Sim-Diasca Dataflow HOWTO

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Creation Date: Thursday, February 25, 2016

Lastly updated: Thursday, September 28, 2023

Version: 2.4.6

Status: Stable

Website: http://sim-diasca.com

Dedication: For the implementers for Sim-Diasca dataflow-based models.

Abstract: This document describes how dataflows, i.e. data-driven graphs of blocks, are to be defined and evaluated in the Sim-Diasca simulations relying on them.

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1 Foreword

The simulation of complex systems often relies on loosely-coupled agents exchanging signals based on a dynamic, potentially complex applicative protocol over a very flexible scheduling.

However, in some cases, the modelling activity results alternatively in the computations being at least partly described as *a static network of interconnected tasks that can send values to each other over channels* that applies to a simulated world - i.e. a **dataflow**.

Both approaches will be detailed and contrasted below, before focusing on how dataflows can be defined and used with Sim-Diasca.

> **Note**
>
> Most of the dataflow-related concepts mentioned in this document are illustrated on a **complete, runnable simulation case**: the `Dataflow Urban Example`, whose sources are located in the `mock-simulators/dataflow-urban-example` directory of the standard Sim-Diasca distribution.
> Besides these case-specific elements, the sources of the **generic dataflow infrastructure** are also available, in the `sim-diasca/src/core/src/dataflow` directory.
> Please feel free to skim in these respective sources for a better practical understanding of the dataflow infrastructure.

2 Usual Organization of the Model Evaluation

In most simulations of complex systems, the simulated world is sufficiently **disaggregated into numerous autonomous model instances** (be they named agents or actors) so that **the evaluation of their respective behaviours and interactions naturally leads to processing the simulation**. In this context, trying to constrain or even hard-code static sequences of events is often neither possible nor desirable.

For example, one can see a city as a set of buildings, roads, people, etc., each with its own state and behaviour, the overall city (including its districts, precincts, etc.) being the byproduct of their varied interactions - a possibly hierarchical, certainly *emergent* organisation.

This approach is probably the most commonly used when modelling a complex system, hence it is the one natively supported by Sim-Diasca: the target system is meant to be described as a (potentially large) collection of model instances (a.k.a. actors) possibly affected by scenarios and, provided that their respective state and behaviour have been adequately modelled, the engine is able to evaluate them in the course of the simulation, concurrently, while actors feed the probes that are needed in order to generate the intended results.

The (engine-synchronised) interactions between actors are at the very core of these simulations, which are determined by how actors get to know each other, exchange information, opt for a course of action, create or destroy others and, more generally, interact through an **implicit overall applicative protocol resulting from the superposition of their individual, respective behaviours**.

However other, quite different, organisational schemes can be devised, including the one discussed in this section, the **dataflow** paradigm.

3 An Alternate Mode of Operation: the Dataflow

Let's define first what is a dataflow.

> **Note**
> A dataflow is a way of describing a set of interdependent processings whose evaluation is driven by the availability of the data they are to handle.

In this more constrained organisation, rather than having actors freely exchanging various symbols and messages according to dynamically-decided patterns, we rely here on quite specialised actors that embody *dataflow blocks*, which are:

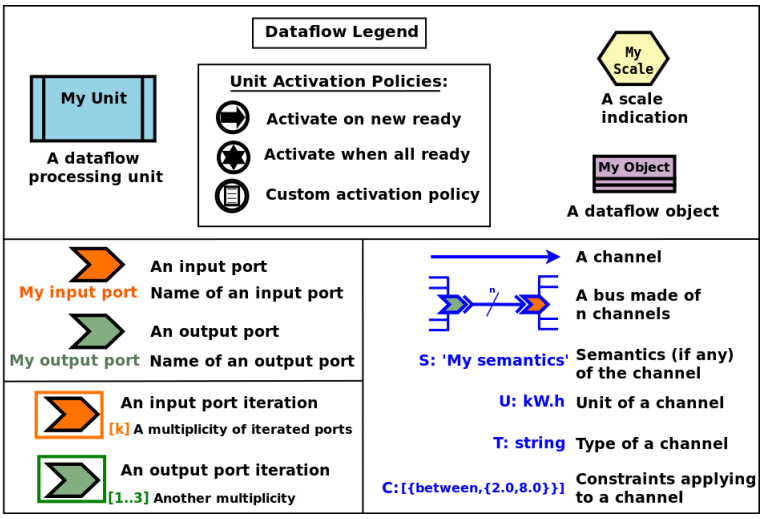
- either *dataflow processing units* (instances of the `DataflowProcessingUnit` class), which set and listen for *values*, through *channels* that are delimited each by an *input port* and an *output port*, and perform associated computations
- or *dataflow objects* (instances of the `DataflowObject` class) that stores *attributes* that can be set and read respectively thanks to their associated input and output ports

All these dataflow blocks and the channels linking them form altogether a graph (whose nodes are the blocks, and whose edges are the channels). This graph is by default:

- **statically defined**: its structure can be established before the simulation starts
- **static**: in the general case, its structure is not expected to change in the course of the simulation
- **directed**: channels are unidirectional, only from an output port of a block to an input port of a block
- **acyclic**: by following the declared (directed) channels, no path should go through the same block more than once

The graph can be explicit or not: either it is described as a whole (as a single, standalone entity), or it can be merely extrapolated from the union of the channels drawn between the declared blocks.

Dataflows of course have an immediate graphical counterpart. The conventional symbols we elected are represented in this key:



By convention, input ports are in orange, output ports in green, dataflow objects in light purple, dataflow units (ex: processing or mock-up ones) are in light blue and comprise the symbol of their activation policy, and channels are in various shades of blue[1].

Still in blue, the SUTC quadruplet:

- the channel *Semantics* (i.e. the meaning of the conveyed values) can be specified, as an arbitrary domain-specific symbol prefixed with `"S:"` (like in `"S: 'produced heat'"`); project conventions may apply, notably in order to adopt the RDF format, like in:

  `S:'http://foobar.org/urban/1.1/energy/demand'`

- the *Unit* of the value, prefixed with `"U:"` (ex: `"U: kW.h"`, or `"U: g/Gmol.s^-2"`); often the unit information implies a type (described in next point): for example the unit `"U: W"` implies the type `"T: float"`; in this case the type information can be safely omitted

- the *Type* of the values conveyed by the channel, prefixed with `"T:"` (ex: `"T: string"` or `"T: {integer,boolean}"`)

- the *Constraints* (if any) applying to the exchanged value, as a list of elementary constraints (ex: `"C: [ {between,{2.0,8.0}} ]"` means that a single constraint applies to the exchanged values, which is that they must be between 2 and 8)

These SUTC information shall preferably be specified close to the associated channel (if any) or output port.

Unit activation, semantics, units, types and constraints are discussed more in-depth later in this document.

Specifying the names of dataflow units and ports is mandatory.

As a processing unit is in charge of *performing* a specific task included in a more general computation graph (the dataflow), its name shall reflect that;

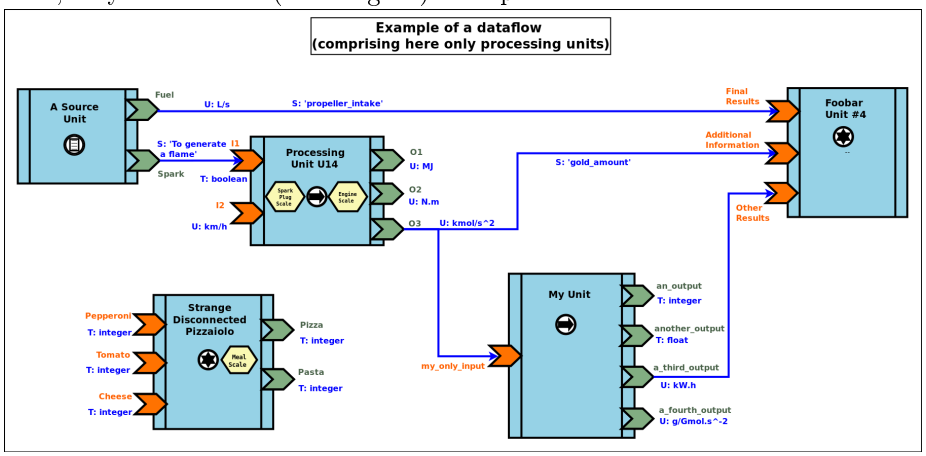
[1] Please refer to Annex 3: Conventions for the Graphical Representation of Dataflows for more information.

one may consider that the name of such a unit is implicitly prefixed with a verb like `compute_`. For example, a processing unit named `fuel_intake` could be understood as `compute_fuel_intake` (and we expect it to have at least one output port dealing with fuel intake).

Finally, as some dataflow units have for purpose to aggregate metrics across time and/or space, some scale indication may be given for documentation purposes, enclosed in an hexagon in pale yellow.

The dataflow objects are specifically discussed in a section of their own later in this document.

As a result, a dataflow, which shall be interpreted as **a graph of computations**, may look as this (meaningless) example:



We can see that a dataflow does not need to be fully connected (the blocks may form disjoint subgraphs) and that ports (input and output ones alike) may not be connected either.

The global progress of the computations happens here from left to right.

A more complete example is given later in this document.

Now let's detail a bit all the elements involved.

4 On Dataflows & Experiments

4.1 Dataflow Definition

As mentioned, a dataflow is a *graph of computations whose evaluation is driven by the availability of the data they are to handle.*

In practice, it is a set of interlinked dataflow blocks, typically dataflow processing units and dataflow objects.

Even though dataflows could remain only implicit data-structures (they would just correspond to an actual set of interlinked dataflow elements), we preferred introducing an actual **dataflow class**, in order to ease the interaction with such instances and provide a reference point.

So overall operations on a given dataflow (ex: creations, modifications, report inquiries) shall be operated only through its corresponding federating `class_Dataflow` instance.

Multiple dataflow instances may exist, and they are collectively managed by the overall experiment manager, introduced later in this document.

4.2 Experiment Definition

An experiment corresponds to the overall evaluation task that is to be performed by a (here: dataflow-based) simulation, as it is described by the corresponding simulation case.

For that such an experiment aggregates any number of dataflows, which progress in parallel, typically through a series of steps[2].

During each step, each dataflow instance, based on any update of its input ports, is fully evaluated (i.e. until it reaches a fully stable state).

More in-depth information can be found in the Experiments section.

5 On Dataflow Processing Units

A (processing) unit is, with dataflow objects, the most common type of dataflow block.

A dataflow unit encapsulates a *kind of computation*. For example, if an energy demand has to be computed in a dataflow, an `EnergyDemandUnit` processing unit can be defined.

Such a unit is a *type*, in the sense that it is an abstract blueprint that shall be instantiated in order to rely on actual units to perform the expected computations. Therefore, in our example, a `class_EnergyDemandUnit` processing unit shall be defined (specified and implemented), so that we can obtain various unit instances out of it in order to populate our dataflow.

As discussed in the next section, each of the instances of a given dataflow unit defines input and output ports.

[2] In engine-related terms, an experiment step of the dataflow infrastructure corresponds to a simulation tick of the engine. During such a step, dataflows are evaluated over diascas, resulting on their elements exchanging values, until none of the output port is set anymore. Then the next step (tick) can be evaluated, etc.

Note

It shall be noted that, additionally, each processing unit instance benefits from a **state** of its own (that it may or may not use): the attributes that the unit class introduced are available in order to implement any memory needed by the unit, and of course these attributes will retain their values through the whole lifetime of that instance (hence through simulation ticks and diascas).
So a unit may encapsulate any processing between a pure, stateless function to a more autonomous, stateful, agent.

6 On Dataflow Ports, Channels and Buses

A port is the only way by which a dataflow block (typically a unit) may interact (propagate a value) with other blocks.

Following rules apply:

- a port is either an **input** one (listening to the update of a value conveyed by the corresponding channel) or an **output** one (able to update its corresponding value and notify its registered input listeners); this is reflected by their type (either `input_port` or `output_port`)
- each port is **named** (as a non-empty string[3], ex: `"my foobar port"`) and no two input ports of a block can bear the same name, nor output ones can (however an input port and an output port of the same block *can* have the same name - they will be differentiated by their nature)
- a **port identifier** is defined from a pair made of an identifier of the block that defined it and from the name of that port[4] (ex: it could be `("My Unit","Port 24")`, or based on more technical identifiers)
- a port (input or output) may either hold a value (arbitrary data can be set; the port is then considered as ready, i.e. as `set`), or not - in which case it holds the `unset` symbol (the port is then itself considered as `unset`)
- an **output** port can be considered as being always unset: as soon as a new value is available, it notifies all its connected input ports and then reverts back to the unset status; therefore the set/unset status can be abstracted out for output ports, which just get punctually activated
- conversely, this status matters for **input** ports: a block starts with all its input ports to `unset`, and, each time an input port is notified by an output port, this input port switches to `set`; how a block is to react depending on none, one, some or all of its input ports being set is discussed below
- an **output port will send downstream the value it holds** whenever:
  - it gets **set**: exactly one sending will be performed per setting (regardless of the value that is set) to each of the input ports it is linked to; as a result, setting explicitly a port to a value that happens to be the same as the one that it was already holding will nevertheless trigger a sending (therefore "not setting a value" vs "setting the current value again" are operations that differ semantically)

  - it gets **connected** (i.e. a channel is created from this output port to an input port) *whereas this output port has already been set at least once in the past*; then, on channel creation, the latest value it sent will be re-emitted, only to the newly connected input port

- ports can convey arbitrary data (i.e. any Erlang term), yet any given port has a **type**, which defines what are the licit the values that it can hold (ex: "this port can be set to any pair of non-negative floats")[5]
- **a block can declare any number of output ports** (possibly none, in which case it is an *exit block*, a sink)
- **a block can declare any number of input ports** (possibly none, in which case it is an *entry block*, a source)
- **a channel links exactly one output port to one input port**, and these two ports shall have the same types, units and semantics (which are the ones of the channel)
- **any number of channels may originate from an output port** (possibly none); when an output port is being set (i.e. when it performs a punctual transition from `unset` to `set`), then all the input ports listening to it are notified of that[6]
- **an input port may be the target of up to one channel**; if no channel feeds a port, then it remains in the `unset` state
- a port records the timestamp (in simulation time) of the last notification (possibly `none`) it either sent (for output ports) or received (for input ones)
- a **bus** corresponds to a set of channels ; it shall be seen, at least currently, only as a graphical convention introduced in order to avoid that too many parallel channels are drawn, which would obfuscate the representation of a dataflow (note that no bus per se is considered when evaluating the dataflow; the runtime is only aware of ports being connected to others, so buses - and even channels - are abstracted out)

Even if conceptually it is sufficient that only the output port knows the input ports it may notify (and not the other way round), technically the input ports also know the (single, if any) output port that may notify them, for example for a simpler support of unsubscribing schemes.

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[3] The only restriction is that the `"_iterated_"` substring cannot exist in a user-defined port name (so for example `"foo_iterated_bar_42"` will be rejected by the dataflow infrastructure).

[4] A port identifier is typed as `-type port_id() :: {dataflow_object_pid(),port_name()}.` where `dataflow_object_pid()` is a PID (the one of the block) and `port_name()` is a binary string.

[5] The dataflow system may or may not check that typing information.

[6] Indeed the `onInputPortSet/3` actor oneway of their respective block is executed, specifying the port identifier of the triggered input port and the corresponding timestamped value (specifying the tick and diasca of the notification). Generally this information is not of interest for the block implementer, as defining for example a unit activation policy allows to handle automatically input ports being triggered.

7 On Dataflow Values

We saw that a value designates **a piece of data carried by a channel**, from an output port to any number of input ports.

Various information are associated to the output ports and to the values they carry (they are metadata), notably the `SUTC` quadruplet (for *Semantics-Units-Type-Constraints*), which the next sections detail in turn, yet in a different order for the sake of clarity - roughly from the most concrete to the highest-level.

7.1 Type of a Value

7.1.1 Type Basics

A channel is **typed**, in the sense that all the values that it conveys shall be of the same type (in terms of programming language; ex: a floating-point value), which is the one specified for the channel. The `T` in `SUTC` stands for this *type* information.

The *name* of a type must be a series of alphanumerical characters, in lowercase, starting with an alphabetical one, and possibly containing underscore (`_`) characters; example of a type name: `integer` or `this_is_my_type_name_221`.

The complete type specification in a dataflow (typically used to describe a port) shall be prefixed with `"T:"` (for example `"T: integer"` would mean that the corresponding port handles values of type `integer`).

In the absence of *unit* information (see next section), the *type* information is mandatory and must be specified by both port endpoints. It may or may not be checked, at build and/or run time.

> **Note**
>
> The specified typing information is currently *not* used: as a consequence, the values conveyed by the dataflow are *not* yet checked against their declared type.

A set of *built-in* and *derived* types is provided, and many port specifications rely directly on them in order to define simple, scalar, atomic values (often floating-point ones) - as opposed to compound ones. Specifications may also define and use any additional type that they may need.

Moreover, if deemed useful, more complex data structures may be specified, based on *polymorphic* types like tuples (denoted as `{}`), on lists (denoted as `[]`) or even, in the future, on associative tables.

All these constructs enable the specification of all the typing information needed by the user in order to describe, in computing terms, the values exchanged over the dataflow.

Let's discuss the basic typing primitives first, i.e. the built-in types.

