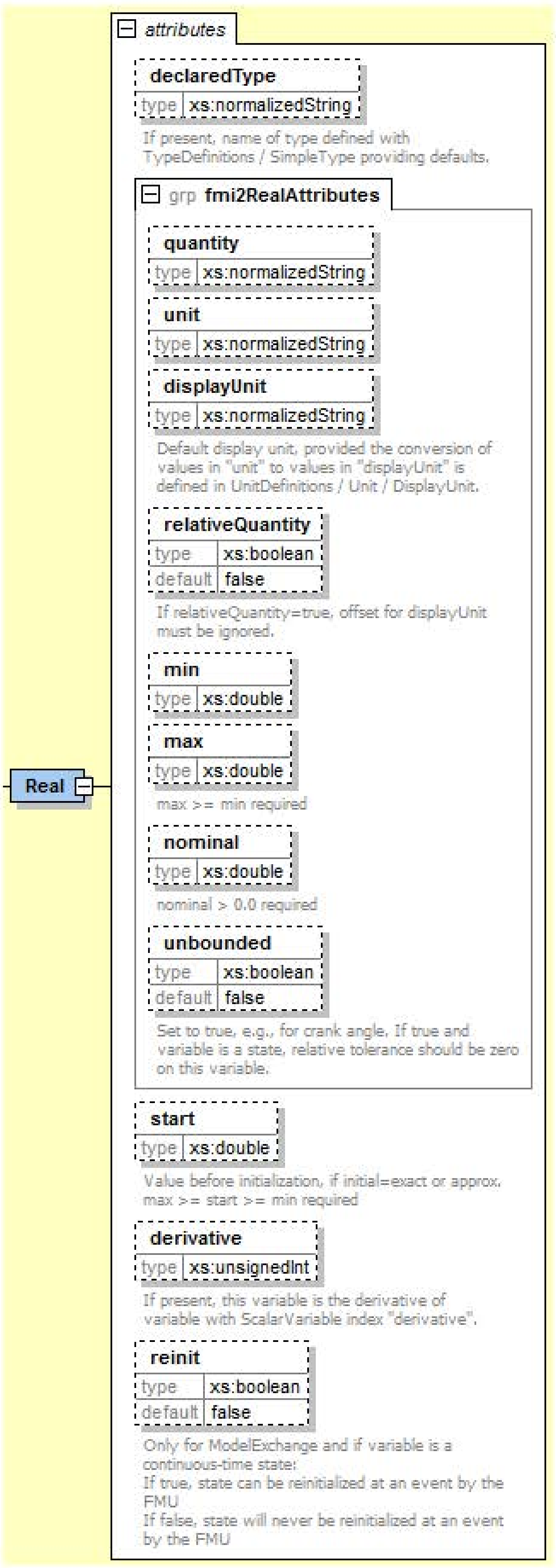
3. A variable with `variability = "constant"` can only be aliased to another variable with `variability = "constant"`. It is then required that the `start` values of all aliased (constant) variables are identical.

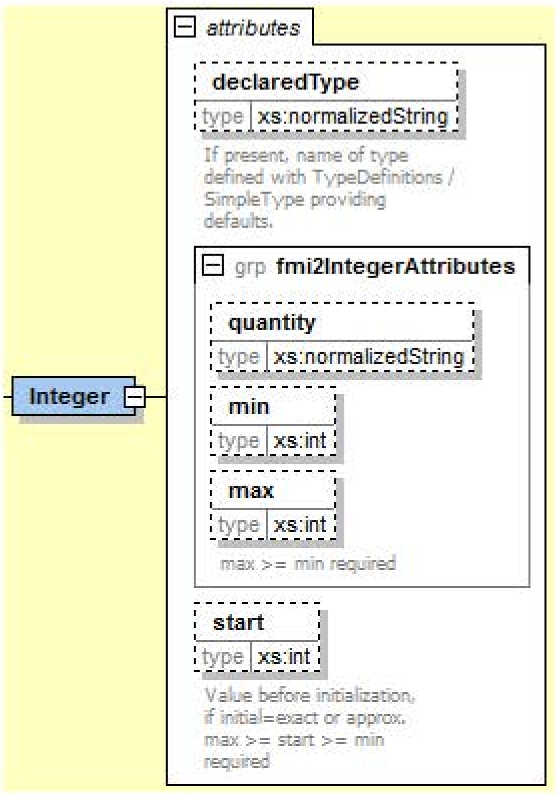
4. All variables of the same alias set must all have either no `<Unit>` element defined or all of them must have the same `<Unit name>` and the same `<Unit><BaseUnit>` definitions.

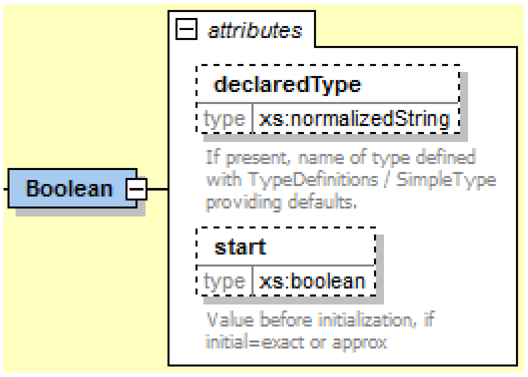
The aliasing of variables only means that the "value" of the variables is always identical. However, aliased variables may have different attributes, like min/max/nominal values or description texts. [*For example if v1, v2 are two alias variables with v1=v2 and v1.max=10 and v2.max=5, then the FMU will trigger an error if either v1 or v2 becomes larger than 5.*]

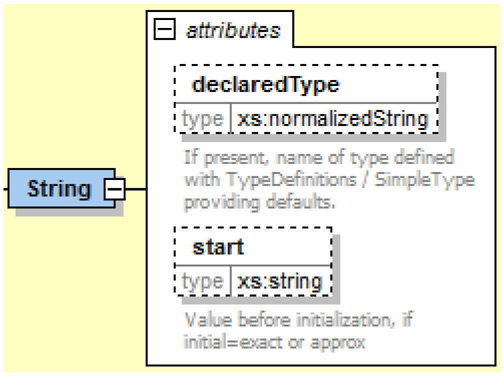
[*The dependency definition in `fmiModelDescription.ModelStructure` is completely unrelated to the alias definition. In particular, the "direct dependency" definition can be a super set of the "real" direct dependency definition, even if the "alias" information shows that this is too conservative. For example if it is stated that the output y1 depends on input u1 and the output y2 depends on input u2, and y1 is an alias to y2, then this definition is fine, although it can be deduced that in reality neither y1 nor y2 depend on any input.*].

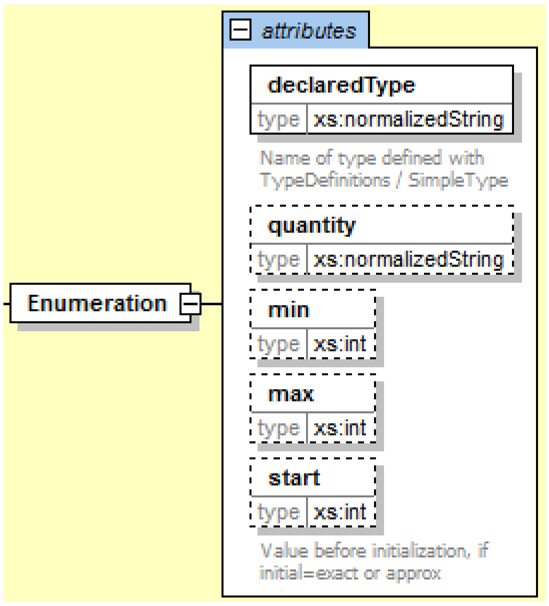
Type specific properties are defined in the required choice element, where exactly one of "`Real`", "`Integer`", "`Boolean`", "`String`", "`Enumeration`" must be present in the XML file:


Real
attributes
declaredType
type xs:normalizedString
If present, name of type defined with TypeDefinitions / SimpleType providing defaults.
grp fmi2RealAttributes
quantity
type xs:normalizedString
unit
type xs:normalizedString
displayUnit
type xs:normalizedString
Default display unit, provided the conversion of values in "unit" to values in "displayUnit" is defined in UnitDefinitions / Unit / DisplayUnit.
relativeQuantity
type xs:boolean
default false
If relativeQuantity=true, offset for displayUnit must be ignored.
min
type xs:double
max
type xs:double
max >= min required
nominal
type xs:double
nominal > 0.0 required
unbounded
type xs:boolean
default false
Set to true, e.g., for crank angle. If true and variable is a state, relative tolerance should be zero on this variable.
start
type xs:double
Value before initialization, if initial=exact or approx. max >= start >= min required
derivative
type xs:unsignedInt
If present, this variable is the derivative of variable with ScalarVariable index "derivative".
reinit
type xs:boolean
default false
Only for ModelExchange and if variable is a continuous-time state:
If true, state can be reinitialized at an event by the FMU
If false, state will never be reinitialized at an event by the FMU


Integer
attributes
declaredType
type xs:normalizedString
If present, name of type defined with TypeDefinitions / SimpleType providing defaults.
grp fmi2IntegerAttributes
quantity
type xs:normalizedString
min
type xs:int
max
type xs:int
max >= min required
start
type xs:int
Value before initialization, if initial=exact or approx. max >= start >= min required


Boolean
attributes
declaredType
type xs:normalizedString
If present, name of type defined with TypeDefinitions / SimpleType providing defaults.
start
type xs:boolean
Value before initialization, if initial=exact or approx


String
attributes
declaredType
type xs:normalizedString
If present, name of type defined with TypeDefinitions / SimpleType providing defaults.
start
type xs:string
Value before initialization, if initial=exact or approx

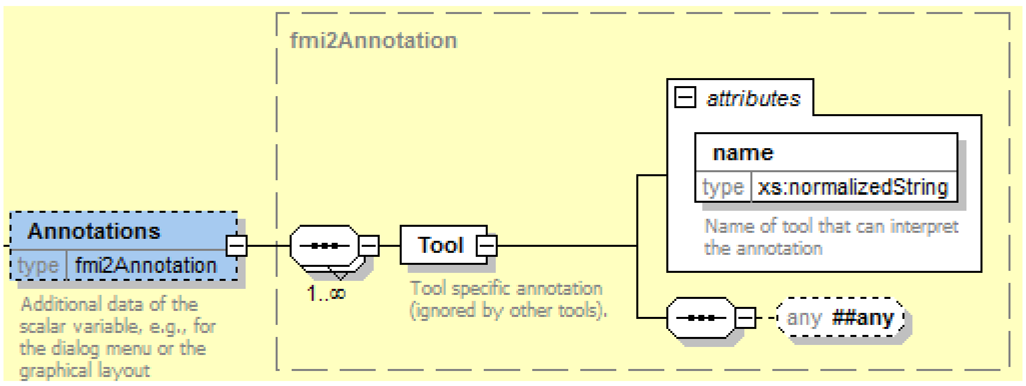


The attributes are defined in section 2.2.3 ("`TypeDefinitions`"), except:

Attribute-Name	*Description*
`declaredType`	If present, name of type defined with `TypeDefinitions` / `SimpleType`. The value defined in the corresponding `TypeDefinition` (see section 2.2.3) is used as default. [*If, for example "`min`" is present both in `Real` (of `TypeDefinition`) and in "`Real`" (of `ScalarVariable`), then the "`min`" of `ScalarVariable` is actually used.*] For `Real, Integer, Boolean, String`, this attribute is optional. For `Enumeration` it is required, because the `Enumeration` items are defined in `TypeDefinitions` / `SimpleType`.
`start`	Initial or guess value of variable. **This value is also stored in the C functions** [*Therefore, calling `fmi2SetXXX` to set start values is only necessary, if a different value as stored in the xml file is desired.*] The interpretation of `start` is defined by `ScalarVariable` / `initial`. A different start value can be provided with an `fmi2SetXXX` function before `fmi2ExitInitializationMode` is called (but not for variables with `variability` = "`constant`"). [*The standard approach is to set the start value before `fmi2EnterInitializationMode`. However, if the initialization shall be modified in the calling environment (e.g. changing from initialization of states to steady-state initialization), it is also possible to use the start value as iteration variable of an algebraic loop: Via an additional condition in the environment, such as $\dot{x} = 0$, the actual start value is determined.*]

	If `initial` = `"exact"` or `"approx"` or `causality = "input"`, a `start` value must be provided. If `initial` = `"calculated"` or `causality = "independent"`, it is not allowed to provide a `start` value. Variables with `causality = "parameter"` or `"input"`, as well as variables with `variability = "constant"`, must have a `"start"` value. • If `causality = "parameter"`, the `start`-value is the value of it. • If `causality = "input"`, the `start` value is used by the model as value of the input, if the input is not set by the environment. • If `variability = "constant"`, the `start` value is the value of the constant. • If `causality = "output"` or `"local"` then the `start` value is either an “initial” or a “guess” value, depending on the setting of attribute `"initial"`.
`derivative`	If present, this variable is the derivative of variable with ScalarVariable index "derivative". [*For example, if there are 10 ScalarVariables and derivative = 3 for ScalarVariable 8, then ScalarVariable 8 is the derivative of ScalarVariable 3 with respect to the independent variable (usually time). This information might be especially used if an input or an output is the derivative of another input or output, or to define the states.*] The state derivatives of an FMU are listed under element `<ModelStructure><Derivatives>`. All ScalarVariables listed in this element must have attribute `derivative` (in order that the continuous-time states are uniquely defined).
`reinit`	Only for ModelExchange (if only CoSimulation FMU, this attribute must not be present. If both ModelExchange and CoSimulation FMU, this attribute is ignored for CoSimulation): Can only be present for a continuous-time state. If true, state can be reinitialized at an event by the FMU If false, state will not be reinitialized at an event by the FMU
`min / max`	The optional attributes “`min`” and “`max`” in element “`Enumeration`” restrict the allowed values of the enumeration. The min/max definitions are an information from the FMU to the environment defining the region in which the FMU is designed to operate, see also comment in section 2.2.3. [*If, for example an* `Enumeration` *is defined with “name1 = -4”, “name2 = 1”, “name3 = 5”, “name4 = 11” and min=-2, max = 5, then only “name2” and “name3” are allowed*].

With element “`Annotations`” additional, tool specific data can be defined:


fmi2Annotation
attributes
name
type xs:normalizedString
Name of tool that can interpret the annotation
Annotations
type fmi2Annotation
Additional data of the scalar variable, e.g., for the dialog menu or the graphical layout
1..∞
Tool
Tool specific annotation (ignored by other tools).
any ##any

With `Tool.name` the name of the tool is defined that can interpret the "`any`" element. The "`any`" element can be an arbitrary XML data structure defined by the tool. [*Typically, additional data is defined here how to build up the menu for the variable, including the graphical layout and enabling/disabling an input field based on the values of other parameters.*]

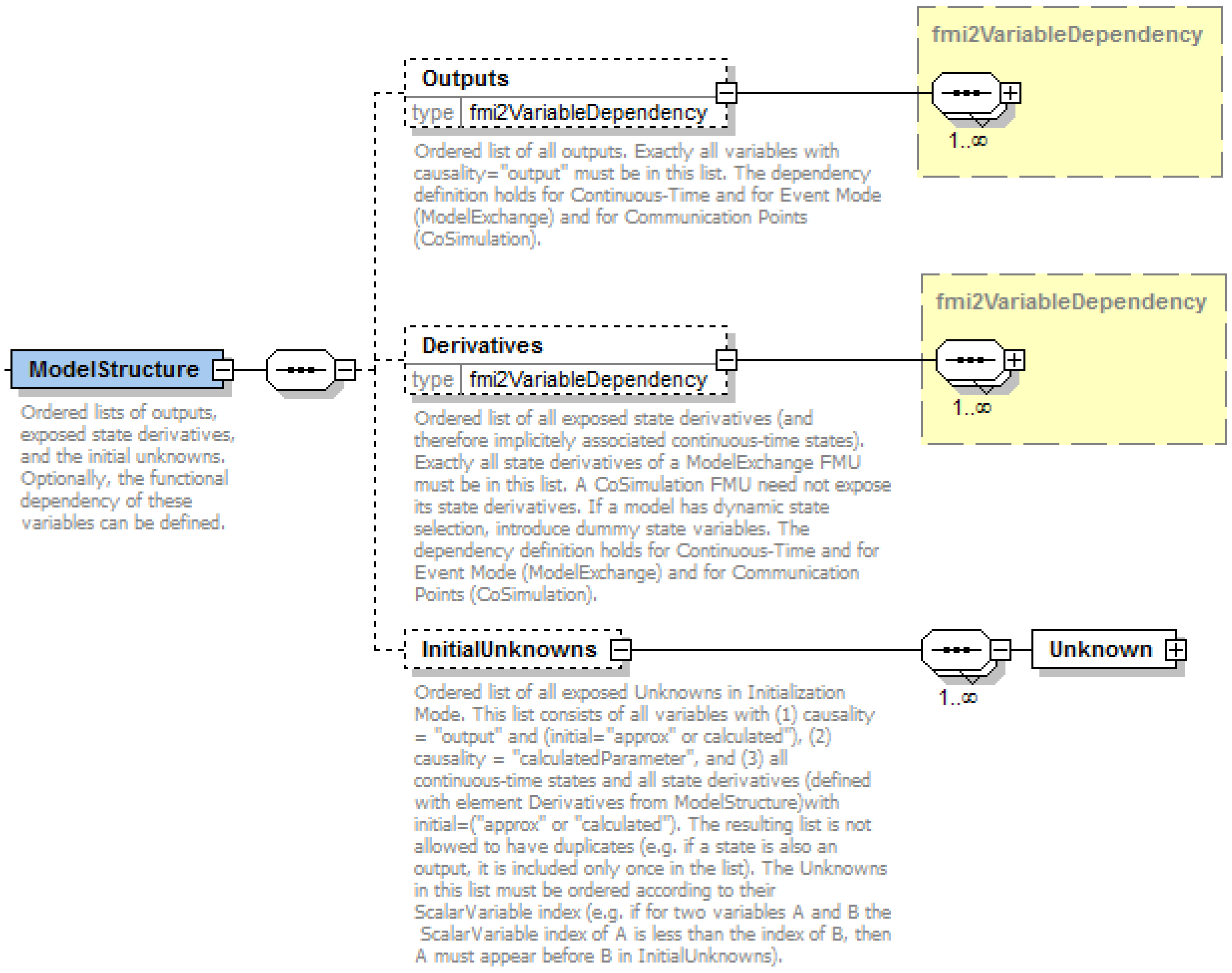
2.2.8 Definition of the Model Structure (ModelStructure)

The structure of the model is defined in element "**`ModelStructure`**" within "`fmiModelDescription`". This structure is with respect to the underlying model equations, independently how these model equations are solved. [*For example, when exporting a model both in Model-Exchange and in Co-Simulation format, then the model structure is identical in both cases. The Co-Simulation FMU has either an integrator included that solves the model equations, or the discretization formula of the integrator and the model equations are solved together ("inline integration"). In both cases the model has the same continuous-time states. In the second case the internal implementation is a discrete-time system, but from the outside this is still a continuous-time model that is solved with an integration method.*]

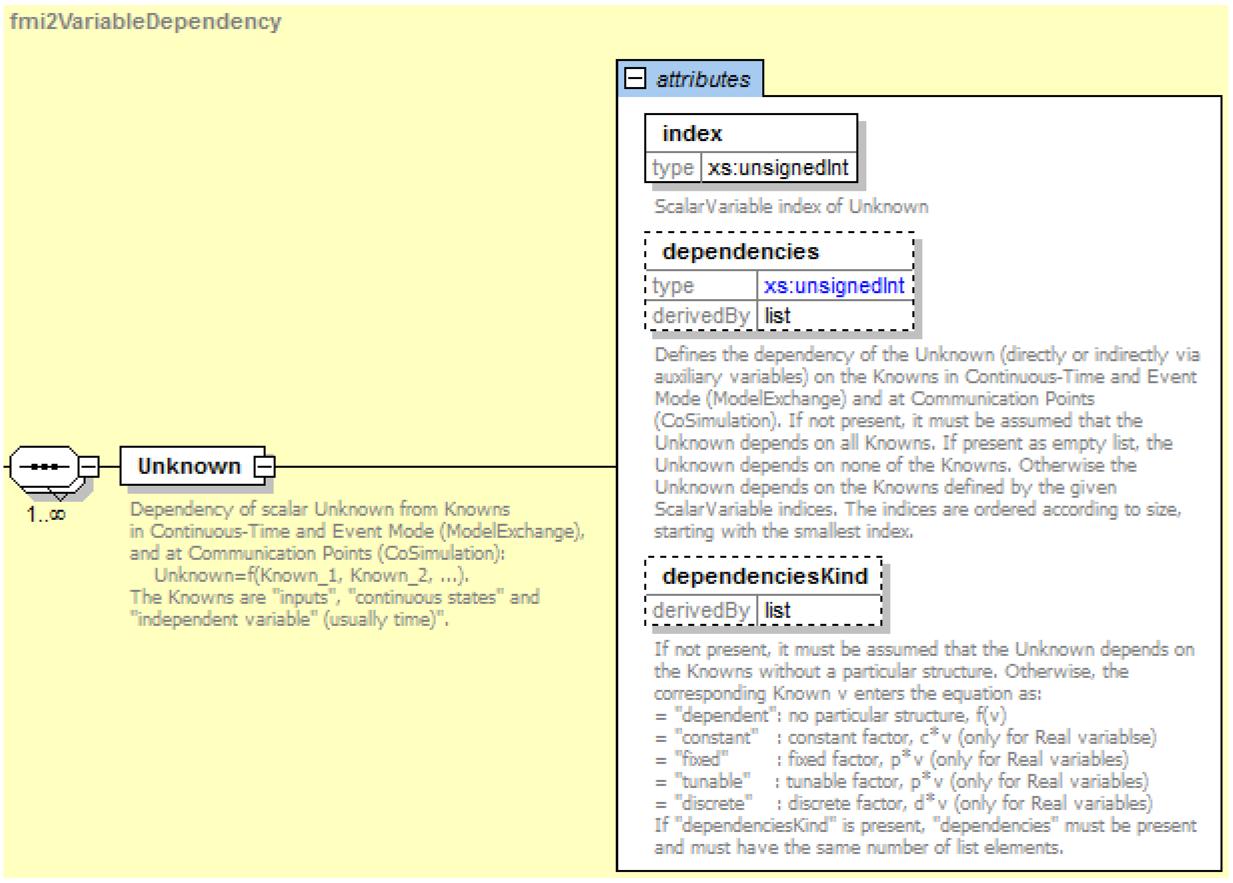
The required part defines an ordering of the outputs and of the (exposed) derivatives, and defines the unknowns that are available during Initialization [*Therefore, when linearizing an FMU, every tool will use the same ordering for the outputs, states, and derivatives for the linearized model. The ordering of the inputs should be performed in this case according to the ordering in ModelVariables.*] A ModelExchange FMU must expose all derivatives of its continuous-time states in element `<Derivatives>`. A Co-Simulation FMU need not to expose these state derivatives. [*If a Co-Simulation FMU exposes its state derivatives, they are usually not utilized for the co-simulation, but, e.g., to linearize the FMU at a communication point.*]

The optional part defines in which way derivatives and outputs depend on inputs, and continuous-time states at the current super dense time instant (ModelExchange) or at the current Communication Point (CoSimulation). [*A simulation environment can utilize this information to improve the efficiency, e.g., when connecting FMUs together, or when computing the partial derivative of the derivatives with respect to the states in the simulation engine.*].

`ModelStructure` has the following definition:


ModelStructure
Ordered lists of outputs, exposed state derivatives, and the initial unknowns. Optionally, the functional dependency of these variables can be defined.
Outputs
type fmi2VariableDependency
Ordered list of all outputs. Exactly all variables with causality="output" must be in this list. The dependency definition holds for Continuous-Time and for Event Mode (ModelExchange) and for Communication Points (CoSimulation).
fmi2VariableDependency
1..∞
Derivatives
type fmi2VariableDependency
Ordered list of all exposed state derivatives (and therefore implicitely associated continuous-time states). Exactly all state derivatives of a ModelExchange FMU must be in this list. A CoSimulation FMU need not expose its state derivatives. If a model has dynamic state selection, introduce dummy state variables. The dependency definition holds for Continuous-Time and for Event Mode (ModelExchange) and for Communication Points (CoSimulation).
fmi2VariableDependency
1..∞
InitialUnknowns
Ordered list of all exposed Unknowns in Initialization Mode. This list consists of all variables with (1) causality = "output" and (initial="approx" or calculated"), (2) causality = "calculatedParameter", and (3) all continuous-time states and all state derivatives (defined with element Derivatives from ModelStructure)with initial=("approx" or "calculated"). The resulting list is not allowed to have duplicates (e.g. if a state is also an output, it is included only once in the list). The Unknowns in this list must be ordered according to their ScalarVariable index (e.g. if for two variables A and B the ScalarVariable index of A is less than the index of B, then A must appear before B in InitialUnknowns).
1..∞
Unknown

`fmi2VariableDependency` is defined as



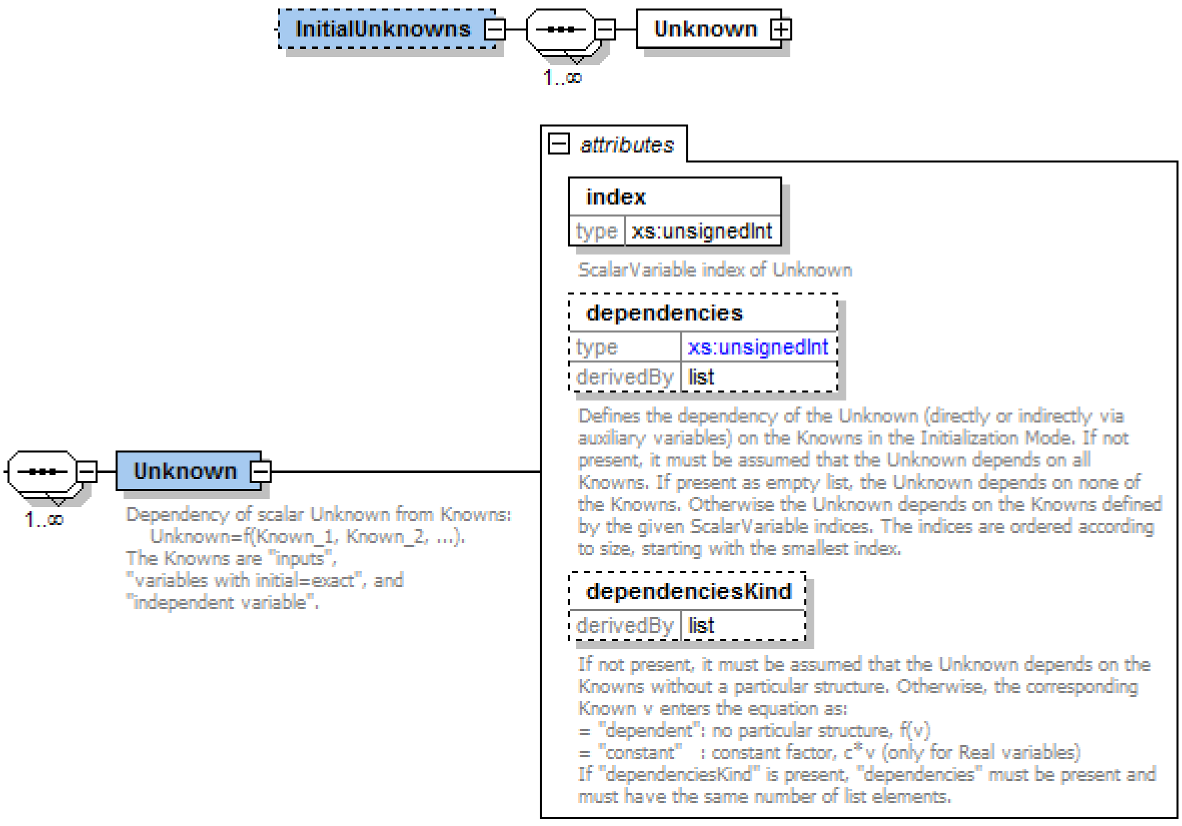
Dependency of scalar Unknown from Knowns in Continuous-Time and Event Mode (ModelExchange), and at Communication Points (CoSimulation):
Unknown=f(Known_1, Known_2, ...).
The Knowns are "inputs", "continuous states" and "independent variable" (usually time)".

