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SysML and FMI in INTO-CPS

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Abstract

This deliverable describes how the INTO-CPS SysML profile has evolved during Year 3 of INTO-CPS project. During Year 1, INTO-CPS SysML profile mainly focussed on the architectural modelling of Cyber Physical Systems (CPSs) see D4.1.c INTO-CPS Deliverable. During Year 2, Design Space Exploration was added the INTO-CPS SysML see D4.2.c INTO-CPS Deliverable. The main contribution of Year 3 concerns Unit and Structured Type modelling inside INTO-CPS profile and their mapping into FMI. The deliverable starts by describing both SysML and FMI Unit and Structured Type definition. Then it describes how these concepts are modelled using INTO-CPS SysML profile and then mapped to FMI modelDescription.

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1 Introduction

When modelling systems, designers often define their architecture and/or behaviour, but all this work needs to be built on top of solid foundations of well-defined libraries of units, quantities, and dimensions. A strong and well-documented definition must be shared such that it can be reused as much as possible between many models and projects. Sections 2 and 3 describe how, respectively, FMI and SysML define such foundation. Section 4 shows how INTO-CPS project handles this topic. Finally, Section 5 provides an overview of future work required.

2 FMI

The Functional Mockup Interface (FMI) is a tool-independent standard to support both model exchange and co-simulation of dynamic models using a combination of XML-files and compiled C-code [4]. The part of the FMI standard dedicated to model exchange specification is an XML file, named “*modelDescription*”, which supplies a description of all properties of a model. The main content of this *modelDescription* consist of a list of “*ScalarVariable*” representing the inputs, outputs, and parameters of the model. By default, these *ScalarVariables* represent arrays or structured entities mapped to scalars of the following PrimitiveType: Real, Integer, Boolean, String, and Enumeration. In addition, FMI standard defines a set of *Units* and *Types* (aka Simple Type and not Structured Type) to help designers and limit errors.

2.1 Unit Definition

The “*UnitDefinitions*” element has been defined in the FMI standard cf. Figure 1 as an entry to list all “*Unit*” defined inside a given FMI *modelDescription* (this list is not shared among different model descriptions).

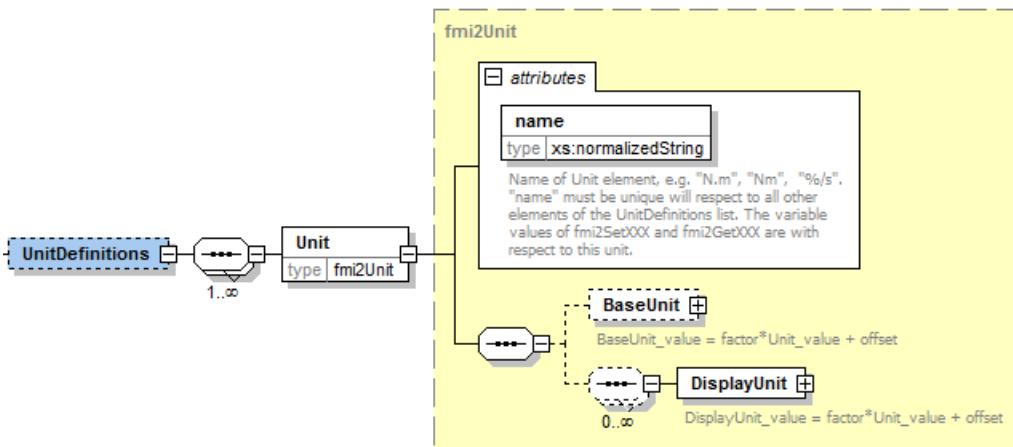


Figure 1: FMI UnitDefinition Element

A *Unit* is defined by its *name* such as “N.m”, “N*m” or “Nm”. This name must be unique within the *UnitDefinitions* list. The FMI standard also defines a set *BaseUnit* which is composed of the 7 SI base units i.e. “kg”, “m”, “s”, “A”, “K”, “mol”, “cd”, and the optional SI derived unit “rad”. *Unit* values can be also be converted with respect to *BaseUnit* using the *conversion factor* and *offset* attributes by the following formula:

$$\text{BaseUnit value} = \text{factor} * \text{Unit value} + \text{offset}$$

Figure 2 shows an example of a *UnitDefinitions* containing three *Units*:

1. A first *Unit*, named “rad”, which is based on the “rad” *BaseUnit* with “1” as exponent. It also defines a *DisplayUnit*, named “deg”, with a *factor* of “57.2957795130823”. This means that a “deg” is equals to “57.2957795130823” * “rad”;
2. A second *Unit*, named “rad/s”, which is based on the “s” *BaseUnit* with “-1” as exponent (i.e. per second) and on the “rad” *BaseUnit* with “1” as exponent;
3. Finally a third *Unit*, named “kg.m2”, which is based on the “kg” *BaseUnit* with “1” as exponent and on the “m” *BaseUnit* with “2” as exponent (i.e. square meter);

```

<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>

```

Figure 2: FMI UnitDefinition Example

2.2 Type Definition

In the same way, the “*TypeDefinitions*” element has been defined in the FMI standard cf. Figure 3 as an entry to list all “*SimpleType*” defined inside a given FMI *modelDescription*. A “*SimpleType*” is defined by a “*name*” and a “*description*”. The *name* must be unique within the *TypeDefinitions* list. Furthermore, this *name* must be different to all *ScalarVariables* names. Finally, a *SimpleType* must be refer to one of the Primitive Type elements i.e. Real, Integer, Boolean, String, or Enumeration.

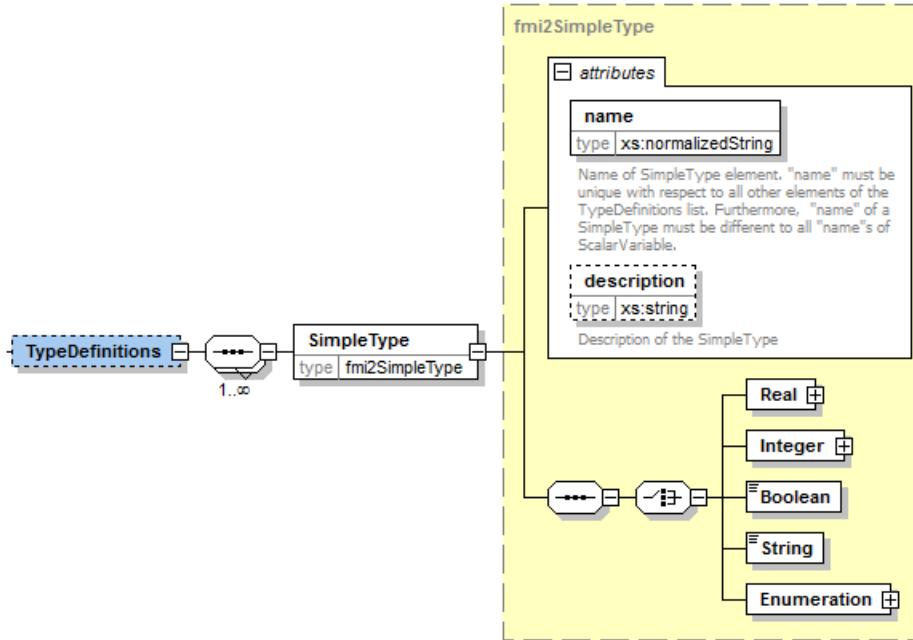


Figure 3: FMI TypeDefinition Element

In Figure 4 an example of *TypeDefinitions* is depicted. The latter is composed of one unique *SimpleType*. This *SimpleType*, named “Modelica.SIunits.Inertia”, is a *Real* representing a “MomentOfInertia”. Its *Unit*,