7.1.2 Built-in Types

Following **built-in types** are available (they map to Erlang native types; some related technical details put between parentheses or in footnotes may be safely ignored by the reader):

Name of the built-in type	Description	Example value
`integer`	Any (unbounded; positive or negative) integer value.	`-112`
`float`	Any floating-point value (in double precision).	`3.14159`
`number`	Any number (either an integer or a float)[7].	`1.1`
`string`	Any series of characters delimited by double quotes[8].	`"Hello world!"`
`boolean`	Either `'true'` or `'false'`.	`'true'`
`count`	A non-negative integer, to mention a number of elements (possibly zero).	`17`
`percent`	A floating-point percentage (alias of `float`), the value `1.0` corresponding to 100%.	`-1.4`
`json_content`	An opaque, stringified JSON representation of a value.	(undisclosed, as meant to be opaque)
`any`	Wildcard type, corresponding to any type (no information given, hence no type checking can be performed in this case).	`"I am a value."`

Note

Indiscriminate use of the `any` type is strictly prohibited; typically it should *never* be used operationally (ex: when defining actual ports), as it would then be a way of bypassing the type system.
For advanced users: the main use of `any` lies in the very specific context of "polymorphic units", i.e. units that may be able to process values of all kinds of types.

7.1.3 Derived Types

These types are not built-in, they are to be specifically derived (possibly by the user directly) from other types (which themselves may be built-in or derived).

7.1.3.1 Type Definition Often, a new type definition has to be used in several occurrences (ex: when having different ports that happen to rely on the same type). Rather than repeating the same type definition each time, we recommend that, as soon as a type definition is used more than once for the

[7] Note that some types overlap, notably some of them are special cases of others, like integers and numbers. So, for a given value, multiple type specifications apply (ex: `any` will always match).

[8] Mapped as an Erlang binary string, displayed as a basic string.

same purpose, a (derived) type is defined from it and named one time for all - and then referred to as often as needed.

Indeed, being (new) types, derived types have their own name (ex: `my_own_type`), knowing that the names of all built-in types are reserved.

So, in order to define a derived type named `my_own_type` according to any kind of definition (designated here by `A_TYPE_DEFINITION`), the following syntax shall be used:

```
my_own_type :: A_TYPE_DEFINITION
```

For example, if various ports had to handle a number of vehicles, then it may be advisable to introduce a specific type for this purpose, which could be named `vehicle_count`.

In this case, this derived type would happen to be simply a synonym of the `integer` built-in type (the `vehicle_count` type would then be here an *alias* a the `integer` built-in one):

```
vehicle_count :: integer
```

Then, this new type being defined, ports may use it and specify that they handle channel values of that type, thanks to `T: vehicle_count`.

7.1.3.2 Type Constructs Aliases are of course useful, yet one may have to specify types that are more complex than exact synonyms of the built-in types.

For that, the user can rely on following type constructs, which allow introducing new types, or combinations thereof:

- *union types*, i.e. types that regroup other types and whose values can be of either one of these types
  - in the specification of such an union type, the listed types are separated by the pipe (`|`) character, representing the OR operator
  - for example, the union of types T1, T2 and T3 is: `T1|T2|T3`; the aforementioned `number` built-in type can be defined as: `integer|float`
- *symbol types*, each of which being a simple label (a non-empty series of characters delimited by single quotes), like `'my_symbol'` or `'Red Alert'`; a symbol is both a type and a value, in the sense that defining a symbol is defining a type which happens to have a single value (itself)[9]; moreover type names are themselves symbols (without their single quotes); so defining `my_type` as, for example, `integer`, corresponds to the definition of an alias type, a synonym of integer which can be used in other type definitions (such as in `[my_type]`)
- *enumerated types* (a.k.a. enumerations) is a user-defined union of *symbols*, simply obtained from the two previous constructs; for example a `burner_status` enumeration type might be defined as:

```
'burner_enabled' | 'burner_disabled' | 'burner_on_operation'
```

and a value of that type (a symbol) may be, for example: `'burner_disabled'`

One can see that the `boolean` type is actually nothing but a `'true'|'false'` enumeration.

Defining a single-type enumeration corresponds to defining a symbol type.

7.1.4 Polymorphic Types

Finally, in addition to all the atomic types (built-in or derived) presented above, following built-in **polymorphic types** (types that depend on others) are supported as well:

- *list* of type `T`, noted as `list(T)` or `[T]`: any kind of (proper, homogeneous) list (empty or not), represented between square brackets, to account for a variable-size sequential container containing values of type `T`
  - ex: `list(integer)` and `[integer]` denote the same type, a list containing any number of integers; values of that type can thus be: `[4,-17]`, `[]`, etc.
  - `list()` refers to any kind of list (alias of `list(any)`)
- *tuple* containing elements of types T1, T2, T3, etc., noted as `{T1,T2,T3,...}`: any kind of tuple (fixed-size container, homogeneous or not), delimited by curly braces
  - ex: a value of the `{burner_status,float,[bool]}` type might be `{'burner_on_operation',14.7,['false','false']}`
  - `tuple(T)` refers to tuples whose elements are all of type `T`, and whose number is not specified (ex: `{2,46,5}` is of type `tuple(integer)`), while `tuple()` refers to any kind of tuple
- in later versions: *associative tables*, whose keys are of type `Tk` and values are of type `Tv`, noted as `table(Tk,Tv)`

Note that *recursive* types (ex: a type `tree` being defined as `{tree,tree,node_content}`), are, at least currently, not allowed (they can be expressed yet no specific support for them is provided).

7.1.5 Implementation-wise

The dataflow infrastructure includes a `TypeServer`, which tracks statically (i.e. on a per-class level) or dynamically (for any dynamically-created port) the type declarations and uses, to provide a first, very basic support for typing enforcement.

[9] Symbols are mapped to Erlang atoms.

7.2 Unit of a Value

A value of a given type (typically a float) can actually correspond to quantities as different as meters and kilowatts per hour.

Therefore **units shall preferably be specified alongside with values**, and a language to express these units must be retained. The `U` in `SUTC` stands for this *unit* information.

One should refer to the documentation of the `Myriad` layer[10] for a description of how units can be specified, compared, checked and used.

In a dataflow, the unit of the values that will be held by a port shall preferably be specified when declaring that port. This is done thanks to a string, prefixed with `"U:"` (ex: `"U: kW.h"`, `"U: g/Gmol.s^-2"` or `"U: {mm,mm,mm}"` for a 3D vector in millimeters).

Specifying the unit of a scalar value implies declaring its type as `float`.

If, for a value, no unit is given, then its type, as discussed in Type of a Value, shall be specified.

7.3 Semantics of a Value

Specifying the type and unit of a value is certainly useful, yet it would generally be insufficient to convey its *meaning*, i.e. to express how that value shall be interpreted.

For example, knowing that a port accepts floating-point values in kilojoules does not tell whether this value corresponds to an energy demand, an actual consumption or a production.

Therefore this domain-specific information shall be specified separately. It is to be done thanks to the specification of a symbol (similar to a string, corresponding to an Erlang atom), prefixed with `"S:"`, standing for **semantics** (which is the `S` in `SUTC`). For example: `"S: 'security credentials'"` or `"S: 'energy_demand'"`.

We recommend that semantics are specified according to a well-defined, standard format: RDF (standing for *Resource Description Framework*).

RDF statements (potentially expressed as RDF triples) about subjects (ex: a block or a port) clarify the intents (made them explicit and expressed in an uniform way) and may allow the use of tools able to perform queries and inference. This may enable, in the future, the automatic checking and even generation of proper dataflows.

Typically a port semantics is then a *subject* in RDF parlance, like in:

```
S:'http://foobar.org/urban/1.1/energy/demand'
```

where:

- the normalising organisation is designated by its domain name `foobar.org`
- it published a `urban` ontology, whose version in use here is `1.1`
- it addresses potentially multiple fields of interest, including the one of `energy`

[10] Please refer to the *Description of the Management of Units* section, in the technical manual of the Myriad layer (in `Ceylan-Myriad-Layer-technical-manual-english.pdf`).

- one sub-topic of which is the `demand` (of energy)

As a result, the full chain (the output port, the channels, the value itself and the related input ports) can perform a basic check of the semantic consistency for each exchange over the dataflow, and have an extra chance of detecting and rejecting any erroneous port connection (even if in technical terms, i.e. in terms of typing and unit, it may look perfectly legit).

Currently a minimum lexicographic distance (the Levenshtein one) is enforced (by the `SemanticServer` of the dataflow infrastructure) between any two semantic elements, so that any spelling mistake can be more easily detected.

Generally the channel is shown as bearing the semantics, implying that this formalised meaning is shared by the corresponding output port, the associated input ports and by the values that they exchange.

7.4 Constraints Applying to a Value

The `C` in `SUTC` stands for this *constraints* information.

They allow to specify a set of rules by which the value must abide.

> **Note**
>
> Unlike most of the other meta-data (ex: semantics or type), constraints are not considered as being intrinsic to a value; they are generally seen as a property (on values) that is enforced at the port level.

The following constraints can be mixed and matched:

- `{greater_than,G}` means that the (scalar) value must be greater than, or equal to, the number `G`
- `{lower_than,L}` means that the (scalar) value must be lower than, or equal to, the number `L`
- `{between,A,B}` means that the (scalar) value must be greater than, or equal to, the number `A` and lower than, or equal to, the number `B`
- `{in,L}` means that the value must be an element of the list `L`
- `positive` means that the (scalar) value must be positive (possibly null)
- `strictly_positive` means that the (scalar) value must be strictly positive (null not allowed)
- `negative` means that the (scalar) value must be negative (possibly null)
- `strictly_negative` means that the (scalar) value must be strictly negative (null not allowed)
- `non_null` means that the (scalar) value must not be null (strictly positive or negative, zero not allowed)

For example, constraints applying to a value could be:

```
C: [ {between,2020,2040}, {in, [1989,2021,2030,2988]} ]
```

Note

As mentioned, for all numerical comparisons (ex: `greater_than`), the value of interest is expected to be a (scalar) number.
Otherwise (ex: the value is a triplet, or the value is not a number), the associated constraint is considered as *not* satisfied.

All constraints have to apply (as if they were associated by `AND` operators). The previous example would thus allow only two possible values, `2021` and `2030`.

Various additional kinds of constraints may be supported, based on encountered needs.

Constraints are currently parametrised by *constants* (ex: `{greather_than,10.0}`); maybe in the future they could also accept *references* onto other local ports (ex: to compare their values or base some constraints on operations, like `sum`, performed on their values).

7.5 Accuracy of a Value

This may be the next value-level metadata to be handled by the dataflow infrastructure.

Depending on various factors like data quality and numerical errors (ex: floating-point rounding), the computed values might show a good precision and many digits, yet a poor accuracy.

The first step to prevent it is to measure how accurate a computation is. This can be evaluated thanks to relative error and ulps (for *units in the last place*).

So an accuracy may be associated to each value exchanged over the dataflow, and it may then be updated by each processing unit relying on it.

By default accuracy is best measured in terms of relative error, as, if ulps are the most natural way to measure rounding error, they are less suitable to analyse the error caused by various formulas.

Anyway, often only the order of magnitude of rounding errors is of interest, and ulps and relative errors may be used interchangeably since their magnitude differ by at most a constant factor, the radix, typically equal to 2 (binary representation), or less frequently 10 (decimal one).

Another measure could be the "precision", once defined as the number of bits used to represent the significand of a floating-point number. Libraries like MPFR can be given a target, arbitrary precision and may enforce it (hence we would expect the accuracy of the corresponding values to be constant across the corresponding ports).

Each project is free to retain its own conventions regarding how the accuracy is quantified (usually as a floating-point number). The dataflow infrastructure provides the mechanisms to keep track of it, and, in processing units, update it. An accuracy specification is to be prefixed with `"A:"`, like in `"A: 8"`.

Should no accuracy be used for a given value, it should be replaced by the `'unknown_accuracy'` atom (which is the default).

The accuracy could be also translated as a confidence interval, i.e. an interval that covers an unknown parameter with probability `P=1-alpha`, where `P` is the confidence level, and `alpha` should be as close as possibly to 0 (typical values of `P`: 0.95, 0.99 or 0.999) thanks to a sufficiently large number of samples.

As no general consensus exists about accuracy, it has not been included among the usual metadata associated to values. In the future this could added, accuracy becoming the `A` of `SUTCA`.

7.6 Wrapping Up About Values

So an output port may send a notification to a set of input ports, with the following information being associated:

- a semantics, like in `S: 'energy_demand'`
- a unit, like in `U: kW.h`
- a type, like in `T: float`
- constraints, like in `C: [{lower_than,100}]`
- an accuracy, like in `A: 11.0`, to be understood here as the number of bits for the precision of the significand
- a value, like in `6.7121`
- a timestamp, like in `{117,3}`, i.e. tick offset #117, diasca 3
- the port identifier of the sender

The semantics, the unit, the type carried by endpoints and the sender port identifier are exchanged and checked at the channel creation, i.e. when the input port is linked to its output one.

The unit of the value, its associated constraints, its accuracy, its actual value and its timestamp are checked and sent to the input port each time it is triggered by its output port.

8 Logic of the Dataflow Block Activation

We saw that a key element of a dataflow lies in its blocks, notably in its processing units.

> **Note**
> Blocks are either dataflow objects or dataflow units. We will discuss here mainly of the latter (i.e., of units), as the activation of a dataflow object offers no flexibility: it will be activated iff at least one of its input ports has been assigned, leading to its corresponding attribute(s) being set, and to the associated outport(s) being in turn assigned.

For a given dataflow block, it must be decided:

- at which logical step the block is to be activated, i.e. *when* the activation of a block shall be examined
- on which additional condition(s) it shall be activated, i.e. *how* in practice the block update shall be determined as having to be triggered
- what results from such an activation, i.e. *what* are the operations this block should then perform

Such an activation translates to the execution of the `activate/1` method of that block (at this point, it is most probably a processing unit). The role of this method is to be **the place where the unit defines its actual processing**; for that, the unit most probably overrode the corresponding default do-nothing implementation.

During this processing, as for any actor oneway, the unit is free to perform **computations**, to send **actor messages** and to operate **state changes**. This includes notably reverting any of its input ports to the `unset` state, and activating any of its output ports.

Now that it has been determined *what* an activation entails (pretty much anything within the degrees of freedom of an actor), the conditions ruling *when* an activation shall occur are to be specified. Various policies are available for that.

For a given **activation policy**, these conditions should only depend on the readiness of the input ports of that unit, and of its state.

Even if a given processing unit might define its own activation rules, the set of built-in activation policies described below should be sufficient for most uses.

In all cases, under the hood the unit will be notified thanks to an actor message that one of its input ports has been triggered, knowing that during a diasca any number of such messages may be received (indeed a unit may have multiple input ports; moreover, even if it may not be usual practice, an upstream block might have triggered one of its output ports more than once) and then reordered before being processed on the next diasca.

8.1 The 'Activate On New Set' Policy

The first built-in activation policy consists in updating the unit when **at least one of its input ports** went from `unset` to `set`.

This policy, named `activate_on_new_set`, will activate the unit at most *once per diasca*, at the one immediately following the diasca at which these input ports were triggered, no matter of how many input ports were triggered on the previous diasca nor on how many times they were each triggered.

An (unordered) list of input port triggers, together with the corresponding values then set, will be available to the `activate/1` method when it will be automatically executed.

Either a bulk update may follow (the unit taking them into account as a whole), or it may perform a fold on that list to react in turn to each trigger (to emulate the case where they would be received and processed one after the other[11]).

It is up to the unit to reset the input ports (i.e. to set each of them back to the `unset` state) when deemed appropriate.

This *Activate On New Set* policy (sometimes shortened as the "On New" policy) is graphically symbolized as an arrow, to denote that any update of an input port directly triggers the associated unit computation.

8.2 The 'Activate When All Set' Policy

The second built-in activation policy, named `activate_when_all_set`, is to update the unit if and only if **all of its input ports have been set**: each time an input port is triggered, this policy automatically determines if it was the last one still unset and, if yes, it executes the `activate/1` method.

> **Note**
>
> This policy used also to take care, once that method had been executed, of automatically setting back all input ports to their `unset` state.
> As at least some models rely on "stable" inputs (inputs that vary infrequently, if ever - and thus may be set only once, but read multiple times), we preferred disabling that mechanism. So, now, in all cases, *input ports are never automatically unset.*

This *Activate When All Set* policy (sometimes shortened as the "When All" policy) is graphically symbolized as a star resembling to a lock, to denote that no associated unit computation will take place until all input ports have been enabled (i.e. are set).

[11] Note that, as all actor messages, the triggers have been reordered by the engine according to the simulation mode.

8.3 Custom Activation Policies

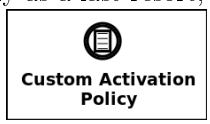
Some units may require, under rare circumstances, a custom policy, i.e. **a policy of their own** that does not match any of the built-in ones.

For example source units, i.e. units not having any input port, can be defined, but of course then none of the policies above can apply (as they can never be triggered). Nevertheless such source units are typically needed in order to bootstrap the processing of a dataflow.

To solve this, rather than forcing the definition of at least one "dummy" input port per unit, **all units can also be explicitly triggered**: they can rely on their `activateExplicitly/2` actor oneway for that, in charge of calling their `activate/1` oneway as other policies do.

This policy may for example also be used to account for units having fixed, active temporalities. A daily-activated unit may schedule itself every 24 hours (declaring such a regular spontaneous scheduling, during which it may activate its output ports), while another unit may be ruled per-hour.

So dataflows can federate mixed temporalities, knowing that the use of this policy of explicit activation is fully optional (as by default a dataflow is fully passive and is only driven by changes in its input ports) and shall be regarded only as a last resort, should the built-in policies be insufficient.



This *Custom* policy is graphically symbolized as a sheet of paper, to denote that the unit activation is driven by a freely chosen user-specified logic.