ScalarVariable index of Unknown

Defines the dependency of the Unknown (directly or indirectly via auxiliary variables) on the Knowns in Continuous-Time and Event Mode (ModelExchange) and at Communication Points (CoSimulation). If not present, it must be assumed that the Unknown depends on all Knowns. If present as empty list, the Unknown depends on none of the Knowns. Otherwise the Unknown depends on the Knowns defined by the given ScalarVariable indices. The indices are ordered according to size, starting with the smallest index.

If not present, it must be assumed that the Unknown depends on the Knowns without a particular structure. Otherwise, the corresponding Known v enters the equation as:
= "dependent": no particular structure, f(v)
= "constant" : constant factor, c*v (only for Real variablse)
= "fixed" : fixed factor, p*v (only for Real variables)
= "tunable" : tunable factor, p*v (only for Real variables)
= "discrete" : discrete factor, d*v (only for Real variables)
If "dependenciesKind" is present, "dependencies" must be present and must have the same number of list elements.

Elements of the InitialUnknowns list:



Dependency of scalar Unknown from Knowns:
Unknown=f(Known_1, Known_2, ...).
The Knowns are "inputs",
"variables with initial=exact", and
"independent variable".

ScalarVariable index of Unknown

Defines the dependency of the Unknown (directly or indirectly via auxiliary variables) on the Knowns in the Initialization Mode. If not present, it must be assumed that the Unknown depends on all Knowns. If present as empty list, the Unknown depends on none of the Knowns. Otherwise the Unknown depends on the Knowns defined by the given ScalarVariable indices. The indices are ordered according to size, starting with the smallest index.

If not present, it must be assumed that the Unknown depends on the Knowns without a particular structure. Otherwise, the corresponding Known v enters the equation as:
= "dependent": no particular structure, f(v)
= "constant" : constant factor, c*v (only for Real variables)
If "dependenciesKind" is present, "dependencies" must be present and must have the same number of list elements.

Note, that attribute `dependenciesKind` for element `InitialUnknowns` has less enumeration values as `dependenciesKind` in the other lists.

ModelStructure consists of the following elements (see also figures above; the symbols of the mathematical equations describing the dependency are defined in section 3.1):

Element-Name	*Description*
`Outputs`	Ordered list of all outputs, in other words a list of `ScalarVariable indices` where every corresponding `ScalarVariable` must have `causality = "output"` (and **every variable with `causality="output"` must be listed here**). [*Note, all output variables are listed here, especially discrete and continuous outputs. The ordering of the variables in this list is defined by the exporting tool. Usually, it is best to order according to the declaration order in the source model, since then the <Outputs> list does not change, if the declaration order of outputs in the source model is not changed. This is e.g. important for linearization, in order that the interpretation of the output vector does not change for a re-exported FMU.*]. Attribute `dependencies` defines the dependencies of the outputs from the knowns at the current super dense time instant in *Event* and in *Continuous-Time Mode* (ModelExchange) and at the current *Communication Point* (CoSimulation). The functional dependency is defined as (dependencies of variables that are fixed in *Event* and *Continuous-Time Mode* and at *Communication Points* are not shown): $$(\mathbf{y}_c, \mathbf{y}_d) := \mathbf{f}_{output}(\mathbf{x}_c, \boldsymbol{u}_c, \boldsymbol{u}_d, t, \boldsymbol{p}_{tune})$$
`Derivatives`	Ordered list of all state derivatives, in other words a list of `ScalarVariable indices` where every corresponding `ScalarVariable` must be a state derivative. *[Note, only continuous Real variables are listed here. If a state or a derivative of a state shall not be exposed from the FMU, or if states are not statically associated with a variable (due to dynamic state selection), then dummy ScalarVariables have to be introduced, for example x[4], or xDynamicStateSet2[5]. The ordering of the variables in this list is defined by the exporting tool. Usually, it is best to order according to the declaration order of the states in the source model, since then the <Derivatives> list does not change, if the declaration order of states in the source model is not changed. This is e.g. important for linearization, in order that the interpretation of the state vector does not change for a re-exported FMU.*]. The corresponding continuous-time states are defined by attribute **`derivative`** of the corresponding ScalarVariable state derivative element. [*Note, higher order derivatives must be mapped to first order derivatives but the mapping definition can be preserved due to attribute `derivative`. Example: $\frac{ds}{dt} = v, \frac{dv}{dt} = f(..)$, then $\left\{v, \frac{dv}{dt}\right\}$is the vector of state derivatives and attribute `derivative` of v references s, and attribute `derivative` of $\frac{dv}{dt}$ references v.*] For Co-Simulation, element "`Derivatives`" is ignored if capability flag `providesDirectionalDerivative` has a value of `false`, in other words cannot be computed [*which is the default. If an FMU supports both ModelExchange and CoSimulation, then the "Derivatives" element might be present, since it is needed for ModelExchange. If the above flag is set to false for the CoSimulation case, then the "Derivatives" element is ignored for CoSimulation. If "inline integration" is used for a CoSimulation slave, then the model still has continuous-time states and just a special solver is used (internally the implementation results in a discrete-*

	time system, but from the outside, it is still a continuous-time system)]. Attribute `dependencies` defines the dependencies of the state derivatives from the knowns at the current super dense time instant in *Event* and in *Continuous-Time Mode* (ModelExchange) and at the current *Communication Point* (CoSimulation). The functional dependency is defined as (dependencies of variables that are fixed in *Event* and *Continuous-Time Mode* and at *Communication Points* are not shown): $$\dot{\mathbf{x}}_c := \mathbf{f}_{der}(\mathbf{x}_c, \boldsymbol{u}_c, \boldsymbol{u}_d, t, \boldsymbol{p}_{tune})$$

`InitialUnknowns`	Ordered list of all exposed Unknowns in Initialization Mode. This list consists of all variables with (1) `causality = "output"` and (`initial="approx"` or `"calculated"`), and (2) `causality = "calculatedParameter"` and (3) all continuous-time states and all state derivatives (defined with element `<Derivatives>` from `<ModelStructure>`) with `initial="approx"` or `"calculated"` [*if a Co-Simulation FMU does not define the* `<Derivatives>` *element, (3) cannot be present.*]. The resulting list is not allowed to have duplicates (e.g. if a state is also an output, it is included only once in the list). The Unknowns in this list must be ordered according to their ScalarVariable index (for example if for two variables A and B the ScalarVariable index of A is less than the index of B, then A must appear before B in `InitialUnknowns`). Attribute `dependencies` defines the dependencies of the Unknowns from the Knowns in *Initialization Mode* at the initial time. The functional dependency is defined as: $$\mathbf{v}_{InitialUnknowns} \coloneqq \mathbf{f}_{init}(\boldsymbol{u}_c, \boldsymbol{u}_d, t_0, \mathbf{v}_{initial=exact})$$ Since outputs, continuous-time states and state derivatives are either present as Knowns (if `initial="exact"`) or as Unknowns (if `initial="approx"` or `"calculated"`), they can be inquired with `fmiGetXXX` in InitializationMode. [*Example: Assume an FMU is defined in the following way:* $$(\mathbf{y}_{c+d}, \dot{\mathbf{x}}_c) \coloneqq \mathbf{f}_{init}(\mathbf{x}_c, \mathbf{u}_{c+d}, t_0, \mathbf{p})$$ $$(\mathbf{y}_{c+d}, \dot{\mathbf{x}}_c) \coloneqq \mathbf{f}_{sim}(\mathbf{x}_c, \mathbf{u}_{c+d}, t_i, \mathbf{p})$$ *Therefore, the initial state* $\mathbf{x}_c(t_0)$ *has* `initial="exact"` *and the initial state derivative* $\dot{\mathbf{x}}_c(t_0)$ *has* `initial="calculated"`*. The environment can still initialize this FMU in steady-state, by using* $\mathbf{x}_c(t_0)$ *as iteration variables and adding the equations* $\dot{\mathbf{x}}_c(t_0) = \mathbf{0}$ *in the environment.]*
`Unknown`	An element of one of the lists above defining the unknown with a reference to the corresponding `ScalarVariable` element. It is assumed that at a super-dense time instant $t = (t_R, t_I)$ (ModelExchange) and at a Communication Point (CoSimulation) the following relationship holds: $$v_{unknown} = h(\mathbf{v}_{known}, \mathbf{v}_{freeze})$$ where • $v_{unknown}$ is the unknown variable defined with this element [*for example an output or a state derivative].* • $\mathbf{v}_{known}$ is the vector of input arguments of function *h* that changes its value in the actual Mode [*for example continuous-time inputs in Continuous-Time Mode*]. • $\mathbf{v}_{freeze}$ is the set of input arguments of function *h* that do not change their values in this Mode, but change their values in other Modes [*for example fixed parameters in Continuous-Time Mode*]. Attribute `dependencies` of `Unknown` defines the dependency of $v_{unknown}$ with respect to $\mathbf{v}_{known}$. [*If for example a continuous-time output* y_2 *is a function of the continuous-time inputs* u_3 *and* u_5 *and these inputs have changed then* `fmi2SetXXX` *on* u_3 *and* u_5 *must always be called before calling* `fmi2GetXXX` *on* y_2.]

Element `Unknown` in `Outputs`, `Derivatives` and `InitialUnknowns` has the following attributes:

Attribute-Name	*Description*
`index`	The ScalarVariable index of the Unknown $v_{unknown}$. [*For example, if there are 10 ScalarVariables and index = 3, then the third ScalarVariable is the unknown defined with this element.*]
`dependencies`	Optional attribute defining the dependencies of the unknown $v_{unknown}$ (directly or indirectly via auxiliary variables) with respect to $\mathbf{v}_{known}$. If not present, it must be assumed that the Unknown depends on all Knowns. If present as empty list, the Unknown depends on none of the Knowns. Otherwise the Unknown depends on the Knowns defined by the given ScalarVariable indices. The indices are ordered according to magnitude, starting with the smallest index. Knowns $\mathbf{v}_{known}$ in *Event* and *Continuous-Time Mode* (ModelExchange) and at *Communication Points* (CoSimulation) for elements `Outputs`, `Derivatives`: • inputs (variables with `causality = "input"`) • continuous-time states • independent variable (usually time; `causality = "independent"`). If an independent variable is not explicitely defined under `ScalarVariables`, it is assumed that the Unknown depends explicitely on the independent variable. Knowns $\mathbf{v}_{known}$ in *Initialization Mode* (for elements `InitialUnknowns`): • inputs (variables with `causality = "input"`) • variables with `initial = "exact"` [*for example independent parameters or initial states.*] • independent variable (usually time; `causality = "independent"`). If an independent variable is not explicitely defined under `ScalarVariables`, it is assumed that the Unknown depends explicitely on the independent variable. For Co-Simulation, ”`dependencies`” does not list the dependency on continuous-time, if the capability flag `providesDirectionalDerivative` has a value of `false`, in other words the respective partial derivatives cannot be computed.
`dependenciesKind`	If not present, it must be assumed that the Unknown $v_{unknown}$ depends on the Knowns $\mathbf{v}_{known}$ without a particular structure. Otherwise, the corresponding Known $v_{known,i}$ enters the equation as: If "dependenciesKind" is present, "dependencies" must be present and must have the same number of list elements. `= dependent:` no particular structure, $h(..,v_{known,i},..)$ Only for Real unknowns $v_{unknown}$: `= constant:` constant factor, $c \cdot v_{known,i}$ where c is an expression that is evaluated before `fmi2EnterInitializationMode` is called. Only for Real unknowns $v_{unknown}$ in Event and Continuous-Time Mode (ModelExchange) and at *Communication Points* (CoSimulation), and not for `InitialUnknowns` for Initialization Mode:

	`= fixed:` fixed factor, $p \cdot v_{known,i}$ where p is an expression that is evaluated before `fmi2ExitInitializationMode` is called. `= tunable:` tunable factor, $p \cdot v_{known,i}$ where p is an expression that is evaluated before `fmi2ExitInitializationMode` is called and in Event Mode due to an external event (ModelExchange) or at a Communication Point (CoSimulation) `= discrete:` discrete factor, $d \cdot v_{known,i}$ where d is an expression that is evaluated before `fmi2ExitInitializationMode` is called and in Event Mode due to an external or internal event or at a Communication Point (CoSimulation). If `"dependenciesKind"` is present, `"dependencies"` must be present and must have the same number of list elements.

[*Example 1:*

An FMU is defined by the following equations:

$$\frac{d}{dt}\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} f_1(x_2) \\ f_2(x_1) + 3 \cdot p^2 \cdot x_2 + 2 \cdot u_1 + 3 \cdot u_3 \\ f_3(x_1, x_3, u_1, u_2, u_3) \end{bmatrix}$$
$$y = g_1(x_2, x_3)$$

where u_1 is a continuous-time input (variability=”continuous”), u_2 is any type of input, u_3 is a Real discrete-time input (variability=”discrete”), and p is a fixed parameter (variability=”fixed”). The initialization is defined by:

$$x_1 = 1.1, \frac{dx_2}{dt} = 0, y = 3.3$$

and therefore the initialization equations are:

$$x_2 = \frac{1}{3 \cdot p^2} \cdot (f_2(x_1) + 2 \cdot u_1 + 3 \cdot u_3)$$
$$x_3 = g_1^{-1}(x_2, y)$$

This equation system can be defined as:

```
<ModelVariables>
   <ScalarVariable name="p"      , ...> … </ScalarVariable>  <!—index="1" -->
   <ScalarVariable name="u1"     , ...> … </ScalarVariable>  <!—index="2" -->
   <ScalarVariable name="u2"     , ...> … </ScalarVariable>  <!—index="3" -->
   <ScalarVariable name="u3"     , ...> … </ScalarVariable>  <!—index="4" -->
   <ScalarVariable name="x1"     , ...> … </ScalarVariable>  <!—index="5" -->
   <ScalarVariable name="x2"     , ...> … </ScalarVariable>  <!—index="6" -->
   <ScalarVariable name="x3"     , ...> … </ScalarVariable>  <!—index="7" -->
   <ScalarVariable name="der(x1)", ...> … </ScalarVariable>  <!—index="8" -->
   <ScalarVariable name="der(x2)", ...> … </ScalarVariable>  <!—index="9" -->
   <ScalarVariable name="der(x3)", ...> … </ScalarVariable>  <!—index="10" -->
   <ScalarVariable name="y"      , ...> … </ScalarVariable>  <!—index="11" -->
</ModelVariables>

<ModelStructure>
   <Outputs>
     <Unknown index="11" dependencies="6 7" />
   </Outputs>
```

```
    <Derivatives>
      <Unknown index="8"  dependencies="6" />
      <Unknown index="9"  dependencies="2 4 5 6"
                          dependenciesKind="constant constant dependent fixed"/>
      <Unknown index="10" dependencies="2 3 4 5 6" />
    </Derivatives>

    <InitialUnknowns>
      <Unknown index="6" dependencies="2 4 5" />
      <Unknown index="7" dependencies="2 4 5 11" />
      <Unknown index="8" ... />
      <Unknown index="10" ... />
    </InitialUnknowns>
 </ModelStructure>
```

Example 2:

$$y = \begin{cases} 2 \cdot u & \text{if } u > 0 \\ 3 \cdot u & \text{else} \end{cases}$$

where u is a continuous-time input with index="1" and y is a continuous-time output with index="2". The definition of the model structure is then:

```
 <ModelStructure>
    <Outputs>
      <Unknown index="2" dependencies="1" dependenciesKind="discrete"/>
    </Outputs>
 </ModelStructure>
```

Note, $y = d \cdot u$ where d changes only during Event Mode ($d = 2 \cdot u$ or $3 \cdot u$ depending on relation $u > 0$ that changes only at Event Mode). Therefore dependenciesKind="discrete".

Example 3:

$$y = \begin{cases} 2 & \text{if } u > 0 \\ 3 & \text{else} \end{cases}$$

where u is a continuous-time input with index="1" and y is a continuous-time output with index="2". The definition of the model structure is then:

```
 <ModelStructure>
    <Outputs>
      <Unknown index="2" dependencies="1" dependenciesKind="dependent"/>
    </Outputs>
 </ModelStructure>
```

Note, $y = c$ where c changes only during Event Mode ($c = 2$ or 3 depending on relation $u > 0$ that changes only at Event Mode). Therefore dependenciesKind="dependent" because it is not a linear relationship on u.

Defining FMU features with the `dependencies` list:

Note, via the `dependencies` list the supported features of the FMU can be defined. Examples:

- *If a state derivative `der_x` is a function of a parameter `p` (so of a start value of a variable with `causality = "parameter"` and `variability = "fixed"`), and the FMU does not support an iteration over `p` during InitializationMode (e.g. to iterate over `p` such that the state derivative `der_x` is zero), then the dependencies list of `der_x` should not include `p`. If an FMU is imported in an environment and such an iteration is setup, then the tool can figure out that the resulting algebraic system of equations is structurally singular and therefore can reject such a definition.*

- *For standard CoSimulation FMUs it is common that no algebraic loops over the input/output variables nor over start-values is supported. In such a case, all `dependencies` lists for output variables under the `InitialUnknowns` element should be defined as empty lists defining that the setting of inputs and/or of start values does not influence the outputs. As a result, it is not possible to formulate algebraic loops of connected FMUs during InitializationMode.*

]

2.2.9 Variable Naming Conventions (variableNamingConvention)

With attribute “variableNamingConvention” of element “`fmiModelDescription`”, the convention is defined how the ScalarVariable.names have been constructed. If this information is known, the environment may be able to represent the names in a better way (for example as tree and not as a linear list).

In the following definitions, the EBNF is used:

=	production rule
[ ]	optional
{ }	repeat zero or more times
|	or

The following conventions for scalar names are defined:

`variableNamingConvention = "flat"`

```
name = Unicode-char { Unicode-char }   // identical to xs:normalizedString
Unicode-char = any Unicode character without carriage return (#xD), line feed (#xA)
               nor tab (#x9)
```

The names must be unique, non-empty strings.
[*It is recommended that the names are visually clearly different from each other; but it is not required.*]

`variableNamingConvention = "structured"`

Structured names are hierarchical using “.” as a separator between hierarchies. A name consists of “_”, letters and digits or may consist of any characters enclosed in single apostrophes. A name may identify an array element on every hierarchical level using “[...]” to identify the respective array index. A derivative of a variable is defined with “`der(name)`” for the first time derivative and “`der(name,N)`” for the N-th derivative. Examples:

```
vehicle.engine.speed
resistor12.u
v_min
robot.axis.'motor #234'
der(pipe[3,4].T[14],2)    // second time derivative of pipe[3,4].T[14]
```

The precise syntax is[9]:.

```
name            = identifier | "der(" identifier ["," unsignedInteger ] ")"
identifier      = B-name [ arrayIndices  ] {"." B-name [ arrayIndices ] }
B-name          = nondigit { digit | nondigit } | Q-name
nondigit        = "_" | letters "a" to "z" | letters "A" to "Z"
digit           = "0" | "1" | "2" | "3" | "4" | "5" | "6" | "7" | "8" | "9"
Q-name          = "'" ( Q-char | escape ) { Q-char | escape } "'"
Q-char          = nondigit | digit | "!" | "#" | "$" | "%" | "&" | "(" | ")" |
                                     "*" | "+" | "," | "-" | "." | "/" | ":" |
```

[9] This definition is identical to the syntax of an identifier in Modelica version 3.2.

```
                                  ";" | "<" | ">" | "=" | "?" | "@" | "[" |
                                  "]" | "^" | "{" | "}"  | "|" | "~" | " "
escape          = "\'" | "\"" | "\?" | "\\" | "\a" | "\b" |
                  "\f" | "\n" | "\r" | "\t" | "\v"
arrayIndices    = "[" unsignedInteger {"," unsignedInteger} "]"
unsignedInteger = digit { digit }
```

The tree of names is mapped to an ordered list of ScalarVariable.name's in depth-first order. Example:

```
vehicle
  transmission
    ratio
    outputSpeed
  engine
    inputSpeed
    temperature
```

is mapped to the following list of ScalarVariable.name's:

```
vehicle.transmission.ratio
vehicle.transmission.outputSpeed
vehicle.engine.inputSpeed
vehicle.engine.temperature
```

All array elements are given in a consecutive sequence of `ScalarVariables`. Elements of multi-dimensional arrays are ordered according to "row major" order that is elements of the last index are given in sequence.

[*For example the vector "centerOfMass" in body "arm1" is mapped to the following ScalarVariables:*

```
robot.arm1.centerOfMass[1]
robot.arm1.centerOfMass[2]
robot.arm1.centerOfMass[3]
```

For example, a table T[4,3,2] (first dimension 4 entries, second dimension 3 entries, third dimension 2 entries) is mapped to the following ScalarVariables:

```
T[1,1,1]
T[1,1,2]
T[1,2,1]
T[1,2,2]
T[1,3,1]
T[1,3,2]
T[2,1,1]
T[2,1,2]
T[2,3,1]
  …
```

]

It might be that not all elements of an array are present. If they are present, they are given in consecutive order in the XML file.

2.3 FMU Distribution

An FMU description consists of several files. An FMU implementation may be distributed in source code and/or in binary format. All relevant files are stored in a zip file with a pre-defined structure. The implementation must either implement all the functions of FMI for Model Exchange or all the functions of FMI for Co-Simulation or both. The extension of the zip file must be "**.fmu**", for example "HybridVehicle.fmu". The compression method used for the zip file must be "deflate" [*(most free tools, for example zlib, offer only the common compression method "deflate")*].

Every FMU is distributed with its own zip file. This zip file has the following structure:

```
// Structure of zip file of an FMU
modelDescription.xml         // Description of FMU (required file)
model.png                    // Optional image file of FMU icon
documentation                // Optional directory containing the FMU documentation
   index.html                // Entry point of the documentation
   <other documentation files>
sources                      // Optional directory containing all C sources
   // all needed C sources and C header files to compile and link the FMU
   // with exception of: fmi2TypesPlatform.h , fmi2FunctionTypes.h and fmi2Functions.h
   // The files to be compiled (but not the files included from these files)
   // have to be reported in the xml-file under the structure
   // <ModelExchange><SourceFiles> … and <CoSimulation><SourceFiles>
binaries                     // Optional directory containing the binaries
   win32                     // Optional binaries for 32-bit Windows
      <modelIdentifier>.dll  // DLL of the FMI implementation
                             // (build with option "MT" to include run-time environment)
      <other DLLs>           // The DLL can include other DLLs
      // Optional object Libraries for a particular compiler
      VisualStudio8        // Binaries for 32-bit Windows generated with
                           // Microsoft Visual Studio 8 (2005)
         <modelIdentifier>.lib   // Binary libraries
      gcc3.1               // Binaries for gcc 3.1.
        ...
   win64    // Optional binaries for 64-bit Windows
      ...
   linux32  // Optional binaries for 32-bit Linux
      <modelIdentifier>.so  // Shared library of the FMI implementation
      ...
   linux64  // Optional binaries for 64-bit Linux
      ...
resources  // Optional resources needed by the FMU
   < data in FMU specific files which will be read during initialization;
     also more folders can be added under resources (tool/model specific).
     In order for the FMU to access these resource files, the resource directory
     must be available in unzipped form and the absolute path to this directory
     must be reported via argument "fmuResourceLocation" via fmi2Instantiate.
   >
```

An FMU has to implement all common functions (according to tables in sections 3.2.3 and 4.2.4). ModelExchange FMUs have to provide additionally the respective Model Exchange function, CoSimulation FMUs the Co-Simulation functions.

The FMU must be distributed with at least one implementation, in other words either sources or one of the binaries for a particular machine. It is also possible to provide the sources and binaries for different target machines together in one zip file. The following names are standardized: For Windows: “win32”, “win64”- For Linux: “linux32”, “linux64”. For Mac: “darwin32“, “darwin64” Futhermore, also the names “VisualStudioX” and “gccX” are standardized and define the compiler with which the binary has been generated [*, for example VisualStudio8*]. Further names can be introduced by vendors. Dynamic link libraries must include all referenced resources that are not available on a standard target machine [*for example DLLs on Windows machines must be built with option “MT” to include the run-time environment of VisualStudio in the DLL, and not use the option “MD” where this is not the case*]. When compiling a shared object on Linux, RPATH=“$ORIGIN“ has to be set when generating the shared object in order that shared objects used from it, can be dynamically loaded.

Typical scenarios are to provide binaries only for one machine type (for example on the machine where the target simulator is running and for which licenses of run-time libraries are available) or to provide only sources (for example for translation and download for a particular micro-processor). If run-time libraries cannot be shipped due to licensing, special handling is needed, for example by providing the run-time libraries at appropriate places by the receiver.

FMI provides the means for two kinds of implementation: `needsExecutionTool=true` and `needsExecutionTool=false`. In the first case a tool specific wrapper DLL/SharedObject has to be provided as the binary, in the second a compiled or source code version of the model with its solver is stored (see section 4.3.1 for details).

In an FMU both a version for ModelExchange and for CoSimulation might be present. If in both cases the executable part is provided as DLL/SharedObject, then two different or only one library can be provided. The library names are defined in the `modelIdentifier` attribute of elements "`fmiModelDescription.ModelExchange`" and "`fmiModelDescription.CoSimulation`":

```
[Example for different libraries:
  binaries
     win32
        MyModel_ModelExchange.dll   // ModelExchange.modelIdentifier =
                                    //    "MyModel_ModelExchange"
        MyModel_CoSimulation.dll    // CoSimulation.modelIdentifier =
                                    //    "MyModel_CoSimulation"
]
```

The usual distribution of an FMU will be with DLLs/SharedObjects because then further automatic processing [*(for example importing into another tool)*] is possible.

If run-time libraries are needed by the FMU that have to be present on the target machine, then automatic processing is likely impossible. The requirements and the expected processing should be documented in the "`documentation`" directory in this case.