named “kg.m2”, has been defined inside the *UnitDefinitions*, cf. Figure 2. Finally its value can never be less than “0.0”.

```
<TypeDefinitions>
  <SimpleType name="Modelica.SIunits.Inertia">
    <Real quantity="MomentOfInertia" unit="kg.m2" min="0.0"/> </SimpleType>
</TypeDefinitions>
```

Figure 4: FMI TypeDefinition Example

2.3 Libraries

The FMI standard defines one unique library of *PrimitiveType*. This library is composed of five *PrimitiveTypes*:

- Real,
- Integer,
- Boolean,
- String and
- Enumeration.

2.4 Equivalence

When two *ScalarVariables*, sv1 and sv2 for example, are connected, the FMI Standard specifies how a tool implementing the standard can verify the connection:

- If only one *ScalarVariable* refers to a *BaseUnit*, then the connection equation means that “sv1 = sv2”.
- If both *ScalarVariables* refer to the same *BaseUnit* with same factor and offset, the connection still means that “sv1 = sv2”.
- If both *ScalarVariables* reference the same *BaseUnit* with a different factor and/or offset, the connection means that “sv1_factor*sv1_value + sv1_offset = sv2_factor * sv2_value + sv2_offset”
- Of course, if both *ScalarVariables* do not reference the same *BaseUnit*, the tool must raise an error. The connection is invalid in that case.

Note that the FMI standard recommends standardizing *BaseUnit* names among models and projects, to tackle the case where connected *ScalarVariables* reference the same *BaseUnit* but with different quantities (aka *TypeDefinition*), such as “Energy” and “Torque”, or “AngularVelocity” and “Frequency”. To handle such cases *TypeDefinition* must be taken into account (see Section 2.2).

3 SysML

The Systems Modelling Language (SysML) is a subset and extension of UML for System Engineering. The main goal of SysML is to provide a graphical notation to support Systems Engineering. As mentioned in the introduction, this must be based on a well-founded and well-defined libraries of Units and Types, so, it is not surprising that SysML provides a way of defining such concepts described in the following sections.

3.1 Unit Definition

To define units, SysML introduces two related concepts, cf. Figure 5, named *Unit* and *QuantityKind*.

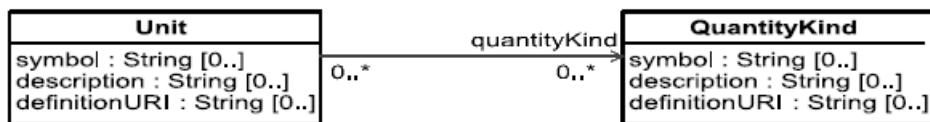


Figure 5: SysML Unit and QuantityKind definitions

A SysML “*QuantityKind* is a kind of quantity that may be stated by means of defined units” [3]. For example, time may be measured by units of seconds, hours, days, or years. Still according to the SysML specification, “two *QuantityKind* represent the same kind of quantity if and only if their *definitionURIs* have values and their values are equal” [3]. A *QuantityKind* is defined by:

- Its name which should be unique;
- Its symbol which is a short symbolic name of the quantity kind;
- Its description which is a textual description of the quantity kind;
- definitionURI which is a URI that references an external definition of the quantity kind.

A SysML “*Unit* is a quantity in terms of which the magnitudes of other quantities that have the same quantity kind can be stated” [3]. *Unit* is defined by:

- Its name which should be unique;
- Its symbol which is a short symbolic representation(s) of the *Unit* name;
- Its description which is a textual description of the *Unit*;
- Its definitionURI that references an external definition of the *Unit*;
- Its quantityKind(s) which is(are) *QuantityKind*(s) associated to the *Unit*.

SysML allows a *Unit* to be associated to zero or many *QuantityKind*. This relation expresses the fact that a *Unit* with a given name and a given symbol can have different kind of quantities. For example, SysML describes the example of the joule per kelvin and J/K which are respectively the name and symbol of both a measurement unit of heat capacity and a measurement unit of entropy, which are generally not considered to be quantities of the same kind.

Note that in addition the *Unit* and *QuantityKind* concepts presented above, SysML specifies – as a Non-Normative Extensions – a model library for Quantities, Units, Dimensions, and Values (QUDV). This model library reuse and extends the *Unit* and *QuantityKind* stereotype to allow specification of libraries. The

following diagrams illustrate the mechanism used for that. Examples of libraries can be found in Section E.6 of the SysML specification.