9 On Dataflow Objects

We asserted previously that the most common form of dataflow block is the processing unit; the other major form is the *dataflow object*, discussed here.

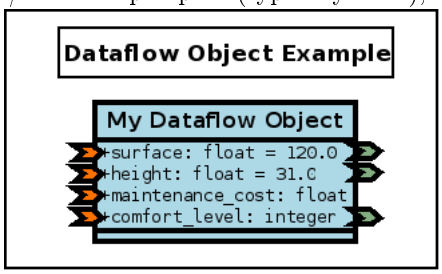
Indeed, if dataflow units allow to describe the computations that shall be performed, generally they have to rely on the structure of the simulated world in order to feed their computations with relevant data.

Holding these information, and possibly making them change over time, is the purpose of the **dataflow objects**. They are plain, standard (Sim-Diasca) actors, except that they may define *dataflow attributes*, i.e. their own state attributes that can be involved in dataflows.

To a dataflow attribute is indeed generally associated a pair of ports, an input one and an output one. These ports allow to bridge the gap between two worlds:

- the one of the **multi-agent, dynamic, loosely coupled actors**, serving the purpose of *describing* a disaggregated target system and its evolution
- the one of the (mostly statically connected) **dataflow units**, in charge of performing *computations* over a target system

A dataflow object is represented with the light-blue background that is common to all dataflow blocks, while each of its attributes is associated to an input and/or an output port (typically both), like in:



In this example, all attributes are standard, "bidirectional" attributes (they can be read and/or written by other dataflow blocks), except the maintenance cost, which is a "terminal" attribute (in the sense that it can be set, yet cannot be read by other blocks of the dataflow).

10 On Model Assemblies

10.1 Defining the Notion of Assembly

As seen already, within simulations, the target system (ex: a city) is translated into a set of instances of dataflow objects of various types (ex: `Building`, `Household`, etc.), on which models - themselves made of a set of instances of processing units of various types (ex: `EnergyDemand`, `PollutionExhausted`, etc.), complemented with at least one unit manager - are to operate.

The (generally interconnected) set of models involved into a single simulation is named a **model assembly**.

Assemblies may comprise any number of models: generally at least one, most often multiple ones, since the purpose of this dataflow approach is to perform model coupling.

Let's from now adopt the convention that a *model name* is a series of alphanumerical characters (ex: `FoobarBazv2`) and that its *canonical name* is the lowercase version of it (ex: `foobarbazv2`).

10.2 Ad-hoc Assemblies

One option is that a `FoobarBazv2` model is *directly* integrated in a dataflow thanks to an ad-hoc simulation case for a target assembly, a case whose name could be freely chosen (ex: `my_foobarbazv2_case.erl`).

Then, in this simulation case (accounting for the corresponding assembly), all relevant `FoobarBazv2`-specific settings would have to be directly specified (ex: the elements to deploy for it, the unit managers it is to rely on, etc.); note that these model-specific information would be somewhat hardcoded there.

10.3 Dynamic, Composable Assemblies

Alternatively, rather than potentially duplicating these settings in all cases including that model, one may define instead a `foobarbazv2-model.info` file (note the use of its canonical name) that would centralise all the settings relevant for that model, in the Erlang term format[12].

For example it could result in this file having for content (note that these settings can be specified in any order):

```
% The elements specific to FoobarBazv2 that shall be deployed:
{ elements_to_deploy, [ { "../csv/Foobar/Baz/version-2", data },
                        { "../models/Foobar-Baz", code } ] }.

% To locate any Python module accounting for a processing unit:
{ language_bindings, [ { python, [ "my-project/Foobar-Baz/v2" ] } ] }.

% Here this model relies on two unit managers:
{ unit_managers, [ class_FoobarBazEnergyUnitManager,
                   class_FoobarBazPollutionUnitManager ] }.
```

Defining the needs of a model as such enables the definition and use of dynamic assemblies, that can be freely be mixed and matched.

Indeed, should all the models of interest have their configuration file available, defining an assembly would just boil down to specify the names of the models it comprises (ex: `FoobarBazv2`, `ACME` and `ComputeShading`; that's it).

10.4 Envisioned Extensions

In the future, the **disaggregated view** of the simulation regarding the target system (decomposing it based on dataflow objects) could be the **automatic byproduct of the gathering of the models within an assembly**: each model would declare the dataflow objects it expects to plug into and the corresponding attributes (with metadata), then an automated merge would check that this coupling makes sense (and would generate a disaggregated view out of it.

In said model-specific configuration file, we could have for example:

```
{ dataflow_objects, [
  { class_Building, [
     % Name of the first attribute:
     { surface,
       % Corresponding SUTC metadata:
       % First the semantics:
       [ "http://foobar.org/surface" ],
       % Then the unit, type (no constraint here):
       "m^2", float }.
     { construction_date, ... } ] },

  { class_Household, [
     { child_count, ... } ] } ] }.
```

Then, before the start of the simulation, each model of the assembly could be requested about its dataflow objects, and they could be dynamically defined that way, if and only if, of each attribute of each dataflow object mentioned, all definitions agreed (equality operation to be defined for the SUTC metadata).

[12] Hence this file will simply store a series of lines containing Erlang terms, each line ending with a dot (i.e. the format notably used by file:consult/1). We preferred this format over JSON as the scope of these information is strictly limited to the simulation, and being able to introduce comments here (i.e. lines starting with `%`) is certainly useful.

11 A More Complete Example

Here we took the case of an hypothetical modelling of a city, in which the target system happens to be disaggregated into districts, buildings, etc.

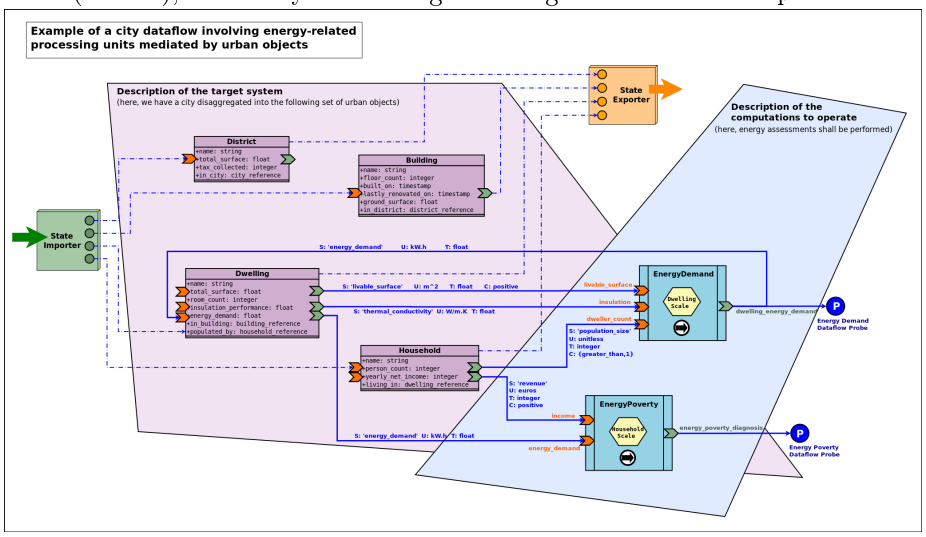
11.1 A View Onto a Theoretical Simulation

Here we propose to enforce an additional, stricter convention, which is that no two computation processing units shall interact **directly** (i.e. with an output port of one being linked to an input port of the other); their exchanges shall be **mediated** by at least one dataflow object instead. As a consequence a unit interacts solely with the target system.

Respecting such a convention allows to **uncouple the processing units** more completely: one can be used autonomously, even if the other is not used (or does not even exist).

As a result, this example simulation consists on the **intersection of two mostly independent planes**, the one of the target system (in light purple, based on dataflow objects) and the one of the computations applied on it (in light blue, based on computation units).

This intersection is implemented thanks to *dataflow objects* and the related channels (in blue), since they are making the bridge between the two planes.



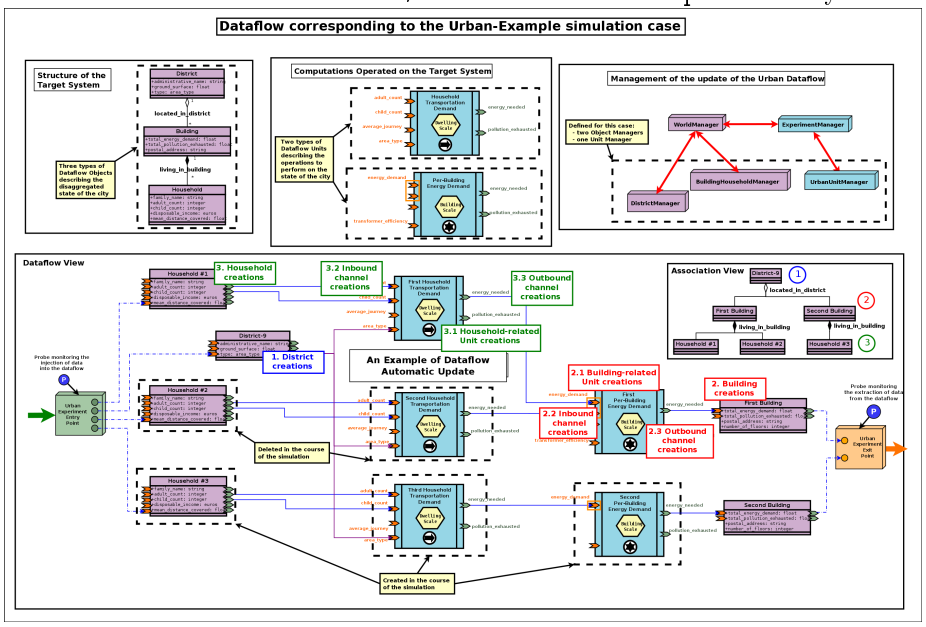
One can also notice:

- two **dataflow probes** (on the right), should specific results have to be extracted from the dataflow (read here from the output ports of some blocks)
- external **state importer and exporter**, supposing here that this simulation is integrated into a wider computation chain (respectively in charge of providing an input state of the world at each time step, and, once evaluated and updated by the dataflow, of reading back this state and possibly transferring it to other, third-party, computational components; they are specialised versions of experiment entry and exit points).

We can see that we have still here a rather high-level, abstract view of the dataflow: types are mentioned (ex: `Building`) instead of instances (ex: `building_11`, `building_12`, etc.), and managers (discussed later in this document) are omitted.

11.2 A View Onto an Actual Simulation

The following instance-level diagram describes the simulation case whose sources are available in the `mock-simulators/dataflow-urban-example` directory:



This case demonstrates the following elements:

- two specific entry and exit experiment points
- two types of processing units, one of which relies on an (input) port iteration
- four unit instances
- two unit activation policies

To run that example:

```
$ cd mock-simulators/dataflow-urban-example/src
$ make batch
```

Alternatively, to run a display-enabled version thereof, one may run `make run` instead.

12 Developing Dataflow Elements in Other Programming Languages

The dataflow infrastructure, like the rest of Sim-Diasca, uses a single implementation language, Erlang, which may be readily used in order to implement, notably, dataflow processing units.

However it may be useful to introduce, in one's simulation, dataflow blocks (ex: a set of processing units corresponding to at least one model) that are implemented in other programming languages, especially if they are for the most part already developed and complex: integrating them in a dataflow might involve less efforts than redeveloping them.

To ease these integrations, **language bindings** have been defined, currently for the `Python` and the `Java` languages - still to be used from GNU/Linux. These bindings provide **APIs in order to develop dataflow constructs** in these languages and have them take part to the simulations.

Note that a language binding often induces the use of a specific version of the associated programming language (ex: the Python binding may target a specific version of Python). We tend to prefer the latest stable versions for these languages (as they are generally more stable and provide more features), however in some cases some helper libraries that might be proposed for inclusion by models (for their internal use) may not be updated yet.

In that case, should these extra dependencies be acknowledged, a language downgrade *may* be feasible, until these libraries are made compliant again with the current language version.

One should refer to the *Sim-Diasca Coupling HOWTO* for further information regarding how third-party code can be introduced in a Sim-Diasca simulation, whether or not it is done in a dataflow context.

12.1 Python Dataflow Binding

12.1.1 General Information

This binding allows to use the Python programming language, typically to write dataflow processing units.

The Python version `3.6.0` (released on December 23rd, 2016) or more recent is to be used. We recommend to stick to the latest stable one (available here). Let's designate by `A.B.C` the actual version of Python that is used (ex: `A.B.C=3.6.0`).

A Python virtual environment, named `sim-diasca-dataflow-env`, is provided to ease developments.

12.1.2 Binding Archive

All necessary binding elements (notably the virtual environment and the sources) are provided in a separate archive (which includes notably a full Python install), which bears the same version number as the one of the associated Sim-Diasca install[13].

This binding archive has to be extracted first:

```
$ tar xvjf Sim-Diasca-x.y.z-dataflow-python-binding.tar.bz2
$ cd Sim-Diasca-x.y.z-dataflow-python-binding
```

12.1.3 Python Virtual Environment

It should be ensured first that `pip` (actually `pipA.B`, like in `pip3.6`) and `virtualenv` are installed.

For example, in Arch Linux (as root), supposing that a direct Internet connection available:

```
$ pacman -Sy python-pip
$ pip install virtualenv
```

We will make here direct use of the virtual environment that will be obtained next; one may alternatively use virtualenvwrapper for easier operations.

12.1.3.1 Recommended: Getting this Virtual Environment Directly from the Binding Archive

The virtual environment corresponding to this binding is located at the root of the archive, in the `sim-diasca-dataflow-env` tree.

It can be used as it is, without further effort.

12.1.3.2 Alternate Mode of Operation: Recreating this Virtual Environment

If using directly the binding archive is the recommended approach, in some cases one may nevertheless want to recreate the virtual environment by oneself.

[13] The sources of this binding in the Sim-Diasca repository can be found in `sim-diasca/src/core/src/dataflow/bindings/python/src` (from now it is called "the binding repository").

Then, as a normal user, an empty environment shall be created, activated and populated with the right packages:

```
$ virtualenv sim-diasca-dataflow-env --python=pythonA.B
$ source sim-diasca-dataflow-env/bin/activate
$ pip install -r sim-diasca-dataflow-env-requirements.txt
```

> **Note**
> Care must be taken so that the same `A.B` Python version as the one in the archive is specified here.
> We hereby supposed that the `Bash` shell is used. If `csh` or `fish` is used instead, use the `activate.csh` or `activate.fish` counterpart scripts.

12.1.3.3 Using this Virtual Environment To begin using it, if not already done, one should activate it first:

```
$ source sim-diasca-dataflow-env/bin/activate
```

Then all shell commands will use a prompt starting with `"(sim-diasca-dataflow-env)"` to avoid that the user forgets that this environment is enabled.

Packages provided in this environment shall be managed thanks to pip.

The list of the packages used by default by the binding is maintained in the `sim-diasca-dataflow-env-requirements.txt` file (available at the root of both the binding archive and repository)[14].

From now on, any additional package that one installs (using `pip`) will be placed in this `sim-diasca-dataflow-env` directory, in isolation from the global Python installation.

The list of the packages currently used (in the context of this virtual environment) can be obtained thanks to:

```
$ pip list
```

Once finished with it, the virtual environment can be deactivated with `deactivate` (now directly available from the `PATH`):

```
$ deactivate
```

12.1.4 Sources of the Binding

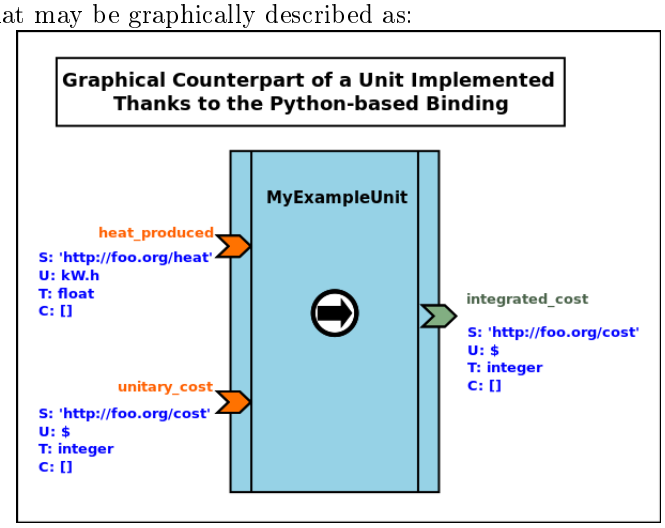
The binding itself, relying for its execution on the aforementioned virtual environment, is a regular (as opposed to a namespace one) Python package named `sim_diasca_dataflow_binding`, located under the same name at the root of the binding archive[15].

[14] It is obtained thanks to: `pip freeze > sim-diasca-dataflow-env-requirements.txt`.

[15] As mentioned before, its sources in our repository are located in the `sim-diasca/src/core/src/dataflow/bindings/python/src` directory.