A source-based distribution might require manual interaction in order that it can be utilized. The intention is to support platforms that are not known in advance (such as HIL-platforms or micro-controllers). Typically, in such a case the complete source code in ANSI-C is provided (for example one C source file that includes all other needed C files with the "#include" directive). All C source file names that need to be defined in a compiler directive have to be defined in the xml-file under structure `<ModelExchange><SourceFiles>` and `<CoSimulation><SourceFiles>`. These files may include other files. `#include` directive with `""` should be used for header-filers distributed in the FMU instead of using <…>. If default options of the compiler are sufficient, it might be then possible to automatically process such source code FMUs. An exporting tool should give documentation how to build an executable, either via a documentation file and/or a template makefile for a particular platform, from which a user can construct the makefile for his/her target platform. This documentation should be stored in the "`documentation`" directory, possibly with a link to the template makefile (stored in the "`sources`" directory). [*As template makefile, CMake (www.cmake.org), a cross-platform, open-source build system might be used.*]

In directory "`resources`", additional data can be provided in FMU specific formats, typically for tables and maps used in the FMU. This data must be read into the model at latest during initialization (that is before "`fmi2ExitInitializationMode`" is called). The actual file names in the zip file to access the data files can either be hard-coded in the generated FMU functions, or the file names can be provided as string parameters via the "`fmi2SetString`" function. [*Note, the absolute file name of the resource directory is provided by the initialization functions*]. In the case of a co-simulation implementation of `needsExecutionTool=true` type, the "resources" directory can contain the model file in the tool specific file format.

[*Note, the header files `fmi2TypesPlatform.h` and `fmi2FunctionTypes.h/fmi2Functions.h` are not included in the FMU due to the following reasons:*

*`fmi2TypesPlatform.h` makes no sense in the "**`sources`**" directory, because if sources are provided, then the target simulator defines this header file and not the FMU.*
*This header file is not included in the "**`binaries`**" directory, because it is implicitly defined by the platform*

directory (for example win32 for 32-bit machine or linux64 for 64-bit machine). Furthermore, the version that was used to construct the FMU can also be inquired via function `fmi2GetTypesPlatform()`.

`fmi2FunctionTypes.h/fmi2Functions.h` *are not needed in the "***`sources`***" directory, because they are implicitly defined by attribute* `fmiVersion` *in file* **`modelDescription.xml`***. Furthermore, in order that the C-compiler can check for consistent function arguments, the header file from the target simulator should be used when compiling the C sources. It would therefore be counter productive (unsafe), if this header file would be present.*
*These header files are not included in the "***`binaries`***" directory, since they are already utilized to build the target simulator executable. Via attribute* `fmiVersion` *in file* **`modelDescription.xml`** *or via function call* `fmi2GetVersion()` *the version number of the header file used to construct the FMU can be deduced.*]

3. FMI for Model Exchange

This chapter contains the interface description to access the equations of a dynamic system from a C program. A schematic view of a model in "FMI for Model Exchange" format is shown in the next figure:

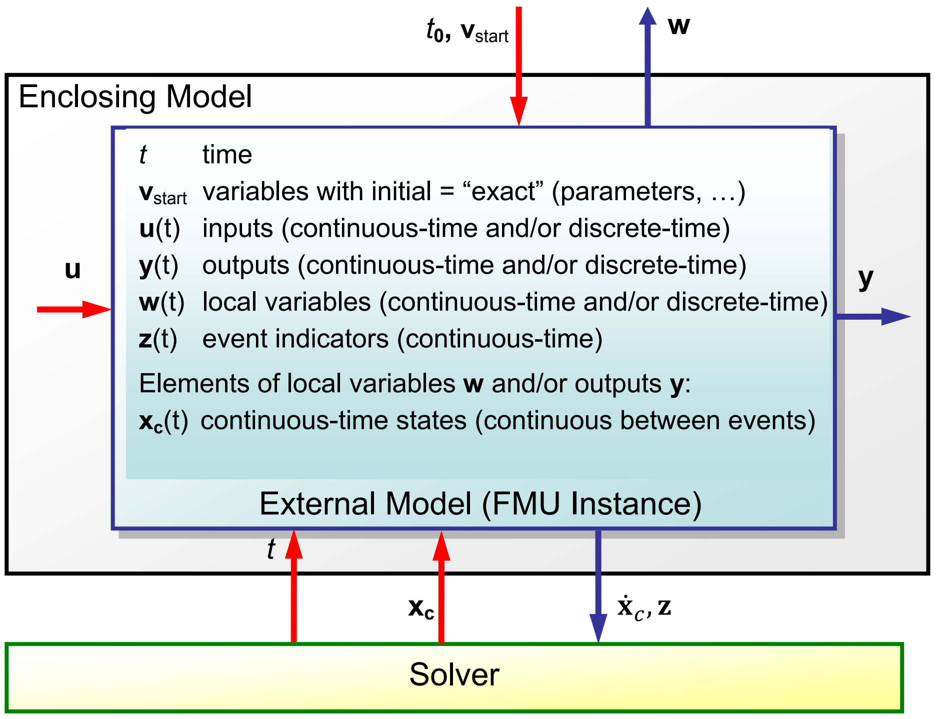

t_0, $\mathbf{v}_{start}$
w
Enclosing Model
t time
$\mathbf{v}_{start}$ variables with initial = "exact" (parameters, …)
u(t) inputs (continuous-time and/or discrete-time)
y(t) outputs (continuous-time and/or discrete-time)
w(t) local variables (continuous-time and/or discrete-time)
z(t) event indicators (continuous-time)
Elements of local variables **w** and/or outputs **y**:
$\mathbf{x}_c$(t) continuous-time states (continuous between events)
External Model (FMU Instance)
u
y
t
$\mathbf{x}_c$
$\dot{\mathbf{x}}_c$, **z**
Solver

Figure 2: Data flow between the environment and an FMU for Model Exchange:
Blue arrows: Information provided by the FMU.
Red arrows : Information provided to the FMU.
$\mathbf{v}_{start}$,**u**,**y**,**w**,$\mathbf{x}_d$ are of type Real, Integer, Boolean, String; t,$\mathbf{x}_c$,**z** are of type Real.

3.1 Mathematical Description

The goal of the Model Exchange interface is to numerically solve a system of differential, algebraic and discrete-time equations. In this version of the interface, ordinary differential equations in state space form with events are handled (abbreviated as "hybrid ODE"). Algebraic equation systems might be contained inside the FMU. Also, the FMU might consist of discrete-time equations only, for example describing a sampled-data controller.

The independent variable time $t \in \mathbb{T}$ is a tuple $t = (t_R, t_I)$ where $t_R \in \mathbb{R}$, $t_I \in \mathbb{N} = \{0,1,2,\ldots\}$. The real part t_R of this tuple is the independent variable of the FMU for describing the continuous-time behavior of the model between events. In this phase $t_I = 0$. The integer part t_I of this tuple is a counter to enumerate (and therefore distinguish) the events at the same continuous-time instant t_R. This time definition is also called "super dense time" in literature, see e.g. (*Lee and Zheng 2007*). An ordering is defined on $\mathbb{T}$ leading to the following notation[10]:

Operation	*Mathematical meaning*	*Description*
$t_1 < t_2$	$(t_{R1}, t_{I1}) < (t_{R2}, t_{I2}) \Leftrightarrow t_{R1} < t_{R2}$ **or** $t_{R1} = t_{R2}$ **and** $t_{I1} < t_{I2}$	t_1 is before t_2
$t_1 = t_2$	$(t_{R1}, t_{I1}) = (t_{R2}, t_{I2}) \Leftrightarrow t_{R1} = t_{R2}$ **and** $t_{I1} = t_{I2}$	t_1 is identical to t_2

[10] The notation $^{\bullet}t$ is from (*Benveniste et.al. 2010*) adapted from non-standard analysis to super-dense time, in order to precisely define the value from the previous event iteration.

t^+	$(t_R, t_I)^+ \Leftrightarrow (\lim_{\varepsilon\to 0}(t_R+\varepsilon), t_{Imax})$	right limit at *t*. $t_{Imax}$is the largest occurring Integer index of super dense time
^-t	$^-(t_R, t_I) \Leftrightarrow (\lim_{\varepsilon\to 0}(t_R-\varepsilon), 0)$	left limit at *t*
$^\bullet t$	$^\bullet(t_R, t_I) \Leftrightarrow \begin{cases} ^-t & \textbf{if } t_I = 0 \\ (t_R, t_I - 1) & \textbf{if } t_I > 0 \end{cases}$	previous time instant (= either left limit or previous event instant).
v^+	$v(t^+)$	value at the right limit of *t*
^-v	$v(^-t)$	value at the left limit of t
$^\bullet v$	$v(^\bullet t)$	previous value (= either left limit or value from the previous event)

[*Assume that an FMU has an event at t_R=2.1 s and here a signal changes discontinuously. If no event iteration occurs, the time instant when the event occurs is defined as (2.1, 0), and the time instant when the integration is restarted is defined as (2.1, 1).*]

The hybrid ODEs supported by FMI are described as piecewise continuous-time systems. Discontinuities can occur at time instants $t_0, t_1, \cdots, t_n$ where $t_i < t_{i+1}$. These time instants are called "events". Events can be known before hand (= time event), or are defined implicitly (= state and step events), see below. Between events, variables are either continuous or do not change their value. A variable is called discrete-time, if it changes its value only at an event instant. Otherwise the variable is called continuous-time. Only real variables can be continuous-time.

The following variable indices are used to describe the timing behavior of the corresponding variable (e.g. v_d is a discrete-time variable).

Index	*Description*
c	A **continuous-time** variable, that is a variable that is a continuous function of time inside each interval $t_i^+ \leq t \leq {}^-t_{i+1}$
d	A **discrete-time** variable, that is a variable that changes its value only at an event instant t_i.
c+d	A set of **continuous-time** and **discrete-time** variables

At every event instant t_i, variables might be discontinuous, see next figure:

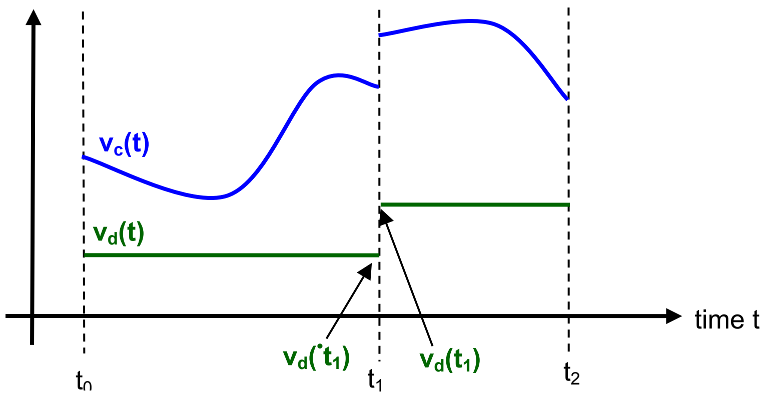


Figure 3: Piecewise-continuous variables of an FMU: continuous-time (v_c) and discrete-time (v_d).

An event instant t_i is defined by one of the following conditions that give the smallest time instant:

1. The environment of the FMU triggers an event at the current time instant because at least one discrete-time input changes its value, a continuous-time input has a discontinuous change, or a tunable parameter changes its value. Such an event is called external event. [*Note, if an FMU A is connected to an FMU B, and an event is triggered for A, then potentially all outputs of A will be*

discontinuous at this time instant. It is therefore adviceable to trigger an external event for B at this time instant too, if an output of A is connected to B. This means to call `fmi2EnterEventMode` *on B.*]
All the following events are internal events.

2. At a predefined time instant $t_i = (T_{next}(t_{i-1}), 0)$ that was defined at the previous event instant t_{i-1} by the FMU. Such an event is called <u>time event</u>.
3. At a time instant, where an <u>event indicator</u> $z_j(t)$ changes its domain from $z_j > 0$ to $z_j \le 0$ or from $z_j \le 0$ to $z_j > 0$ (see Figure 4 below). More precisely: An event $t = t_i$ occurs at the smallest time instant "min t" with $t > t_{i-1}$ where "$(z_j(t) > 0) \ne (z_j(t_{i-1}) > 0)$". Such an event is called <u>state event</u>[11]. All event indicators are piecewise continuous and are collected together in one vector of real numbers $\mathbf{z}(t)$.

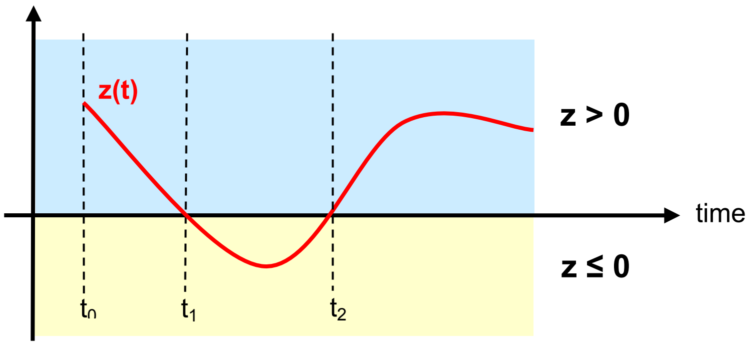


Figure 4: An event occurs when the event indicator changes its domain from z > 0 to z ≤ 0 or vice versa.

4. At every completed step of an integrator, `fmi2CompletedIntegratorStep` must be called (provided the capability flag `ModelDescription.completedIntegratorStepNotNeeded = false`). An event occurs at this time instant, if indicated by the return argument `nextMode = EventMode`. Such an event is called <u>step event</u>. [*Step events are, for example, used to dynamically change the (continuous) states of a model internally in the FMU, because the previous states are no longer suited numerically.*]

An FMI Model-Exchange model is described by the following variables:

Variable	*Description*
t	Independent variable time ∈ 𝕋. (Variable defined with `causality = "independent"`).
$\mathbf{v}$	A vector of all exposed variables (all variables defined in element `<ModelVariables>`, see section 2.2.7). Via a subscript, a subset of the variables is selected. Example: $\mathbf{v}_{\text{initial=exact}}$ are variables defined with attribute `initial = "exact"`, see section 2.2.7. These are independent parameters and start values of other variables, such as initial values for states, state derivatives or outputs.
$\mathbf{p}$	Parameters that are constant during simulation. The symbol without a sub-script references independent parameters (variables with `causality = "parameter"`). Dependent parameters (variables with `causality = "calculatedParameter"`) are denoted as $\mathbf{p}_{calculated}$.
$\mathbf{u}(t)$	Input variables. The values of these variables are defined outside of the model. Variables of this type are defined with attribute `causality = "input"`. Via attribute `variability = "discrete"` or `"continuous"` it is defined whether the input is a discrete-time or continuous-time variable, see section 2.2.7.
$\mathbf{y}(t)$	Output variables. The values of these variables are computed in the FMU and they are designed to be used in a model connection. So output variables might be used in the environment as input values to other FMUs or other submodels. Variables of this type are

[11] This definition is slightly different from the standard definition of state events: "$z_j(t) \cdot z_j(t_{i-1}) \le 0$". This often used definition has the severe drawback that $z_j(t_{i-1}) \ne 0$ is required in order to be well-defined and this condition cannot be guaranteed.

	defined with attribute `causality = "output"`. Via attribute `variability = "discrete"` or `"continuous"` it is defined whether the output is a discrete-time or continuous-time variable, see section 2.2.7.
w(t)	Local variables of the FMU that cannot be used for FMU connections. Variables of this type are defined with attribute `causality = "local"`, see section 2.2.7.
z(t)	A vector of real continuous-time variables utilized to define state events, see below.
$\mathbf{x}_c(t)$	A vector of real continuous-time variables representing the continuous-time states. For notational convenience, a continuous-time state is conceptually treated as a different type of variable as an output or a local variable for the mathematical description below. In reality, a continuous-time state is however part of the outputs **y** or the local variables **w** of an FMU.
$\mathbf{x}_d(t)$ $^\bullet\mathbf{x}_d(t)$	$\mathbf{x}_d(t)$ is a vector of (internal) discrete-time variables (of any type) representing the discrete states. $^\bullet\mathbf{x}_d(t)$ is the value of $\mathbf{x}_d(t)$ at the previous super dense time instant, so $^\bullet\mathbf{x}_d(t) = \mathbf{x}_d(^\bullet t)$. Given the previous values of the discrete-time states, $^\bullet\mathbf{x}_d(t)$, at the actual time instant *t*, all other discrete-time variables, especially the discrete states $\mathbf{x}_d(t)$, can be computed. Discrete states are not visible in the interface of an FMU and are only introduced here to clarify the mathematical description. Formally, a discrete state is part of the outputs **y** or the local variables **w** of an FMU.
$T_{next}(t_i)$	At initialization or at an event instant, an FMU can define the next time instant T_{next}, at which the next event occurs (see also the definition of events above). Note, every event removes automatically a previous definition of T_{next}, and it must be explicitely defined again, if a previously defined T_{next} was not triggered at the current event instant.
$\mathbf{r}(t_i)$	A vector of Boolean variables with $r_i \coloneqq z_i > 0$. When entering Continuous-Time Mode all relations reported via the event indicators $\mathbf{z}$ are fixed and during this Mode these relations are replaced by $\mathbf{r}$. Only during Initialization or Event Mode the domains $z_i > 0$ can be changed. For notational convenience, $\mathbf{r} \coloneqq \mathbf{z} > 0$ is an abbreviation for $\mathbf{r} \coloneqq \{z_1 > 0, z_2 > 0, \ldots\}$. [*For more details, see “Remark 3” below.*]

Computing the solution of an FMI model means to split the solution process in different phases and in every phase different equations and solution methods are utilized. The phases can be categorized according to the following modes:

1. **Initialization Mode:**
   This mode is used to compute at the start time t_0 initial values for continuous-time states, $\mathbf{x}_c(t_0)$, and for the previous (internal) discrete-time states, $^\bullet\mathbf{x}_d(t_0)$, by utilizing extra equations not present in the other modes (for example equations to define the start value for a state or for the derivative of a state).

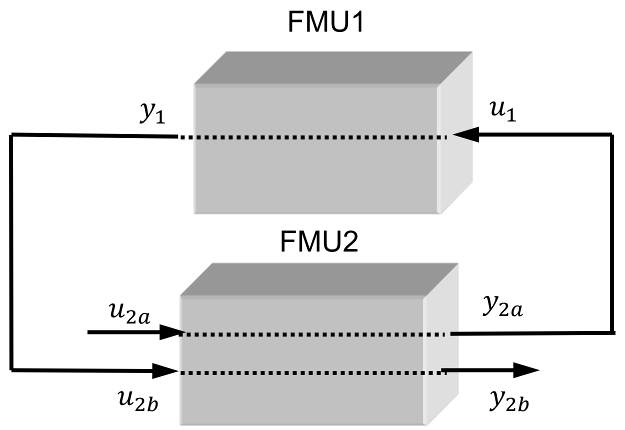
2. **Continuous-Time Mode:**
   This mode is used to compute the values of all (real) continuous-time variables between events by numerically solving ordinary differential and algebraic equations. All discrete-time variables are fixed during this phase and the corresponding discrete-time equations are not evaluated.

3. **Event Mode:**
   This mode is used to compute new values for all continuous-time variables, as well as for all discrete-time variables that are activated at the current event instant t, given the values of the variables from the previous instant$^\bullet t$. This is performed by solving algebraic equations consisting of all continuous-time and all active discrete-time equations. In FMI 2.0 there is no mechanism that the FMU can provide the information whether a discrete-time variable is active or is not active (is not computed) at an event instant. Therefore, the environment has to assume that at an event instant always all discrete-time variables are computed, although internally in the FMU only a subset might be newly computed.

When connecting FMUs together, loop structures can occur that lead to particular difficulties because linear or non-linear algebraic systems of equations in Real variables but also in Boolean or Integer variables might be present. In order to solve such systems of equations over FMUs efficiently the dependency information is needed stating, for example, which outputs depend directly on inputs. This data is optionally provided in the xml file under element `<ModelStructure>`. If this data is not provided, the worst case must be assumed (for example, all output variables depend algebraically on all input variables).

[*Example: In the next Figure two different types of connected FMUs are shown (the "dotted lines" characterize the dependency information):*

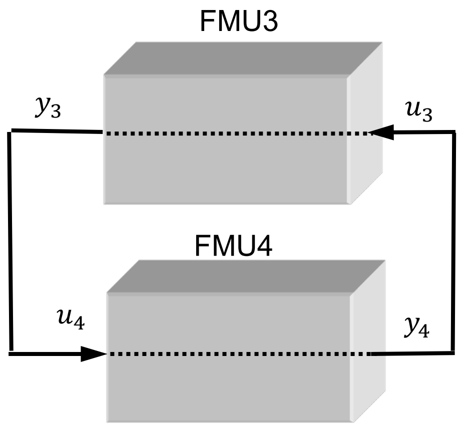
artifical algebraic loop



sequential calling sequence:

```
fmiSetXXX(m2,< $u_{2a}$>, …)
$y_{2a}$ ≔ fmiGetXXX(m2, ...)
fmiSetXXX(m1, < $u_1$ ≔ $y_{2a}$ >, ...)
$y_1$  ≔ fmiGetXXX(m1,..)
fmiSetXXX(m2, < $u_{2b}$ ≔ $y_1$ >, ...)
$y_{2b}$ ≔ fmiGetXXX(m2, ...)
```

"real" algebraic loop



iterative calling sequence:

```
In every Newton iteration evaluate:
input: $u_4$           // provided by solver
output: residue  // provided to solver
   fmiSetXXX(m4,< $u_4$>, …)
   $y_4$ ≔ fmiGetXXX(m4, ...)
   fmiSetXXX(m3, < $u_3$ ≔ $y_4$ >, ...)
   $y_3$ ≔ fmiGetXXX(m3,..)
   residue ≔ $u_4 - y_3$
```

Figure 5: Calling sequences for FMUs that are connected in a loop.

In the upper diagram FMU1 and FMU2 are connected in such a way that by an appropriate sequence of fmi2SetXXX and fmi2GetXXX calls the FMU variables can be computed.

In the lower diagram FMU3 and FMU4 are connected in such a way that a "real" algebraic loop is present. This loop might be solved iteratively with a Newton method. In every iteration the iteration variable u_4 is provided by the solver and via the shown sequence of fmi2SetXXX and fmi2GetXXX calls the residue is computed and is provided back to the solver. Based on the residue a new value of u_4 is provided. The iteration is terminated when the residue is close to zero.

These types of artifical or real algebraic loops can occur in all the different modes, Initialization Mode, Event Mode, and Continuous-Time Mode. Since different variables are computed in every Mode and the

causality of variable computation can be different in Initialization Mode as with respect to the other two Modes, it might be necessary to solve different kinds of loops in the different Modes.
]

In Table 1 the equations are defined that can be evaluated in the respective Mode. The following color coding is used in the table:

grey	If a variable in an argument list is marked in grey, then this variable is not changing in this mode and just the last calculated value from the previous mode is internally used. For an input argument it is not allowed to call `fmi2SetXXX`. For an output argument, calling `fmi2GetXXX` on such a variable returns always the same value in this mode.
green	Functions marked in green are special functions to enter or leave a mode.
blue	Equations and functions marked in blue define the actual computations to be performed in the respective mode.

Function `fmi2SetXXX` is an abbreviation for functions `fmi2SetReal`, `fmi2SetBoolean`, `fmi2SetInteger` and `fmi2SetString` respectively. Function `fmi2GetXXX` is an abbreviation for functions `fmi2GetReal`, `fmi2GetBoolean`, `fmi2GetInteger` and `fmi2GetString` respectively.

[*In the following table the setting of the super dense time,*(t_R, t_I)*, is precisely described. Tools will usually not have such a representation of time. However, super-dense time defines precisely when a new "model evaluation" starts and therefore which variable values belong to the same "model evaluation" at the same (super dense) time instant and should be stored together.*
]

Equations	**FMI functions**
Equations before Initialization Mode	
Set independent variable time t_{R0} and define $t_0 := (t_{R0}, 0)$	`fmi2SetupExperiment`
Set variables $\mathbf{v}_{initial=exact}$ and $\mathbf{v}_{initial=approx}$ that have a start value (`initial` = `"exact"` or `"approx"`)	`fmi2SetXXX`
Equations during Initialization Mode	
Enter Initialization Mode at $t = t_0$ (activate initialization, discrete-time and continuous-time equations)	`fmi2EnterInitializationMode`
Set variables $\mathbf{v}_{initial=exact}$ that have a start value with `initial="exact"` (independent parameters $\mathbf{p}$ and continuous-time states with start values $\mathbf{x}_{c,initial=exact}$ are included here)	`fmi2SetXXX`
Set continuous-time and discrete-time inputs $\mathbf{u}(t_0)$	`fmi2SetXXX`
$\mathbf{v}_{InitialUnknowns} := \mathbf{f}_{init}(\boldsymbol{u}_c, \boldsymbol{u}_d, t_0, \mathbf{v}_{initial=exact})$	`fmi2GetXXX`, `fmi2GetContinuousStates`
Exit Initialization Mode (de-activate initialization equations)	`fmi2ExitInitializationMode`
Equations during Event Mode	
Enter Event Mode at $t = t_i$ with $t_i := (t_R, t_I + 1)$ **if** $externalEvent$ **or** $nextMode \equiv EventMode$ **or** $t_i = (T_{next}(t_{i-1}), 0)$ **or** $\min\limits_{t>t_{i-1}} t{:}\left[z_j(t) > 0 \neq z_j(t_{i-1}) > 0\right]$ (activate discrete-time equations)	`fmi2EnterEventMode` (only from Continuous-Time Mode or after calling `fmi2SetTime` if FMU has no continuous-time equations)
Set independent tunable parameters $\mathbf{p}_{tune}$	`fmi2SetXXX`

(and do not set other parameters $\mathbf{p}_{other}$)	
Set continuous-time and discrete-time inputs $\mathbf{u}(t_i)$	`fmi2SetXXX`
Set continuous-time states $\mathbf{x}_c(t_i)$	`fmi2SetXXX`, `fmi2SetContinuousStates`

$(\mathbf{y}_{c+d}, \dot{\mathbf{x}}_c, \boldsymbol{w}_{c+d}, \mathbf{z}, \mathbf{x}_{c,reinit}) := \mathbf{f}_{sim}(\mathbf{x}_c, \boldsymbol{u}_{c+d}, t_i, \mathbf{p}_{tune}, \mathbf{p}_{other})$
$\mathbf{f}_{sim}$ is also a function of the internal variables ${}^\bullet\mathbf{x}_d$
	`fmi2GetXXX`,
	`fmi2GetContinuousStates`,
	`fmi2GetDerivatives`
	`fmi2GetEventIndicators`

Increment super dense time and define with `newDiscreteStatesNeeded` whether a new event iteration is required. **if not** newDiscreteStatesNeeded **then** $T_{next} := T_{next}(\mathbf{x}_c, {}^\bullet\mathbf{x}_d, \boldsymbol{u}_{c+d}, t_i, \mathbf{p}_{tune}, \mathbf{p}_{other})$ **end if** $t := (t_R, t_I + 1)$ ${}^\bullet\mathbf{x}_d := \mathbf{x}_d$	`fmi2NewDiscreteStates`
Set independent variable time $t_i := (T_{next}, 0)$	`fmi2SetTime` (if no continuous-time equations)
Equations during Continuous-Time Mode	
Enter Continuous-Time Mode: // de-activate discrete-time equations // "freeze" variables: $\mathbf{r} := \mathbf{z} > 0$ // all relations $\mathbf{y}_d, \boldsymbol{w}_d$ // all discrete - time variables	`fmi2EnterContinuousTimeMode`
Set independent variable time $t\ (> t_{enter\ mode})$: $t := (t_R, 0)$	`fmi2SetTime`
Set continuous-time inputs $\mathbf{u}_c(t)$	`fmi2SetXXX`
Set continuous-time states $\mathbf{x}_c(t)$	`fmi2SetXXX`, `fmi2SetContinuousStates`
$(\mathbf{y}_c, \mathrm{y}_d, \dot{\mathbf{x}}_c, \boldsymbol{w}_c, w_d, \mathbf{z}, \mathrm{x}_{c,reinit}) := \mathbf{f}_{sim}(\mathbf{x}_c, \boldsymbol{u}_c, u_d, t, \mathrm{p}_{tune}, \mathrm{p}_{other})$ $\mathbf{f}_{sim}$ is also a function of the internal variables ${}^\bullet\mathrm{x}_d, \mathbf{r}$.	`fmi2GetXXX`, `fmi2GetDerivatives`, `fmi2GetEventIndicators`
Complete integrator step and return *enterEventMode*	`fmi2CompletedIntegratorStep`
Data types	
$t \in \mathbb{R}, \mathbf{p} \in \mathbb{P}^{np}, \mathbf{u}(t) \in \mathbb{P}^{nu}, \mathbf{y}(t) \in \mathbb{P}^{ny}, \mathbf{x}_c(t) \in \mathbb{R}^{nxc}, \mathbf{x}_d(t) \in \mathbb{P}^{nxd}, \mathbf{w}(t) \in \mathbb{P}^{nw}, \mathbf{z}(t) \in \mathbb{R}^{nz}$ $\mathbb{R}$: real variable, $\mathbb{P}$: real **or** Boolean **or** integer **or** enumeration **or** string variable $\mathbf{f}_{init}, \mathbf{f}_{sim} \in C^0$ (= continuous functions with respect to all input arguments inside the respective mode).	