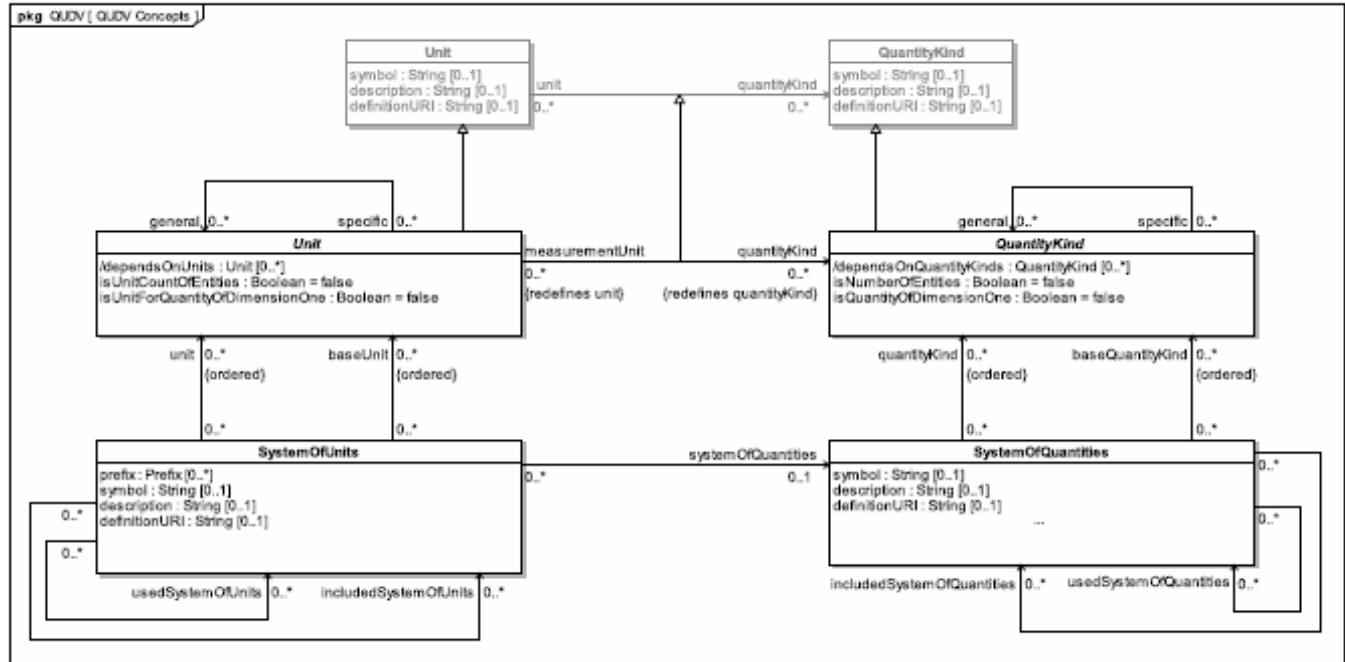


Figure 6: SysML QUDV Concepts diagrams

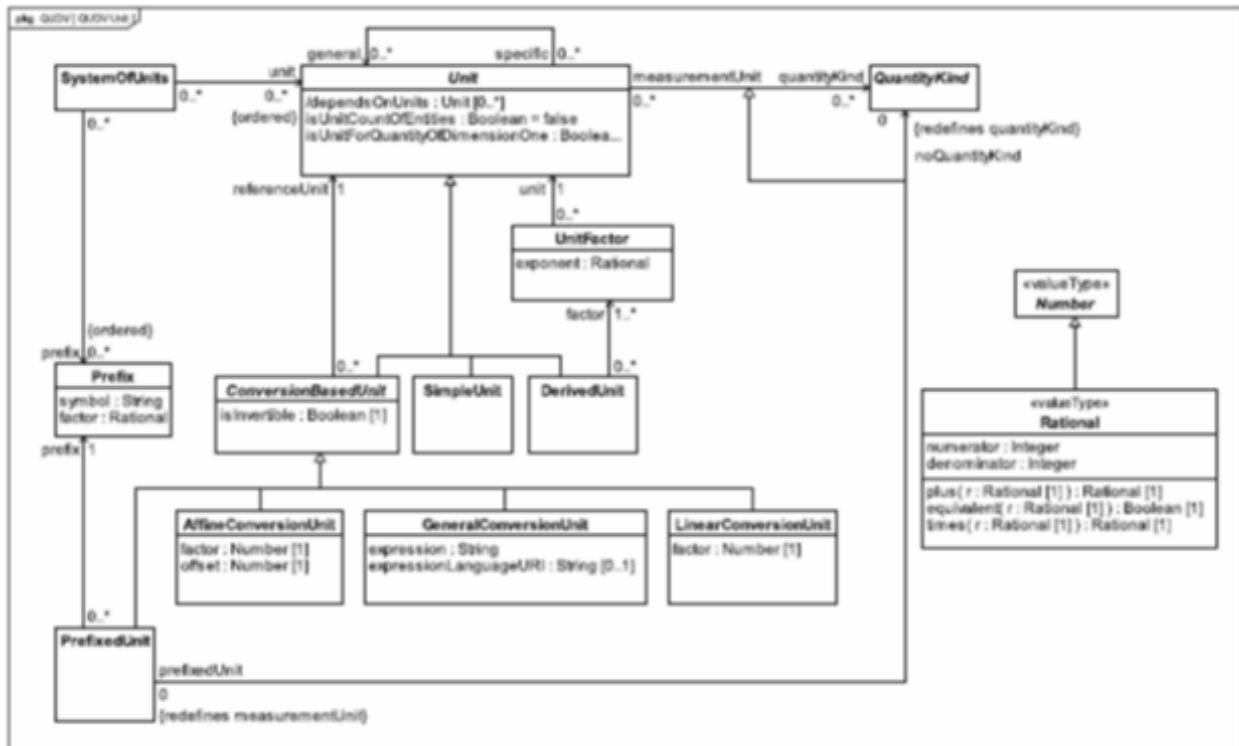


Figure 7: QUDV Units diagram

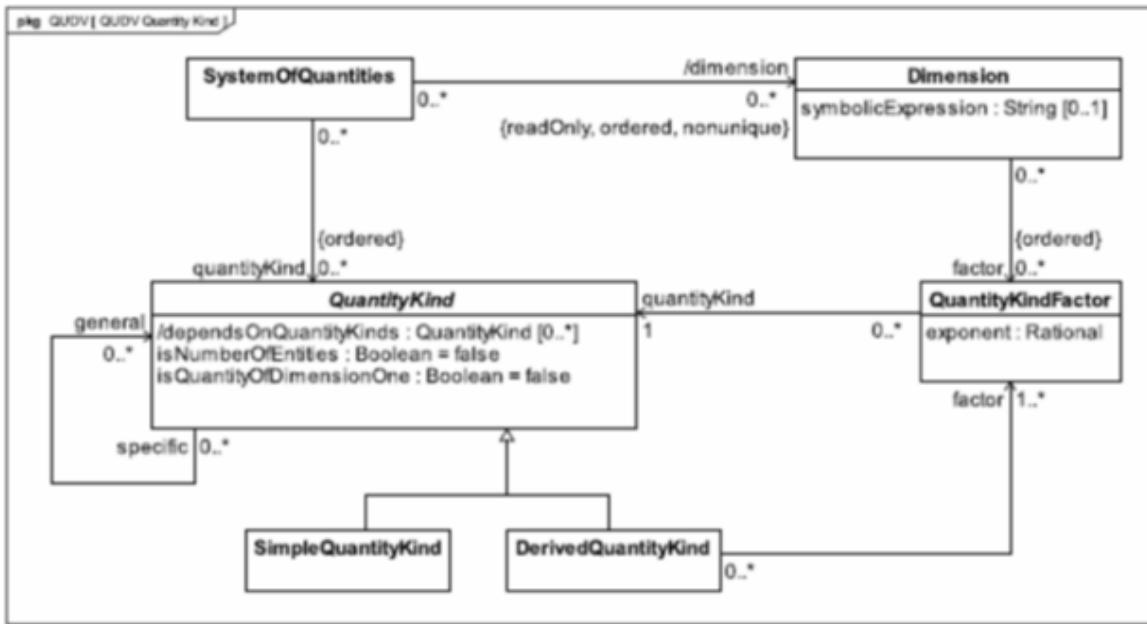


Figure 8: QUDV Quantity Kinds diagram

3.2 Type Definition

To define types, SysML introduces the *ValueType* concept as shown in Figure 9.