12.1.5 Use of the Binding

Let's take the example of a user-defined processing unit, let's say in `my_example_unit.py`, that may be graphically described as:



Its corresponding Python-based full implementation may be:

```
from sim_diasca_dataflow_binding.common import trace
from sim_diasca_dataflow_binding.common import error
from sim_diasca_dataflow_binding.dataflow import unit

class MyExampleUnit(unit.ProcessingUnit):
  """A unit computing heat and fees; 2 input ports, 1 output one."""

  def __init__(self,name:UnitName,relative_fee:float):

    # A static, constant fee applied to some costs:
    self.fixed_fee = 115.0

    # An instance-specific proportional fee:
    self.relative_fee = relative_fee

    my_input_specs = [
      InputPortSpec('heat_produced','http://foo.org/heat','kW.h','float'),
      InputPortSpec('unitary_cost','http://foo.org/cost','$','integer') ]

    my_output_specs = [ OutputPortSpec('integrated_cost',
      'http://foo.org/cost','$','float') ]

    unit.ProcessingUnit.__init__(self,name,my_input_specs,
      my_output_specs,ActivationPolicy.on_new_set)

  def activate(self) -> None:
    """Automatically called by the dataflow, as requested by
       the selected activation policy."""
```

```
    input_cost_port='unitary_cost'
    # 'Activate On New Set' policy, hence may be unset:
    if self.is_set(input_cost_port):
      self.debug("Computing fees.")
      cost = self.get_input_port_value(input_cost_port)
      new_cost = self.apply_fees(cost)
      self.set_output_port_value('integrated_cost',
          new_cost)

  # The domain-specific logic is best placed outside of the
  # dataflow logic:
  def apply_fees(self,cost:float) -> float:
    """Applies all fees to specified cost."""

    return self.fee + cost * self.relative_fee
```

For reference, in `sim_diasca_dataflow_binding/dataflow/unit.py`, we may have the following definitions (used in our example unit above):

```
from enum import Enum

# Type aliases (mostly for documentation purposes):

Semantics = str
Unit = str
Type = str
Constraint = str

BlockName = str

PortName = str
InputPortName = PortName
OutputPortName = PortName

PortValue = Any

# Taken from https://docs.python.org/3/library/enum.html#functional-api:
class AutoNumberedEnum(Enum):
   def __new__(cls):
       value = len(cls.__members__) + 1
       obj = object.__new__(cls)
       obj._value_ = value
       return obj


class ActivationPolicy(AutoNumberedEnum):
   on_new_set = ()
   when_all_set = ()
   custom = ()
```

```
class InputPortSpec():

  def __init__(self, name:InputPortName, semantics:Semantics,
      unit:Unit, type:Type, constraints=List[Constraint] ):
    [...]


class OutputPortSpec():
    [...]

class Port():
    [...]

class InputPort(Port):
    [...]

class OutputPort(Port):
    [...]


class ProcessingUnit(trace.Emitter):
  """Base, abstract, dataflow processing unit."""

  def __init__(self, name:UnitName, input_specs:List[InputPortSpec],
                 output_specs:List[OutputPortSpec],
                 activation_policy:ActivationPolicy):

    # Class-specific attribute declaration:
    #  - input_ports={} : Mapping[InputPort]
    #  - output_ports={}: Mapping[OutputPort]
    #  - activation_policy: ActivationPolicy

    trace.Emitter.__init__(self,name,category="dataflow.unit")
    self.trace("Being initialised.")
    self.register_input_ports(input_specs)
    self.register_output_ports(output_specs)
    self.activation_policy=validate_activation_policy(activation_policy)

  def register_input_ports(self, specs:List[InputPortSpec]) -> None:
    [...]

  def register_output_ports(self, specs:List[OutputPortSpec]) -> None:
    [...]

  def validate_activation_policy(policy:Any) -> ActivationPolicy:
    [...]

  def is_set(self,name:InputPortName) -> bool:
    """Tells whether specified input port is currently set."""
    [...]
```

```
def get_input_port_value(self,name:InputPortName) -> PortValue:
  """Returns the value to which the specified input port is set.
     Raises ValueNotSetError if the port is not set.
  """
  [...]

def set_output_port_value(self,name:OutputPortName,PortValue) -> None:
  [...]


def activate(self) -> None:
  """Evaluates the processing borne by that unit.

  Once a unit gets activated, it is typically expected that it reads
  its (set) input ports and, based on their value and on its own state,
  that it set its output ports accordingly.
  """
  pass
```

12.1.6 Binding Implementation

The Python dataflow binding relies on ErlPort for its mode of operation.

Please refer to the `Sim-Diasca Technical Manual` to properly install this binding.

12.2 Java Dataflow Binding

This binding allows to use the Java programming language, typically to write dataflow processing units.

The Java version `8` or higher is recommended.

> **Note**
> Unlike the Python one, the Java Binding is not ready for use yet.

12.3 Other Language Bindings

A low-hanging fruit could be Ruby, whose binding could be provided relatively easily thanks to ErlPort.

Rust could be quite useful to support as well.

13 More Advanced Dataflow Uses

13.1 Dynamic Update of the Dataflow

One may imagine, dynamically (i.e. in the course of the simulation):

- creating or destroying blocks
- creating or destroying channels
- updating the connectivity of channels and blocks
- creating or destroying input or output ports of a block

This would be useful as soon as the target system is itself **dynamic** in some way (ex: buildings being created in a city over the years, each building relying on its associated computation units - which thus have to be dynamic as well, at least with varying multiplicities).

Moreover, often all the overall layout cannot be statically defined, and the dataflow as a whole has to be dynamically connected to the components feeding it or waiting for its outputs (ex: a database reader having to connect in some way to some input ports) - so some amount of **flexibility** is definitively needed.

13.2 Iteration Specification & Iterated Ports

13.2.1 Usage Overview

In some cases, a given type of unit may support instances that can have, each, **an arbitrary number of ports relying on identical metadata** (i.e. ports that have to obey the exact same specifications).

An example of that is a processing unit aggregating a given metrics associated to each building of a given area: each instance of that unit may have as many input ports (all having then exactly the same metadata) as there are different buildings in its associated area, and the class cannot anticipate the number of such ports that shall exist in its various instances[16].

Supporting **iterated ports** spares the need of defining many ports that would happen to all obey the same specification; typically, instead of declaring by hand an `energy_demand` port and similar look-alike ports (that could be named `energy_demand_second`, `energy_demand_third`, etc.) with the same settings, an `energy_demand(initial,min,max)` port iteration can be specified.

This leads, for each instance of this unit, to the creation of `initial` different iterated ports, all respecting the `energy_demand` port specification.

At any time, for each of these unit instances, there would be at least `min` instances of such ports, and no more than `max` - that can be either a positive integer, a named variable or the `*` (wildcard) symbol, meaning here that a finite yet unspecified and unbounded number of these ports can exist.

More precisely, in a way relatively similar to the UML conventions regarding multiplicities, for a given port iteration one may specify either a fixed number of iterated ports, or a range:

[16] Not to mention that buildings may be created and destroyed in the course of the simulation, so, even for any given instance, the number of ports may have to change over simulation time...

Multiplicity	Examples	Meaning: for this iteration, at all times there will be:
Fixed constant	7	Exactly 7 iterated ports
Variable name	`n`	Exactly `n` iterated ports
*	*	Any number of iterated ports
Min..Max	0..4,a..b, 2..*	Between Min and Max iterated ports (bounds included)

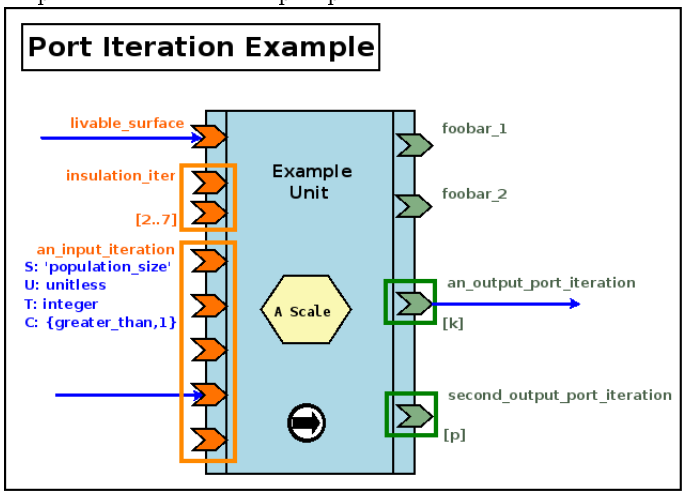
In a given dataflow, variable names (ex: `m`, `n`, `o`, etc.) are expected to match. For example, if the variable `n` is referenced more than once in the dataflow, then all its occurrences refer to the same value (which is let unspecified in the diagram).

Iterated ports are automatically named by the runtime (ex: `energy_demand_iterated_1`, `energy_demand_iterated_2`); they are standard ports and thus their name shall remain an identifier[17].

Graphically, the set of ports corresponding to an iteration is represented as a rectangle enclosing these iterated ports (when representing actual instances, the rectangle may be empty); multiplicities are to be specified between brackets (to distinguish them from the iteration name) and preferably at the bottom of the associated rectangle.

All these elements shall be of the same color as the one of the port. Any common metadata shall preferably be listed once.

An example of these conventions is the following processing unit, featuring two input and and two output port iterations:



We can see above that, at any time, the first input iteration shall have between 2 and 7 (included) iterated ports, while the second input iterations is detailed graphically and has exactly 5 iterated ports (`[5]` is thus implied).

[17] This is why the runtime enforces the single restriction that applies to port names, which is that the `_iterated_` substring cannot exist in such a user-defined name.

As for the output iterations, both have a certain number of iterated ports, and, as `k` is different from `p`, their respective counts of iterated ports may not match (ex: we can have `k=2` and `p=0`).

13.2.2 In Terms of Implementation

An **iteration specification** enables the creation of multiple (input or output) ports of the same type, each of these instances being designated as an **iterated port** (technically an iterated port is nothing but a standard port).

For example, defining an iteration specification of 3 instances named `foobar` will result in the creation of 3 actual (iterated) ports, each complying to this specification, and named `foobar_iterated_1`, `foobar_iterated_2` and `foobar_iterated_3`[18].

By default, port specifications are not iterated: in implementation terms, the `is_iterated` field of a port specification is set to `false`.

To enable the creation of iterated ports, the `is_iteration` field of the corresponding port specification shall be set to either of these three forms:

- `{Initial,{Min,Max}}` where `Initial` is the initial number of iterated ports to be created according to this specification, and `Min` and `Max` are respectively the minimum and maximum counts of corresponding iterated ports that are allowed to exist
  - then the runtime will create the corresponding initial number of instances (whose name is suffixed as mentioned with an incremented number starting from 1), and ensure that, even in the presence of runtime port creations, the number of the corresponding iterated ports will remain within specified bounds
  - `Initial` and `Min` are positive integers, while `Max` can also be set to the `unbounded` atom to allow for an unlimited number of such iterated ports; of course `Initial` must be in the `{Min,Max}` range
- `{Initial,Max}`, which is a shorthand of `{Initial,{_Min=0,Max}}`
- `Initial`, which is a shorthand of `{Initial,{_Min=0,_Max=unbounded}}`

[18] As mentioned, once created, these three ports will be fully standard ports; the `_iterated_` substring helps avoiding that the names of iterated ports clash with other ports (it convey no specific meaning as such).

13.3 Domain-Specific Timestamps

By default, engine ticks directly translate to a real, quantified simulation time: depending on the starting timestamp and on the selected simulation frequency, a given tick corresponds to an **exact time and date** in the Gregorian calendar (ex: each month and year lasting for the right number of days - not respectively, for example, 30 and 365, a simplification that is done in some cases in order to remain in a constant time-step setting).

However, in some simulations, models are ruled by such a strange simplified time[19], so domain-specific timestamps may be useful. Their general form is `{timescale(),index()}`, where `timescale()` designates the selected time granularity for the underlying channel (ex: `constant_year`, `month_of_30_days`) and `index()` is a counter (a positive integer corresponding to as many periods of the specified time granularity).

For example, in a simulation some models may be evaluated at a yearly timescale, while others would be at a daily one. Considering that initial year and day have been set beforehand, a timestamp may become `{yearly,5}` or `{daily,421}`. This could be used to check that connected ports have indeed the same temporality (ex: no yearly port linked to a daily - a *timescale convertor unit* needing to be inserted in that case), and that none of such timescale-specific timesteps (i.e. index) went amiss in the channel.

13.4 Usefulness of Cyclic Dataflows?

One can notice that cyclic dataflow graphs are allowed by this scheme based on input and output ports, and that even "recursive dataflow objects" (i.e. dataflow objects having one of their output port connected to one of their input ones) can exist.

Of course some convergence criterion is needed in order to avoid a never-ending evaluation.

[19] Even if this oversimplification just by itself yields already significant relative errors (greater than 10%).

14 Experiments

As mentioned in the Experiment Definition section, an experiment is the top-level abstraction in charge of **driving the computations applying to a simulated world**.

14.1 Purpose of Experiment Endpoints

Depending on the project, it may be convenient for a given experiment relying on any number of dataflows to define a pair of components in charge of triggering and terminating its evaluation (typically once a specified number of steps were performed), as points of entry and exit, respectively.

For that, base classes are provided (`ExperimentEntryPoint` and `ExperimentExitPoint`) that are meant, if needed, to be subclassed on a per-project basis.

The purpose of these (optional) endpoints is to drive multiple dataflow instances, possibly on par with some external software (ex: any overall integration platform).

Their impact in the progress of an experiment is discussed next.

14.2 Experiment Progress

In terms of logical ordering, the usual **course of action of a dataflow-oriented simulation** discussed here is[20]:

1. a new simulation tick `T` begins: the experiment entry point (which is an actor) is scheduled
2. a synchronisation stage, detailed in the next sections, occurs: the dataflows are suspended, and the state of the simulated world is updated first, then the computations that shall be applied on it are modified accordingly
3. then the dataflows are resumed, and it usually triggers (based on intermediate logical moments, i.e. diascas) in turn (source) dataflow objects and/or processing units
4. this may trigger cascading updates of dataflow elements over diascas
5. once all evaluations are done, the experiment exit point (another actor) is to wrap up all information and perform any related tick-termination operation (ex: sending an update regarding the newer state of the simulated world to a third-party platform)
6. then the next planned tick begins (usually this corresponds to `T+1`), and the process continues until a termination criterion is met (typically a final timestamp is reached, or the simulation is notified that no changes are to be expected anymore)

As a result, the **processing of a given timestep** may boil down to an overall three-step process:

[20] To shed some light on the related implementation (as the technical organisation is a bit different), please refer to the Scheduling Cycle of Experiments.

A. synchronisation of the state of the simulation from an external source (thanks to a state importer - generally an experiment entry point)

B. then evaluation of the corresponding dataflow

C. then update of an external target, based on the resulting state of the simulation (thanks a state exporter - generally an experiment exit point)

These external source and target may actually correspond to the same data repository, held by a more general platform.

The rest of that HOWTO explained with great detail how step B is tackled. We will thereafter focus thus on step A, knowing that step C in many ways is a reciprocal of this step, and thus may be at least partly deduced from the understanding of step A.

15 A General View on the Dataflow Synchronisation

The goal is to properly manage the **transformation of a source dataflow into a target one**, in the context of the simulation of a system.

More precisely, here the *source* dataflow is the one obtained after the evaluation of a timestep, while the *target* dataflow is the one that shall be evaluated at the next timestep.

In-between, an external operator may apply any kind of changes to the simulated system, and of course these changes shall be reflected onto its dataflow counterpart.

Such **changes** may be **defined programmatically**[21] or be **discovered at runtime from an external source**[22]. The next sections will focus on the latter case, which is the trickier to handle.

As already mentioned, dataflows are made of blocks, linked by channels, and two different sorts of blocks exists here:

- the *dataflow blocks*, which are in charge of describing the current state of the simulated world
- the *dataflow processing units*, which are in charge of performing domain-specific computations onto that state

Let's introduce first, and in a few words only, the main elements that are provided in order to transform a dataflow into another:

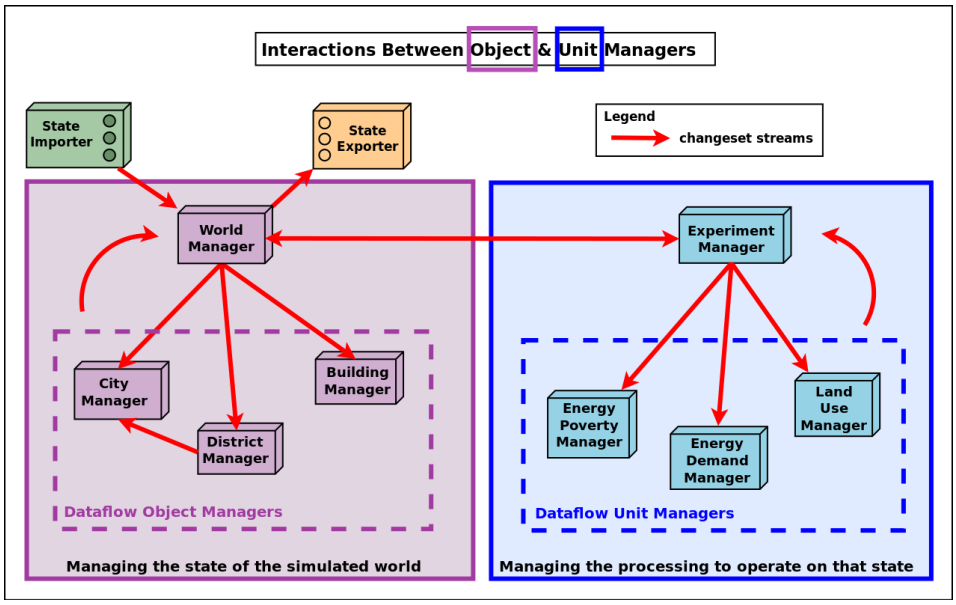
- the changes in the state of the simulated world are orchestrated by the **World Manager**, driving the various **Object Managers** for that

[21] If the dataflow is to be managed programmatically (i.e. thanks to specific code), then a user-defined program is to use the various dataflow-relative primitives in order to create the initial state of the dataflow and possibly update it in the course of the simulation; see, in `mock-simulators/dataflow-urban-example`, the `dataflow_urban_example_programmatic_case.erl` test case for that.