Table 1: Mathematical description of an FMU for Model Exchange.

[*Remark 1 – Calling Sequences:*
In the table above, for notational convenience in every Mode one function call is defined to compute all output arguments from all inputs arguments. In reality, every scalar output argument is computed by one `fmi2GetXXX` *function call. Additionally, the output argument need not be a function of all input arguments, but of only a subset from it, as defined in the xml file under* `<ModelStructure>`*. This is essential when FMUs are connected in a loop, as shown in* Figure 6*: For example, since y_{2a} depends only on u_{1a}, but not on u_{1b}, it is possible to call* `fmi2SetXXX` *to set u_{1a}, and then inquire y_{2a} with* `fmi2GetXXX` *without setting u_{1b} beforehand.*

It is non-trivial to provide code for `fmi2SetXXX`, `fmi2GetXXX`, *if the environment can call* `fmi2SetXXX` *on the inputs in quite different orders. A simple remedy is to provide the* *dependency information* *not according to the "real" functional dependency, but according to the* *sorted equations in the generated code*. *Example*

Assume an FMU is described by the following equations (`u1,u2` *are inputs,* `y1,y2` *are outputs,* `w1,w2` *are internal variables):*

```
w1 = w2 + u1
w2 = u2
y1 = w1
y2 = w2
```

Sorting of the equations might result in (this ordering is not unique):

```
w2 := u2
y2 := w2
w1 := w2 + u1
y1 := w1
```

With this ordering, the dependency should be defined as `y2 = f(u2), y1 = f(u1,u2)`. *When* `y2` *is called first with* `fmi2GetXXX`, *then only* `u2` *must be set first (since* `y2 = f(u2)`*), and the first two equations are evaluated. If later* `y1` *is inquired as well, then the first two equations are not evaluated again and only the last two equations are evaluated. On the other hand, if* `y1` *is inquired first, then* `u1` *and* `u2` *must be set first (since* `y1 = f(u1,u2)`*) and then all equations are computed. When* `y2` *is inquired afterwards, the cached value is returned.*

If sorting of the equations in this example would instead result in the following code:

```
w2 := u2
w1 := w2 + u1
y1 := w1
y2 := w2
```

then the dependency should be defined as `y2 = f(u1,u2), y1 = f(u1,u2)`, *because* `u1` *and* `u2` *must be first set, before* `y2` *can be inquired with* `fmi2GetXXX` *when executing this code.*

Remark 2 – Mathematical Model of Discrete-Time FMUs:
There are many different ways discrete-time systems are described. For FMI the following basic mathematical model for discrete-time systems is used (other description forms must be mapped, as sketched below):

```
while $T_{next} \le t_{end}$ loop
  $t_R := T_{next}$
  $t_I := 0$
  $t := (t_R, t_I)$
  loop // super dense time iteration (e.g. since state machine in FMU)
    repeat // algebraic loop iteration (due to connected FMUs)
      // either sequence or solve algebraic loops over FMUs iteratively
      $\mathbf{x}_d := \mathbf{f}({}^\bullet\mathbf{x}_d, \mathbf{u}_d)$
      $\mathbf{y}_d := \mathbf{g}({}^\bullet\mathbf{x}_d, \mathbf{u}_d)$
    until <algebraic loops solved>
    // function fmi2NewDiscreteStates:
    $T_{next} := T({}^\bullet\mathbf{x}_d, \mathbf{u}_d)$
    if $\mathbf{x}_d \equiv {}^\bullet\mathbf{x}_d$ then exit
    ${}^\bullet\mathbf{x}_d := \mathbf{x}_d$
    $t := (t_R, t_I + 1)$
  end loop
end while
```

At an event instant, the discrete system is described by algebraic equations as function of the previous (internal) discrete-time states $^\bullet\mathbf{x}_d$ and the discrete-time inputs $\mathbf{u}_d$. If FMUs are connected in a loop, these algebraic equations are called iteratively, until the solution is found. If the actual discrete-time states $\mathbf{x}_d$ and the previous discrete-time states $^\bullet\mathbf{x}_d$ are not identical, the discrete-time states are updated, the Integer part of the time is incremented and a new event iteration is performed. Other discrete-time models must be mapped to this description form. Examples:

- *Synchronous systems:*
  A synchronous system, such as Lucid Synchrone (Pouzet 2006) or Modelica 3.3 (Modelica 2012), is called periodically and at every sample instant the discrete-time equations are evaluated exactly once. An FMU of this type can be implemented by activating the model equations only at the first event iteration and returning always $newNewDiscreteStatesNeeded := false$ from `fmi2NewDiscreteStates`. Furthermore, the discrete-time states are not updated by `fmi2NewDiscreteStates`, but as first action before the discrete-time equations are evaluated, in order that $^\bullet\mathbf{x}_d$ (= value at the previous clock tick) and $\mathbf{x}_d$ (value at the latest clock tick) have reasonable values between clock ticks.
- *State machines with one memory location for a state:*
  In such a system there is only one memory location for a discrete-time state and not two, and therefore a discrete-time state is updated in the statement where it is assigned (and not in `fmi2NewDiscreteStates`). As a result, `fmi2NewDiscreteStates` is basically just used to start a new (super dense) time instant. This is unproblematic, as long as no algebraic loops occur. FMUs of this type can therefore not be used in "real" algebraic loops if the involved variables depend on a discrete-time state. This restriction is communicated to the environment of the FMU by the ScalarVariable definition of the corresponding input with flag `canHandleMultipleSetPerTimeInstant=false` (so an input with this flag is not allowed to be called in an algebraic loop).

Remark 3 – Event Indicators / Freezing Relations:
In the above table vector **r** *is used to collect all relations together that are utilized in the event indicators* **z**. *In Continuous-Time Mode all these relations are "frozen" and do not change during the evaluations in the respective Mode. This is indicated in the table above by computing* **r** *when entering the Continuous-Time Mode and providing* **r** *as (internal) input argument to the evaluation functions. Example:*

An equation of the form

```
y = if x1 > x2 or x1 < x3 then +1 else -1;
```

can be implemented in the FMU as:

```
z1 := x1 – x2;
z2 := x3 – x1;
if InitializationMode or EventMode then
   r1 := z1 > 0;
   r2 := z2 > 0;
end if;
y = if r1 or r2 then +1 else -1
```

Therefore, the original if-clause is evaluated in this form only during Initialization and Event Mode. In Continuous-Time Mode this equation is evaluated as:

```
z1 = x1 – x2;
z2 = x3 – x1
y = if r1 or r2 then +1 else -1;
```

and when entering Continuous-Time Mode r1 and r2 are computed as

r1 = z1 > 0
r2 = z2 > 0

When z1 changes from z1 > 0 to z1 <= 0 or vice versa, or z2 correspondingly, the integration is halted and the environment must call fmi2EnterEventMode.

An actual implementation will pack the code in an impure function, say Greater(...), resulting in:

y = **if** Greater(*x1-x2,...)* **or** Greater(x3-x1,...) **then** +1 **else** -1;

Furthermore, a hysteresis should be added for the event indicators. For more details see the companion document FunctionalMockupInterface-ImplementationHints.docx.

Remark 4 – Pure Discrete-Time FMUs:
If an FMU has only discrete-time equations (and no variables with variability = "continuous"), then the environment need not to call `fmi2EnterContinuousTimeMode` *but can directly call* `fmi2SetTime` *to set the value of the next event instant, before* `fmi2EnterEventMode` *is called.*

]

An FMU is initialized in Initialization Mode with $\mathbf{f}_{init}(\ldots)$. The input arguments to this function consist of the input variables (= variables with `causality = "input"`), of the independent variable (= variable with `causality = "independent"`; usually the default value `"time"`) and of all variables that have a start value with (explicitely or implicitely) `initial = "exact"` in order to compute the continuous-time states and the output variables at the initial time t_0. In the above table, the variables with `initial = exact` are collected together in variable $\mathbf{v}_{initial=exact}$. For example initialization might be defined by providing initial start values for the states, $\mathbf{x}_{c0}$, or by stating that the state derivatives are zero ($\dot{\mathbf{x}}_c = \mathbf{0}$). Initialization is a difficult topic by itself and it is required that an FMU solves a well-defined initialization problem inside the FMU in Initialization Mode.

After calling `fmi2ExitInitializationMode` the FMU is implicitely in Event Mode and all discrete-time and continuous-time variables at the initial time instant $(t_R, 0)$ can be calculated, if needed also iteratively due to an algebraic loop. Once finalized, `fmi2NewDiscreteStates` must be called, and depending on the value of the return argument, the FMU either continues the event iteration at the initial time instant or switches to Continuous-Time Mode.

After switching to Continuous-Time Mode, the integration is started. Basically, in this phase the derivatives of the continuous states are computed. If FMUs and/or submodels are connected together, then the inputs of these models are the outputs of other models and therefore the corresponding FMU outputs must be computed. Whenever result values shall be stored, usually at output points defined before the start of the simulation, the `fmi2GetXXX` function with respect to the desired variables must be called.

Continuous integration is stopped at an event instant. An event instant is determined by a time, state, or step event, or by an external event triggered by the environment. In order to determine a state event, the event indicators **z** have to be inquired at every completed integrator step. Once the event indicators signal a change of their domain, an iteration over time is performed between the previous and the actual completed integrator step, in order to determine the time instant of the domain change up to a certain precision.

After an event is triggered, the FMU needs to be switched to Event Mode. In this mode systems of equations over connected FMUs might be solved (similarily as in Continuous-Time Mode). Once convergence is reached, `fmi2NewDiscreteStates(..)` must be called to increment super dense time (and conceptually update the discrete-time states defined internally in the FMU by $^{\bullet}\mathbf{x}_d \coloneqq \mathbf{x}_d$). Depending on the discrete-time model, a new event iteration might be needed (e.g. because the FMU describes internally a state machine, and transitions are still able to fire, but new inputs shall be taken into account).

The function calls in the table above describe precisely, which input arguments are needed to compute the desired output argument(s). There is no 1:1 mapping of these mathematical functions to C functions. Instead, all input arguments are set with `fmi2SetXXX(..)` C-function calls and then the result argument(s) can be determined with the C functions defined in the right column of the above table. This technique is discussed in detail in section 3.2.1. [*In short: For efficiency reasons, all equations from the table above will usually be available in one (internal) C-function. With the C functions described in the next sections, input arguments are copied into the internal model data structure only when their value has changed in the environment. With the C functions in the right column of the table above, the internal function is called in such a way, that only the minimum needed equations are evaluated. Hereby, variable values calculated from previous calls can be reused. This technique is called "caching" and can significantly enhance the simulation efficiency of real-world models.*]

3.2 FMI Application Programming Interface

This section contains the interface description to evaluate different model parts from a C program.

3.2.1 Providing Independent Variables and Re-initialization of Caching

Depending on the situation, different variables need to be computed. In order to be efficient, it is important that the interface requires only the computation of variables that are needed in the present context. For example during the iteration of an integrator step, only the state derivatives need to be computed, provided the output of a model is not connected. It might be that at the same time instant other variables are needed. For example if an integrator step is completed, the event indicator functions need to be computed as well. For efficiency it is then important that in the call to compute the event indicator functions, the state derivatives are not newly computed, if they have been computed already at the present time instant. This means, the state derivatives shall be reused from the previous call. This feature is called "caching of variables" in the sequel.

Caching requires that the model evaluation can detect when the input arguments, like time or states, have changed. This is achieved by setting them explicitly with a function call, since every such function call signals precisely a change of the corresponding variables. For this reason, this section contains functions to set the input arguments of the equation evaluation functions. This is unproblematic for time and states, but is more involved for parameters and inputs, since the latter may have different data types.

```
fmi2Status fmi2SetTime(fmi2Component c, fmi2Real time);
```

Set a new time instant and re-initialize caching of variables that depend on time, provided the newly provided time value is different to the previously set time value (variables that depend solely on constants or parameters need not to be newly computed in the sequel, but the previously computed values can be reused).

```
fmi2Status fmi2SetContinuousStates(fmi2Component c, const fmi2Real x[],
                                                     size_t nx);
```

Set a new (continuous) state vector and re-initialize caching of variables that depend on the states. Argument `nx` is the length of vector `x` and is provided for checking purposes (variables that depend solely on constants, parameters, time, and inputs do not need to be newly computed in the sequel, but the previously computed values can be reused). Note, the continuous states might also be changed in Event Mode.
Note: `fmi2Status = fmi2Discard` is possible.

```
fmi2Status fmi2SetXXX(..);
```

Set new values for (independent) parameters, start values and inputs and re-initialize caching of variables that depend on these variables. The details of these functions are defined in section 2.1.7.

[*The functions above have the slight drawback that values must always be copied, for example a call to "`fmi2SetContinuousStates`" will provide the actual states in a vector and this function has to copy the values in to the internal model data structure "`c`" so that subsequent evaluation calls can utilize these* *values. If this turns out to be an efficiency issue, a future release of FMI might provide additional functions to provide the address of a memory area where the variable values are present.*]

3.2.2 Evaluation of Model Equations

This section contains the core functions to evaluate the model equations. Before one of these functions can be called, the appropriate functions from the previous section have to be used, to set the input arguments to the current model evaluation.

```
fmi2Status fmi2EnterEventMode(fmi2Component c);
```

The model enters Event Mode from the Continuous-Time Mode and discrete-time equations may become active (and relations are not “frozen”).

```
fmi2Status fmi2NewDiscreteStates(fmi2Component  c,
                                 fmi2EventInfo* fmi2eventInfo);
  typedef struct{
    fmi2Boolean newDiscreteStatesNeeded;
    fmi2Boolean terminateSimulation;
    fmi2Boolean nominalsOfContinuousStatesChanged;
    fmi2Boolean valuesOfContinuousStatesChanged;
    fmi2Boolean nextEventTimeDefined;
    fmi2Real    nextEventTime; // next event if nextEventTimeDefined=fmi2True
  } fmi2EventInfo;
```

The FMU is in Event Mode and the super dense time is incremented by this call.
If the super dense time before a call to `fmi2NewDiscreteStates` was (t_R, t_I) then the time instant after the call is $(t_R, t_I + 1)$.

If return argument `fmi2eventInfo->newDiscreteStatesNeeded = fmi2True`, the FMU should stay in Event Mode and the FMU requires to set new inputs to the FMU (`fmi2SetXXX` on inputs), to compute and get the outputs (`fmi2GetXXX` on outputs) and to call `fmi2NewDiscreteStates` again. Depending on the connection with other FMUs, the environment shall

- call `fmi2Terminate`, if `terminateSimulation = fmi2True` is returned by at least one FMU,
- call `fmi2EnterContinuousTimeMode` if all FMUs return `newDiscreteStatesNeeded = fmi2False`.
- stay in Event Mode otherwise.

When the FMU is terminated, it is assumed that an appropriate message is printed by the logger function (see section 2.1.5) to explain the reason for the termination.

If `nominalsOfContinuousStatesChanged = fmi2True` then the nominal values of the states have changed due to the function call and can be inquired with `fmi2GetNominalsOfContinuousStates`.

If `valuesOfContinuousStatesChanged = fmi2True` then at least one element of the continuous state vector has changed its value due to the function call. The new values of the states can be inquired with `fmi2GetContinuousStates`. If no element of the continuous state vector has changed its value, `valuesOfContinuousStatesChanged` must return `fmi2False`. [*if fmi2True would be returned in this case, an infinite event loop may occur.*]

If `nextEventTimeDefined = fmi2True`, then the simulation shall integrate at most until time = `nextEventTime`, and shall call `fmi2EnterEventMode` at this time instant. If integration is stopped before `nextEventTime`, for example due to a state event, the definition of `nextEventTime` becomes obsolete.

```
fmi2Status fmi2EnterContinuousTimeMode(fmi2Component c);
```

The model enters Continuous-Time Mode and all discrete-time equations become inactive and all relations are "frozen".

This function has to be called when changing from Event Mode (after the global event iteration in Event Mode over all involved FMUs and other models has converged) into Continuous-Time Mode.

[*This function might be used for the following purposes:*

- *If the FMU stores results internally on file, then the results after the initialization and/or the event has been processed can be stored.*
- *If the FMU contains dynamically changing states, then a new state selection might be performed with this function.*

]

```
fmi2Status fmi2CompletedIntegratorStep(fmi2Component c,
                                        fmi2Boolean  noSetFMUStatePriorToCurrentPoint,
                                        fmi2Boolean* enterEventMode,
                                        fmi2Boolean* terminateSimulation);
```

This function must be called by the environment after every completed step of the integrator provided the capability flag `completedIntegratorStepNotNeeded = false`.
Argument `noSetFMUStatePriorToCurrentPoint` is `fmi2True` if `fmi2SetFMUState` will no longer be called for time instants prior to current time in this simulation run [*the FMU can use this flag to flush a result buffer*].

The function returns `enterEventMode` to signal to the environment if the FMU shall call fmi2EnterEventMode, and it returns `terminateSimulation` to signal if the simulation shall be terminated. If `enterEventMode = fmi2False` and `terminateSimulation = fmi2False` the FMU stays in Continuous-Time Mode without calling `fmi2EnterContinuousTimeMode` again.

When the integrator step is completed and the states are modified by the integrator afterwards (for example correction by a BDF method), then `fmi2SetContinuousStates(..)` has to be called with the updated states before `fmi2CompletedIntegratorStep(..)` is called.

When the integrator step is completed and one or more event indicators change sign (with respect to the previously completed integrator step), then the integrator or the environment has to determine the time instant of the sign change that is closest to the previous completed step up to a certain precision (usually a small multiple of the machine epsilon). This is usually performed by an iteration where time is varied and state variables needed during the iteration are determined by interpolation. Function `fmi2CompletedIntegratorStep` must be called *after* this state event location procedure and *not* after the successful computation of the time step by the integration algorithm. The intended purpose of the function call is to indicate to the FMU that at this stage all inputs and state variables have valid (accepted) values.

After `fmi2CompletedIntegratorStep` is called, it is still allowed to go back in time (calling `fmi2SetTime`) and inquire values of variables at previous time instants with `fmi2GetXXX` [*for example to determine values of non-state variables at output points*]: However, it is not allowed to go back in time over the previous `completedIntegratorStep` or the previous `fmi2EnterEventMode` call.

[*This function might be used, for example for the following purposes:*

1. *Delays:*
   All variables that are used in a "delay(..)" operator are stored in an appropriate buffer and the function returns with `nextMode = fmi2ContinuousTimeMode`.
2. *Dynamic state selection:*
   It is checked whether the dynamically selected states are still numerically appropriate. If yes, the function returns with `enterEventMode = fmi2False` otherwise with `enterEventMode`

= fmi2True. In the latter case, fmi2EnterEventMode(..) has to be called and the states are dynamically changed by a subsequent fmi2NewDiscreteStates(..).

Note, this function is not used to detect time or state events, e.g., by comparing event indicators of the previous with the current call of fmi2CompletedIntegratorStep(..). These types of events are detected in the environment and the environment has to call fmi2EnterEventMode(..) in these cases, independently whether the return argument enterEventMode of fmi2CompletedIntegratorStep(..) is fmi2True or fmi2False.
]

```
fmi2Status fmi2GetDerivatives    (fmi2Component c, fmi2Real derivatives[],
                                  size_t nx);
fmi2Status fmi2GetEventIndicators(fmi2Component c, fmi2Real eventIndicators[],
                                  size_t ni);
```

Compute state derivatives and event indicators at the current time instant and for the current states. The derivatives are returned as a vector with "nx" elements. A state event is triggered when the domain of an event indicator changes from $z_j > 0$ to $z_j \leq 0$ or vice versa. The FMU must guarantee that at an event restart $z_j \neq 0$, for example by shifting z_j with a small value. Furthermore, z_j should be scaled in the FMU with its nominal value (so all elements of the returned vector "eventIndicators" should be in the order of "one"). The event indicators are returned as a vector with "ni" elements.

The ordering of the elements of the derivatives vector is identical to the ordering of the state vector (for example derivatives[2] is the derivative of x[2]). Event indicators are not necessarily related to variables on the Model Description File.

Note: fmi2Status = fmi2Discard is possible for both functions.

```
fmi2Status fmi2GetContinuousStates(fmi2Component c, fmi2Real x[], size_t nx);
```

Return the new (continuous) state vector x. This function has to be called directly after calling function fmi2EnterContinuousTimeMode if it returns with eventInfo->valuesOfContinuousStatesChanged = fmi2True (indicating that the (continuous-time) state vector has changed).

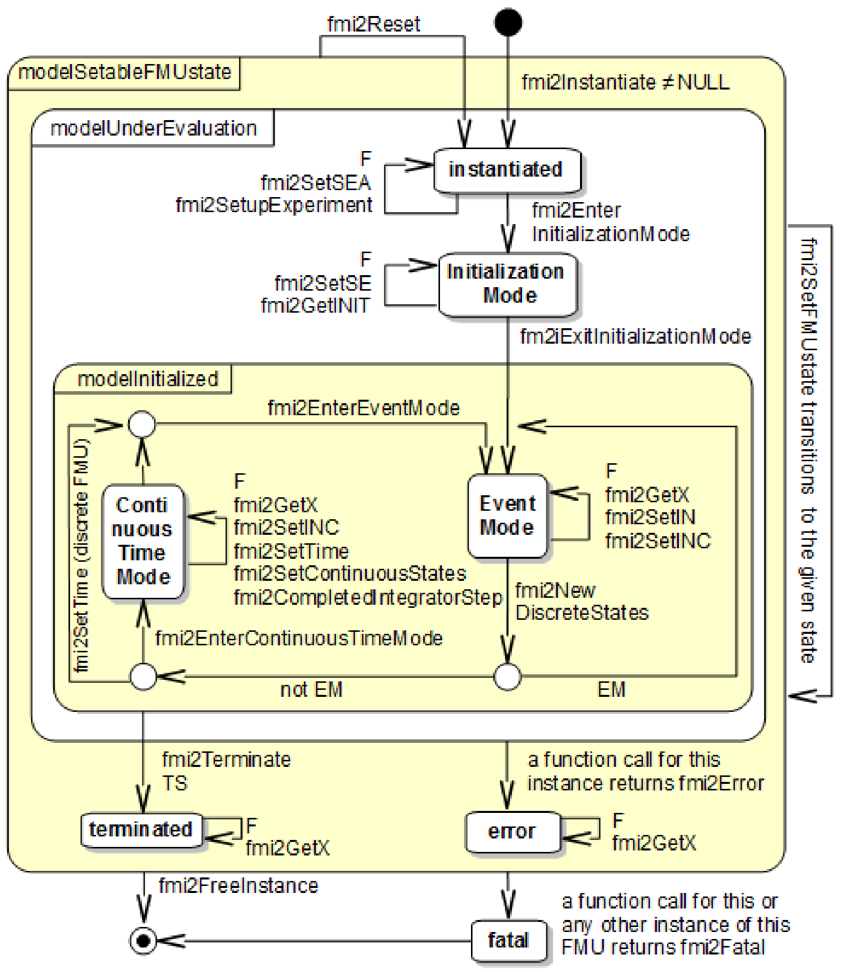
```
fmi2Status fmi2GetNominalsOfContinuousStates(fmi2Component c,
                                             fmi2Real x_nominal[], size_t nx);
```

Return the nominal values of the continuous states. This function should always be called after calling function fmi2NewDiscreteStates if it returns with eventInfo-> nominalsOfContinuousStatesChanged = fmi2True since then the nominal values of the continuous states have changed [*e.g. because the association of the continuous states to variables has changed due to internal dynamic state selection*]. If the FMU does not have information about the nominal value of a continuous state i, a nominal value x_nominal[i] = 1.0 should be returned. Note, it is required that x_nominal[i] > 0.0 [*Typically, the nominal values of the continuous states are used to compute the absolute tolerance required by the integrator. Example:*

```
absoluteTolerance[i] = 0.01*tolerance*x_nominal[i];]
```

3.2.3 State Machine of Calling Sequence

Every implementation of the FMI must support calling sequences of the functions according to the following state chart:



Abbreviations used in transition labels

F is one of
- *fmi2GetTypesPlatform*
- *fmi2GetVersion*
- *fmi2SetDebugLogging*
- *fmi2GetFMUstate*
- *fmi2FreeFMUstate*
- *fmi2SerializedFMUstateSize*
- *fmi2SerializeFMUstate*
- *fmi2DeSerializeFMUstate*
- *fmi2GetNominalsOfContinuousStates*

X is one of
- *Real, Integer, Boolean, String*
- *Derivatives*
- *ContinuousStates*
- *EventIndicators*
- *DirectionalDerivative*

SEA is one of Real, Integer, Boolean, String for a variable with variability ≠ "constant" that has initial = "exact" or "approx"

SE is one of Real, Integer, Boolean, String for a variable with variability ≠ "constant" that has initial = "exact" or causality="input"

INC is Real for a variable with causality="input" and variability="continuous"

IN is one of Real, Integer, Boolean, String for a variable that has either (variability="discrete" and causality="input") or variability="tunable"

INIT is one of
- *Real, Integer, Boolean, String for variables with causality="output", continuous-time states and state derivatives*
- *ContinuousStates*
- *DirectionalDerivative*

TS: terminateSimulation is returned by at least one FMU or the simulation run ended successfully

EM: newDiscreteStatesNeeded is returned by at least one FMU and no FMU returns terminateSimulation

Figure 6: Calling sequence of Model Exchange C functions in form of an UML 2.0 state machine.

The objective of the start chart is to define the allowed calling sequences for functions of the FMI: Calling sequences not accepted by the state chart are not supported by the FMI. The behaviour of an FMU is undefined for such a calling sequence. For example, the state chart indicates that when an FMU for Model Exchange is in state “Continuous-Time Mode”, a call to fmi2SetReal for a discrete input is not supported. The state chart is given here as UML 2.0 state machine. If a transition is labelled with one or more function names (for example fmi2GetReal, fmi2GetInteger) this means that the transition is taken if any of these functions is successfully called. Note the FMU can always determine in which state it is since every state is entered by a particular function call (such as `fmi2EnterEventMode`), or a particular return value (such as fmi2Fatal).