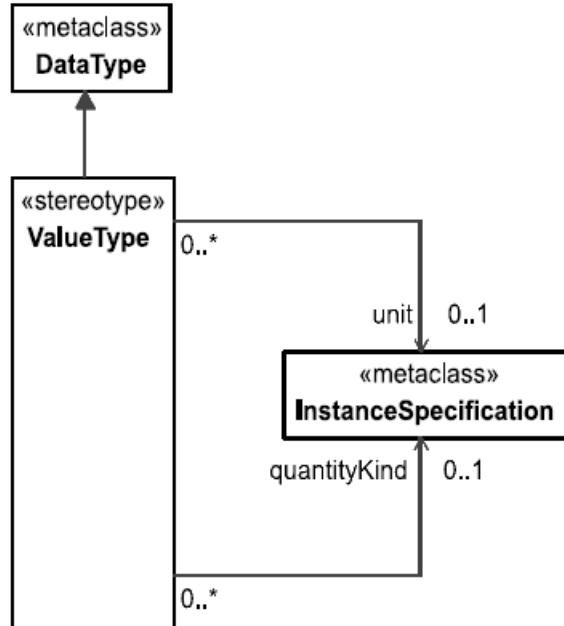


Figure 9: SysML ValueType definition

A *ValueType* is not used for architectural purposes but to assign a type to parameters or potentially other SysML block properties. For example, the SysML “Real” *ValueType* expresses the concept of a real number. The latter can be redefined in order to impose a concrete data representation. According to the definition above, *ValueType* might be associated to a *Unit* and a *QuantityKind* (cf. Section 3.1)

A *ValueType* is described by:

- a name,
- a unit which references an existing *Unit*,
- a quantityKind (reference to an existing *QuantityKind*) representing the meaning of the unit.

Figure 10 shows how four - respectively named “s”, “kg”, “m”, and “N” - of the seven SI units can be defined by using the SysML *ValueType* concept. All of them are “Real” by extending the “Real” *ValueType* and their *units* are “second”, “kilogram”, “meter”, and “newton”.

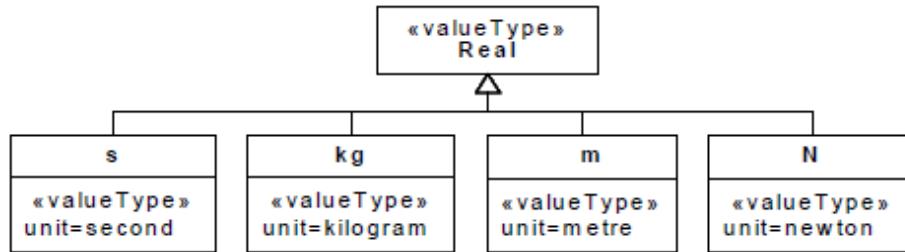


Figure 10: Example of *ValueType* usage

3.3 Libraries

The SysML standard defines one library named “PrimitiveValueType”. It is depicted in Figure 11.

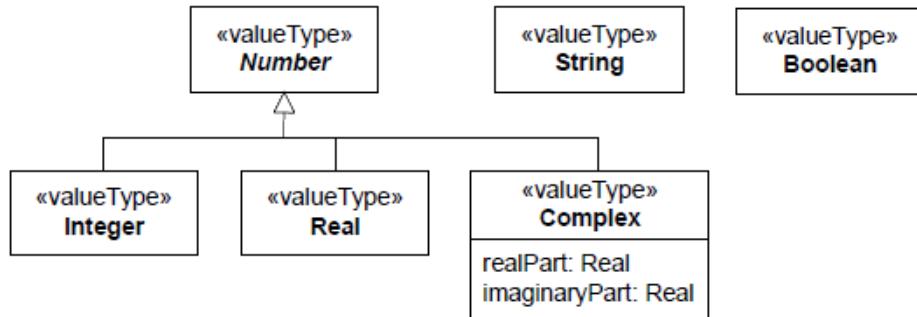


Figure 11: SysML PrimitiveValueType library

The latter is composed of six *ValueTypes* respectively name “Number”, “String”, “Boolean”, “Integer”, “Real”, and “Complex”. The SysML standard provides a modelling example of SI definition (cf. Figure 12).