[22] This setting is illustrated by the `dataflow_urban_example_platform_emulating_case.erl` test case.

- the changes in the computations to be operated are orchestrated by the **Experiment Manager**, driving the various **Unit Managers** for that
- each change is described by an individual **World Synchronisation Event**, meant to affect potentially both the state of the simulated world and, in turn, the computations operated on it
- a **Changeset** may aggregate many of these events, and a dataflow can be turned into another by simply applying a series of changesets

The diagram below gives a synthetic, example view of the overall mode of operation in action:



Let's discuss now more precisely the various elements of the solution, and how they interact.

16 The World Manager and its Dataflow Object Managers

16.1 Purpose of the World Manager

This manager (singleton instance of the `WorldManager` class), whose shorthand is `WM`, is used in order to **create, update and keep track of the simulated world and its structure**; this world is itself made of the target system of interest (ex: a city) and of its context (ex: its associated weather system, the other cities in the vicinity, etc.).

As a result, the world manager is generic, yet its use is specific to a given modelling structure (ex: to some way of describing a city), and bears no direct relationship with the computations that will be performed on it (one of its purposes is indeed to help uncoupling the description of the world of interest from the models operating on it, so that they can themselves be defined independently, one from another).

This virtual world is to be modelled based on **various types of dataflow objects**. For example, if the target system is a city, then districts, roads, buildings, weather elements, other cities, etc. may be defined (as types first, before planning their instantiaton) in order to represent the whole.

These dataflow objects, which account for the state of the simulation world, are to be defined **individually** (in terms of internal state; ex: a building has a `surface` and an `height` attributes, of corresponding SUTC metadata) and **collectively** (in terms of structure and relationships; ex: a building must be included in a district, and may comprise any number of dwellings).

16.2 Purpose of the Object Managers

For each of these types of dataflow objects, an **object manager**, in charge of taking care of the corresponding dataflow objects (i.e. the instances of that type) must be defined[23]. For example the `BuildingManager` will take care of (all) `Building` instances.

Note that a given object manager is to take care of *at least* one type of objects, possibly multiple ones (ex: if deemed more appropriate, a single object manager may be defined in order to take care of the buildings *and* of the households *and* and the districts).

The purpose of an object manager is to be the entry point whenever having to **perform dataflow-level operations on the object instances** of the type(s) it is in charge of (ex: actual buildings): in the course of the simulation, instances may indeed have to be properly created, associated, connected, modified, deleted, etc.

Finally, all dataflow object managers are federated by this `WM` (*World Manager*), which is their direct parent, in charge of driving them all.

The main use of the world manager and of its associated dataflow object managers is the enabling of **external state synchronization**.

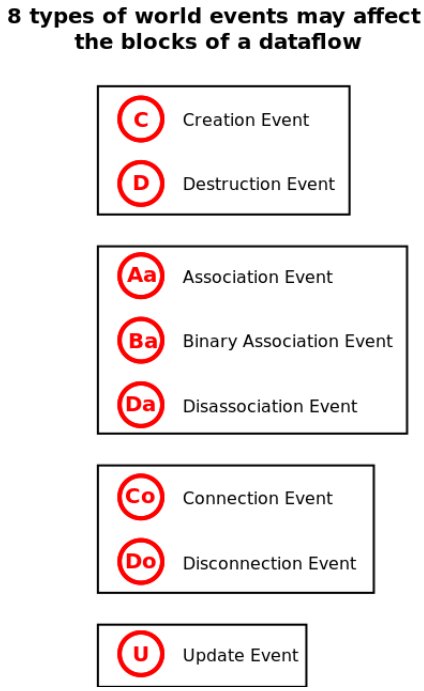
Should, for example, an overall, targeted simulation be actually performed by a pipe-line of platforms (including of course at least the one at hand, which is based on this dataflow infrastructure), at each time step the state of the simulation would need to be updated from these other platforms and, reciprocally, once modified by the dataflow-based one, would need to be passed to the next platforms.

The various dataflow objects involved in the simulation have to reflect the current state of the world; for that, from one timestep to the next, changes have to be applied onto them. For example, if the evaluation runs on a yearly timestep, handling simulation year 2026 requires that changes that happened since the end of the dataflow evaluation of 2025 are taken into account before starting to simulate year 2026.

16.3 Expressing Dataflow Changes Through World Events

These changes are expressed at the dataflow level thanks to **world (synchronisation) events**. Following types of world events[24] have been defined:

[23] All actual dataflow managers are either instances of the `DataflowObjectManager` class (for the simpler cases), or child classes thereof (ex: to support specifically some kind of associations). All these managers are themselves simulation actors, as interacting with them in the course of the simulation may be necessary (ex: to create new object instances).



More precisely:

- a **creation** event describes the creation of a block, typically of a dataflow object (ex: building B2 being built in the city on the current year)
- a **deletion** event describes the deletion of a block, typically of a dataflow object (ex: district D7 being destructed)
- an **association** event describes the creation of an association between dataflow objects; a *binary* association is a very common, special case thereof (ex: building B2 is "located in" neighborhood N3)
- a **disassociation** event describes the removal of an association between dataflow objects (ex: household H1 is not "living in" building B2 anymore)
- a **connection** event describes the creation of a dataflow channel between two ports of blocks, from an output one to an input one (ex: from the `surface` output port of building B6, to the `average_area` input port of the land-use processing unit L9)
- a **disconnection** event describes the deletion of a dataflow channel that used to exist between two ports
- an **update** event describes the modification of the value of attributes of a dataflow object (ex: for building B2, the `surface` attribute is set to 120.0 m^2, while its `inhabitant_count` is set to 7)

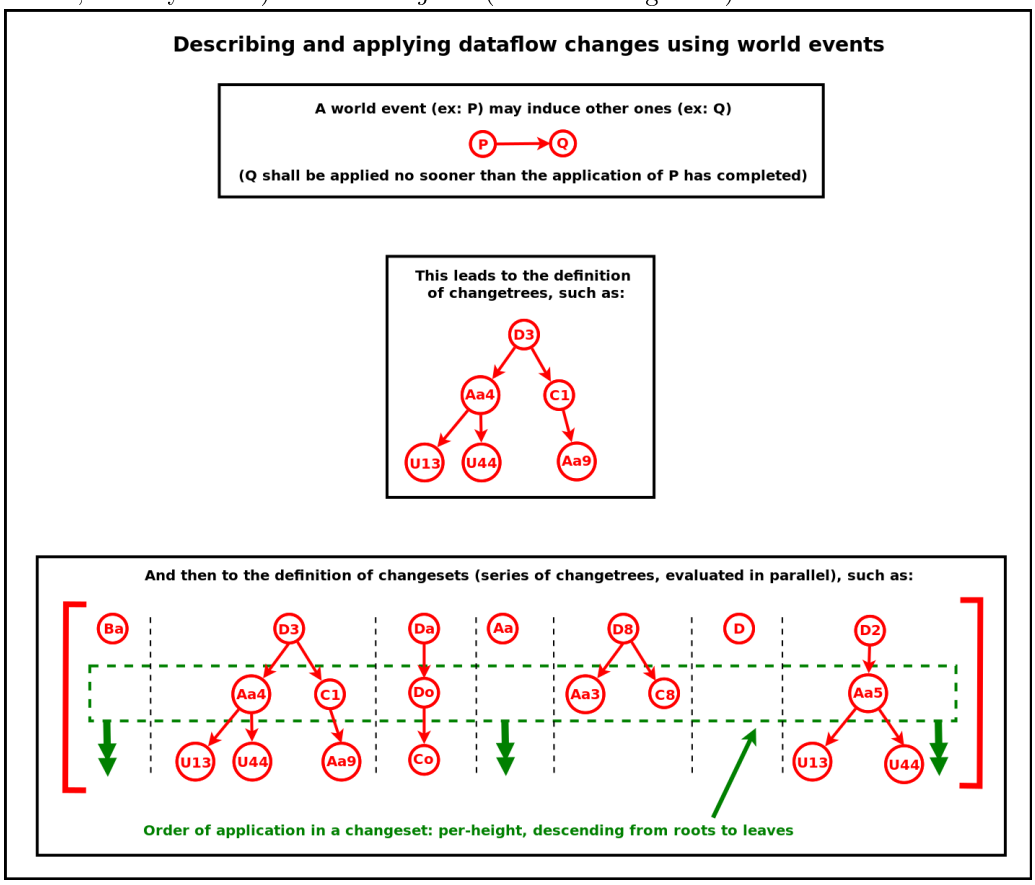
[24] Refer to `dataflow_changesets_defines.hrl` for their actual definitions: for each type of event, a corresponding datastructure is defined in order to store the identifier of each event, the type of dataflow object it refers to, the external and internal identifier of the instance(s) involved, extra type-specific information, etc.

Should, for a given project, the incoming dataflow updates deal only with the *state* of the simulated world (not directly with the *computations* themselves - whose changes may be automatically deduced from the state ones at a latter step), only a subset of the types of world events are to be supported (by the world manager), namely all types of events but connections and disconnections.

16.4 Changetrees and Changesets

A given event may induce any number of other events (ex: a creation of a building may induce its association with a given district), which themselves may induce in turn other events, and so on.

As a result, we define the concept of *changetree* (an event and all the ones it induces, directly or not) and of *changeset* (a list of changetrees):



It is the role of the dataflow entry point (typically fetching its informations from an external source) to stream the corresponding changesets to the world manager, and to notify it when the synchronisation has been fully described (i.e. when all changesets have been transmitted).

16.5 Changeset Crunching

When the world manager receives a changeset, **it dispatches each event in turn to the relevant object manager**, based on the type of the dataflow

object to which this event applies. For example an event about the creation of a building will be transmitted to the object manager which declared it was in charge of the dataflow objects of type `Building`.

Events are processed by the world manager based on their height on the pending changetrees, so that **their order of induction is preserved** : first the root events of all changetrees of the current changeset are dispatched (in an asynchronous way, all in parallel, during the same logical moment), then, when one of these events is reported (by the corresponding object manager) as completed, the world manager dispatches in turn the events that it is inducing, and so on (as a result, if event E1 induces event E2, the processing of E2 will not start before the completion of the processing of E1[25]). **All the changetrees progress in parallel, and each at its maximum rate** (knowing that not all operations triggered require the same number of diascas to complete).

Moreover, when an object manager reports to the world manager the completion of event(s), **it may as well inject new events**. For example, if creating a building entails creating three lifts, then the building object manager may inject three additional lift creation events. Then these events will be processed, among the pending others, by the world manager, and thus will be dispatched to the lift object manager. This allows for an indirect communication between object managers, and to embed, if needed, domain-specific rules in order to structure appropriately the state of the simulated system.

> **Note**
>
> During the whole synchronisation phase, the blocks of the dataflow that are affected (ex: created or updated) are put in stasis, i.e. they are suspended.
> Otherwise their evaluation could start whereas the dataflow did not reach yet a stable state, which could lead to an incorrect evaluation of the overall dataflow.
> To anticipate a bit, the actual evaluation will take place when the dataflow(s) will resume their suspended blocks, which will happen later - once the experiment manager will have finished its own synchronisation work.

As changesets are streamed and processed, the world manager collects the completed events, in a flat, ordered list: all events are enumerated there according to their processing/induction order (i.e. if E2 is induced by E1, E1 will be listed *before* E2), and they will not embed induced events anymore (so that each event is present exactly once in this flattened list).

Once in a final state (all changesets transmitted and processed), **the corresponding overall aggregated completed changeset is sent to the next stage** of the dataflow update, dealing this time with the computational part thereof - as explained in the next section.

[25] This is a necessary feature; for example, if E1 is a creation of a building and E2 is its association, E2 will need to rely on an already fully created object before being able to define any association involving it.

17 The Experiment Manager and its Unit Managers

17.1 Purpose of the Experiment Manager

The *Experiment Manager* is a component (singleton instance of the `ExperimentManager` class), whose shorthand is `EM`, and that is responsible for the **management of the processing part of the dataflow(s)**, i.e. of the **computations** that are to be operated on the simulated world, accounting for the experiment that is to take place onto the simulated world.

These (model-specific) computations are implemented by **processing units**, which are driven by the **unit managers** - which are themselves federated by the **experiment manager**.

As a result, the experiment manager is generic (while its use is domain-specific), and it can be seen as an orthogonal counterpart of the world manager, according to this table matching concepts:

State of the Simulated World	**Computations to be Operated**
Dataflow Object	Dataflow Processing Unit
Object Manager	Unit Manager
World Manager	Experiment Manager

Having them separated allows to isolate and uncouple more easily the operations to be performed from the elements they are to operate on. They however both rely on changesets to perform their operations.

17.2 Purpose of the Unit Managers

Dataflows may rely on any number of unit managers.

A **Unit Manager** is in charge of taking care of all instances of at least one **type of units** involved in the dataflow[26], for a given model; as such, a unit manager may typically create, delete, modify (including reconnecting) the units of the type(s) it supports.

Let's say for example that, for a given model, we have, among other ones, two types of processing units, `EnergyDemandUnit` and `WaterDemandUnit` that are to operate each on a given building.

A unit manager named `ResourceDemandUnitManager` may be in charge of all instances of these two types of units, for example so that it can be ensured that the two kinds of demands are appropriately interlinked and applied consistently (ex: exactly to the same buildings).

[26] All actual unit managers are child classes of the `UnitManager` base class, to handle the operations specific to the types of the processing units that they support.

Note

Most models rely on multiple types of processing units - yet on a *single*, unified unit manager instance that drives them all.
However one can instead define, for a given model, **multiple unit managers**, each in charge of a subset of the types of processing units involved - provided that these unit managers partition these unit types, i.e. that each unit type is driven by exactly one unit manager instance.
If such a scheme allows the work on the processing units to be split in more autonomous parts, it induces limitations: relying on a single unit manager allows to store in its state *all* unified information about dataflow objects (based on the world events it listens to) and units (as, for that model, it is their sole manager), which is often necessary to perform proper channel creations (ex: to determine the right instance of processing unit to be connected to a given dataflow object).
As a result, unit managers tend to define various associative tables, to keep track of which processing unit they created (ex: a pollution computation) in response to the creation of which dataflow object (ex: a car). Unit managers are then able to connect these units adequately, once they are reported as created.

As a result, each unit manager federates the units of specific types, so that it can perform - for computations and on behalf of the EM - what dataflow object managers perform for the simulated world on behalf of the WM[27]: **a unit manager will synchronise the computation part of the dataflow regarding these unit types**.

17.3 Mode of Operation

This synchronisation of the computational part of the dataflow could be explicitly dictated by an external source, as done previously for the part of the dataflow devoted to the description of the state of the simulated system. However, more often than not, **the changes in the computation part may be determined automatically from the changes done on the state part, based on relevant rules**. The purpose of the unit managers is to *implement* said rules.

To do so, each unit manager is to declare not only the types of processing units it is to manage (ex: `ResourceDemandUnitManager` taking care of `EnergyDemandUnit` and `WaterDemandUnit`), but also the **world synchronisation events it listens to**, and **how it is to react to them**.

For example, `ResourceDemandUnitManager` may request to be notified whenever a building is created and/or whenever the current operating state of a given heat pump changed (ex: from nominal mode to degraded mode). It may then choose to apply the relevant domain-specific actions in order to adapt the computations performed by the dataflow, such as, respectively, creating one instance of `EnergyDemandUnit` and of `WaterDemandUnit` and connecting them to the new building, or linking said heat pump to a different processing unit implementing

[27] Similarly to object managers, unit managers typically take part to the simulation (ex: they may create processing units) and therefore must be properly synchronized; as such they are simulation actors as well.

a model corresponding to its new mode of operation (by updating their dataflow connectivity).

In practice, a given unit manager may declare (to the experiment manager) any number of **event match clauses**[28], whose granularity can be finely tuned (from a non-discriminating unit manager listening to all events of all types, to one focusing only on very precise matches[29]).

Then, when the World Manager will transmit the aggregated changeset[30] to the Experiment Manager, this latter simulation agent will iterate through the events in turn, and notify the unit managers whose event clauses matched[31].

This unit manager will then be **free to react appropriately to this listened event, by performing changes onto the computational part** of the underlying dataflow. As hinted in the `ResourceDemandUnitManager` example, typical changes are to create or delete a processing unit, or to connect or disconnect ports of a processing unit to ports of dataflow objects[32].

---

[28] Refer to `dataflow_changesets_defines.hrl` for their actual definitions: for each type of event match (ex: `creation_event_match`), a corresponding datastructure is defined in order to store against which element(s) of the corresponding event the match shall be done (ex: "the (created) object type shall be of type `Building`, it should occur in the context of this dataflow, involve a dataflow object bearing this external identifier and/or this internal one, specify these construction parameters, etc.).

[29] Of course a unit manager is free to perform any additional, arbitrary filtering it may need, simply by ignoring the notified events that would not be deemed of interest.

[30] A single, aggregated changeset is relied upon on purpose: if changesets were streamed by the World Manager to the Experiment Manager as they complete, unit managers would have to be able to operate on an unstable dataflow view of the system state (i.e. subject to changes due to further changesets), which could jeopardize the correctness of the synchronisation of the computational part.

[31] Translating to calling their appropriate event handler; for example, should a given event match a `binary_association_event_match` declared by a unit manager, the experiment manager will transmit this event to this unit manager, by calling its `onBinaryAssociationEventMatched` method.

[32] As a result, unit managers have to rely on a corresponding API, possibly implemented also in the language bindings. For example, a Python-based unit manager would use methods inherited from the `UnitManager` base class, such as the self-explanatory `create_unit` or `connect_unit` methods.