The transition conditions "external event", "time event", and "state event" are defined in section 3.1. Each state of the state machine corresponds to a certain phase of a simulation as follows:

instantiated:
In this state, start and guess values (= variables that have `initial = "exact"` or `"approx"`) can be set.

Initialization Mode:
In this state equations are active to determine all continuous-time states, as well as all outputs (and optionally other variables exposed by the exporting tool). The variables that can be retrieved by fmi2GetXXX calls are (1) defined in the xml file under `<ModelStructure><InitialUnknowns>` and (2) variables with `causality = "output"`. Variables with `initial = "exact"`, as well as variables with `variability = "input"` can be set.

Continuous-Time Mode:
In this state the continuous-time model equations are active and integrator steps are performed. The event time of a state event may be determined if a domain change of at least one event indicator is detected at the end of a completed integrator step.

Event Mode:
If an event is triggered in Continuous-Time Mode, then Event Mode is entered by calling `fmi2EnterEventMode`. In this mode all continuous-time and discrete-time equations are active and the unknowns at an event can be computed and retrieved. After an event is completely processed, `fmi2NewDiscreteStates` must be called and depending on the return argument, `newDiscreteStatesNeeded`, the state chart stays in Event Mode or switches to Continuous-Time Mode. When the Initialization Mode is terminated with fmi2ExitInitializationMode, then Event Mode is directly entered, and the continuous-time and discrete-time variables at the initial time are computed based on the initial continuous-time states determined in the Initialization Mode.

terminated:
In this state, the solution at the final time of a simulation can be retrieved.

Note, that simulation backward in time is only allowed over continuous time intervals. As soon as an event occured (`fmi2EnterEventMode` was called) going back in time is forbidden, because `fmi2EnterEventMode`/`fmi2NewDiscreteStates` can only compute the next discrete state, not the previous one.

Note, during Initialization, Event, and Continuous-Time Mode input variables can be set with `fmi2SetXXX` and output variables can be get with `fmi2GetXXX` interchangeably according to the model structure defined under element `<ModelStructure>` in the xml-file. [*For example if one output* `y1` *depends on two inputs* `u1`*,* `u2`*, then these two inputs must be set, before* `y1` *can be get. If additionally an output* `y2` *depends on an input* `u3`*, then* `u3` *can be set and* `y2` *can be get afterwards. As a result, artificial or "real" algebraic loops over connected FMUs in any of these three modes can be handled by using appropriate numerical algorithms.*]

The allowed function calls in the respective states are summarized in the following table (functions marked in "yellow" are only available for "Model Exchange", the other functions are available both for "Model Exchange" and "Co-Simulation"):

	FMI 2.0 for Model Exchange							
Function	start, end	instantiated	Initialization Mode	Event Mode	Continuous-Time Mode	terminated	error	fatal
fmi2GetTypesPlatform	x	x	x	x	x	x	x	
fmi2GetVersion	x	x	x	x	x	x	x	
fmi2SetDebugLogging		x	x	x	x	x	x	
fmi2Instantiate	x							
fmi2FreeInstance		x	x	x	x	x	x	
fmi2SetupExperiment		x						
fmi2EnterInitializationMode		x						
fmi2ExitInitializationMode			x					
fmi2Terminate				x	x			
fmi2Reset		x	x	x	x	x	x	
fmi2GetReal			2	x	x	x	7	
fmi2GetInteger			2	x	x	x	7	
fmi2GetBoolean			2	x	x	x	7	
fmi2GetString			2	x	x	x	7	
fmi2SetReal		1	3	4	5			
fmi2SetInteger		1	3	4				
fmi2SetBoolean		1	3	4				
fmi2SetString		1	3	4				
fmi2GetFMUstate		x	x	x	x	x	7	
fmi2SetFMUstate		x	x	x	x	x	x	
fmi2FreeFMUstate		x	x	x	x	x	x	
fmi2SerializedFMUstateSize		x	x	x	x	x	x	
fmi2SerializeFMUstate		x	x	x	x	x	x	
fmi2DeSerializeFMUstate		x	x	x	x	x	x	
fmi2GetDirectionalDerivative			x	x	x	x	7	
fmi2EnterEventMode				x	x			
fmi2NewDiscreteStates				x				
fmi2EnterContinuousTimeMode				x				
fmi2CompletedIntegratorStep					x			
fmi2SetTime				x	x			
fmi2SetContinuousStates					x			
fmi2GetEventIndicators			x	x	x	x	7	
fmi2GetContinuousStates			x	x	x	x	7	
fmi2GetDerivatives			x	x	x	x	7	
fmi2GetNominalsOfContinuousStates		x		x	x	x	7	

x means: call is allowed in the corresponding state

number means: call is allowed if the indicated condition holds:

1 for a variable with `variability ≠ "constant"` that has `initial = "exact"` or `"approx"`

2 for a variable with `causality = "output"`, or continuous-time states or state derivatives

3 for a variable with `variability≠"constant"` that has `initial="exact"`, or `causality="input"`

4 for a variable with `causality = "input"`, or
(`causality = "parameter"` and `variability = "tunable"`)

5 for a variable with `causality = "input"` and `variability = "continuous"`
7 always, but retrieved values are usable for debugging only

3.2.4 Pseudo Code Example

In the following example, the usage of the fmi2XXX functions is sketched in order to clarify the typical calling sequence of the functions in a simulation environment. The example is given in a mix of pseudo-code and “C”, in order to keep it small and understandable. Furthermore, it is assumed that one FMU is directly integrated in a simulation environment. If the FMU would be used inside another model, additional code is needed, especially initialization and event iteration has to be adapted.

```
m = M_fmi2Instantiate("m", ...)  // "m" is the instance name
                                // "M_" is the MODEL_IDENTIFIER
nx     = ...   // number of states, from XML file
nz     = ...   // number of event indicators, from XML file
Tstart = 0     // could also be retrieved from XML file
Tend   = 10    // could also be retrieved from XML file
dt     = 0.01  // fixed step size of 10 milli-seconds

// set the start time
Tnext = Tend
time  = Tstart
M_fmi2SetTime(m, time)

// set all variable start values (of "ScalarVariable / <type> / start") and
// set the input values at time = Tstart
M_fmi2SetReal/Integer/Boolean/String(m, ...)

// initialize
   // determine continuous and discrete states
   M_fmi2SetupExperiment(m,fmi2False,0.0, Tstart, fmi2True,Tend)
   M_fmi2EnterInitializationMode(m)
   M_fmi2ExitInitializationMode(m)

   // event iteration
   eventInfo.newDiscreteStatesNeeded = true;
   while eventInfo.newDiscreteStatesNeeded loop
     // update discrete states
     M_fmi2NewDiscreteStates(m, &eventInfo)
     if eventInfo.terminateSimulation then goto TERMINATE_MODEL
   end while

// enter Continuous-Time Mode
M_fmi2EnterContinuousTimeMode(m)

// retrieve initial state x and
// nominal values of x (if absolute tolerance is needed)
M_fmi2GetContinuousStates(m, x, nx)
M_fmi2GetNominalsOfContinuousStates(m, x_nominal, nx)

// retrieve solution at t=Tstart, for example for outputs
M_fmi2GetReal/Integer/Boolean/String(m, ...)
```

```
while time < Tend loop
  // compute derivatives
  M_fmi2GetDerivatives(m, der_x, nx)

  // advance time
  h    = min(dt, Tnext-time)
  time = time + h
  M_fmi2SetTime(m, time)

  // set inputs at t = time
  M_fmi2SetReal/Integer/Boolean/String(m, ...)

  // set states at t = time and perform one step
  x = x + h*der_x  // forward Euler method
  M_fmi2SetContinuousStates(m, x, nx)

  // get event indicators at t = time
  M_fmi2GetEventIndicators(m, z, nz)

  // detect  events, if any
  time_event  = abs(time - Tnext) <= eps
  state_event = ...        // compare sign of z with previous z

  // inform the model about an accepted step
  M_fmi2CompletedIntegratorStep(m, fmi2True, &enterEventMode,
                                           &terminateSimulation)
  if terminateSimulation then goto TERMINATE_MODEL

  // handle events
  if entertEventMode or time_event or state_event then
    M_fmi2EnterEventMode(m)

    // event iteration
    eventInfo.newDiscreteStatesNeeded = true;
    while eventInfo.newDiscreteStatesNeeded loop
      // update discrete states
      M_fmi2NewDiscreteStates(m, &eventInfo)
      if eventInfo.terminateSimulation then goto TERMINATE_MODEL
    end while

    // enter Continuous-Time Mode
    M_fmi2EnterContinuousTimeMode(m)

    // retrieve solution at simulation restart
    M_fmi2GetReal/Integer/Boolean/String(m, ...)
    if eventInfo.valuesOfContinuousStatesChanged == fmi2True then
      //the model signals a value change of states, retrieve them
      M_fmi2GetContinuousStates(m, x, nx)
    end if

    if eventInfo.nominalsOfContinuousStatesChanged = fmi2True then
```

```
        //the meaning of states has changed; retrieve new nominal values
        M_fmi2GetNominalsOfContinuousStates(m, x_nominal, nx)
      end if

      if eventInfo.nextEventTimeDefined then
         Tnext = min(eventInfo.nextEventTime, Tend)
      else
         Tnext = Tend
      end if
    end if
  end while

  // terminate simulation and retrieve final values
  TERMINATE_MODEL:
  M_fmi2Terminate(m)
  M_fmi2GetReal/Integer/Boolean/String(m, ...)

  // cleanup
  M_fmi2FreeInstance(m)
```

Above, errors are not handled. Typically, `fmi2XXX` function calls are performed in the following way:

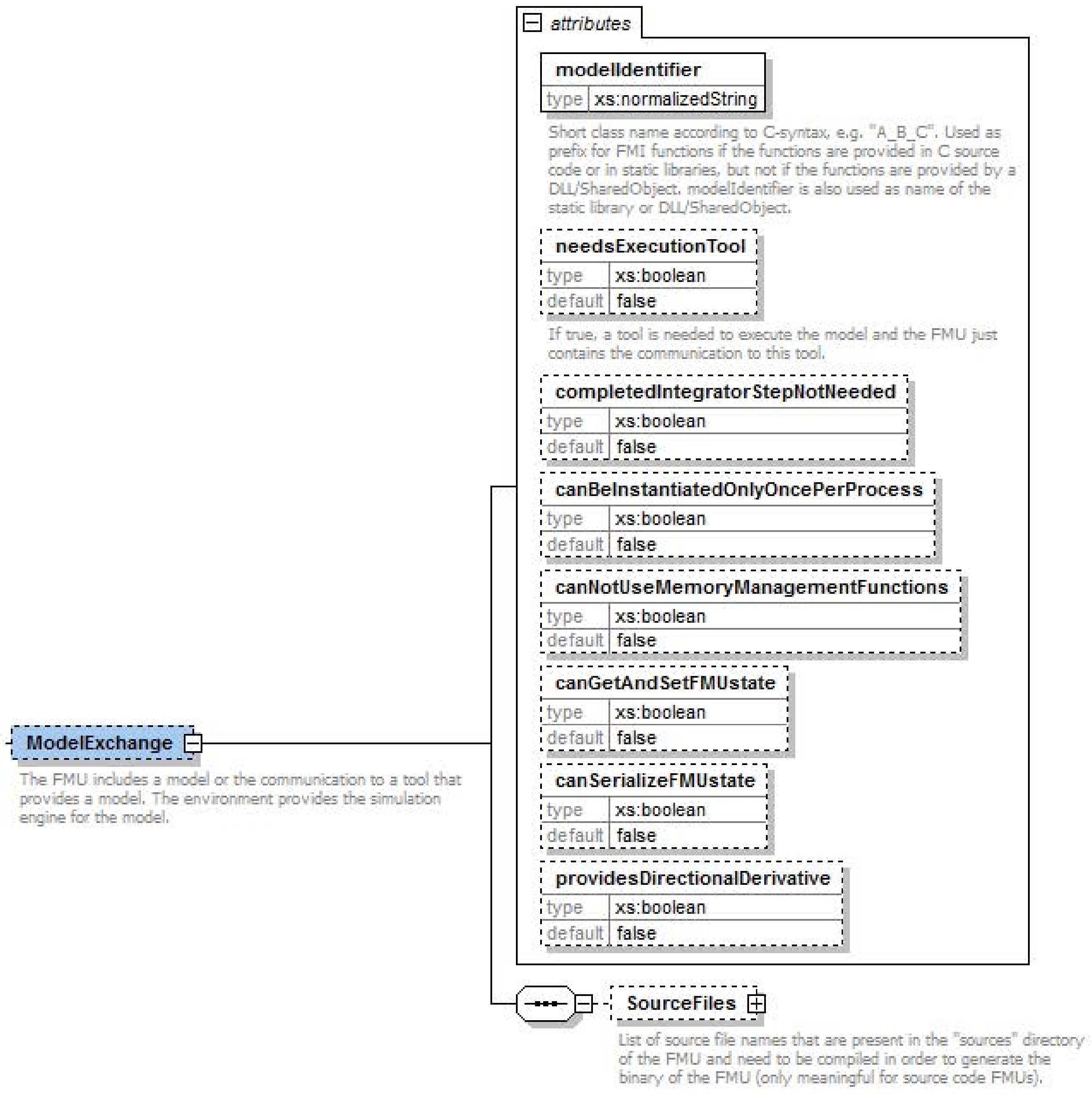
```
status = M_fmi2GetDerivatives(m, der_x, nx);
switch ( status ) { case fmi2Discard: ....; break; // reduce step size and try again
                    case fmi2Error  : ....; break; // cleanup and stop simulation
                    case fmi2Fatal  : ....; }      // stop using the model
The switch statement could also be stored in a macro to simplify the code.
```

3.3 FMI Description Schema

This is defined in 2.2. Additionally, the “Model Exchange” specific element “ModelExchange” is defined in the next section.

3.3.1 Model Exchange FMU (ModelExchange)

If the XML file defines an FMU for Model Exchange, element "ModelExchange" must be present. It is defined as:

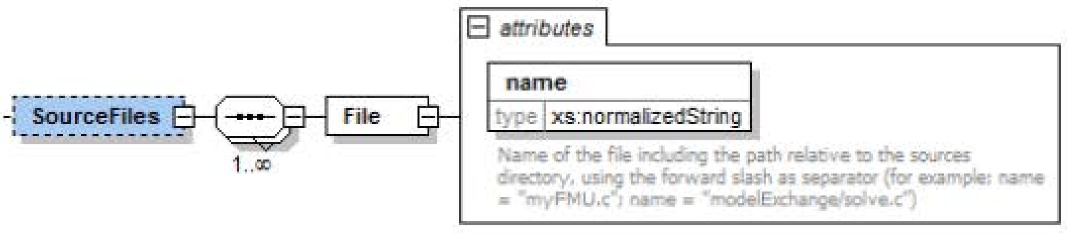


Short class name according to C-syntax, e.g. "A_B_C". Used as prefix for FMI functions if the functions are provided in C source code or in static libraries, but not if the functions are provided by a DLL/SharedObject. modelIdentifier is also used as name of the static library or DLL/SharedObject.

If true, a tool is needed to execute the model and the FMU just contains the communication to this tool.

The FMU includes a model or the communication to a tool that provides a model. The environment provides the simulation engine for the model.

List of source file names that are present in the "sources" directory of the FMU and need to be compiled in order to generate the binary of the FMU (only meaningful for source code FMUs).



Name of the file including the path relative to the sources directory, using the forward slash as separator (for example: name = "myFMU.c"; name = "modelExchange/solve.c")

The following attributes are defined (all of them are optional, with exception of "`modelIdentifier`"):

Attribute Name	*Description*
`modelIdentifier`	Short class name according to C syntax, for example "A_B_C". Used as prefix for FMI functions if the functions are provided in C source code or in static libraries, but not if the functions are provided by a DLL/SharedObject. `modelIdentifier` is also used as name of the static library or DLL/SharedObject . See also section 2.1.1.
`needsExecutionTool`	If true, a tool is needed to execute the model and the FMU just contains the communication to this tool. [*Typically, this information is only utilized for information purposes. For example when loading an FMU with* `needsExecutionTool = true`, *the environment can inform the user that a tool has to be available on the computer where the model is instantiated. The name of the tool can be taken from attribute* `generationTool` *of* `fmiModelDescription`.]
`completedIntegratorStepNotNeeded`	If `true`, function `fmi2CompletedIntegratorStep` need not to be called (which gives a slightly more efficient integration). If it is called, it has no effect. If `false` (the default), the function must be called after every completed integrator step, see section 3.2.2.
`canBeInstantiatedOnlyOncePerProcess`	This flag indicates cases (especially for embedded code), where only one instance per FMU is possible (multiple instantiation is default `= false`; if multiple instances are needed and this flag `= true`, the FMUs must be instantiated in different processes).
`canNotUseMemoryManagementFunctions`	If `true`, the FMU uses its own functions for memory allocation and freeing only. The callback functions `allocateMemory` and `freeMemory` given in `fmi2Instantiate` are ignored.
`canGetAndSetFMUstate`	If `true`, the environment can inquire the internal FMU state and can restore it. That is, functions `fmi2GetFMUstate`, `fmi2SetFMUstate`, and `fmi2FreeFMUstate` are supported by the FMU.
`canSerializeFMUstate`	If `true`, the environment can serialize the internal FMU state, in other words functions `fmi2SerializedFMUstateSize`, `fmi2SerializeFMUstate`,

	`fmi2DeSerializeFMUstate` are supported by the FMU. If this is the case, then flag `canGetAndSetFMUstate` must be `true` as well.
`providesDirectionalDerivative`	If `true`, the directional derivative of the equations can be computed with `fmi2GetDirectionalDerivative(..)`

The flags have the following default values.

boolean: false
unsignedInt: 0

3.3.2 Example XML Description File

When generating an FMU from the hypothetical model "MyLibrary.SpringMassDamper", the XML file may have the following content:

```
<?xml version="1.0" encoding="UTF8"?>
<fmiModelDescription
  fmiVersion="2.0"
  modelName="MyLibrary.SpringMassDamper"
  guid="{8c4e810f-3df3-4a00-8276-176fa3c9f9e0}"
  description="Rotational Spring Mass Damper System"
  version="1.0"
  generationDateAndTime="2011-09-23T16:57:33Z"
  variableNamingConvention="structured"
  numberOfEventIndicators="2">

  <ModelExchange
    modelIdentifier="MyLibrary_SpringMassDamper"/>

  <UnitDefinitions>
    <Unit name="rad">
      <BaseUnit rad="1"/>
      <DisplayUnit name="deg" factor="57.2957795130823"/>
    </Unit>
    <Unit name="rad/s">
      <BaseUnit s="-1" rad="1"/>
    </Unit>
    <Unit name="kg.m2">
      <BaseUnit kg="1" m="2"/>
    </Unit>
  </UnitDefinitions>

  <TypeDefinitions>    <SimpleType name="Modelica.SIunits.Inertia">
      <Real quantity="MomentOfInertia" unit="kg.m2" min="0.0"/>
    </SimpleType>
    <SimpleType name="Modelica.SIunits.Torque">
      <Real quantity="Torque" unit="N.m"/>
    </SimpleType>
    <SimpleType name="Modelica.SIunits.AngularVelocity">
      <Real quantity="AngularVelocity" unit="rad/s"/>
    </SimpleType>
    <SimpleType name="Modelica.SIunits.Angle">
      <Real quantity="Angle" unit="rad"/>
    </SimpleType>
  </TypeDefinitions>
  <DefaultExperiment startTime="0.0" stopTime="3.0" tolerance="0.0001"/>

  <ModelVariables>
    <ScalarVariable
      name="inertia1.J"
      valueReference="1073741824"
      description="Moment of load inertia"
      causality="parameter"
      variability="fixed">
      <Real declaredType="Modelica.SIunits.Inertia" start="1"/>
    </ScalarVariable>   <!—index="1" -->

    <ScalarVariable
      name="torque.tau"
      valueReference="536870912"
      description="Accelerating torque acting at flange (= -flange.tau)"
      causality="input">
      <Real declaredType="Modelica.SIunits.Torque" start="0" />
    </ScalarVariable>   <!—index="2" -->

    <ScalarVariable
      name="inertia1.phi"
      valueReference="805306368"
      description="Absolute rotation angle of component"
      causality="output">
      <Real declaredType="Modelica.SIunits.Angle" />
    </ScalarVariable>   <!—index="3" -->

    <ScalarVariable
      name="inertia1.w"
      valueReference="805306369"
      description="Absolute angular velocity of component (= der(phi))"
      causality="output">
      <Real declaredType="Modelica.SIunits.AngularVelocity" />
    </ScalarVariable>   <!—index="4" -->

    <ScalarVariable name="x[1]" valueReference="0", initial="exact"> <Real/>
                    </ScalarVariable>   <!—index="5" -->
    <ScalarVariable name="x[2]" valueReference="1", initial="exact"> <Real/>
                    </ScalarVariable>   <!—index="6" -->
    <ScalarVariable name="der(x[1])" valueReference="2">
      <Real derivative="5"/> </ScalarVariable>   <!—index="7" -->
    <ScalarVariable name="der(x[2])" valueReference="3">
      <Real derivative="6"/> </ScalarVariable>   <!—index="8" -->
  </ModelVariables>

  <ModelStructure>
    <Outputs>          <Unknown index="3" /> <Unknown index="4" /> </Outputs>
    <Derivatives>      <Unknown index="7" /> <Unknown index="8" /> </Derivatives>
    <InitialUnknowns> <Unknown index="3" /> <Unknown index="4" />
                      <Unknown index="7" dependencies="5 2" />
                      <Unknown index="8" dependencies="5 6" /> </InitialUnknowns>
  </ModelStructure>
</fmiModelDescription>
```

4. FMI for Co-Simulation

This chapter defines the Functional Mock-up Interface (FMI) for the coupling of two or more simulation models in a co-simulation environment (*FMI for Co-Simulation*). Co-simulation is a rather general approach to the simulation of coupled technical systems and coupled physical phenomena in engineering with focus on instationary (time-dependent) problems.

FMI for Co-Simulation is designed both for coupling with subsystem models, which have been exported by their simulators together with its solvers as runnable code (Figure 7), and for coupling of simulation tools (*simulator coupling*, *tool coupling* (Figure 8 and Figure 7)).

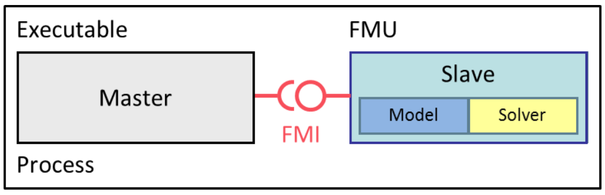


Figure 7: Co-simulation with generated code on a single computer (for simplicity shown for one slave only).

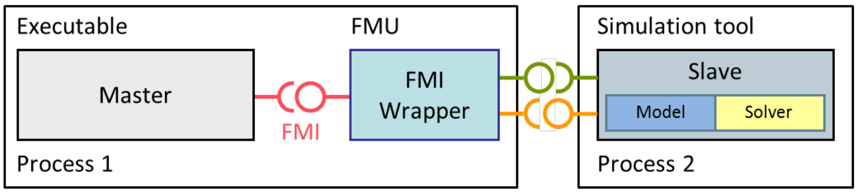


Figure 8: Co-simulation with tool coupling on a single computer (for simplicity shown for one slave only).

In the tool coupling case the FMU implementation wraps the FMI function calls to API calls which are provided by the simulation tool (for example a COM or CORBA API). Additionally to the FMU the simulation tool is needed to run a co-simulation.

In its most general form, a tool coupling based co-simulation is implemented on distributed hardware with subsystems being handled by different computers with maybe different OS (cluster computer, computer farm, computers at different locations). The data exchange and communication between the subsystems is typically done using one of the network communication technologies (for example MPI, TCP/IP). The definition of this communication layer is not part of the FMI standard. However distributed co-simulation scenarios can be implemented using FMI as shown in Figure 9.

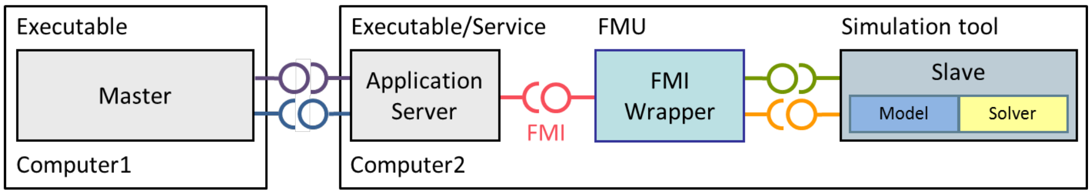


Figure 9: Distributed co-simulation infrastructure (for simplicity shown for one slave only).

The master has to implement the communication layer. Additional parameters for establishing the network communication (for example identification of the remote computer, port numbers, user account) are to be set via the GUI of the master. These data are not transferred via the FMI API.

4.1 Mathematical Description

4.1.1 Basics

Co-simulation exploits the modular structure of coupled problems in all stages of the simulation process beginning with the separate model setup and preprocessing for the individual *subsystems* in different *simulation tools* (which can be powerful simulators as well as simple C programs). During time integration, the simulation is again performed independently for all subsystems restricting the data exchange between subsystems to discrete *communication points* tc_i. For simulator coupling, also the visualization and post-processing of simulation data is done individually for each subsystem in its own native simulation tool. In different contexts, the communication points tc_i, the *communication steps* $tc_i \rightarrow tc_{i+1}$ and the *communication step sizes* $hc_i := tc_{i+1} - tc_i$ are also known as sampling points (synchronization points), macro steps and sampling rates, respectively. The term "communication point" in FMI for Co-Simulation refers to the communication between subsystems in a co-simulation environment and should not be mixed with the output points for saving simulation results to file.

FMI for Co-Simulation provides an interface standard for the solution of time dependent *coupled systems* consisting of subsystems that are continuous in time (model components that are described by instationary differential equations) or time-discrete (model components that are described by difference equations like, for example discrete controllers). In a block representation of the coupled system, the subsystems are represented by blocks with (internal) *state variables* $x(t)$ that are connected to other subsystems (blocks) of the coupled problem by *subsystem inputs* $u(t)$ and *subsystem outputs* $y(t)$. In this framework, the physical connections between subsystems are represented by mathematical coupling conditions between the inputs $u(t)$ and the outputs $y(t)$ of all subsystems, *Kübler and Schiehlen (2000)*.