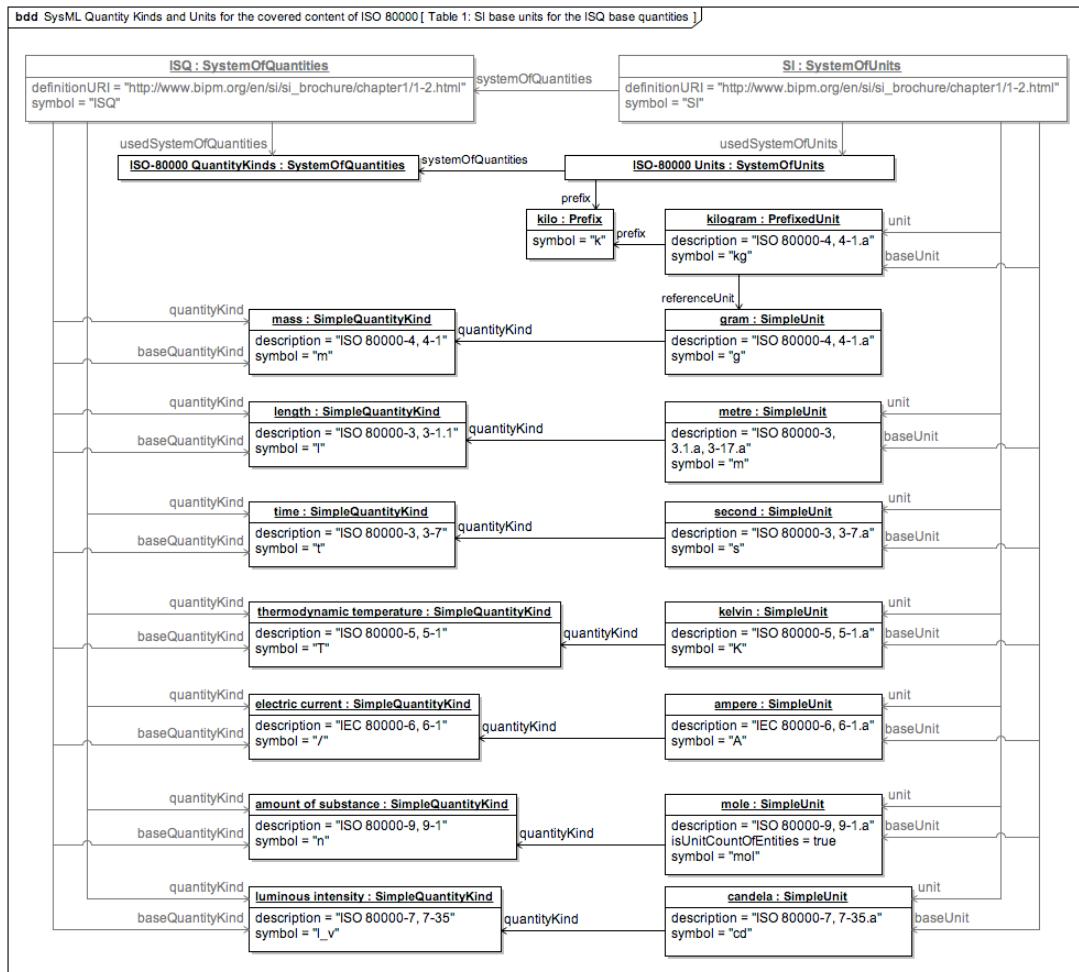


Figure 12: Some of the SI base units model by using SysML Unit and QuantityKind

3.4 Equivalence

To check if a connection is well defined, SysML inspects the inheritance graph of each connected type.

Figure 13 and Figure 14 show how a Radiator, a Water Heater, and a Water Distiller are connected through ports and connectors.

In this example, the Radiator has an input port of type Distilled Water which is connected to the output port of type Water for the Water Heater. The connection is valid because Figure 14 also specifies that the item coming through the connection is Distilled Water.

The second connection existing between the *Water Heater* and the *Water Distiller* is also valid although it is less intuitive. The *Water Heater* has as an input port of type *Water* and the *Water Distiller* as an output port of type *DistilledWater*. The connection between them is valid because *DistilledWater* is a sub type of *Water*. The unintuitive thing here that the conveyed Element, i.e. *Fluid*, does not need to be more specific.

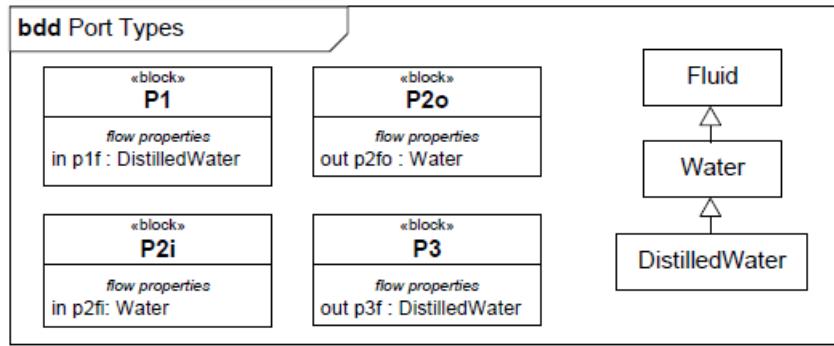


Figure 13: SysML Flow Type Definitions

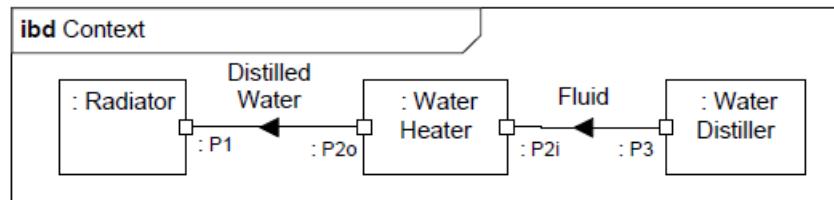


Figure 14: SysML Flow connections

4 INTO-CPS SysML Profile

During Year 3, the INTO-CPS SysML Profile and related mechanisms have been updated to handle the Unit and Structured Type Definition. This has been done by improving the INTO-CPS SysML profile itself for a better Unit specification as described in Section 4.1. Concerning the specification of Structured Type, the INTO-CPS SysML profile has not evolved but the corresponding FMI mapping and the related constraints have evolved.

4.1 Unit Definition

At the end of Year 1, the INTO-CPS SysML profile was able to specify *PrimitiveType* (*PType*), *DerivedType* (*DType*) and *Unit* as depicted in Figure 15.

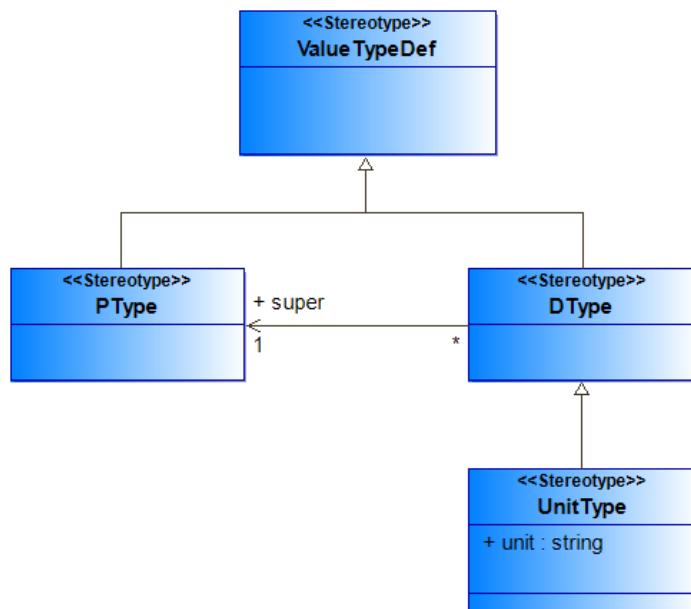


Figure 15: PType, DType, and UnitType definitions after Year 1

All relevant concepts were already in place but some relations and properties were missing for the *Unit* definition. In particular, a *DType* or a *UnitType* was only able to redefine *PType*. In addition, a *Unit* was not able to redefine another *UnitType* and it was not possible to specify how this redefinition might be done. In Year 3, the relations between these three concepts have been redefined as depicted in Figure 16. Now, *DType* and *UnitType* are sub types of *PType* and by keeping the “super” relation, INTO-CPS SysML profile now allows a *UnitType* to redefine another *UnitType*. This redefinition now has two attributes, respectively named *factor* and *offset*. So, the redefinition of *UnitType* *U1* by another *UnitType* *U2* can be described by the following formulae:

$$\text{Value_u1} = \text{factor_u2} * \text{Value_U2} + \text{offset_u2}$$

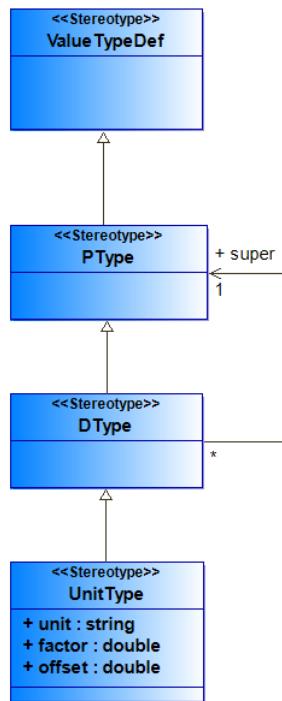


Figure 16: PType, DType, and UnitType definitions at Year 3

We can also use this mechanism to redefine specific *PrimitiveType* (*PType*) as custom *DerivedType* (*Dtype*) for clarification purpose, for example. Figure 17 shows the specification of the Real32 and Real64 *DTypes*, which represent Real encoded respectively on 32Bit or 64Bit.