18 About Mock-up Units

Mock-up units are units that, instead of implementing a computation logic, **directly compose the state of their output ports based on the one of their input ports**, relying for that on the static information (data, not code) that they embed.

As such, mock-up units merely *associate* pre-recorded outputs to inputs, instead of *implementing* computations allowing to determine the former from the latter ones.

These mock-up units can act as "termination plugs", i.e. placeholders inserted in a dataflow in order for example:

- to replace an actual unit (ex: to wait until it is delivered)
- to emulate the context of another unit in order to better test it
- to validate an implemented unit against reference input/output datasets
- to provide a simpler, less computation-demanding version of a unit (see model order reduction, called metamodel in some communities)

  In practice, these mock-up units are instances of the `DataflowMockupUnit` class (or of a child class thereof), which provides a generic mock-up unit able to be fed with data basically describing, in terms of ports, which outputs are to correspond to which inputs.

They are instantiated and managed by a *unit manager*, just like any *processing unit* would do. The only difference is that, since their construction parameters are slightly different from classical units, they have to be created by dedicated methods that have been added to the `DataflowUnitManager` class.

18.1 Definition of a Mock-up Unit

A mock-up unit is specified exactly as any other dataflow unit (ex: with a name, a temporality, a description of its input and output ports), yet it has to replace the inner computation logic that would be included in any standard unit by a (static) **association determining its outputs from its inputs**.

This association can be seen as a **simple function** which, based on a given (optional) simulation time and an *input match specification* operating on its input ports, tells in which state the output ports of this mock-up unit shall be.

One should note that the result returned by this function (the actual state of the output ports) will depend **only** on its input parameters (the specified time and the input match specs); for example no contextual data can intervene, because this (pure) function is stateless (i.e. it has no memory).

The general form of this mock-up function is:

```
f(time(), input_match_spec()) -> output_state()
```

This means that the purpose of this mock-up function is **to tell, for a given simulation time and for a configuration of the input ports that matches the supplied specification, what is the corresponding updated state of at least some of the output ports of that unit**.

Multiple clauses can be specified in order to fully define that function: at runtime, **at each activation**, each of these clauses will have its time and input specifications matched against the current simulation time and the state of the input ports. **The first clause to match will be the only one executed during this activation**, leading to applying the state changes on the output ports that it specifies. Should no clause match, the mock-up unit will simply stay inactive until the next activation (no specific signal will be sent to the downstream connected blocks).

Examples in the next sections will clarify this mode of operation; let's call from now the mock-up function `f/2`, i.e. a function named `f` taking two parameters, respectively the time and the input match spec.

18.2 Simulation Time Specification

A mock-up function may **react differently at different time steps** of the simulation. So a clause of that function may specify, for its first parameter:

- either the precise time step at which it shall be applied, for example `f(127,...)->...`, to denote here that this clause corresponds to the simulation step #127
- or the `any_time` atom, to tell that the application of this clause does not depend on simulation time; as a result, `f(any_time,...)->...` will match irrespectively of the current time step

Of course units (hence mock-up ones) may be atemporal, in which case only timeless clauses (using `any_time`) would be used.

18.3 Input Match Specification

This second parameter of the mock-up function allows to specify the **configuration of input ports to which this clause is meant to match**: the match specification describes the possible states in which the input ports of interest for the mock-up unit shall be, for this clause to be selected. That clause determines in turn the state of the output ports that will be consequently retained.

In practice, an input match spec is an (unordered) list of pairs, whose first element designates an input port, and whose second one specifies the associated state(s) that would match.

This first element is the name of the input port (ex: `"I1"`), as, in the context of a unit, it is an identifier (it is unique).

The second element of the pair associated to a listed input port is among:

- the `any_state` atom, to specify that the state of this input port will be ignored, i.e. that it may or may not be set (if set, its value will not matter for the clause)
- the `unset` atom, to specify that this input port should *not* be set
- the `set` atom, telling that this input port may have any value, *provided it is set at all*
- a `{set,V}` pair, requiring that input port to be set exactly to this value `V`

- a `{between,A,B}` pair, requiring that input port to be set to a scalar, numerical value in the `[A,B]` range (hence including bounds)
- a `{around,V,E}` pair, requiring that input port to be set to a value around `V`, with a relative error[33] of up to `E`; this is a way of better supporting floating-point values - for which strict equality is usually not meaningful
- a `{around,V}` pair, requiring that input port to be set to a value around `V` with a default relative error of `1.0e-6`
- a `{among,[V1,V2,..,Vn]}` pair, this input port having to be set to one value in that list for the clause to possibly match

Any input port that is not listed in the spec may be in any state (unset, or set to any value); the `any_state` atom is therefore a way of specifying the same, yet in an explicit manner.

For example, if a unit has six input ports named `"I1"`, `"I2"`, `"I3"`, `"I4"`, `"I5"` and `"I6"`[34], and the input match specification is:

```
[{"I2", {set, 14.0}}, {"I5", set}, {"I4", {between, {2,8}}},
  {"I1", unset}, {"I6", {among, [3,4,6]}}]
```

Then this function will match iff (if and only if), in terms of input ports for that mock-up unit:

- `"I1"` is unset (i.e. not set to any value)
- and `"I2"` is (exactly) set to 14.00
- and `"I4"` is set to a value in [2,8]
- and `"I5"` is set (to any value)
- and `"I6"` is set to 3, 4 or 6

One can note that the order of the pairs does not matter, and that the input port `"I3"`, not being listed, can thus be in strictly any state.

18.4 Output State Specification

When a given clause is evaluated (implying none of the previous ones could apply), if both its **current time and input specifications are matching the current runtime and state information**, then this clause is selected, and the **output ports of the mock-up unit are then set as this clause specifies**.

---

[33] The relative error between X and Y being the absolute value of their difference divided by their average value: `2*abs((X-Y)/(X+Y))`, for X different from -Y (otherwise `abs(X-Y)` is used instead).

[34] Please note that the coupling layer allows port names to be any string; input ports do not have to be named `"I1"`, `"I2"`, etc.; therefore `"attila woz here"` and `"FelixTheCat-1337"` would be perfectly suitable (and of course the same applies to the name of output ports as well).

An output state is defined as an (unordered) list of pairs, whose first element designates an output port (identified by its name), and whose second one specifies the associated state it should be set to.

Possible specified states are:

- the `reassign` atom to set again this port to the same state, whatever it is
- the `unset` atom, so that the corresponding output port is (becomes or remains) explicitly not set
- a `{set,V}` pair, where `V` is the value to which this output port shall be set
- a `{state_of,I}` pair, where `I` is the name of an input port of that unit, in which case the state of the output port will be assigned to the one of the specified input port

If an output port is not listed in the specification, then it will be kept in its current state, knowing that all output ports are initially, once created, `unset`.

The `reassign` atom is therefore a way to feed again the connected channel with the same value as it held previously. If this port was previously unset, it will simply stay so.

Knowing that the setting of an output port is punctual (i.e. a one-time event is sent, then the output port comes back to its `unset` base state), we can see that, in a clause, an output port can be considered as always being initially `unset`. As a consequence, specifying the `unset` atom for its new status is optional (since not specifying at all that output port does the same).

For example, if the output state specification of a clause is:

```
[ {"O7", reassign}, {"O1", {set,6}},
  {"O2", {set,3.14}}, {"O5", {state_of,"I2"}} ]
```

then, should this clause be selected, the output ports of this mock-up unit will be assigned to the following state:

- `"O1"` set to 6
- `"O2"` set to 3.14
- `"O5"` having the same state as input port `"I2"`
- `"O7"` staying unchanged
- all other ports being inactive (as if they were unset)

18.5 Consistency and Checking

Of course, both the input match specifications and the output state specifications must respect the typing information (the `T` in `SUTC`) of the ports that they may reference.

For example:

- `{between,1.1,1.7}` cannot apply to an input port typed as a boolean one

- `{state_of,I}` should not be specified if the corresponding output port has not the same associated type information as the input port `I`

The dataflow infrastructure will perform some basic checking at runtime, yet some care should be taken by the user to inject only legit data.

18.6 Examples of a Mock-up Function

Now such a definition should be quite easy to interpret:

```
f( 0, [ {"ip_1", {set,true}}, {"ip_3", {set,3}} ] ) ->
   [ {"op_2", {set,89}}, {"op_4", {set,false}} ];

f( 0, [] ) ->
   [ {"op_1", {set,1}}, {"op_2",unset} ];

f( 1, []) ->
   [ {"op_2", {state_of, "ip_7"}} ];

f( any_time, [] ) ->
   [ {"op_4", {set,true}} ].
```

Indeed that mock-up function `f` is defined thanks to four clauses, to be read as detailed below.

The **first clause** will require, if at time step `0`, an exact match for both the input ports named `"ip_1"` (which must be set to `true`) and `"ip_3"` (which must be set to `3`). If this occurs, then the evaluation of `f` is over and output ports `"op_2"` and `"op_4"` will be set respectively to `89` and `false`, while the other ones will be unchanged.

Should this first clause not match, the **second one** will be tried. It references the same time step `0`, yet has an empty input match spec. This means that, for that time step, it will be a "catch-all" clause, i.e. a clause that will match necessarily, regardless of the state of the input ports. In this case `"op_1"` will be set to `1`, `"op_2"` will be explicitly unset, and the state of the other output ports will remain as it is.

As the **third clause** deals with another time step than `0`, it has a chance to match (the previous clauses covered all possible cases for time step `0`). We see that it behaves as a catch-all for time step `1`, resulting in the `"op_2"` output port having the same state as the `"ip_7"` input port.

Finally, the **fourth clause** is an universal catch-all, for all time steps and all configurations of input ports. This implies that the corresponding mock-up unit will be able to be evaluated in all possible cases; the role of this particular clause here is only to set the `"op_4"` output port to `true`.

Another example is a very simple one, the universally defined **identity mock-up function**, defined as:

```
f(any_time,[]) ->
 [].
```

18.7 Data-Based Mock-up Definition

A mock-up unit can be seen more as data (output sets being matched to input ones) than as code.

Therefore, rather than *implementing* a mock-up function as done in the previous section, a means is provided in order to define such a function based on an information stream (typically a file).

Defining the syntax of these data is the purpose of our *Dataflow Unit Mockup Format* (abbreviated as `DUMF`), described here. As a consequence, we recommend that the file extension for such a content is `dumf`, like in: `my_model_v4.dumf`.

Fortunately, the corresponding data-based descriptions are directly similar to the implementations that have been detailed above:

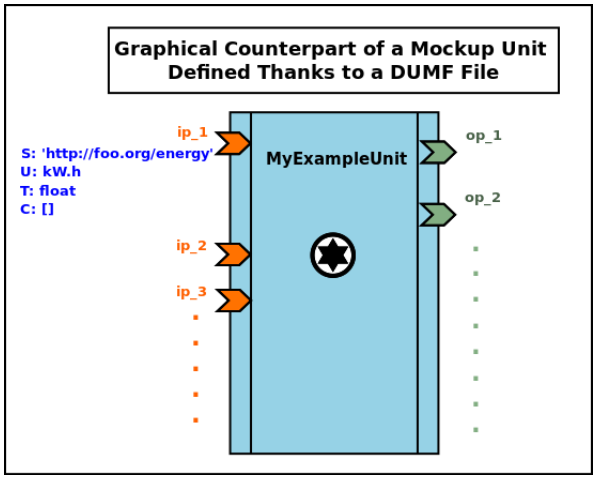
- a mock-up function was implemented as a series of clauses, its data counterpart is an (ordered) list of clause definitions
- each implemented clause of that function corresponds then to an item of that list, i.e. a clause definition made of two elements:
  - the first element is a pair defining the time information and input match specification corresponding to this clause
  - the second element details the output state definition that will be applied, should the first element match

So the full, data-based version of a unit relying on the same clauses as specified in the first mock-up function example section may simply be a `my_mockup_example.dumf` file whose content may read as (note the few ellipses done with `"..."`, in order to shorten the listing):

```
% This DUMF data file defines the mock-up version of the
% 'class_MyExampleUnit' unit.

% First the metadata for this unit:
{ unit_type, 'class_MyExampleUnit' }.
{ mockup_author, "Jiminy Cricket" }.
{ mockup_author_contact, "jc@fantasy-world.org" }.
{ mockup_version, "1.0.3" }.
{ mockup_date, "16/2/2017" }.
{ activation_policy, activate_when_all_set }.

% Then the definition of its input ports:
{ input_port_specs, [
   [   { input_port_name, "ip_1" },
       { value_semantics, 'http://foo.org/energy' },
       { value_unit, "kW.h" },
       { value_type_description, "float" },
       { value_constraints, [ positive ] } ],
   [   { input_port_name, "ip_2" }, ... ],
   [   { input_port_name, "ip_3" }, ... ],
   ... ] }.

% Followed by the definition of its output ports:
{ output_port_specs, [
   [   { output_port_name, "op_1" }, ... ],
   [   { output_port_name, "op_2" }, ... ],
   ... ] }.

% Finally we define in which state the output ports of this unit
% shall be, based on the following input match specs:
{ mockup_clauses, [
   { {0,[{"ip_1",{set,true}},{"ip_3",{set,3}}]},
        [{"op_2",89},{"op_4",false}]},
   { {0,[]},
        [{"op_1",1},{"op_2",unset}]},
   { {1,[]},
       [{"op_2",{state_of,"ip_7"}}]},
   { {any_time,[]},
       [{"op_4",true}]}
 ] }.

% End of the mock-up definition.
```

These two forms (these `mockup_clauses` and the previous function `f/2`) are basically the same.

As a result, this DUMF file fully describes a mock-up unit that may be represented as:



Once the clauses are expressed according to this format, one may think of creating mock-up units directly from such a stream of information, without writing any code.

For that, the DUMF format includes not only these clauses, but also all the other informations that a mock-up unit - as any other processing unit - must provide. Namely:

- metadata such as its name, the type of this unit (ex: of use for its (unit) manager), etc.
- the specification of its input and output ports

These three blocks of data, with the final addition of the clauses, form a complete description of a mock-up unit, and thus an operational DUMF stream.

See below an example of conforming file, `ReferenceExampleMockup.dumf`:

```
% This DUMF data file defines the mock-up version of the unit named:
% class_MyExampleUnit
%
%
% Please refer to the 'Sim-Diasca Dataflow HOWTO' for more information
% about Mock-up Units.
%
% Generated on 21/03/2017 18:04:31, by user 'jiminy'.
%

{ dumf_version, "0.3.1" }.

{ unit_type, 'class_MyExampleUnit' }.

{ mockup_author, "Jiminy Cricket" }.
{ mockup_author_contact, "jc@fantasy-world.org" }.
```

```
{ mockup_version, "1.0.0" }.
{ mockup_date, "16/02/2017" }.

{ activation_policy, 'activate_when_all_set' }.


{ input_port_specs, [

    [
        { input_port_name, "ip_1" },
        { comment, "This is my first input port" },
        { is_iteration, 'false' },
        { value_semantics, 'http://foo.org/energy' },
        { value_unit, "kW.h" },
        { value_type_description, "integer" },
        { value_constraints, [positive] }
    ],

    [
        { input_port_name, "ip_2" },
        { comment, "This is my second input port" },
        { is_iteration, 'false' },
        { value_semantics, 'http://foo.org/pollution' },
        { value_unit, "g.cm^-3" },
        { value_type_description, "float" },
        { value_constraints, [] }
    ],

    [
        { input_port_name, "ip_3" },
        { comment, "This is my third input port" },
        { is_iteration, 'true' },
        { value_semantics, 'http://foo.org/length' },
        { value_unit, "m" },
        { value_type_description, "integer" },
        { value_constraints, [non_null] }
    ]

] }.


{ output_port_specs, [

    [
        { output_port_name, "op_1" },
        { comment, "This is my first output port" },
        { is_iteration, 'false' },
        { value_semantics, 'http://foo.org/adult_count' },
        { value_unit, "dimensionless" },
        { value_type_description, "integer" },
```

```
        { value_constraints, [positive] }
    ],

    [
        { output_port_name, "op_2" },
        { comment, "This is my second output port" },
        { is_iteration, 'true' },
        { value_semantics, 'http://foo.org/operation_status' },
        { value_unit, "dimensionless" },
        { value_type_description, "boolean" },
        { value_constraints, [] }
    ],

    [
        { output_port_name, "op_3" },
        { comment, "This is my third output port" },
        { is_iteration, 'false' },
        { value_semantics, 'http://foo.org/operation_status' },
        { value_unit, "dimensionless" },
        { value_type_description, "boolean" },
        { value_constraints, [] }
    ],

    [
        { output_port_name, "op_4" },
        { comment, "This is my fourth output port" },
        { is_iteration, 'false' },
        { value_semantics, 'http://foo.org/pollution' },
        { value_unit, "g.cm^-3" },
        { value_type_description, "float" },
        { value_constraints, [] }
    ]

] }.


{ mockup_clauses, [

  { 0,
    [
        { "ip_1", { between, 2, 5 } },
        { "ip_3", { set, 3 } }
    ],
    [
        { "op_2", { set, false } },
        { "op_4", { set, 89.5 } }
    ] },

  { 0,
    [
```

```
            { "ip_2", { around, 42.0, 0.0001 } }
        ],
        [
            { "op_1", { set, 1 } },
            { "op_2", unset }
        ] },

      { 1,
        [
            { "ip_3", { among, [1,2,3] } }
        ],
        [
            { "op_4",
              { state_of, "ip_2" } }
        ] },

      { any_time,
        [
            { "ip_1", unset }
        ],
        [
            { "op_2", { set, true } }
        ] }

    ] }.
```

Such a complete description of a mock-up may simply be stored in a file, so that it can be later re-used through the `read_mockup_unit_spec/1` static method of the `DataflowMockupUnit` class, allowing a unit manager to create instances of this mock-up unit, for example thanks to the `create_initial_mockup_units/4` static method of the `DataflowUnitManager` class.