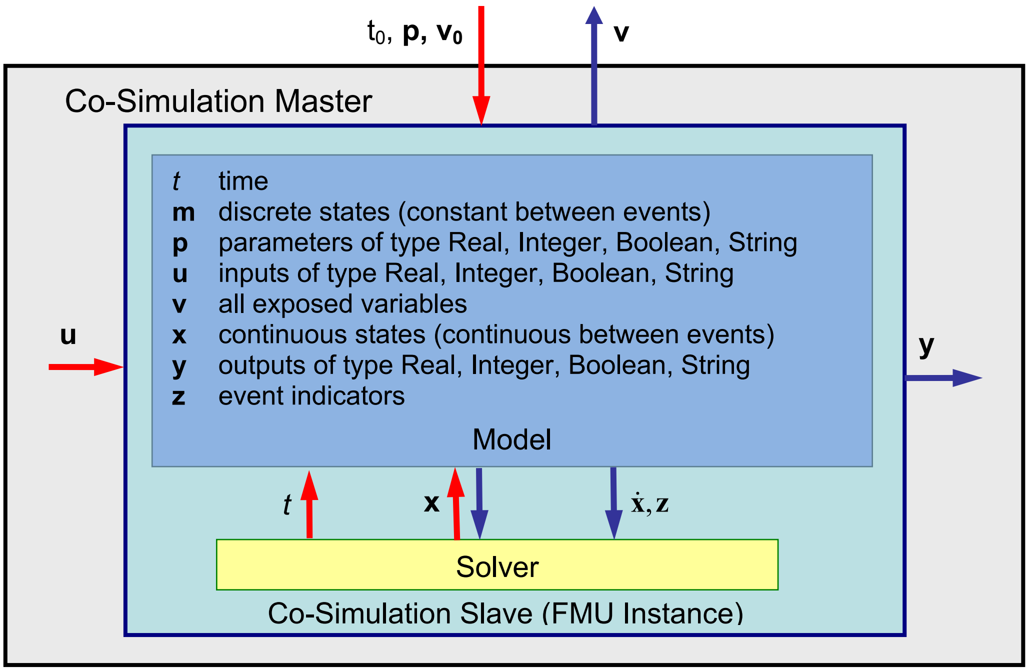

t0, p, v0
v
Co-Simulation Master
t time
m discrete states (constant between events)
p parameters of type Real, Integer, Boolean, String
u inputs of type Real, Integer, Boolean, String
v all exposed variables
x continuous states (continuous between events)
y outputs of type Real, Integer, Boolean, String
z event indicators
Model
u
y
t
x
ẋ, z
Solver
Co-Simulation Slave (FMU Instance)

Figure 10: Data flow at communication points.

For co-simulation two basic groups of functions have to be realized:

1. functions for the data exchange between subsystems and
2. functions for algorithmic issues to synchronize the simulation of *all* subsystems and to proceed in communication steps $tc_i \rightarrow tc_{i+1}$ from initial time $tc_0 := t_{start}$ to end time $tc_N := t_{stop}$.

In FMI for Co-Simulation both functions are implemented in one software component, the co-simulation *master*. The data exchange between the subsystems (*slaves*) is handled via the master only. There is no direct communication between the slaves. The master functionality can be implemented by a special software tool (a separate simulation backplane) or by one of the involved simulation tools. In its most general form, the coupled system may be simulated in *nested* co-simulation environments and FMI for Co-Simulation applies to each level of the hierarchy.

FMI for Co-Simulation defines interface routines for the communication between the master and all slaves (subsystems) in a co-simulation environment. The most common master algorithm stops at each communication point tc_i the simulation (time integration) of all slaves, collects the outputs $y(tc_i)$ from all subsystems, evaluates the subsystem inputs $u(tc_i)$, distributes these subsystem inputs to the slaves and continues the (co-)simulation with the next communication step $tc_i \rightarrow tc_{i+1} = tc_i + hc$ with fixed communication step size hc. In each slave, an appropriate solver is used to integrate one of the subsystems for a given communication step $tc_i \rightarrow tc_{i+1}$. The most simple co-simulation algorithms approximate the (unknown) subsystem inputs $u(t), (t > tc_i)$ by frozen data $u(tc_i)$ for $tc_i \leq t < tc_{i+1}$. FMI for Co-Simulation supports this classical brute force approach as well as more sophisticated master algorithms. FMI for Co-Simulation is designed to support a very general class of master algorithms but it does *not* define the master algorithm itself.

The ability of slaves to support more sophisticated master algorithms is characterized by a set of *capability flags* inside the XML description of the slave (see section 4.3.1). Typical examples are:

- the ability to handle variable communication step sizes hc_i,
- the ability to repeat a rejected communication step $tc_i \rightarrow tc_{i+1}$ with reduced communication step size,
- the ability to provide derivatives w.r.t. time of outputs to allow interpolation (section 4.2.1),
- or the ability to provide Jacobians.

FMI for Co-Simulation is restricted to slaves with the following properties:

1. All calculated values $v(t)$ are time dependent functions within an a priori defined time interval $t_{start} \leq t \leq t_{stop}$ (provided `stopTimeDefined = fmi2True` when calling `fmi2SetupExperiment`).
2. All calculations (simulations) are carried out with increasing time in general. The current time t is running step by step from t_{start} to t_{stop}. The algorithm of the slave may have the property to be able to repeat the simulation of parts of $[t_{start}, t_{stop}]$ or the whole time interval $[t_{start}, t_{stop}]$.
3. The slave can be given a time value tc_i, $t_{start} \leq tc_i \leq t_{stop}$.
4. The slave is able to interrupt the simulation when tc_i is reached.
5. During the interrupted simulation the slave (and its individual solver) can receive values for inputs $u(tc_i)$ and send values of outputs $y(tc_i)$.
6. Whenever the simulation in a slave is interrupted, a new time value tc_{i+1}, $tc_i \leq tc_{i+1} \leq t_{stop}$ can be given to simulate the time subinterval $tc_i < t \leq tc_{i+1}$
7. The subinterval length hc_i is the communication step size of the i^{th} communication step, $hc_i = tc_{i+1} - tc_i$. The communication step size has to be greater than zero.

FMI for Co-Simulation allows a co-simulation flow which starts with instantiation and initialization (all slaves are prepared for computation, the communication links are established), followed by simulation (the slaves are forced to simulate a communication step), and finishes with shutdown. In detail the flow is defined in the state machine of the calling sequences from master to slave (section 4.2.4).

4.1.2 Mathematical Model

This section contains a formal mathematical model of a Co-Simulation FMU. The following fundamental assumptions are made:

The slave simulators are seen by the master simulator as purely sampled-data systems. Such a sampled-data system can be

- either a "real" sampled-data system (so a sampled discrete controller; the inputs and outputs can be of type Real, Integer, Boolean, String, or enumeration. Variables of this type are defined with `variability = "discrete"`; the smallest sample period as accessible by the outside of the FMU is defined by attribute `stepSize` in element `DefaultExperiment`).
- or a hybrid ODE that is integrated between communication points (known as "sampled access to time continuous systems") where internal events may occur and be handled, but events are not visible from the outside of the FMU. It is assumed here that all inputs and all outputs of this hybrid ODE are Real signals (defined with `variability = "continuous"`),
- or a combination of the systems above.

The communication between the master and a slave takes only place at a discrete set of time instants, called *communication points.*

An FMI Co-Simulation model is described by the following variables:

Variable	*Description*
t	Independent variable time $\in \mathbb{R}$. (Variable defined with `causality = "independent"`). The i-th communication point is denoted as $t = tc_i$ The communication step size is denoted as $hc_i = tc_{i+1} - tc_i$
$\mathbf{v}$	A vector of all exposed variables (all variables defined in element `<ModelVariables>`, see section 2.2.7). Via a subscript, a subset of the variables is selected. Example: $\mathbf{v}_{\text{initial=exact}}$ are variables defined with attribute `initial = "exact"`, see section 2.2.7. These are independent parameters and start values of other variables, such as initial values for states, state derivatives or outputs.
$\mathbf{p}$	Parameters that are constant during simulation. The symbol without a sub-script references independent parameters (variables with `causality = "parameter"`). Dependent parameters (variables with `causality = "calculatedParameter"`) are denoted as $\mathbf{p}_{calculated}$ and tunable parameters (variables with `causality = "parameter"` and `variability = "tunable"`) are denoted as $\mathbf{p}_{tune}$.
$\mathbf{u}(tc_i)$	Input variables. The values of these variables are defined outside of the model. Variables of this type are defined with attribute `causality = "input"`. Via attribute `variability = "discrete"` or `"continuous"` it is defined whether the input is a discrete-time or continuous-time variable, see section 2.2.7.
$\mathbf{y}(tc_i)$	Output variables. The values of these variables are computed in the FMU and they are designed to be used in a model connection. So output variables might be used in the environment as input values to other FMUs or other submodels. Variables of this type are defined with attribute `causality = "output"`. Via attribute `variability = "discrete"` or `"continuous"` it is defined whether the output is a discrete-time or continuous-time variable, see section 2.2.7.
$\mathbf{w}(tc_i)$	Local variables of the FMU that cannot be used for FMU connections. Variables of this type are defined with attribute `causality = "local"`, see section 2.2.7.
$\mathbf{x}_c(t)$	A vector of real continuous-time variables representing the continuous-time states. For notational convenience, a continuous-time state is conceptually treated as a different type of variable as an output or a local variable for the mathematical description

	below. However, at a communication point a continuous-time state is part of the outputs $\mathbf{y}$ or the local variables $\mathbf{w}$ of an FMU.
$\mathbf{x}_d(t)$ $^\bullet\mathbf{x}_d(t)$	$\mathbf{x}_d(t)$ is a vector of (internal) discrete-time variables (of any type) representing the (internal) discrete states. $^\bullet\mathbf{x}_d(t)$ is the value of $\mathbf{x}_d(t)$ at the previous sample time instant, so $^\bullet\mathbf{x}_d(t) = \mathbf{x}_d(^\bullet t)$. Given the previous values of the discrete-time states, $^\bullet\mathbf{x}_d(t)$, at the actual time instant *t*, all other discrete-time variables, especially the discrete states $\mathbf{x}_d(t)$, can be computed. Discrete states are not visible in the interface of an FMU and are only introduced here to clarify the mathematical description. Formally, a discrete state is part of the outputs **y** or the local variables **w** of an FMU.

When the transient simulation of the coupled system through co-simulation is completed, the sequence of evaluations is the following (here $\mathbf{x} = [x_c; \mathbf{x}_d]^T$ is the combined vector of continuous-time and discrete-time states, and $\mathbf{y} = [y_c; \mathbf{y}_d]^T$) is the combined vector of continuous-time and discrete-time outputs):

$$\text{for } i = 0, \cdots, n-1 \begin{cases} \mathbf{x}_{i+1} = \Phi_i\left(\mathbf{x}_i, \left\{\mathbf{u}_i^{(j)}\right\}_{j=0,\cdots,m_{ido}}, \mathbf{p}_{tune,i}, hc_i\right) \\ \left(\left\{\mathbf{y}_{i+1}^{(j)}\right\}_{j=0,\cdots,m_{odo}}, \mathbf{w}_{i+1}\right) = \mathbf{\Gamma}_i\left(\mathbf{x}_i, \left\{\mathbf{u}_i^{(j)}\right\}_{j=0,\cdots,m_{ido}}, \mathbf{p}_{tune,i}, hc_i\right) \end{cases} \tag{4.1}$$

where $\mathbf{\Phi}_i$ and $\mathbf{\Gamma}_i$ define the system behavior for the time interval $tc_i \le t < tc_{i+1}$, with $tc_i = tc_0 + \sum_{k=0}^{i-1} hc_k$

[*For the part of the co-simulation slave that is based on an ODE, a differential equation is solved between communication points:*

$$\dot{\mathbf{x}}_c = \boldsymbol{\varphi}(\mathbf{x}_c(t), \mathbf{u}_c(t), \boldsymbol{p}_{tune})$$

In this case, the following relationship should hold (note the use of $\mathbf{x}_{i+1}$ *here):*

$$\frac{\partial \mathbf{\Phi}_i}{\partial hc_i} = \boldsymbol{\varphi}\left(\mathbf{x}_{c,i+1}, \sum_{j=0}^{m_{ido}} \mathbf{u}_{c,i}^{(j)} \frac{hc_i^j}{j!}, \mathbf{p}_{tune,i}\right)$$

This relation is in practice inexact due to using finite precision on machines and stopping iterations early. The slave simulators are responsible for implementing $\mathbf{\Phi}_i$ *and* $\mathbf{\Gamma}_i$*; e.g. to handle stiff differential equations as:*

$$\mathbf{\Phi}_i\left(\mathbf{x}_{c,i}, \left\{\mathbf{u}_{c,i}^{(j)}\right\}_{j=0,\cdots,m_{ido}}, \mathbf{p}_{tune,i}, tc_i\right) = \mathbf{x}_{c,i} + \left(\mathbf{I} - hc_i \frac{\partial \boldsymbol{\varphi}}{\partial \mathbf{x}_c}\right)^{-1} hc_i \boldsymbol{\varphi}\left(\mathbf{x}_{c,i}, \mathbf{u}_{c,i}, \mathbf{p}_{tune,i}\right) + O(hc_i^2).$$

]

Definition (4.1) is consistent with the definition of co-simulation by (Kübler, Schiehlen 2000):

- At the communication points, the master provides generalized inputs to the slave, which can be:
  - the current input variables $\mathbf{u}_i^{(0)}$ of the subsystem (i.e. the input variables of the model contained in the slave simulator, in the sense of system-level simulation), along with some of their successive derivatives $\left\{\mathbf{u}_i^{(j)}\right\}_{j=1,\cdots,m_{ido}}$ (in case of continuous-time variables),
  - varying parameters $\mathbf{p}_{tune,i}$, also known as tunable parameters.
- The slave provides generalized outputs to the master, which are:
  - the current output variables $\boldsymbol{y}_{i+1}^{(0)}$ of the subsystem (same remark as above), along with some of their successive derivatives $\left\{\mathbf{y}_{i+1}^{(j)}\right\}_{j=1,\cdots,m_{odo}}$ (in case of continuous-time variables),
  - observation variables and "calculated" varying parameters $\mathbf{w}_{i+1}$, along with directional derivatives estimated at $t = tc_{i+1}$ (in case of continuous-time variables).
- Initialization: The slave being a sampled-data system, its internal states (being either continuous-time or discrete-time, it does not matter) need to be initialized at $t = tc_0$. This is performed through an auxiliary function [*this relationship is defined in the xml-file under* `<ModelStructure><InitialUnknowns>`]:

Computing the solution of an FMI Co-Simulation model means to split the solution process in two phases and in every phase different equations and solution methods are utilized. The phases can be categorized according to the following modes:

1. **Initialization Mode:**
   This mode is used to compute at the start time t_0 initial values for internal variables of the Co-Simulation slave, especially for continuous-time states, $\mathbf{x}_c(t_0)$, and for the previous discrete-time states, ${}^\bullet\mathbf{x}_d(t_0)$, by utilizing extra equations not present in the other mode [*for example equations to set all derivatives to zero, that is, to initialize in steady-state*]. If the slave is connected in loops with other models, iterations over the FMU equations are possible. In this mode algebraic equations are solved.
2. **Step Mode:**
   This mode is used to compute the values of all (real) continuous-time and discrete-time variables at communication points by numerically solving ordinary differential, algebraic and discrete equations. If the slave is connected in loops with other models, no iterations over the FMU equations are possible.

[*Note, for a Co-Simulation FMU, no super dense time description is used at communication points.*]

In Table 2 the equations are defined that can be evaluated in the respective Mode. The following color coding is used in the table:

grey	If a variable in an argument list is marked in grey, then this variable is not changing in this mode and just the last calculated value from the previous mode is internally used. For an input argument it is not allowed to call `fmi2SetXXX`. For an output argument, calling `fmi2GetXXX` on such a variable returns always the same value in this mode.
green	Functions marked in green are special functions to enter or leave a mode.
blue	Equations and functions marked in blue define the actual computations to be performed in the respective mode.

Function `fmi2SetXXX` used in the table below, is an abbreviation for functions `fmi2SetReal`, `fmi2SetBoolean`, `fmi2SetInteger` and `fmi2SetString` respectively. Function `fmi2GetXXX` is an abbreviation for functions `fmi2GetReal`, `fmi2GetBoolean`, `fmi2GetInteger` and `fmi2GetString` respectively.

Equations	**FMI functions**
Equations before Initialization Mode *("instantiated" in state machine)*	
Set $i = 0$ and set start value of independent variable $tc_{i=0}$	`fmi2SetupExperiment`
Set variables $\mathbf{v}_{initial=exact}$ and $\mathbf{v}_{initial=approx}$ that have a start value (`initial` = `"exact"` or `"approx"`)	`fmi2SetXXX`
Equations during Initialization Mode *("InitializationMode" in state machine)*	
Enter Initialization Mode at $t = tc_0$ (activate initialization, discrete-time and continuous-time equations)	`fmi2EnterInitializationMode`
Set variables $\mathbf{v}_{initial=exact}$ that have a start value with `initial="exact"` (independent parameters $\mathbf{p}$ and continuous-time states with start values $\mathbf{x}_{c,initial=exact}$ are included here)	`fmi2SetXXX`
Set continuous-time and discrete-time inputs $\boldsymbol{u}_{c+d}(tc_0)$ and optionally the derivatives of continuous-time inputs $\boldsymbol{u}_c^{(j)}(tc_0)$	`fmi2SetXXX` `fmi2SetRealInputDerivatives`

$\mathbf{v}_{InitialUnknowns} := \mathbf{f}_{init}(\boldsymbol{u}_c, \boldsymbol{u}_d, t_0, \mathbf{v}_{initial=exact})$	fmi2GetXXX fmi2GetDirectionalDerivative
Exit Initialization Mode (de-activate initialization equations)	fmi2ExitInitializationMode
Equations during Step Mode *(“stepComplete”, “stepInProgress” in state machine)*	
Set independent tunable parameters $\mathbf{p}_{tune}$ (and do not set other parameters $\mathbf{p}_{other}$)	fmi2SetXXX
Set continuous-time and discrete-time inputs $\boldsymbol{u}_{c+d}(tc_i)$ and optionally the derivatives of continuous-time inputs $\boldsymbol{u}_c^{(j)}(tc_i)$	fmi2SetXXX fmi2SetRealInputDerivatives
$tc_{i+1} := tc_i + hc_i$ $(\mathbf{y}_{c+d}, \boldsymbol{y}_c^{(j)}, \boldsymbol{w}_{c+d})_{tc_{i+1}} := \mathbf{f}_{doStep}\left(\boldsymbol{u}_{c+d}, \boldsymbol{u}_c^{(j)}, tc_i, hc_i, \mathbf{p}_{tune}, \mathbf{p}_{other}\right)_{tc_i}$ $tc_i := tc_{i+1}$ $\mathbf{f}_{doStep}$ is also a function of the internal variables $\mathbf{x}_c$, ${}^\bullet\mathbf{x}_d$	fmi2DoStep fmi2GetXXX fmi2GetRealOutputDerivatives fmi2GetDirectionalDerivative
Data types	
$t, tc, hc \in \mathbb{R}, \mathbf{p} \in \mathbb{P}^{np}, \mathbf{u}(tc) \in \mathbb{P}^{nu}, \mathbf{y}(tc) \in \mathbb{P}^{ny}, \mathbf{x}_c(t) \in \mathbb{R}^{nxc}, \mathbf{x}_d(t) \in \mathbb{P}^{nxd}, \mathbf{w}(tc) \in \mathbb{P}^{nw}$ $\mathbb{R}$: real variable, $\mathbb{P}$: real **or** Boolean **or** integer **or** enumeration **or** string variable $\mathbf{f}_{init}, \mathbf{f}_{out} \in C^0$ (= continuous functions with respect to all input arguments inside the respective mode).	

Table 2: Mathematical description of an FMU for Co-Simulation.

[*Remark – Calling Sequences:*

In the table above, for notational convenience in Initialization Mode one function call is defined to compute all output arguments from all inputs arguments. In reality, every scalar output argument is computed by one `fmi2GetXXX` *function call.*

In Step Mode the input arguments to $\boldsymbol{f}_{doStep}$ are defined by calls to `fmi2SetXXX` *and* `fmi2SetRealInputDerivatives` *functions. The variables computed by $\boldsymbol{f}_{doStep}$ can be inquired by* `fmi2GetXXX` *function calls.]*

4.2 FMI Application Programming Interface

This section contains the interface description to access the in/output data and status information of a co-simulation slave from a C program.

4.2.1 Transfer of Input / Output Values and Parameters

Input and output variables and variables are transferred via the `fmi2GetXXX` and `fmi2SetXXX` functions, defined in section 2.1.7.

In order to enable the slave to interpolate the continuous real inputs between communication steps the derivatives of the inputs with respect to time can be provided. To allow higher order interpolation also higher derivatives can be set. Whether a slave is able to interpolate and therefore needs this information is provided by the capability attribute `canInterpolateInputs`.

```
fmi2Status fmi2SetRealInputDerivatives(fmi2Component c,
                                       const fmi2ValueReference vr[], size_t nvr,
                                       const fmi2Integer order[],
                                       const fmi2Real value[]);
```

Sets the n-th time derivative of real input variables. Argument “`vr`” is a vector of value

references that define the variables whose derivatives shall be set. The array "`order`" contains the orders of the respective derivative (1 means the first derivative, 0 is not allowed). Argument "`value`" is a vector with the values of the derivatives. "`nvr`" is the dimension of the vectors.
Restrictions on using the function are the same as for the `fmi2SetReal` function.

Inputs and their derivatives are set with respect to the beginning of a communication time step.

To allow interpolation/approximation of the real output variables between communication steps (if they are used as inputs for other slaves) the derivatives of the outputs with respect to time can be read. Whether the slave is able to provide the derivatives of outputs is given by the unsigned integer capability flag `MaxOutputDerivativeOrder`. It delivers the maximum order of the output derivative. If the actual order is lower (because the order of integration algorithm is low), the retrieved value is 0.

Example: If the internal polynomial is of order 1 and the master inquires the second derivative of an output, the slave will return zero.

The derivatives can be retrieved by:

```
fmi2Status fmi2GetRealOutputDerivatives (fmi2Component c,
                                   const fmi2ValueReference vr[], size_t nvr,
                                   const fmi2Integer order[],
                                         fmi2Real    value[]);
```

Retrieves the n-th derivative of output values. Argument "`vr`" is a vector of "`nvr`" value references that define the variables whose derivatives shall be retrieved. The array "`order`" contains the order of the respective derivative (1 means the first derivative, 0 is not allowed). Argument "`value`" is a vector with the actual values of the derivatives.
Restrictions on using the function are the same as for the `fmi2GetReal` function.

The returned outputs correspond to the current slave time. E. g. after a successful `fmi2DoStep(...)` the returned values are related to the end of the communication time step.

This standard supports polynomial interpolation and extrapolation as well as more sophisticated signal extrapolation schemes like rational extrapolation, see the companion document "FunctionalMockupInterface-ImplementationHints.pdf".

4.2.2 Computation

The computation of time steps is controlled by the following function.

```
fmi2Status fmi2DoStep(fmi2Component c,
                      fmi2Real    currentCommunicationPoint,
                      fmi2Real    communicationStepSize,
                      fmi2Boolean noSetFMUStatePriorToCurrentPoint);
```

The computation of a time step is started.
Argument `currentCommunicationPoint` is the current communication point of the master (tc_i) and argument `communicationStepSize` is the communication step size (hc_i). The latter must be > 0.0. The slave must integrate until time instant $tc_{i+1} = tc_i + hc_i$. [*The calling environment defines the communication points and* `fmi2DoStep` *must synchronize to these points by always integrating exactly to* $tc_i + hc_i$. *It is up to* *`fmi2DoStep`* *how to achieve this.*]
At the first call to *`fmiDoStep`* *after* *`fmi2ExitInitializationMode`* *was called* *`currentCommunicationPoint`* *must be equal to* *`startTime`* *as set with*

fmi2SetupExperiment. [*Formally argument* `currentCommunicationPoint` *is not needed. It is present in order to handle a mismatch between the master and the FMU state of the slave: The* `currentCommunicationPoint` *and the FMU state of the slaves defined by former* `fmi2DoStep` *or* `fmi2SetFMUState` *calls have to be consistent with respect to each other. For example, if the slave does not use the update formula for the independent variable as required above,* $tc_{i+1} = tc_i + hc_i$ *(using argument* $tc_i = currentCommunicationPoint$ of `fmi2DoStep`*) but uses internally an own update formula, such as* $tc_{s,i+1} = tc_{s,i} + hc_{s,i}$ *then the slave could use as time increment* $hc_{s,i} := (tc_i - tc_{s,i}) + hc_i$ *(instead of* $hc_{s,i} := hc_i$,*) to avoid a mismatch between the master time* tc_{i+1} *and the slave internal time* $tc_{s,i+1}$ *for large i.*]

Argument `noSetFMUStatePriorToCurrentPoint` is `fmi2True` if fmi2SetFMUState will no longer be called for time instants prior to currentCommunicationPoint in this simulation run [*the slave can use this flag to flush a result buffer*].