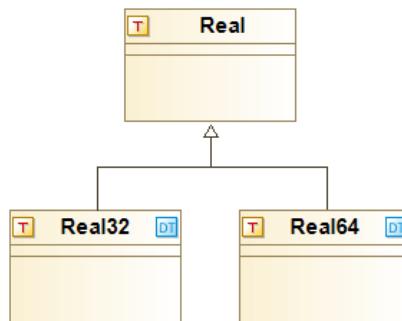


Figure 17: Dtype Modelling Example

Figure 18 depicts the XML representation inside a FMI modelDescription of the previous figure.

```

<TypeDefinitions>
  <SimpleType name="Real32">
    <Real/>
  </SimpleType>
  <SimpleType name="Real64">
    <Real/>
  </SimpleType>
</TypeDefinitions>
  
```

Figure 18: FMI Simple Type Example

Of course, the *UnitType* concept aims to represent physical units, such as Kilogram, Volt, and derived quantities. During Year 3, the primitive type library defined during Year 1 have been enriched by SI units and all derived units. Figure 19 and Figure 20 show how the Degree Celsius has been defined by using the INTO-CPS SysML profile.

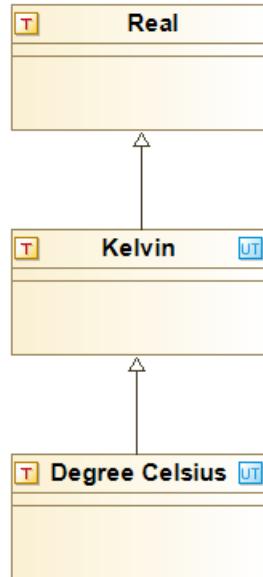


Figure 19: UnitType modelling example

INTO-CPS

Property	Value
Name	Degree Celsius
Super	Kelvin
Unit	C
Factor	1
Offset	-273,15

Figure 20: UnitType property example

The following figure depicts the XML representation inside a FMI modelDescription of the previous “Degree Celsius” model.

```

<UnitDefinitions>
  <Unit name="C">
    <BaseUnit k="1" factor="1" offset="-273.15"/>
  </Unit>
</UnitDefinitions>
  
```

Figure 21: FMI Unit example

Appendix C lists the libraries defined and provided by the INTO-CPS SysML profile. The units composing these libraries have been defined by using the previously introduced mechanisms.

4.2 Structured Type Definition

StructuredType (StrtType) was already defined at the end of Year 1 of the INTO-CPS project. During the following 2 years of the project, this concept, depicted in Figure 22, has not been changed or updated.

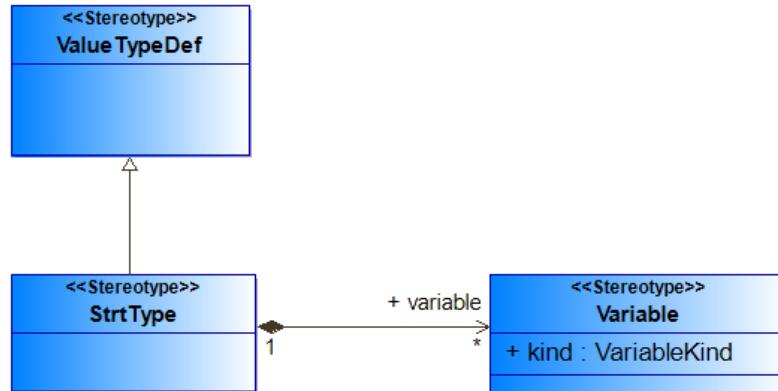


Figure 22: StrtType Definition

Figure 23 illustrates the typical modelling of an *EComponent* made at the end of Year 2. The depicted Controller has four input ports, respectively named pos.x, pos.y, pos.z, and pos.theta, which represent a 3D coordinate and an angle provided by sensors.

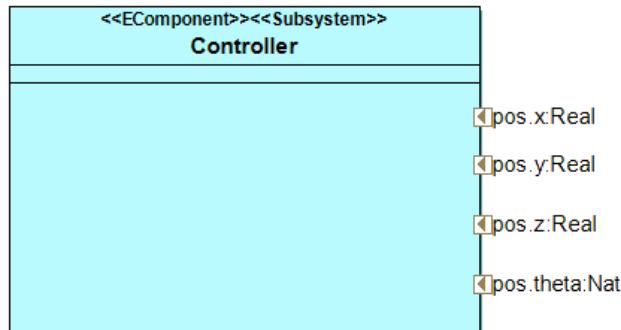


Figure 23: Controller FMI modelling at Year 1

Suppose that all the data is provided by one unique sensor of type SpaSensor. Figure 24 shows a Connections Diagram (CD) defining connections between an instance 'c' of the Controller and an instance 'spaS' of the SpaSensor. In this diagram the fact that all four connections convey Real or Nat data can be omitted because it does not provide any additional values as input and output ports are already typed as Real or Nat ports. The fact that four connections are present could also be simplified into one unique connection.

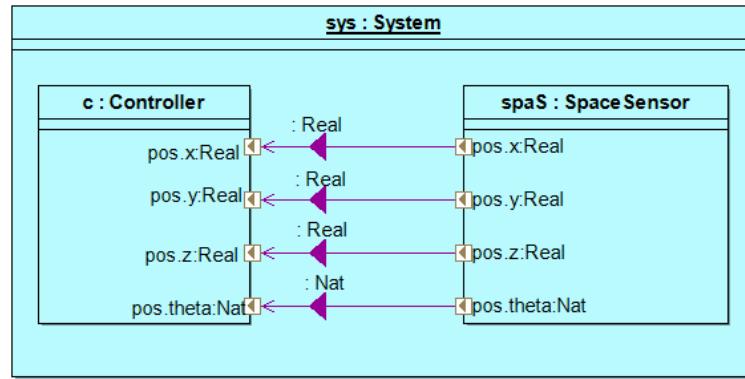


Figure 24: Connections modelling at Year 1

The concept of *StructuredType* can help to clarify the system architecture. So during Year 3, *StructuredType* usage was encouraged by how the tool implements them and by some examples. Figure 25 and Figure 26 represent the same modelling as Figure 23 and Figure 24 but using *StructuredType* instead of *PrimitiveType* only. Figure 25 introduces two *StrtTypes* respectively named “3D position” and “Relative 3D position”. A “3D position” is defined by three *Real* attributes “x”, “y”, and “z”. A “Relative 3D position” is a “3D position” with an additional parameter named “theta” of type *Nat*. The four previous input ports defined at the Controller level are now replaced by one unique port.