The concept of mock-up *variety* is currently purely documentary. Mock-up units are classical processing units to which we attach a set of mock-up clauses (in order to define their behaviour when activated). Thus, it is possible to imagine having two mock-up units sharing all the attributes of a processing unit but acting according to different mock-up clauses: we would then distinguish them as two *varieties* of a same mock-up unit type[35].

About naming the DUMF file, the basic convention is that if one wants to make a mock-up unit emulating a future real model, say a Python unit that would be named `VehicleTypeUnit` and which would be implemented in `vehicle_type_unit.py` for instance, then it should be done in a file named

[35] This vocabulary distinction appears from the fact that we are concerned with emulated models, and each emulated model corresponds to an emulated (mock-up) `unit_type` in the DUMF specifications (since even more generally in dataflows, with the vocabulary of Sim-Diasca, a model is implemented as a type of processing unit). If we imagine a mock-up designer defining two different sets of clauses in two DUMF files which declare a same `unit_type` (and share the same values for everything else but the clauses), then we end up with two *varieties* of this same emulated model (or *varieties* of this mock-up unit type). If it is not clear enough, we can put it in other words: since a fixed set of clauses leads to instantiate identical mock-up units (a *variety*), we can instantiate a different kind of mock-up units by just modifying the clauses (then creating other *varieties*).

`VehicleTypeMockup.dumf`.

Of course, in practice, the DUMF format is most probably too low-level, too textual for domain experts or model implementers to make a direct use of it.

Indeed units can easily have several dozens of input and output ports, and mock-up units may have to be defined over a very large number of time steps.

Two approaches were then imagined to ultimately obtain the mock-up data in that targeted format:

- defining a **lightweight GUI** in order to ease (and check) the entering of these information, storing them in this mock-up format
- defining a **spreadsheet-based template** that would be filled by the persons closer to the models and then automatically translated into a proper mock-up data-based definition
  - such a template, compliant with LibreOffice and Microsoft Office, has been devised in order to streamline the specification of mock-up units
  - the filled templates (saved as OpenDocument file, whose extension is `*.ods`) can then be automatically translated into their canonical DUMF counterpart (see our `spreadsheet-to-dumf.escript` script for that)

While such a GUI is not implemented yet, it is now possible to write a mock-up definition in a spreadsheet and to convert it in the DUMF format seen above.

18.8 Mock-up Definition from a Spreadsheet

The script translating a user-defined spreadsheet to a DUMF file needs the former to stick to a template, which is also provided in the Sim-Diasca repository.

The template spreadsheet was first designed using Microsoft Excel 2013 and is named `MockupReferenceExample.xlsx`. We exported it to the ODF format used for instance by LibreOffice 5, resulting in `MockupReferenceExample.ods`[36].

Both formats are supported by the script.

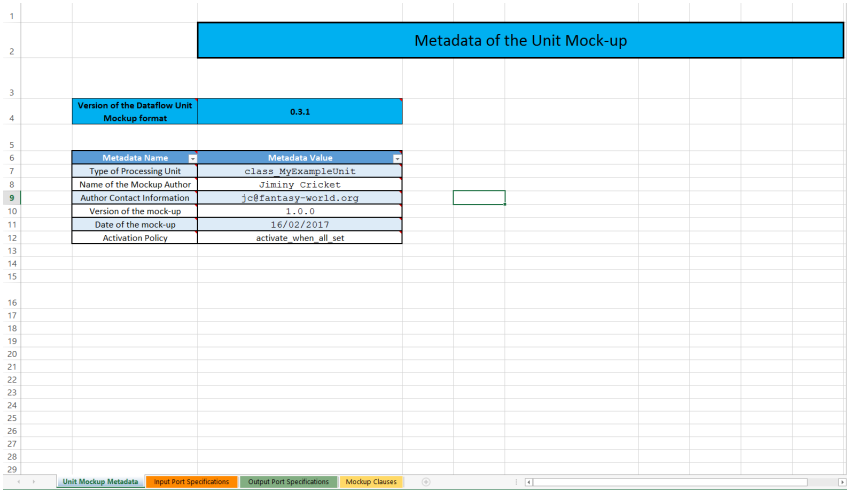
One may note that, for general clarity, the previous naming convention should still hold, by simply adapting the file extensions. Hence for a target model `VehicleTypeUnit`, the Excel version of the mock-up definition file should be `VehicleTypeMockup.xlsx` and the ODF version should be `VehicleTypeMockup.ods`.

Here is the reference Excel spreadsheet cited above, consisting of four worksheets, each representing one of the four blocks of data seen in the previous DUMF example[37].

First, the metadata associated to a mock-up unit:

[36] The path to all the mock-up support in Sim-Diasca is `sim-diasca/src/core/src/dataflow/mockup_support`. The transformation script can be found there, named `mockup_spreadsheet_to_dumf.escript` and the template spreadsheets are in the `tests` subdirectory (alongside the previous example of DUMF file).

[37] The overall structure of `ReferenceExampleMockup.xlsx`, as well as the structures of the individual worksheets, are protected by a password. Currently, this password is *dataflow*.



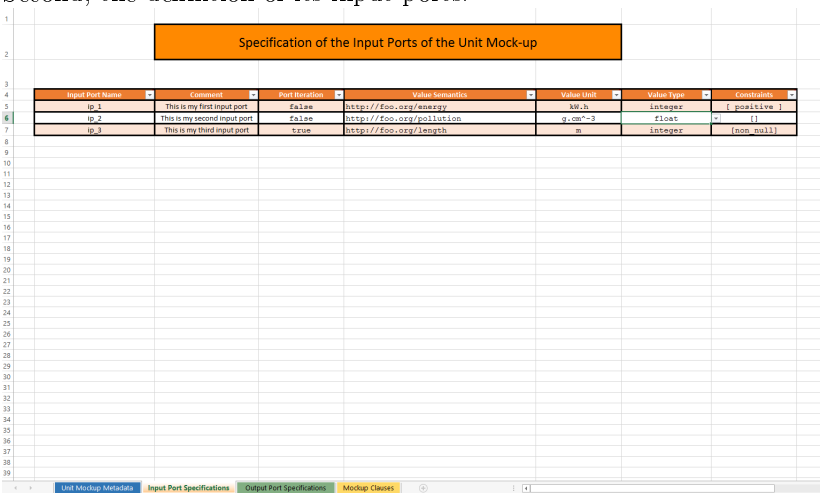
Metadata of the Unit Mock-up

Version of the Dataflow Unit Mockup format	0.3.1

Metadata Name	Metadata Value
Type of Processing Unit	class MyExampleUnit
Name of the Mockup Author	Jiminy Cricket
Author Contact Information	jc@fantasy-world.org
Version of the mock-up	1.0.0
Date of the mock-up	16/02/2017
Activation Policy	activate_when_all_set

Unit Mockup Metadata | Input Port Specifications | Output Port Specifications | Mockup Clauses

Second, the definition of its input ports:

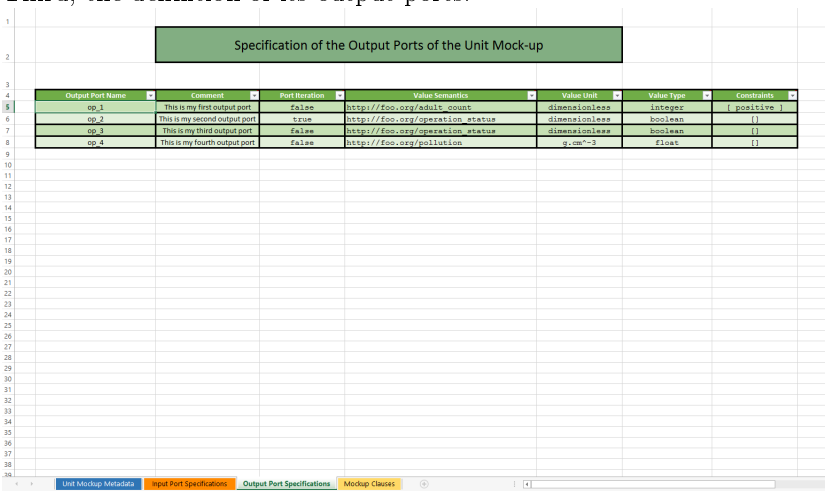


Specification of the Input Ports of the Unit Mock-up

Input Port Name	Comment	Port Iteration	Value Semantics	Value Unit	Value Type	Constraints
ip_1	This is my first input port	false	http://foo.org/energy	kW.h	integer	[positive]
ip_2	This is my second input port	false	http://foo.org/pollution	g.cm^-3	float	[]
ip_3	This is my third input port	true	http://foo.org/length	m	integer	[non_null]

Unit Mockup Metadata | Input Port Specifications | Output Port Specifications | Mockup Clauses

Third, the definition of its output ports:



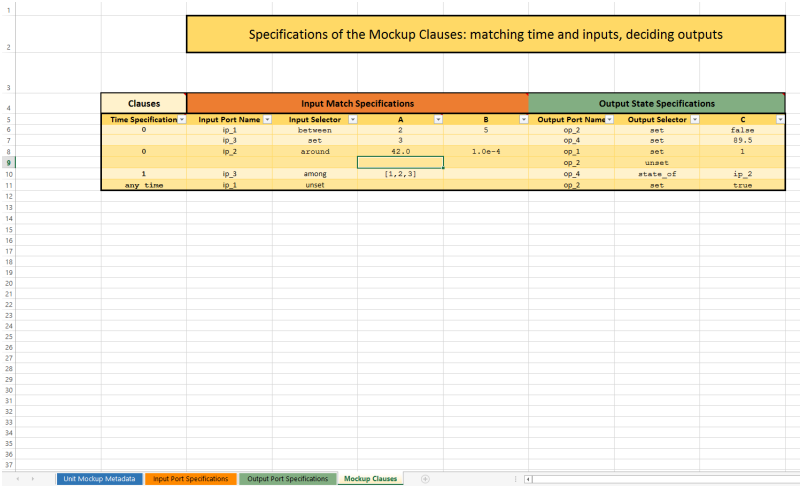
Specification of the Output Ports of the Unit Mock-up

Output Port Name	Comment	Port Iteration	Value Semantics	Value Unit	Value Type	Constraints
op_1	This is my first output port	false	http://foo.org/adult_count	dimensionless	integer	[positive]
op_2	This is my second output port	true	http://foo.org/operation_status	dimensionless	boolean	[]
op_3	This is my third output port	false	http://foo.org/operation_status	dimensionless	boolean	[]
op_4	This is my fourth output port	false	http://foo.org/pollution	g.cm^-3	float	[]

Unit Mockup Metadata | Input Port Specifications | Output Port Specifications | Mockup Clauses

Finally, the definition of its mock-up clauses, specifying the outputs that

shall correspond to specific times and inputs:



18.9 A few Supplementary Pieces of Advice

- inside the metadata worksheet, the first version listed (`Version of the Dataflow Unit Mockup Format`) is read-only, as it is the current version of the mock-up *format* (not the version of the particular mock-up being defined; for that see the `Version of the mock-up` metadata instead); please ensure you are always using a spreadsheet template in the latest, stable version of this DUMF format (otherwise it is bound to be rejected by tools that are in more recent versions)
- the overall structure of the Excel spreadsheet and each of worksheets are protected (locked by default), to avoid erroneous user-originating changes; they can nevertheless be unlocked thanks to the `dataflow` password; use it with care!
- semantics shall be always specified; a warning is emitted otherwise
- exotic, Unicode characters shall be avoided; otherwise a warning will be issued and the corresponding string will be replaced with `(non-ASCII string)`
- when defining a boolean value, it should be specified as following strings: either `"true"` or `"false"` (we recommend not to use Excel-defined boolean constants, which are represented as `TRUE` / `FALSE`, `VRAI` / `FAUX`, etc.)

18.10 Possible Enhancements

- the patterns recognized could include the state of another input port (ex: `{I4,I6}` meaning that `I4` should be in the same state as `I6`), of course provided that the dependency graph remains acyclic
- port names could also be pattern-matched; for example an input match spec could include `{"ip_*",{set,3}}` to specify that any input port whose name is prefixed with `ip_` and that is set to `3` would validate this part of the match

- during a time-step, a given unit might be triggered any number of times (from none to more than once); even if introducing logical moments (i.e. replacing timesteps with a pair made of a timestep and a logical moment, i.e. a diasca) is probably not desirable, maybe specifying whether a unit is allowed to be triggered once (`once`) or any number of times (`always`) could be useful

19 Integrating a Model As a Dataflow: a Short Walkthrough

So you've got a `Foobar` model, maybe pre-existing, maybe just specified, and you want to integrate it in a more general dataflow? Here is a list of simple steps to go through in order to ease that integration.

For the sake of example, let's suppose that this `Foobar` model performs energy-related assessments in the context of cities.

19.1 Preliminary Step (#0): Remembering the Basics

Let's recap first the general structure that we target and the features we need to support.

A model embodies **computations** of some sorts (for example, here, some energy evaluations) that are **intermingled with others** (ex: there may be interrelated evaluations about waste or transportation), the whole **applying to the state of a system** (ex: a city) and **updating it in turn** (ex: all these evaluations are performed for a given year, and the dynamics they capture will lead to an updated city, available for the next simulated year).

To turn such a simulation into a dataflow, both the **state** of the system and the **computations** performed on it have to be modelled thanks to dataflow constructs.

Here the state is typically modelled based on **Dataflow Objects** (ex: the city as a whole may be hierarchically divided into districts, buildings, households, etc. - each of these urban objects being represented by a dedicated dataflow object instance).

The main role of these dataflow objects is to store, thanks to attributes, the relevant state information of these various parts of the system so that the expected computations can be carried, i.e. so that these computations can be fed with the data they need and so that they can as well update that state with their results. As a consequence, **prior to the integration of the computations, an agreement on the structure** (based on dataflow objects) and **on the content** (based on the attributes of these objects) **of the description of the system at hand shall be found**.

As for the computations (including the ones provided by the `Foobar` model), they are to be described macroscopically in terms of a set of **Dataflow Processing Units** (ex: a type of unit can correspond to the energy evaluation, whereas another type of unit may take care of waste and transportation).

Of course **multiple instances of a given type of unit may exist** to account for the underlying multiplicities of dataflow objects. For example, if some computations have to be done strictly on a per building basis, then a corresponding processing unit type may be defined, and a bijection (a one-to-one relationship) between buildings and such unit instances should exist.

Moreover one can note that not only a given unit type may be instantiated more than once, but also that **such a unit may have to be created and deleted dynamically**, in the course of the simulation. In our example, on a given simulated year the creation of a building in the city shall result in the creation of a related instance of our unit type; conversely, destroying a building shall imply the deletion of its associated unit instance.

Finally, whether or not urban objects are created or deleted, *connections* between dataflow elements (processing units and urban objects) are in the general case bound to be modified over simulation time.

These **unit-level operations** (creation, connection, update, deletion, etc.), whether they are done initially or in the course of the simulation, **are to be driven by dedicated unit managers** - whose design and implementation must be planned as well.

19.2 Step #1: Ensure that the Overall Simulated World Can be Structured As a Dataflow

In this step we want to retain a clean dataflow approach in order to:

- describe the `Foobar` model as a whole
- insert in its context

At this step we still see the `Foobar` model simply as a single, monolithic logical unit. We specify here only what are the "high-level" computation features that each of the units involved in the dataflow offers and the information that each unit requires (not how precisely units are to operate internally).

The purpose of this step is:

- to cleanly **separate** the single, consensual description of the system **state** from the usually multiple, diverse **computations** that shall be operated on it; the crucial point is that this state must be defined so that it provides all the information needed by *all* computations to be operated (those of `Foobar` and the ones of all other units) - and preferably only them, while keeping these pieces of data orthogonal, i.e. avoiding any duplication of information[38]
- to establish how these computations are **organised** - including the ones that are to be taken in charge by this `Foobar` model
- to express the whole uniformly, and **in terms of dataflow constructs** (objects and processing units, and also streams of information)

19.3 Step #2: Determine the Specific Relationships Between the Dataflow and this Model

At this step we concentrate on the `Foobar` model and on the units in direct relationship with it.

There will be indeed actual connections between this black box of interest and the rest of the dataflow: the `Foobar` model is to be **fed by inbound dataflow channels**, and reciprocally **outbound channels are to stem from this box** and feed other elements of the overall dataflow.

[38] For example any needed *living space* attribute of a (dataflow object) building shall be defined once for all, instead of introducing as many (attribute) variations of it as there will be different unit types requiring such an information. Otherwise the state of dataflow objects would be bound to become increasingly difficult to maintain, if not silently inconsistent (ex: one version of the livable surface being updated while the others not).

This step requires that all dataflow elements in *direct* interaction with the `Foobar` model box (whether they are upstream or downstream) are listed and **specified in terms of connectivity** with `Foobar`: the corresponding channels shall be named and defined, with their multiplicity and their corresponding SUTC information.

The list of **input and output ports that should be ultimately provided** by the logical unit corresponding to `Foobar` are to be then determined from these channels.

An added bonus of completing this step is that it enables the possibility of defining a mock-up for that `Foobar` model: now that it is more formally specified as a self-standing component, one is able to devise input and output datasets that can emulate its behaviour as a whole. See the section about mock-up units for more details.

Alternatively, the completion of the next step might be awaited, so that *individual* units corresponding to this model can be each represented by a dedicated mock-up.