The function returns:

`fmi2OK` - if the communication step was computed successfully until its end.
`fmi2Discard` – if the slave computed successfully only a subinterval of the communication step. The master can call the appropriate `fmi2GetXXXStatus` functions to get further information. If possible, the master should retry the simulation with a shorter communication step size. [*Redoing a step is only possible if the FMU state has been recorded at the beginning of the current (failed) step with* `fmi2GetFMUState`*. Redoing a step is performed by calling* `fmi2SetFMUState` *and afterwards calling* `fmi2DoStep` *with the new* `communicationStepSize`*. Note, it is not possible to change* `currentCommunicationPoint` *in such a call.*]
`fmi2Error` – the communication step could not be carried out at all. The master can try to repeat the step with other input values and/or a different communication step size in the same way as described in the `fmi2Discard` case above.
`fmi2Fatal` – if an error occurred which corrupted the FMU irreparably. *[The master should stop the simulation run immediatlely.]* See section 2.1.3 for details.
`fmi2Pending` – is returned if the slave executes the function asynchronously. That means the slave starts the computation but returns immediately. The master has to call `fmi2GetStatus(...,fmi2DoStep,...)` to find out, if the slave is done. An alternative is to wait until the callback function `fmi2StepFinished` is called by the slave. `fmi2CancelStep` can be called to cancel the current computation. It is not allowed to call any other function during a pending `fmi2DoStep`.

```
fmi2Status fmi2CancelStep(fmi2Component c);
```

Can be called if `fmi2DoStep` returned `fmi2Pending` in order to stop the current asynchronous execution. The master calls this function if for example the co-simulation run is stopped by the user or one of the slaves. Afterwards it is only allowed to call `fmi2Reset` or `fmi2FreeInstance.`

It depends on the capabilities of the slave which parameter constellations and calling sequences are allowed (see 4.3.1)

4.2.3 Retrieving Status Information from the Slave

Status information is retrieved from the slave by the following functions:

```
fmi2Status fmi2GetStatus       (fmi2Component c, const fmi2StatusKind s,
                                 fmi2Status* value);
fmi2Status fmi2GetRealStatus   (fmi2Component c, const fmi2StatusKind s,
                                 fmi2Real* value);
fmi2Status fmi2GetIntegerStatus(fmi2Component c, const fmi2StatusKind s,
                                 fmi2Integer* value);
fmi2Status fmi2GetBooleanStatus(fmi2Component c, const fmi2StatusKind s,
                                 fmi2Boolean* value);
fmi2Status fmi2GetStringStatus (fmi2Component c, const fmi2StatusKind s,
                                 fmi2String* value);
```

Informs the master about the actual status of the simulation run. Which status information is to be returned is specified by the argument `fmi2StatusKind`. It depends on the capabilities of the slave which status information can be given by the slave (see 4.3.1). If a status is required which cannot be retrieved by the slave it returns `fmi2Discard`.

```
typedef enum {fmi2DoStepStatus,
              fmi2PendingStatus,
              fmi2LastSuccessfulTime,
              fmi2Terminated
             } fmi2StatusKind;
```

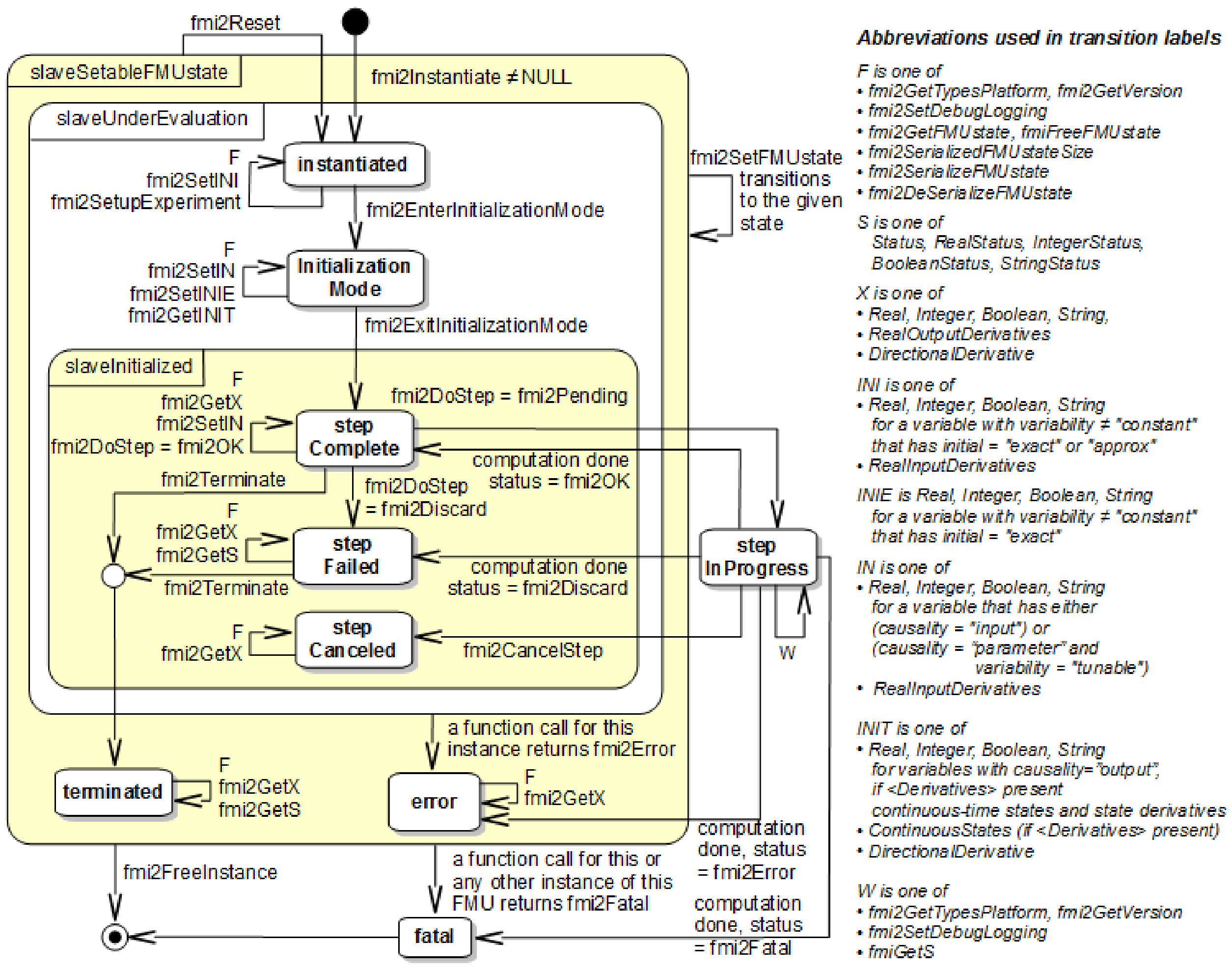
Defines which status is inquired.

The following status information can be retrieved from a slave:

Status	*Type of retrieved value*	*Description*
`fmi2DoStepStatus`	`fmi2Status`	Can be called when the `fmi2DoStep` function returned `fmi2Pending`. The function delivers `fmi2Pending` if the computation is not finished. Otherwise the function returns the result of the asynchronously executed `fmi2DoStep` call.
`fmi2PendingStatus`	`fmi2String`	Can be called when the `fmi2DoStep` function returned `fmi2Pending`. The function delivers a string which informs about the status of the currently running asynchronous `fmi2DoStep` computation.
`fmi2LastSuccessfulTime`	`fmi2Real`	Returns the end time of the last successfully completed communication step. Can be called after `fmi2DoStep(...)` returned `fmi2Discard`.
`fmi2Terminated`	`fmi2Boolean`	Returns true, if the slave wants to terminate the simulation. Can be called after `fmi2DoStep(...)` returned `fmi2Discard`. Use `fmi2LastSuccessfulTime` to determine the time instant at which the slave terminated.

4.2.4 State Machine of Calling Sequence from Master to Slave

The following state machine defines the supported calling sequences.



Abbreviations used in transition labels

F is one of
- *fmi2GetTypesPlatform, fmi2GetVersion*
- *fmi2SetDebugLogging*
- *fmi2GetFMUstate, fmiFreeFMUstate*
- *fmi2SerializedFMUstateSize*
- *fmi2SerializeFMUstate*
- *fmi2DeSerializeFMUstate*

S is one of
Status, RealStatus, IntegerStatus, BooleanStatus, StringStatus

X is one of
- *Real, Integer, Boolean, String,*
- *RealOutputDerivatives*
- *DirectionalDerivative*

INI is one of
- *Real, Integer, Boolean, String for a variable with variability ≠ "constant" that has initial = "exact" or "approx"*
- *RealInputDerivatives*

INIE is Real, Integer, Boolean, String for a variable with variability ≠ "constant" that has initial = "exact"

IN is one of
- *Real, Integer, Boolean, String for a variable that has either (causality = "input") or (causality = "parameter" and variability = "tunable")*
- *RealInputDerivatives*

INIT is one of
- *Real, Integer, Boolean, String for variables with causality="output", if <Derivatives> present continuous-time states and state derivatives*
- *ContinuousStates (if <Derivatives> present)*
- *DirectionalDerivative*

W is one of
- *fmi2GetTypesPlatform, fmi2GetVersion*
- *fmi2SetDebugLogging*
- *fmiGetS*

Figure 11: Calling sequence of Co-Simulation C functions in form of an UML 2.0 state machine.

Each state of the state machine corresponds to a certain phase of a simulation as follows:

instantiated:
In this state, start and guess values (= variables that have `initial = "exact"` or `"approx."`) can be set.

Initialization Mode:
In this state equations are active to determine all outputs (and optionally other variables exposed by the exporting tool). The variables that can be retrieved by fmi2GetXXX calls are (1) defined in the xml file under `<ModelStructure><InitialUnknowns>` and (2) variables with `causality = "output"`. Variables with `initial = "exact"`, as well as variables with `variability = "input"` can be set.

slaveInitialized:
In this state the slave is initialized and the co-simulation computation is performed. The calculation until the next communication point is performed with function "fmi2DoStep". Depending on the return value, the slave is in a different state (step complete, step failed, step canceled).

terminated:
In this state, the solution at the final time of the simulation can be retrieved.

Note, in Initialization Mode input variables can be set with `fmi2SetXXX` and output variables can be get with `fmi2GetXXX` interchangeably according to the model structure defined under element `<ModelStructure><InitialUnknowns>` in the xml-file. [*For example if one output* `y1` *depends on two* *inputs* `u1`, `u2`*, then these two inputs must be set, before* `y1` *can be get. If additionally an output* `y2` *depends on an input* `u3`*, then* `u3` *can be set and* `y2` *can be get afterwards. As a result, artificial or "real" algebraic loops over connected FMUs in Initialization Mode can be handled by using appropriate numerical algorithms.*]

There is the additional restriction in "slaveInitialized" state that it is not allowed to call fmi2GetXXX functions after fmi2SetXXX functions without an fmi2DoStep call in between. [*The reason is to avoid different interpretations of the caching, since contrary to FMI for ModelExchange fmi2DoStep will perform the actual calculation and not fmi2GetXXX and therefore dummy algebraic loops at communication points cannot be handeled by an appropriate sequence of fmi2GetXXX, fmi2SetXXX calls as for ModelExchange.*

Examples:

Correct calling sequence	*Wrong calling sequence*
fmi2SetXXX on inputs *fmi2DoStep* *fmi2GetXXX on outputs* *fmi2SetXXX on inputs* *fmi2DoStep* *fmi2GetXXX on outputs*	*fmi2SetXXX on inputs* *fmi2DoStep* *fmi2GetXXX on outputs* *fmi2SetXXX on inputs* *fmi2GetXXX on outputs // not allowed* *fmi2DoStep* *fmi2GetXXX on outputs*

]

The allowed function calls in the respective states are summarized in the following table (functions marked in "light blue" are only available for "Co-Simulation", the other functions are available both for "Model Exchange" and "Co-Simulation"):

	FMI 2.0 forCo-Simulation									
Function	start, end	instantiated	Initialization Mode	stepComplete	stepInProgress	stepFailed	stepCanceled	terminated	error	fatal
fmi2GetTypesPlatform	x	x	x	x	x	x	x	x	x	
fmi2GetVersion	x	x	x	x	x	x	x	x	x	
fmi2SetDebugLogging		x	x	x	x	x	x	x	x	
fmi2Instantiate	x									
fmi2FreeInstance		x	x	x		x	x	x	x	
fmi2SetupExperiment		x								
fmi2EnterInitializationMode		x								
fmi2ExitInitializationMode			x							
fmi2Terminate				x		x				
fmi2Reset		x	x	x		x	x	x	x	
fmi2GetReal			2	x		8	7	x	7	
fmi2GetInteger			2	x		8	7	x	7	
fmi2GetBoolean			2	x		8	7	x	7	
fmi2GetString			2	x		8	7	x	7	
fmi2SetReal		1	3	6						
fmi2SetInteger		1	3	6						
fmi2SetBoolean		1	3	6						
fmi2SetString		1	3	6						
fmi2GetFMUstate		x	x	x		8	7	x	7	
fmi2SetFMUstate		x	x	x		x	x	x	x	
fmi2FreeFMUstate		x	x	x		x	x	x	x	
fmi2SerializedFMUstateSize		x	x	x		x	x	x	x	
fmi2SerializeFMUstate		x	x	x		x	x	x	x	
fmi2DeSerializeFMUstate		x	x	x		x	x	x	x	
fmi2GetDirectionalDerivative			x	x		8	7	x	7	
fmi2SetRealInputDerivatives		x	x	x						
fmi2GetRealOutputDerivatives				x		8	x	x	7	
fmi2DoStep				x						
fmi2CancelStep					x					
fmi2GetStatus				x	x	x		x		
fmi2GetRealStatus				x	x	x		x		
fmi2GetIntegerStatus				x	x	x		x		
fmi2GetBooleanStatus				x	x	x		x		
fmi2GetStringStatus				x	x	x		x		

x means: call is allowed in the corresponding state
number means: call is allowed if the indicated condition holds:
1 for a variable with `variability ≠ "constant"` that has `initial = "exact"` or `"approx"`
2 for a variable with `causality = "output"` or
continuous-time states or state derivatives (if element `<Derivatives>` is present)
3 for a variable with `variability≠"constant"` that has `initial="exact"`, or `causality="input"`
6 for a variable with `causality = "input"` or
(`causality = "parameter" and variability = "tunable"`)
7 always, but retrieved values are usable for debugging only
8 always, but if status is other than fmi2Terminated, retrieved values are useable for debugging only

4.2.5 Pseudo Code Example

In the following example, the usage of the FMI functions is sketched in order to clarify the typical calling sequence of the functions in a simulation environment. The example is given in a mix of pseudo-code and “C”, in order to keep it small and understandable. We consider two slaves. Both have one continuous real input and one continuous real output which are connected in the following way:

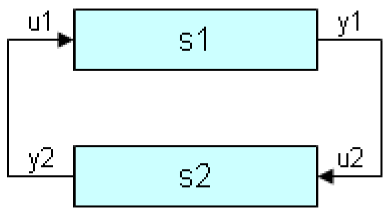


Figure 12: Connection graph of the slaves

We assume no algebraic dependency between input and output of each slave. The code demonstrates the simplest master algorithm as shown in section 4.1.

8. Constant communication step size.
9. No repeating of communication steps.
10. The slaves do not support asynchronous execution of `fmi2DoStep`.

The error handling is implemented in a very rudimentary way.

```
//////////////////////////
//Initialization sub-phase

//Set callback functions,
fmi2CallbackFunctions cbf;
cbf.logger = loggerFunction;   //logger function
cbf.allocateMemory = calloc;
cbf.freeMemory = free;
cbf.stepFinished = NULL;       //synchronous execution
cbf.componentEnvironment = NULL;

//Instantiate both slaves
fmi2Component s1 = s1_fmi2Instantiate("Tool1" , fmi2CoSimulation, GUID1, "",
                                    fmi2False, fmi2False, &cbf, fmi2True);
fmi2Component s2 = s2_fmi2Instantiate("Tool2" , fmi2CoSimulation, GUID2, "",
                                    fmi2False, fmi2False, &cbf, fmi2True);

if ((s1 == NULL) || (s2 == NULL))
      return FAILURE;

// Start and stop time
startTime = 0;
stopTime = 10;

//communication step size
h = 0.01;

// set all variable start values (of "ScalarVariable / <type> / start")
s1_fmi2SetReal/Integer/Boolean/String(s1, ...);
s2_fmi2SetReal/Integer/Boolean/String(s2, ...);


//Initialize slaves
s1_fmi2SetupExperiment(s1, fmi2False, 0.0, startTime, fmi2True, stopTime);
s2_fmi2SetupExperiment(s1, fmi2False, 0.0, startTime, fmi2True, stopTime);
s1_fmi2EnterInitializationMode(s1);
```

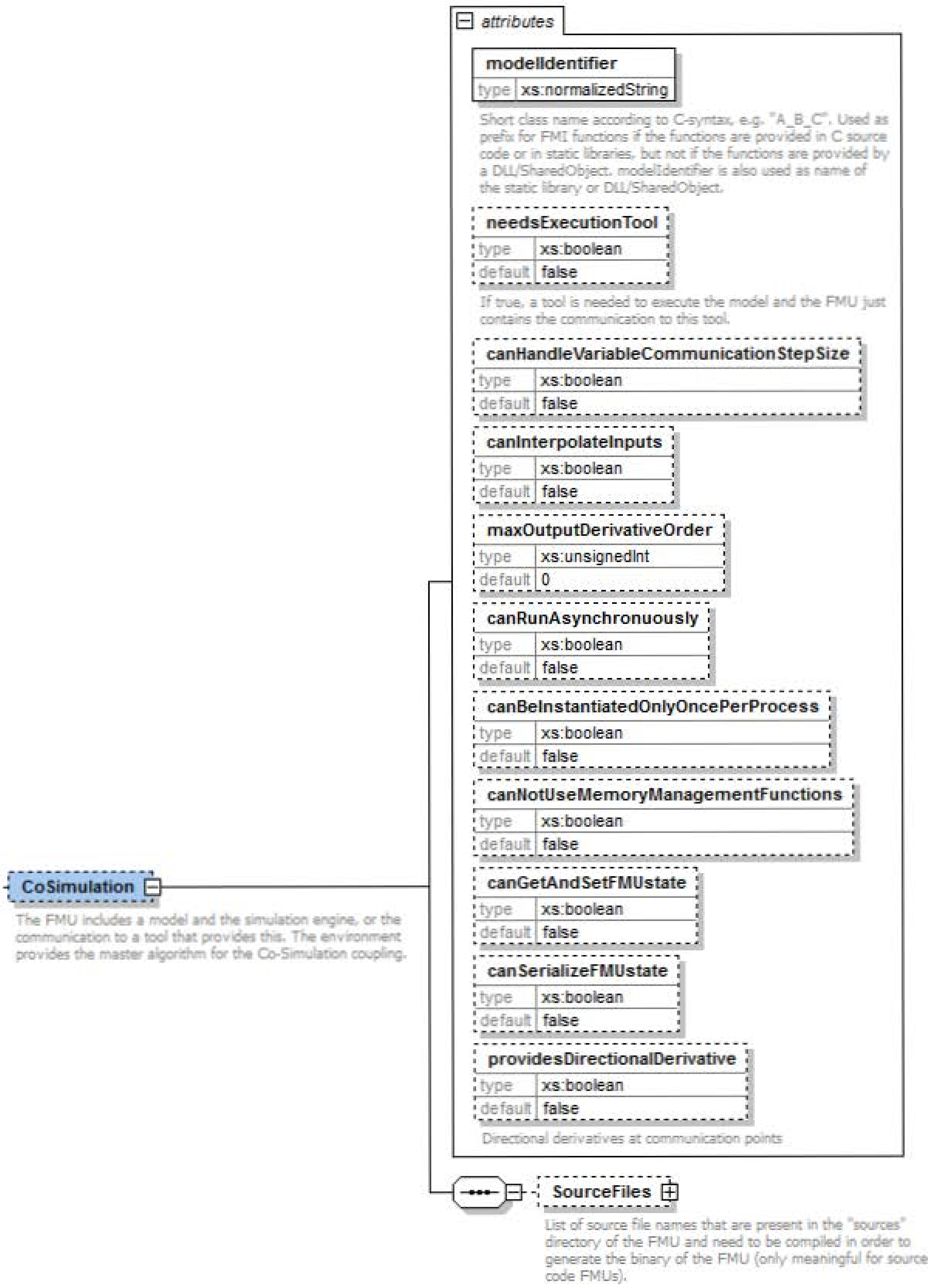
```
s2_fmi2EnterInitializationMode(s2);

   // set the input values at time = startTime
   s1_fmi2SetReal/Integer/Boolean/String(s1, ...);
   s2_fmi2SetReal/Integer/Boolean/String(s2, ...);
s1_fmi2ExitInitializationMode(s1);
s2_fmi2ExitInitializationMode(s2);


//////////////////////////
//Simulation sub-phase

      tc = startTime; //Current master time

      while ((tc < stopTime) && (status == fmi2OK))
      {
            //retrieve outputs
            s1_fmi2GetReal(s1, ..., 1, &y1);
            s2_fmi2GetReal(s2, ..., 1, &y2);
            //set inputs
            s1_fmi2SetReal(s1, ..., 1, &y2);
            s2_fmi2SetReal(s2, ..., 1, &y1);

            //call slave s1 and check status
            status = s1_fmi2DoStep(s1, tc, h, fmi2True);
            switch (status) {
            case fmi2Discard:
                  fmi2GetBooleanStatus(s1, fmi2Terminated, &boolVal);
                  if (boolVal == fmi2True)
                        printf("Slave s1 wants to terminate simulation.");
            case fmi2Error:
            case fmi2Fatal:
                  terminateSimulation = true;
                  break;
            }
            if (terminateSimulation)
                  break;

            //call slave s2 and check status as above
            status = s2_fmi2DoStep(s2, tc, h, fmi2True);
            ...

            //increment master time
            tc += h;
      }
      //////////////////////////
      //Shutdown sub-phase
      if ((status != fmi2Error) && (status != fmi2Fatal))
      {
            s1_fmi2Terminate(s1);
            s2_fmi2Terminate(s2);
      }


if (status != fmi2Fatal)
{
      s1_fmi2FreeInstance(s1);
      s2_fmi2FreeInstance(s2);
}
```

4.3 FMI Description Schema

This is defined in 2.2. Additionally, the co-simulation specific element “Implementation” is defined in the next section.

4.3.1 Co-Simulation FMU (CoSimulation)

If the XML file defines an FMU for Co-Simulation, element “CoSimulation” must be present. It is defined as:



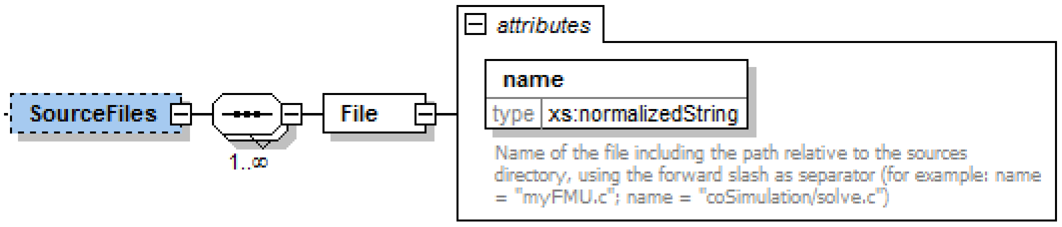
Short class name according to C-syntax, e.g. "A_B_C". Used as prefix for FMI functions if the functions are provided in C source code or in static libraries, but not if the functions are provided by a DLL/SharedObject. modelIdentifier is also used as name of the static library or DLL/SharedObject.

If true, a tool is needed to execute the model and the FMU just contains the communication to this tool.

Directional derivatives at communication points

The FMU includes a model and the simulation engine, or the communication to a tool that provides this. The environment provides the master algorithm for the Co-Simulation coupling.

List of source file names that are present in the "sources" directory of the FMU and need to be compiled in order to generate the binary of the FMU (only meaningful for source code FMUs).


attributes
name
type xs:normalizedString
Name of the file including the path relative to the sources directory, using the forward slash as separator (for example: name = "myFMU.c"; name = "coSimulation/solve.c")
SourceFiles
File
1..∞

These attributes have the following meaning (all attributes are optional with exception of “`modelIdentifier`”):

Attribute Name	*Description*
`modelIdentifier`	Short class name according to C syntax, for example “A_B_C”. Used as prefix for FMI functions if the functions are provided in C source code or in static libraries, but not if the functions are provided by a DLL/SharedObject. `modelIdentifier` is also used as name of the static library or DLL/SharedObject . See also section 2.1.1.
`needsExecutionTool`	If true, a tool is needed to execute the model. The FMU just contains the communication to this tool (see Figure 8). [*Typically, this information is only utilized for information purposes. For example a co-simulation master can inform the user that a tool has to be available on the computer where the slave is instantiated. The name of the tool can be taken from attribute* `generationTool` *of* `fmiModelDescription`.]
`canHandleVariableCommunicationStepSize`	The slave can handle variable communication step size. The communication step size (parameter `communicationStepSize` of `fmi2DoStep(...)`) has not to be constant for each call.
`canInterpolateInputs`	The slave is able to interpolate continuous inputs. Calling of `fmi2SetRealInputDerivatives(...)` has an effect for the slave.
`maxOutputDerivativeOrder`	The slave is able to provide derivatives of outputs with maximum order. Calling of `fmi2GetRealOutputDerivatives(...)` is allowed up to the order defined by `maxOutputDerivativeOrder`.
`canRunAsynchronuously`	This flag describes the ability to carry out the `fmi2DoStep(...)` call asynchronously.

`canBeInstantiatedOnlyOncePerProcess`	This flag indicates cases (especially for embedded code), where only one instance per FMU is possible (multiple instantiation is default = `false`; if multiple instances are needed, the FMUs must be instantiated in different processes).
`canNotUseMemoryManagementFunctions`	If `true`, the slave uses its own functions for memory allocation and freeing only. The callback functions `allocateMemory` and `freeMemory` given in `fmi2Instantiate` are ignored.
`canGetAndSetFMUstate`	If `true`, the environment can inquire the internal FMU state and can restore it. That is, `fmi2GetFMUstate`, `fmi2SetFMUstate`, and `fmi2FreeFMUstate` are supported by the FMU.
`canSerializeFMUstate`	If `true`, the environment can serialize the internal FMU state, in other words `fmi2SerializedFMUstateSize`, `fmi2SerializeFMUstate`, `fmi2DeSerializeFMUstate` are supported by the FMU. If this is the case, then flag `canGetAndSetFMUstate` must be `true` as well.
`providesDirectionalDerivative`	If `true`, the directional derivative of the equations at communication points can be computed with `fmi2GetDirectionalDerivative(..)`

The flags have the following default values.
boolean: false
unsignedInt: 0

Note, if `needsExecutionTool = true`, then it is required that the original tool is available to be executed in co-simulation mode. If `needsExecutionTool = false`, the slave is completely contained inside the FMU in source code or binary format (DLL/SharedObject).

4.3.2 Example XML Description File

The example below is the same one as shown in section 3.3.2 for a ModelExchange FMU. The only difference is the replacement of element ModelExchange by element CoSimulation (with additional attributes) and the removed local variables which are associated with continuous states and their derivatives. The XML file may have the following content:

```xml
<?xml version="1.0" encoding="UTF8"?>
<fmiModelDescription
  fmiVersion="2.0"
  modelName="MyLibrary.SpringMassDamper"
  guid="{8c4e810f-3df3-4a00-8276-176fa3c9f9e0}"
  description="Rotational Spring Mass Damper System"
  version="1.0"
```

```
generationDateAndTime="2011-09-23T16:57:33Z"
variableNamingConvention="structured">

<CoSimulation
  modelIdentifier="MyLibrary_SpringMassDamper"
  canHandleVariableCommunicationStepSize="true"
  canInterpolateInputs="true"/>

<UnitDefinitions>
  <Unit name="rad">
    <BaseUnit rad="1"/>
    <DisplayUnit name="deg" factor="57.2957795130823"/>
  </Unit>
  <Unit name="rad/s">
    <BaseUnit s="-1" rad="1"/>
  </Unit>
  <Unit name="kg.m2">
    <BaseUnit kg="1" m="2"/>
  </Unit>
</UnitDefinitions>

<TypeDefinitions>
  <SimpleType name="Modelica.SIunits.Inertia">
    <Real quantity="MomentOfInertia" unit="kg.m2" min="0.0"/> </SimpleType>
  <SimpleType name="Modelica.SIunits.Torque">
    <Real quantity="Torque" unit="N.m"/> </SimpleType>
  <SimpleType name="Modelica.SIunits.AngularVelocity">
    <Real quantity="AngularVelocity" unit="rad/s"/> </SimpleType>
  <SimpleType name="Modelica.SIunits.Angle">
    <Real quantity="Angle" unit="rad"/> </SimpleType>
</TypeDefinitions>

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    causality="parameter"
    variability="fixed">
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  <ScalarVariable
    name="torque.tau"
    valueReference="536870912"
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    causality="input">
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  </ScalarVariable>

  <ScalarVariable
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    valueReference="805306368"
    description="Absolute rotation angle of component"
    causality="output">
    <Real declaredType="Modelica.SIunits.Angle" />
    </ScalarVariable>

    <ScalarVariable
      name="inertia1.w"
      valueReference="805306369"
      description="Absolute angular velocity of component (= der(phi))"
      causality="output">
      <Real declaredType="Modelica.SIunits.AngularVelocity" />
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</ModelVariables>

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    </Outputs>
    <InitialUnknowns>
      <Unknown index="3"/>
      <Unknown index="4"/>
    </InitialUnknowns>
  </ModelStructure>
</fmiModelDescription>
```

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Appendix A FMI Revision History

This appendix describes the history of the FMI design and its contributors. The current version of this document is available from https://www.fmi-standard.org.

The Functional Mock-up Interface development was initiated and organized by Daimler AG (from Bernd Relovsky and others) as subproject inside the ITEA2 MODELISAR project.