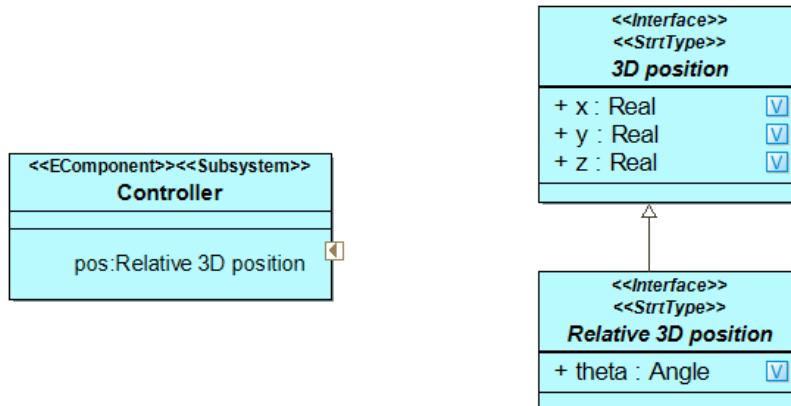


Figure 25: Controller FMI modelling at Year 3

Ports are also defined in the same way for the SpaSensor. As shown in Figure 26, the connections are simplified. Only one unique connection remains and the conveyed Data is omitted.

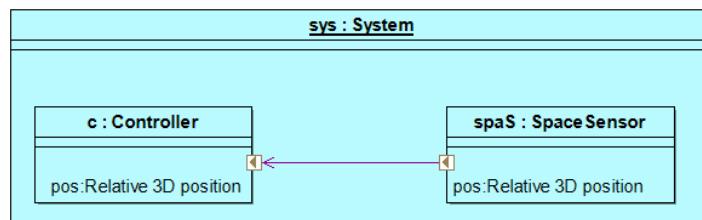


Figure 26: Connections modelling at Year 3

4.3 Equivalence

The main drawback of using the *StructuredType* is related to the Co-Simulation configuration generation as described in Deliverable D4.3a. Having all these connections between atomic ports confuses the modelling but facilitates the FMI modelDescription generation. If two atomic ports are connected, as depicted in Figure 24, the generation only needs to check if the port types are the same. When it comes to *StructuredType*, the generation needs to be able to validate the equivalence. Figure 27 shows the definition of four *EComponents*, respectively named “Controller”, “3DSensor”, “AngleSensor”, and “SpaceSensor”. They all provided one input or output port type by one of *StrtType* defined in Figure 25.

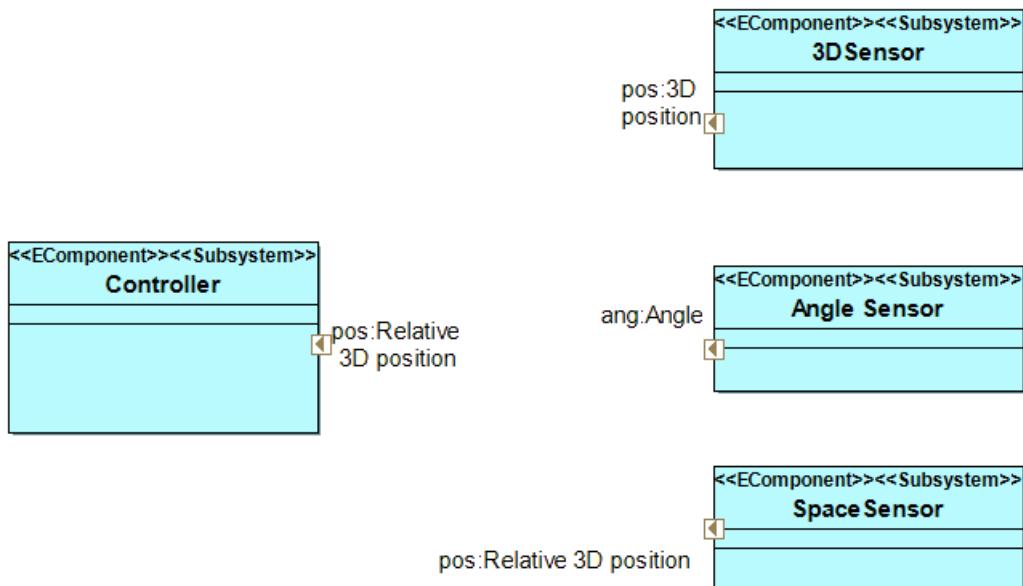


Figure 27: EComponent modelling example

Figure 28 illustrates the fact that data can be provided by more than one *EComponent*.

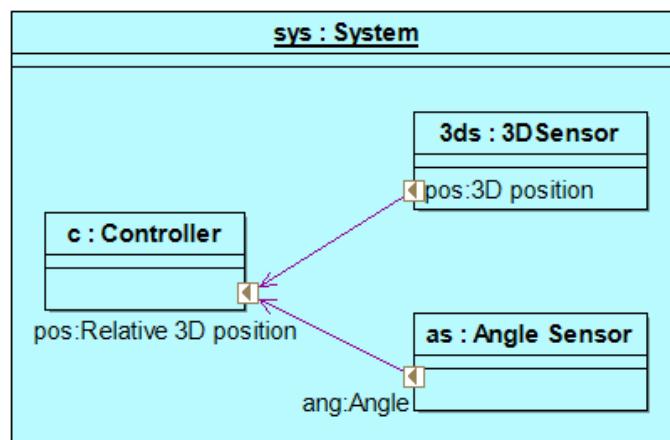


Figure 28: Multiple connection example

In contrast, the connection depicted in Figure 29 is possible because both port have the same type but the data effectively conveyed is less than specified. In this case of only a “3Dposition” data goes through the ports. The “Angle” is not provided.

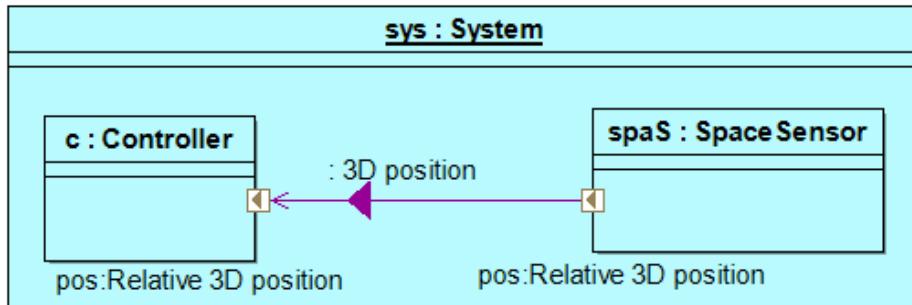


Figure 29: Partial connection example

Matching between attributes is established by checking the types definition and inheritance or in the worst case, the attribute names.

5 Conclusion and Future Work

During the 3 years of INTO-CPS Project, INTO-CPS – the SysML Profile has been defined to mainly provide a standard and graphical interface for FMI co-simulation (including for DS). In parallel, the INTO-CPS Tool chain, including the INTO-CPS Application and COE, have evolved. Some of these improvements are handled by the actual INTO-CPS SysML profile but not all of them. The latest improvement made, and which is relevant for the INTO-CPS SysML scope, concerns the ability to have nested co-simulation. During Year 3 works have been carried out on the COE to allow nested co-simulation i.e. co-simulation inside a co-simulation. The configuration of such nested co-simulation would be easier by using the graphical interface of a SysML Tool.

6 References

- [1] Softeam. Modelio Open-Source Modelling Environment. <http://www.modelio.org/>. 2014.
- [2] Object Management Group (OMG). Unified Modeling Language 2.5. Available: <http://www.omg.org/spec/UML/2.5/>. 2011.
- [3] Object Management Group (OMG). System Modeling Language specification v1.4. Available: <http://www.omg.org/spec/SysML/1.4/>. 2015.

Appencides

A. List of Acronyms

ASD	Architectural Structure Diagram
CD	Connection Diagram
CPS	Cyber-Physical System
DSE	Design Space Exploration
FMI	Functional Mockup Interface
MDE	Model Driven Engineering
SysML	Systems Modeling Language
UML	Unified Modelling Language
XMI	XML Metadata Interexchange
XML	eXtensible Markup Language

B. Unit libraries

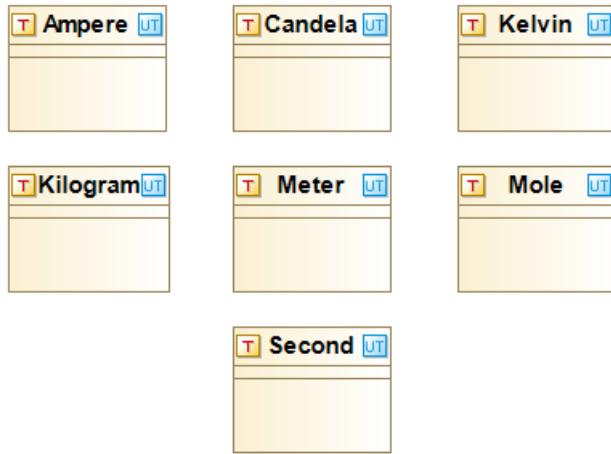


Figure 30: INTOCPS SysML SI Unit

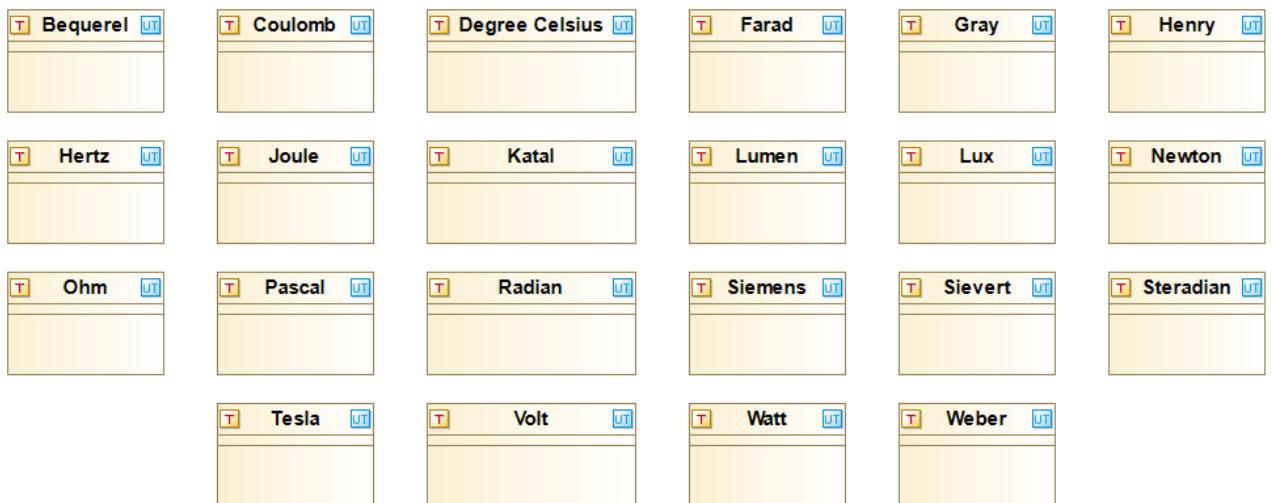


Figure 31: INTOCPS SI Derived Units

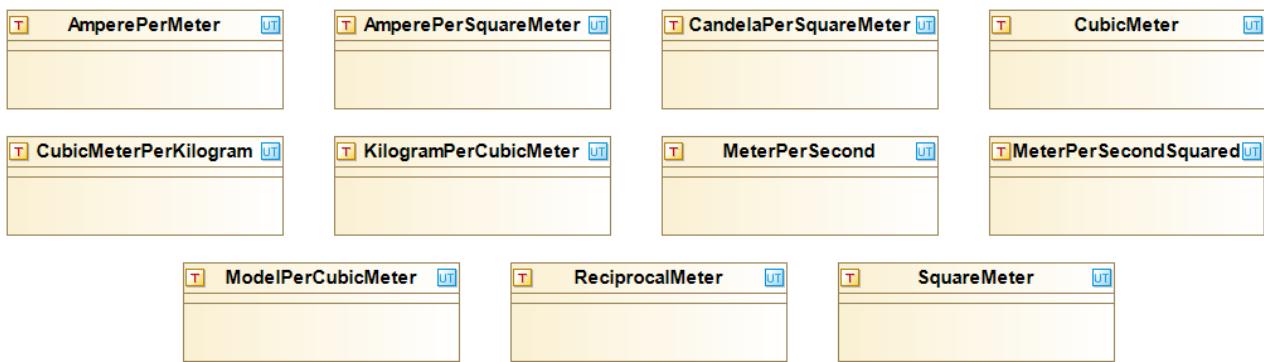


Figure 32: INTOCPS SI Derived Units

C. INTOCPS SysML Profile in XMI format

```

<?xml version="1.0" encoding="UTF-8"?><uml:Profile xmlns:uml="http://www.omg.org/spec/UML/20090901"
xmlns:xmi="http://schema.omg.org/spec/XMI/2.1" xmi:version="2.1" xmi:id="_w0OtUMFHEea9lqxQKxvTJw" name="INTOCPS">
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