The development of versions 1.0 and 2.0 was performed within WP200 of MODELISAR, organized by the WP200 work package leader Dietmar Neumerkel from Daimler.

A.1 Version 1.0 – FMI for Model Exchange

Version 1.0 of FMI for Model Exchange was released on Jan. 26, 2010.

The subgroup “FMI for Model Exchange” was headed by Martin Otter (DLR-RM). The essential part of the design of this version was performed by (alphabetical list):

Torsten Blochwitz, ITI, Germany
Hilding Elmqvist, Dassault Systèmes, Sweden
Andreas Junghanns, QTronic, Germany
Jakob Mauss, QTronic, Germany
Hans Olsson, Dassault Systèmes, Sweden
Martin Otter, DLR-RM, Germany.

This version was evaluated with prototypes implemented for (alphabetical list):

Dymola by Peter Nilsson, Dan Henriksson, Carl Fredrik Abelson, and Sven Erik Mattson, Dassault Systèmes,
JModelica.org by Tove Bergdahl, Modelon AB,
Silver by Andreas Junghanns, and Jakob Mauss, QTronic.

These prototypes have been used to refine the design of “FMI for Model Exchange”.

The following MODELISAR partners participated at FMI design meetings and contributed to the discussion (alphabetical list):

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Hilding Elmqvist, Dassault Systèmes, Lund, Sweden
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Thomas Neidhold, ITI GmbH, Dresden, Germany
Dietmar Neumerkel, Daimler AG, Stuttgart, Germany
Peter Nilsson, Dassault Systèmes, Lund, Sweden
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Antoine Viel, LMS International (Imagine), Roanne, France
Daniel Weil, Dassault Systèmes, Grenoble, France

The following people outside of the MODELISAR consortium contributed with comments:

Johan Akesson, Lund University, Lund, Sweden
Joel Andersson, KU Leuven, The Netherlands
Roberto Parrotto, Politecnico di Milano, Italy

A.2 Version 1.0 – FMI for Co-Simulation

Version 1.0 of FMI for Co-Simulation was released on Oct. 10, 2010.

FMI for Co-Simulation was developed in three subgroups: “Solver Coupling” headed by Martin Arnold (University Halle) and Torsten Blochwitz (ITI), “Tool Coupling” headed by Jörg-Volker Peetz (Fraunhofer SCAI), and “Control Logic” headed by Manuel Monteiro (Atego). The essential part of the design of this version was performed by (alphabetical list):

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Torsten Blochwitz, ITI GmbH, Dresden, Germany
Christoph Clauß, Fraunhofer IIS EAS, Dresden, Germany
Manuel Monteiro, Atego Systems GmbH, Wolfsburg, Germany
Thomas Neidhold, ITI GmbH, Dresden, Germany
Jörg-Volker Peetz, Fraunhofer SCAI, St. Augustin, Germany
Susann Wolf, Fraunhofer IIS EAS, Dresden, Germany

This version was evaluated with prototypes implemented for (alphabetical list):

SimulationX by Torsten Blochwitz and Thomas Neidhold (ITI GmbH),
Master algorithms by Christoph Clauß (Fraunhofer IIS EAS)

The following MODELISAR partners participated at FMI design meetings and contributed to the discussion (alphabetical list):

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Constanze Bausch, Atego Systems GmbH, Wolfsburg, Germany
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Christoph Clauß, Fraunhofer IIS EAS, Dresden, Germany
Manuel Monteiro, Atego Systems GmbH, Wolfsburg, Germany
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Dietmar Neumerkel, Daimler AG, Böblingen, Germany
Martin Otter, DLR, Oberpfaffenhofen, Germany
Jörg-Volker Peetz, Fraunhofer SCAI, St. Augustin, Germany
Tom Schierz, University Halle, Germany
Klaus Wolf, Fraunhofer SCAI, St. Augustin, Germany

A.3 Version 2.0 – FMI for Model Exchange and Co-Simulation

FMI 2.0 for Model Exchange and Co-Simulation was released on July 25, 2014.

A.3.1 Overview

This section gives an overview about the changes with respect to versions 1.0 for Model Exchange and 1.0 for Co-Simulation:

- FMI 2.0 is not backwards compatible to FMI 1.0.
- The documents, schema and header files for Model Exchange and for Co-Simulation have been merged. Due to the merging, some conflicts had to be resolved leading to some non-backwards compatible changes with respect to FMI 1.0.
- Parameters can be declared to be "tunable" in the FMU, in other words during simulation these parameters can be changed (if supported by the simulation environment).
- When enabling logging, log categories to be logged can be defined, so that the FMU needs to only generate logs of the defined categories (in FMI 1.0, logs had to be generated for all log categories and they had to be filtered afterwards). Log categories that are supported by an FMU can be optionally defined in the XML file so that a simulation environment can provide them to the user for selection.
- In order that tools can more simply support importing both FMI 1.0 and 2.0, all file and function names of FMI 2.0 start with "fmi2", whereas they start with "fmi" for FMI 1.0.
- FMI function names are no longer prefixed with the "`modelIdentifier`" if used in a DLL/sharedObject. As a result, FMUs that need a tool, can use a generic communication DLL, and the loading of DLLs is no longer FMU dependent.
- The different modes of an FMU are now clearly signaled with respective function calls (`fmi2EnterInitializationMode`, `fmi2EnterEventMode`, `fmi2EnterContinuousTimeMode`).
- The interfaces have been redesigned, in order that algebraic loops over connected FMUs with Real, Integer, or Boolean unknowns can now be handled reasonably not only in Continuous Time Mode, but also in Initialization and Event Mode. In FMI 1.0, algebraic loops in Initialization and Even Mode could not be handled.
- The termination of every global event iteration over connected FMUs must be reported by a new function call (`fmi2EnterContinuousTimeMode`).
- The unit definitions have been improved: The tool-specific unit-name can optionally be expressed as function of the 7 SI base units and the SI derived unit "rad". It is then possible to check units when FMUs are connected together (without standardizing unit names), or to convert variable values that are provided in different units (for the same physical quantity).
- Enumerations have an arbitrary (but unique) mapping to integers (in FMI 1.0, the mapping was automatically to 1,2,3,...).
- Explicit alias/negatedAlias variable definitions have been removed, to simplify the interface: If variables of the same base type (like `fmi2Real`) have the same `valueReference`, they have identical values. A simulation environment may ignore this completely (this was not possible in FMI 1.0), or can utilize this information to more efficiently store results on file.
- When instantiating an FMU, the absolute path to the FMU resource directory is now reported also in Model Exchange, in order that the FMU can read all of its resources (for example maps, tables, ...) independently of the "current directory" of the simulation environment where the FMU is used.

- An ordering is defined for input, output, and state variables in the XML file of an FMU, in order for this order to be defined in the FMU, and not (arbitrarily) selected by the simulation environment. This is essential, for example when linearizing an FMU, or when providing "sparsity" information (see below).
- Several optional features have been added:
  - The complete FMU state can be saved, restored, and serialized to a byte vector (that can be stored on file). As a result, a simulation (both for Model Exchange and for Co-Simulation) can be restarted from a saved FMU state. Rejecting steps for variable step-size Co-Simulation master algorithms is now performed with this feature (instead of the less powerful method of FMI 1.0).
  - The dependency of state derivatives and of output variables from inputs and states can be defined in the XML file, in other words the sparsity pattern for Jacobians can be defined. This allows simulating stiff FMUs with many states (> 1000 states) since sparse matrix methods can be utilized in the numerical integration method. Furthermore, it can be stated whether this dependency is linear (this allows to transform nonlinear algebraic equation systems into linear equation systems when connecting FMUs).
  - Directional derivatives can be computed for derivatives of continuous-time states and for outputs. This is useful when connecting FMUs and the partial derivatives of the connected FMU shall be computed. If the exported FMU performs this computation analytically, then all numerical algorithms based on these partial derivatives (for example the numerical integration method or nonlinear algebraic solvers) are more efficient and more reliable.
  - Every scalar variable definition can have an additional "annotation" data structure that is arbitrary ("any" element in XML). A tool vendor can store tool-dependent information here (that other tools can ignore), for example to store the graphical layout of parameter menus. The `VendorAnnotations` element was also generalized from (name, value) pairs to any XML data structure.
- Many smaller improvements have been included, due to the experience in using FMI 1.0 (for example the causality/variability attributes have been changed and more clearly defined, the `fmi2ModelFunctions.h` header has been split into two header files (one for the function signature, and one for the function names), in order that the header files can be directly used both for DLLs and for source code distribution).

A.3.2 Main changes

This section gives the details about the changes with respect to versions 1.0 for Model Exchange and 1.0 for Co-Simulation:

In this version, the documents of version 1.0 for Model Exchange and for Co-Simulation have been merged and several new features have been added.

The following changes in FMI 2.0 are <u>not backwards compatible</u> due to the merging:

File fmiModelTypes.h (in FMI for Model Exchange) has been renamed to fmi2TypesPlatform.h (the file name used in FMI for Co-Simulation).

File fmiModelFunctions.h (in FMI for Model Exchange) has been renamed to fmi2Functions.h (the file name used in FMI for Co-Simulation), and the function prototypes in this header files have been merged from "Model Exchange" and from "Co-Simulation"). Additionally, a new header files has been added, `fmi2FunctionTypes.h` that contains a definition of the function signatures. This header file is also used in `fmi2Functions.h` (so the signature is not duplicated). The benefit is that `fmi2FunctionTypes.h` can be directly used when loading a DLL/sharedObject (in FMI 1.0, the tool providers had to provide this header file by themselves).

Fixing ticket #47:
In FMI 1.0 for Model Exchange the fmiModelDescription.version was defined as string, whereas in Co-Simulation it was defined as integer. This has been changed, so that version is a string.

The following backwards compatible improvements have been made in FMI 2.0:

The FMI 1.0 documents have been merged (for example all common definitions have been placed in the new chapter 2).

The following not backwards compatible improvements have been made in FMI 2.0:

Element "fmiModelDescription.Implementation" in the model description schema file has been replaced by a different structure where one hierarchical level is removed. There are now 2 elements directly under fmiModelDescription: "ModelExchange" and "CoSimulation".
File "fmiImplementation.xsd" has been removed.
New capability flags have been introduced both for `ModelExchange` and for `CoSimulation`, such as `canGetAndSetFMUstate`, `canSerializeFMUstate` etc.
Attribute `modelIdentifier` has been moved from an `fmiModelDescription` attribute to an attribute in `ModelExchange` and `CoSimulation`. This allows providing different identifiers, and then an FMU may contain both distribution types with different DLL names (which correspond to the `modelIdentifier` names).
A new attribute `needsExecutionTool` has been introduced both in `ModelExchange` and in `CoSimulation` in order to define whether a tool is needed to execute the FMU. The previous elements in `CoSimulation_Tool` have been removed.

The state machines of ModelExchange and CoSimulation have been improved. Especially, the entering of the states in this state machine are now clearly marked by corresponding function calls (`fmi2EnterInitializationMode`, `fmi2EnterEventMode`, `fmi2EnterContinuousTimeMode`).

Fixing ticket #9:
A new element `LogCategory` was introduced in `fmiModelDescription`. This is an unordered set of strings representing the possible values of the log categories of the FMU (for example `logEvent`).
Function `fmi2SetDebugLogging` has two new arguments to define the categories (from `LogCategory`) to be used in log messages.

Fixing ticket #33:
The `causality` and `variability` attributes of a `ScalarVariable` have not been fully clear. This has been fixed by changing the enumeration values of `variability` from "`constant, parameter, discrete, continuous`" to "`constant, fixed, tunable, discrete, continuous`" and `causality` from "`input output internal none`" to "`parameter, input, output, local`".
This change includes now also the support of parameters that can be tuned (changed) during simulation.

Fixing ticket #35:
In order to simplify implementation (for example no longer an "element event handler" needed in SAX XML parser), the only location where data is not defined by attributes, is changed to an attribute definition: Element `DirectDependency` in `ScalarVariable` is removed. The same information can now be obtained from the `InputDependency` attribute inside `<fmiModelDescription><ModelStructure><Outputs>`.

Fixing ticket #37:

The new status flag `fmi2Terminate` is added to the Co-Simulation definition. This allows a slave to terminate the simulation run before the stop time is reached without triggering an error.

Fixing ticket #39:

Wrong example in the previous section 2.10 of Co-Simulation has been fixed.

Fixing ticket #41:

New types introduced in fmi2TypesPlatform.h :

`fmi2ComponentEnvironment, fmi2FMUstate, fmi2Byte.`

Struct `fmi2CallbackFunctions` gets a new last argument:

`fmi2ComponentEnvironment componentEnvironment`

The first argument of function `logger` is changed from type `fmi2Component` to `fmi2ComponentEnvironment.`

By these changes, a pointer to a data structure from the simulation environment is passed to the `logger` and allows the `logger`, for example to transform a `valueReference` in the log message to a variable name.

Fixing ticket #42:

Enumerations defined in fmi2Type.xsd are now defined with (name, value) pairs. An enumeration value must be unique within the same enumeration (to have a bijective mapping between enumeration names and values, in order that results can optionally be presented with names and not with values).
Furthermore, the `min/max` values of element `Enumeration` in `TypeDefinition` have been removed, because they are meaningless.

Fixing ticket #43:

The previous header file fmiFunctions.h is split into 2 header files, fmi2FunctionTypes.h and fmi2Functions.h, in order to simplify the dynamic loading of an FMU (the typedefs of the function prototypes defined in fmi2FunctionTypes.h can be used to type case the function pointers of the dynamic loading).

Fixing ticket #45:

Contrary to the ticket proposal, no new function `fmiResetModel` is added. Instead 6 new functions are added to get and set the internal FMU state via a pointer and to serialize and deserialize an FMU state via a byte vector provided by the environment. For details, see section 2.1.8. This feature allows, for example to support more sophisticated co-simulation master algorithms which require the repetition of communication steps. Additionally, two capability flags have been added (`canGetAndSetFMUstate`, `canSerializeFMUstate`) in order to define whether these features are supported by the FMU.

Fixing ticket #46:

The unit definitions have been enhanced by providing an optional mapping to the 7 SI base units and the SI derived unit “rad”, in order for a tool to be able to check whether a signal provided to the FMU or inquired by the FMU has the expected unit.

Fixing ticket #48:

The definition of `fmiBoolean` in `fmiTypesPlatform.h` for “standard32” was changed from `char` to `int`. The main reason is to avoid unnecessary casting of Boolean types when exporting an FMU from a Modelica environment or when importing it into a Modelica environment.
The current definition of `char` for a Boolean was not meaningful, since, for example for embedded code generation usually Booleans are packed on integers and `char` for one Boolean would also not be used. It is planned to add more supported data types to an FMU in the future, which should then also include support for packed Booleans.

Fixing ticket #49:

Argument `fmiComponent` in function pointer `stepFinished` was changed to `fmi2ComponentEnvironment` (when `stepFinished` is called from a co-simulation slave and provides `fmi2ComponentEnvironment`, then this data structure provided by the environment can provide environment specific data to efficiently identify the slave that called the function).

Fixing ticket #54:
In section 2.3 it is now stated, that the FMU must include all referenced resources. This means especially that for Microsoft VisualStudio the option "MT" has to be used when constructing a DLL in order to include the run-time environment of VisualStudio in the DLL.

Fixing ticket #75:
Since states are now explicitly defined in the xml-file, function `fmiGetStateValueReferences` is no longer needed, as well as the special type `fmiUndefinedValueReference` that might be used as return value of this function. Therefore, both elements have been removed in FMI 2.0.

Fixing ticket #85:
New argument `noSetFMUStatePriorToCurrentPoint` to function `fmi2CompletedIntegratorStep`, similarly to `fmi2DoStep`, in order that the FMU can flush a result buffer if necessary.

Fixing ticket #86:
The fmi2TypesPlatform.h header file has been slightly changed: The default value of fmi2TypesPlatform is changed from "standard32" to "default", since this definition holds for most platforms and compilers. Furthermore, the default type of fmi2ValueReference has been changed from "unsigned int" to "size_t".

Fixing ticket #88:
The definition of fmi2Functions.h slightly changed to improve portability (the header file can now be utilized both for Microsoft and gnu compilers, and the danger of name conflicts has been reduced).

Fixing ticket #95:
FMI xml-files need to be UTF-8 encoded (as are xml schema files and strings in the C-API), in order to simplify reading of xml-files.

Fixing ticket #113:
Changed function name "fmiTerminateSlave" to "fmi2Terminate" in order to be consistent with the other function definitions (fmi2EnterSlaveInitializationMode, fmi2Terminate).

Fixing ticket #115:
Clarification added, that the special values NAN, +INF, -INF, are not allowed in the FMI xml-files.

Fixing ticket #127:
Added clarifications in section 2.1, that all C-API functions are not thread safe and that FMUs must not influence each other.

Fixing ticket #218:
Changed all name prefixes from fmi to fmi2 in *.h, *.xsd, *.png files and in the specification to avoid compiler and linker problems when supporting both FMI 1.0 and 2.0 in the same program.

Function `fmiInitialize` was split into two functions: `fmi2EnterInitializationMode` and `fmi2ExitInitializationMode` in order that artificial or "real" algebraic loops over connected FMUs can be handled in an efficient way.

Function `stepEvent` in `struct fmi2CallbackFunctions` had different locations in the FMI documentation and in the header file. This inconsistency has been corrected by using the location in the header file (at the end of the `struct`).

The `struct fmi2CallbackFunctions` is provided as a pointer to the `struct` when instantiating an FMU, and not as the `struct` itself. This simplifies the importing of an FMU into a Modelica environment.

Defined how to utilize the min/max attributes for fmi2SetReal, fmi2SetInteger, fmi2GetReal, fmi2GetInteger calls.

Attributes “numberOfScalarVariables”, “numberOfContinuousStates”, “numberOfInputs”, “numberOfOutputs” available in FMI 1.0 have been removed, because they can be deduced from the remaining xml file (so in FMI 2.0 this would have been redundant information).

A.3.3 Contributors

The development group for this version was headed by Torsten Blochwitz (ITI). The essential part of the design of this version was performed by (alphabetical list):

Johan Akesson, Modelon, Sweden
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The FMI 2.0 document was edited by Martin Otter (DLR), Torsten Blochwitz (ITI), and Martin Arnold (Uni Halle). The State Machines and tables for the Calling Sequences for Model Exchange and Co-Simulation are from Jakob Mauss (QTronic).

This version was evaluated with prototypes implemented for (alphabetical list):

Dymola by Peter Nilsson, Karl Wernersson, and Sven Erik Mattson, Dassault Systèmes, Sweden
FMI Compliance Checker by Iakov Nakhimovski, Modelon AB, Sweden
LMS Imagine.Lab AMESim by Antoine Viel, Siemens PLM Software, France
MapleSim, by Kaska Kowalska, Maplesoft, Canada
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SCALEXIO and VEOS by Irina Zacharias, Andreas Pillekeit, dSPACE GmbH, Germany
xMOD by Mongi ben Gaid, Bertrand Hugon, Bruno Léty, and Fabien Debertolis, IFPEN, France

These prototypes have been used to refine the design of “FMI 2.0 for Model Exchange and Co-Simulation”.

The open source FMITest library (https://svn.fmi-standard.org/fmi/branches/public/Test_FMUs/_FMIModelicaTest/FMITest/help/FMITest.html) to test difficult cases of connected FMUs was implemented by Martin Otter (DLR, Germany) based on suggestions by Hilding Elmqvist (Dassault Systèmes, Sweden) and Torsten Blochwitz (ITI, Germany).

The following partners participated at FMI 2.0 design meetings and contributed to the discussion (alphabetical list):

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Sven Erik Mattsson, Dassault Systèmes, Sweden
Jakob Mauss, QTronic, Germany
Monika Mühlbauer, Siemens AG, Germany
Dietmar Neumerkel, Daimler AG, Germany
Peter Nilsson, Dassault Systèmes, Sweden
Hans Olsson, Dassault Systèmes, Sweden
Martin Otter, DLR RMC-SR, Germany
Nicolas Pernet, IFPEN, France
Andreas Pillekeit, dSPACE GmbH, Germany
Bernd Relovsky, Daimler AG, Germany
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Andreas Pfeiffer, DLR RMC-SR

Appendix B Glossary

This glossary is a subset of (*MODELISAR Glossary, 2009*) with some extensions.

Term	Description
algorithm	A formal recipe for solving a specific type of problem.
application programming interface (API)	A set of functions, procedures, methods or classes together with type conventions/declarations (for example C header files) that an operating system, library or service provides to support requests made by computer programs.
AUTOSAR	AUTomotive Open System Architecture (www.autosar.org). Evolving standard of the automotive industry to define the implementation of embedded systems in vehicles including communication mechanisms. An important part is the standardization of C functions and macros to communicate between software components. AUTOSAR is targeted to built on top of the real-time operating system OSEK (www.osek-vdx.org, de.wikipedia.org/wiki/OSEK). The use of the AUTOSAR standard requires AUTOSAR membership.
communication points	Time grid for data exchange between master and slaves in a co-simulation environment (also known as “sampling points” or “synchronization points”).
communication step size	Distance between two subsequent *communication points* (also known as “sampling rate” or “macro step size”).
co-simulation	Coupling (in other words dynamic mutualexchange and utilization of intermediate results) of several *simulation programs* including their numerical solvers in order to simulate a system consisting of several subsystems.
co-simulation platform	Software used for coupling several *simulation programs* for *co-simulation.*
ECU	Electronic Control Unit (Microprocessor that is used to control a sub-system in a vehicle).
event	Something that occurs instantaneously at a specific time or when a specific condition occurs. At an event, numerical integration is suspended and variables may change their values discontinuously.
FMI	Functional Mock-up Interface: Interface of a functional mock-up in form of a model. In analogy to the term digital mock-up (see *mock-up*), functional mock-up describes a computer-based representation of the functional behaviour of a system for all kinds of analyses.
FMI for Co-Simulation	Functional Mock-up Interface for Co-Simulation: One of the MODELISAR *functional mock-up interfaces.* It connects the *master solver* component with one or more *slave solvers*.
FMI for Model Exchange	Functional Mock-up Interface for Model Exchange: One of the MODELISAR *functional mock-up interfaces.* It consists of the *model description interface* and the *model execution interface*. It connects the *external model* component with the *solver* component.
FMU	Functional Mock-up Unit: A “model class” from which one or more “model instances” can be instantiated for simulation. An FMU is stored in one zip file as defined in section 2.3 consisting basically of one XML file that defines the model variables and a set of C functions (see section 2.1), in source or binary form, to execute the model equations or the simulator slave. In case of tool execution, additionally, the original simulator is required to perform the co-simulation (compare section 4.3.1)
integration algorithm	The numerical algorithm to solve differential equations.

Term	Description
integrator	A *software component*, which implements an *integration algorithm*.
interface	An abstraction of a *software component* that describes its behavior without dealing with the internal implementation. *Software components* communicate with each other via interfaces.
master/slave	A method of communication, where one device or process has unidirectional control over one or more other devices. Once a master/slave relationship between devices or processes is established, the direction of control is always from the master to the slaves. In some systems a master is elected from a group of eligible devices, with the other devices acting in the role of slaves.
mock-up	A full-sized structural, but not necessarily functional model built accurately to scale, used chiefly for study, testing, or display. In the context of computer aided design (CAD), a digital mock-up (DMU) means a computer-based representation of the product geometry with its parts, usually in 3-D, for all kinds of geometrical and mechanical analyses.
model	A model is a mathematical or logical representation of a system of entities, phenomena, or processes. Basically a model is a simplified abstract view of the complex reality. It can be used to compute its expected behavior under specified conditions.
model description file	The model description file is an XML file, which supplies a description of all properties of a *model* (for example input/output variables).
model description interface	An interface description to write or retrieve information from the *model description file*.
Model Description Schema	An *XML* schema that defines how all relevant, non-executable, information about a "model class" (*FMU)* is stored in a text file in *XML* format. Most important, data for every variable is defined (variable name, handle, data type, variability, unit, etc.), see section 2.2.
numerical solver	see *solver*
output points	Tool internal time grid for saving output data to file (in some tools also known as "*communication points*" – but this term is used in a different way in FMI for Co-Simulation, see above).
output step size	Distance between two subsequent *output points*.
parameter	A quantity within a *model*, which remains constant during *simulation (fixed parameter) or may change at event instances (tunable parameter).*Examples are a mass, stiffness, etc.
slave	see *master/slave*
simulation	Compute the behavior of one or several *models* under specified conditions. (see also *co-simulation*)
simulation model	see *model*
simulation program	Software to develop and/or solve simulation *models*. The software includes a *solver*, may include a user interface and methods for post processing (see also: *simulation tool*, *simulation environment*). Examples of simulation programs are: AMESim, Dymola, SIMPACK, SimulationX, SIMULINK.
simulation tool	see *simulation program*
simulator	A simulator can include one or more *simulation programs*, which solve a common simulation task.
solver	*Software component,* which includes algorithms to solve *model*s, for example *integration algorithms* and *event handling* methods.

Term	Description
state	The "continuous states" of a model are all variables that appear differentiated in the model and are independent from each other. The "discrete states" of a model are time-discrete variables that have two values in a model: The value of the variable from the previous *event* instant, and the value of the variable at the actual event instant.
state event	*Event* that is defined by the time instant where the domain $z > 0$ of an event indicator variable z is changed to $z \leq 0$, or vice versa. This definition is slightly different from the usual standard definition of state events: "$z(t)*z(t_{i-1}) \leq 0$" which has the severe drawback that the value of the event indicator at the previous event instant, $z(t_{i-1}) \neq 0$, must be non-zero and this condition cannot be guaranteed. The often used term "zero crossing function" for z is misleading (and is therefore not used in this document), since a state event is defined by a change of a domain and not by a zero crossing of a variable.
step event	*Event* that might occur at a completed integrator step. Since this event type is not defined by a precise time or condition, it is usually not defined by a user. A program may use it, for example to dynamically switch between different states. A step event is handled much more efficiently than a *state event*, because the event is just triggered after performing a check at a completed integrator step, whereas a search procedure is needed for a state event.
super dense time	A precise definition of time taking into account iterations at an event. For an *FMU*, the independent variable time $t \in \mathbb{T}$ is a tuple $t = (t_R, t_I)$ where $t_R \in \mathbb{R}$, $t_I \in \mathbb{N} = \{0,1,2,\ldots\}$. The real part t_R of this tuple is the independent variable of the FMU for describing the continuous-time behavior of the model between events. In this phase $t_I = 0$. The integer part t_I of this tuple is a counter to enumerate (and therefore distinguish) the events at the same continuous-time instant t_R.
time event	*Event* that is defined by a predefined time instant. Since the time instant is known in advance, the integrator can select its step size so that the event point is directly reached. Therefore, this event can be handled efficiently.
user interface	The part of the simulation program that gives the user control over the simulation and allows watching results.
value reference	The value of a scalar variable of an FMU is identified with an Integer handle called *value reference*. This handle is defined in the modelDescription.xml file (as attribute `valueReference` in element `ScalarVariable`). Element `valueReference` might not be unique for all variables. If two or more variables of the same base data type (such as `fmi2Real`) have the same `valueReference`, then they have identical values but other parts of the variable definition might be different (for example min/max attributes).
XML	eXtensible Markup Language (www.w3.org/XML, en.wikipedia.org/wiki/XML) – An open standard to store information in text files in a structured form.