19.4 Step #3: Break the Black Box Into Actual Dataflow Units

In the previous steps, the `Foobar` model was seen as a single black box (one "abstract", logical unit). Now is the time to break the `Foobar` black box into pieces, and to express them as a set of actual dataflow blocks.

Indeed, in the general case, for each model **multiple dataflow units are needed** in order to account for the various computational stages and multiplicities that a model must support.

For example, some aggregations (ex: spatial ones) are often to be done before and after the central, domain-specific computations of the model, and for that they need a varying (runtime-determined) number of input and output ports (ex: an instance of the `Foobar` model may have to accommodate for any number of energy sources).

If simple models may be expressed only thanks to a single processing unit relying on port iterations, more complex models often require to be translated into a *set of interlinked dataflow units*, some of which taking in charge the bulk of the computations while others are in charge of transforming (ex: aggregating, summing, averaging, converting, routing, etc.) information on their behalf.

So the outcome of this step is to have a **design** of the `Foobar` model once it has been translated into **a collection of actual dataflow units** whose superposition provides the combined input and output ports that have been determined in the previous step.

19.5 Step #4: Implement the Corresponding Actual Units

Now that the `Foobar` model has been split into real, dataflow units, in the general case **these units** do not exist yet, and thus **have to be implemented**[39].

[39] Depending on the history of the project, some already available units may be re-used. Similarly, some units may perform fairly standard operations (ex: simple aggregations) and thus may be provided by the dataflow infrastructure as built-in. Usually at least the model-specific computations must be developed.

Each newly-introduced processing unit can either be a *native* unit (i.e. written in Erlang and thus directly developed within the dataflow infrastructure), or a unit relying on a *language-specific binding*.

In this latter case, depending on the programming language that has been preferred, the unit developer will typically rely either on the Python dataflow binding or on the Java one. In both case **the provided dataflow API must be used** in order to define the new unit.

In practice, it boils down simply to:

1. making this new processing unit **inherit** from the base dataflow unit type
2. defining the **construction parameters** needed to create a new instance of such a unit
3. specifying accordingly what its **input and output ports** are (number, name, whether they are iterations, SUTC information, etc.)
4. defining **how this unit should be activated** (typically whether the setting of any, or all, of its input ports is needed)
5. defining **what the unit should do when it is activated** (typically read at least some of its input ports that have been set, compute elements from them and from its state, possibly update in turn some of its output ports and its own state)

19.6 Step #5: Add the Corresponding Unit Manager(s)

The previous steps led to the availability of the whole implementation for the `Foobar` model: now, for this model as well, the overall **dataflow objects bear all necessary information** (step #1), its **connectivity has been established** (step #2) and **its complete counterpart in terms of dataflow units has been designed and implemented** (respectively step #3 and #4). Therefore we defined how the `Foobar` model is to be evaluated once properly set-up.

This last step (#5) consists on the definition or update of the **associated unit manager**, in charge of the correct insertion and management of the units corresponding to `Foobar` in the overall dataflow.

This includes at least how its units shall be created and linked whenever an instance of the `Foobar` model is needed; various dataflow-level events may have to be supported by a unit manager.

In our example, the `Foobar` unit manager should be able to be notified that a new building (dataflow object) has been created, so that this manager can create in turn the appropriate new instance of `Foobar`: the unit manager should ensure that the various units for `Foobar` are then correctly instantiated and also connected (between themselves and also with the rest of the dataflow).

20 Requirements For the Dataflow Integration of a Model

- `R1`: a description of the overall dataflow must be defined, in which the target model is represented by a single, abstract, dataflow unit; its inbound and outbound channels shall be specified
- `R2`: the target model itself shall be defined in terms of dataflow constructs
- `R3`: the general operational rules apply (ex: compliance with the underlying operating system and libraries)

21 Implementation Section

21.1 Mode of Operation

As already mentioned and represented in the class diagram below, **processing units** are implemented as instances of the `DataflowProcessingUnit` class, a child class of the `DataflowBlock` one, itself a child class of the basic (SimDiasca) `Actor` one (note that, actually, *all* classes represented on this diagram are child classes - directly or not - of the `Actor` one).

Most units are *passive* actors: they will be solely scheduled if/when some of their input ports are triggered, which, depending on their policy, might result in their activation. Some units (ex: source ones) may be *active*, in the sense that they may choose to develop a spontaneous behaviour (typically to auto-activate periodically).

A special case of unit has been defined, the `DataflowMockupUnit`. Such **mock-up unit** provides a generic emulation of a unit, associating output values to input ones based on the data (rules) it has been provided with. It is typically used to develop termination plugs that allow to wait until the implementation of the final unit is ready, and to validate it afterwards.

Ports (input and output ones alike) are mere data-structures (records) held by their block (maintaining an associative table for both of them).

We propose the following convention to name the variables holding a port:

- the name of the variable shall reflect the name of the corresponding port (ex: if the port is named `"My distance"`, the variable name may begin with `MyDistance`
- if it is an input port, the variable name may end with `IPort` (ex: `MyDistanceIPort`)
- if it is an output port, the variable name may end with `OPort` (ex: `MyDistanceOPort`)

Implementation-wise, **channels** do not exist per se, they are abstracted out thanks to ports.

The static channel-related information (ex: `SUTC`, for semantics, unit, type, constraints) is held by all endpoints (the output port and its linked input ports); as their metadata are checked for compliance when ports get connected, the exchanged values do not include them, since they are automatically checked in turn for compliance at port sending and receiving.

Dataflow **values** are records that store their accuracy, timestamp and, of course, actual value. As always, they are exchanged through actor messages, managed by the engine.

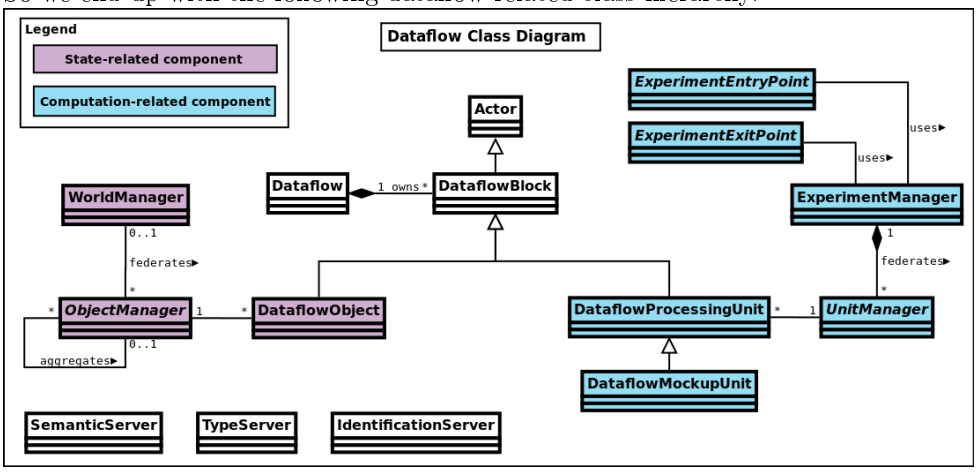
As for the **dataflow objects**, they unsurprisingly inherit from the `DataflowObject` class. These actors participate to the description of the simulated world and, thanks to their **dataflow attributes** (special actor attributes that map to a pair of input and output ports), they are ready to be integrated in a dataflow.

Finally, instances of dataflow objects of a given class (ex: `Building`) are governed by a **dataflow object manager** specific to this class (ex: `BuildingManager`). All these managers inherit from the `DataflowObjectManager` base, abstract class.

Similarly, all instances of a given type of unit (ex: `EnergyDemand`) are governed by a **unit manager** specific to this class (ex: `EnergyDemandManager`), and all these managers inherit from the `UnitManager` base, abstract class.

The overall **dataflow** could have remained implicit (in the sense that no specific instance could have been defined in order to designate it as such, a dataflow being just an abstract concept corresponding to a set of actual, interconnected blocks), yet having it in an explicit form (i.e. as an instance of a well-defined `Dataflow` class) has been deemed more convenient and future-proof.

So we end up with the following dataflow-related class hierarchy:



21.2 Usage: Defining One's Dataflow

Preferably an overall schema of the dataflow is determined first. One must keep in mind that *a dataflow is a graph of computations*, i.e. a description of interlinked *tasks*, processed by units, possibly fueled with information from objects.

Then, for each type of unit (as of course a dataflow may include multiple instances of the same unit), a child class of `DataflowProcessingUnit` shall be defined.

The actual processing done by that kind of unit is to be implemented by overriding its `activate/1` method. It will be based on the unit state, including the value carried by its input ports that are set. In some very rare cases, a spontaneous behaviour might be defined as well, if appropriate for that unit.

Any dataflow object used shall also be defined, which mainly consist on defining its (dataflow) attributes.

Once all object and unit classes are available, the target dataflow instance can be built. This is done by creating first the relevant block instances (either from a data stream listing their construction parameters, or programmatically), interconnecting their ports and registering themselves to their federating dataflow.

Then, once the simulation is started, some source blocks are expected to get activated (possibly thanks to active blocks, or to explicit block activation); their triggered ports shall in turn activate other blocks and trigger other ports, animating the whole dataflow so that it performs the processing that is expected from it.

Please refer to the `Dataflow Urban Example`, whose sources are located in the `mock-simulators/dataflow-urban-example` directory, for a full source of inspiration.

21.3 Class or Instance-level Checking

Any given instance dataflow block (ex: a processing unit) may declare ports, statically or not.

Ports created statically are usually the same for all instances of that type of dataflow element. So, instead of performing checks (ex: in terms of semantics or types) for each of these instances (that are potentially very numerous), the verification is better done once, at the class level - based on its declarations.

For example, for units, any of them should preferably declare statically these information so that its unit manager can check them at simulation startup[40].

To establish whence semantics and typing information come for a given dataflow element, the following rules apply:

- for semantics:
  - any kind of semantics can be reported by this type of dataflow element by having it define and export its `get_declared_semantics/0` static method[41]; this may be a way of specifying the semantics both for the initial ports and for any other port that may be created in the course of the simulation (if specified, must be exhaustive)
  - otherwise (if no `get_declared_semantics/0` method is exported), the semantics may be deduced from its `get_port_specifications/0` static method, if of course it has been defined and exported
  - otherwise, the element does not report any semantics
- for types, a slightly different logic applies: the `get_declared_types/0` static method should be used whenever having to introduce new types, especially so that the types mentioned through `get_port_specifications/0` can be resolved

Defining `get_port_specifications/0` is recommended, as by design the static information that is reported matches the ports that are initially created. Otherwise explicit checking shall be done when creating the actual initial ports, to ensure their information match any one that would be statically defined thanks to `get_declared_{semantic,type}s/0`.

Finally, some amount of runtime checking may still be necessary, as ports may be created dynamically.

21.4 Scheduling Cycle of Experiments

The logical order of the operations involved in the step-by-step evaluation of an experiment has been presented in the section about Experiment Progress.

However dataflows may be arbitrarily complex computation graphs, with various branches and, potentially, cycles, so detecting when the intra-tick evaluation of a given dataflow is over (i.e. when none of its blocks can be triggered

[40] See `class_DataflowElementActor:declare_static_information_for/1`.

[41] For semantics, their name is also their definition (ex: `'my semantics'`), whereas types have to be specifically defined (ex: `my_type` is `[integer]`) before being used (ex: `my_value` is of type `my_type`).

anymore) is not straightforward, as this consists mostly in detecting the *absence* of an event.

The solution elected here, in technical terms, consists on inducing an offset in this three-stage cycle (experiment entry/dataflow evaluations/experiment exit).

Indeed, at each new tick, the experiment *exit* point is triggered first (obviously not doing anything for the very first tick); it is the only actor here having a spontaneous behaviour.

It then triggers (as always thanks to an actor message) the experiment *entry* point, which performs the tick-specific initialisations. This usually leads to the update of various dataflow elements and thus to the evaluation of various dataflow for that tick.

Once none of the dataflow elements set any output port, no other dataflow element can be triggered anymore (no more diasca created), hence the engine determines that this tick is now over, and schedules the next planned one.

Then again the experiment exit point is scheduled and is free to perform any termination action for the dataflow evaluations made at the previous tick. Then it triggers the experiment entry point, which triggers the dataflow evaluations again, and so on.

21.5 Life Cycle

The goal is to rely on a single, shared evaluation infrastructure (taking in charge by a relevant set of singleton managers) allowing for multiple dataflow instances (each with its own object and unit instances).

As a consequence, the dataflow blocks (i.e. the actual dataflow objects and units) are:

- *referenced* by their top-level respective managers (i.e. the world manager and experiment manager, which maintain a per-class list of instances)
- *owned* by the dataflow to which they are registered (which may then delete them appropriately)

As for the various object and unit managers, they are owned by, respectively, the world manager and the experiment one.

Note that all the classes involved here:

- `class_Dataflow`
- `class_Dataflow{Block,Object,ProcessingUnit}`
- `class_Dataflow{Object,Unit}Manager`
- `class_Experiment{Entry,Exit}Point`
- `class_{Experiment,World}Manager`

are child classes of the `class_Actor` one, and as such will have their instances automatically removed at simulation end.

21.6 Implementation Details

The dataflow constructs are defined, in the code base, in the `sim-diasca/src/core/src/dataflow` source tree.

Traces sent by the dataflow architecture are available in the `Core.Dataflow` category and its children categories.

A dataflow initialization file has preferably for extension `.init` (ex: `dataflow-urban-example.init`).

It generally lists the creations of:

- the relevant base components, i.e. the WM and its dataflow object managers, the EM and its dataflow unit managers
- at least one dataflow
- the relevant actual instances of dataflow objects and processing units

22 Appendices

22.1 Annex 1: Design Questions

- Should all output ports of all blocks of the dataflow emit at each diasca a value, even if it did not change (event-based or synchronous)?; if yes, many useless sendings and schedulings, and not all units have the same temporality, so a year-based one, if included in a simulation with a daily one, would have to change its behaviour; so we preferred opting for an **event-based** mode of operation

- As not all state changes/operations are instantaneous, should **delays** (in diascas or ticks) induced by a block be managed? (ex: ignition spark received, explosion happening 4 milliseconds afterwards)

- Would it be possible and useful that units can be **composed**, i.e. that a given unit can actually be recursively made of sub-units? If such a feature was wanted, then ecore could be used to define the corresponding system, and two different approaches could be considered:

  - either defining, directly at this dataflow level, *nested units*, and manage the consequences thereof (ex: when the inputs of a "macro" unit would change, its outputs would change in turn accordingly, yet only *after some delay in terms of logical moments* (i.e. only once some of them elapsed, with state transitions that may be arbitrarily deferred)
  - or introduce new, higher-level concepts, such as the one of *assemblies* that can be nested; an assembly would ultimately translate to a basic, non-nested dataflow, by collapsing a (multi-level, compounded, compact) assembly into a (single-layer, uniform, intricate) dataflow; for that assemblies (either user-defined or generated) would be recursively unboxed and expanded into their parts until only standard dataflow blocks are found (a bit like when going from a higher-level electronic schematics to its full, elementary counterpart at the level of the logic gates)

- Should large datastructures have to be carried by channels, maybe these data currently pushed by an output port shall be pulled by the input ports instead? (anyway this will most probably lead to a term duplication anyway)

- If a model deals with a currency (ex: euros, or US dollars of year 2012), is the best approach to have its unit flagged as `dimensionless` (hence, not `euro`) and complement this information at the semantics level?

22.2 Annex 2: Possible Overall Improvements

- knowing that a given type of unit, thanks to its constructor, can be **parametrised** (leading to its instances behaving differently), this may be represented graphically: instead of designating a unit type as `FoobarUnit`, it may be shown as `FoobarUnit(height,width,color)`

- a type of bus may be named (defining an ordered list of channel types); afterwards, one may consider bus auto-grouping, i.e. having a transparent translation of a bus-as-a-graphical-symbol (thus with N channels underneath) into a single pseudo-channel conveying a N-element tuple containing the related channel values (thus relying on one sending instead of N)

- a group of ports (*portset*?) may be represented by a unique, conventional graphical element (a portset is to ports what buses are to channels); more specific activation policies could rely on portsets

- scale hints could be revamped (as a unit may have one scale, its inputs others, and the same for its outputs)

- a consensual, sufficiently expressive language of types should be defined and enforced all the way regarding the values conveyed by the dataflow (such a check is not done currently)

- the state changes of a dataflow may be collected by a process (should this feature be enabled), which could either write them in a file according to a conventional format (ex: `*.df-state`) or make them available through an ad-hoc http server; in both cases, these information could feed a tool representing graphically (according to the conventions listed in annex 3) the state of a dataflow (as an image), or the changes over time of the state of a dataflow (as a video made out of frames, generated with as few layout changes as possible from one to the next)

- a support for a Python implementation of unit managers (at least the simplest/most classical ones) could be provided

22.3 Annex 3: Conventions for the Graphical Representation of Dataflows

22.3.1 Example Diagrams

When having to represent a given dataflow of interest (typically in a design phase), to favour consistency we recommend that one starts from the diagrams we already made for this document and for the base examples.

For that, one shall use Dia, a free software diagram editor.

Our `dataflow-diagram-toolbox.zip`[42] archive centralizes the best examples for such a reuse, from which more homogeneous user diagrams can be easily derived.

Later, a specific Dia library for dataflows could be devised (should no higher-level tool be available then).

22.3.2 Color Charter

Here are the color definitions that we recommend to respect, for clarity (when two colors are specified, the first is a lighter version of the second):

[42] This archive can be generated from `sim-diasca/doc/dataflow-howto` by running `make`.

Elements to Represent Graphically	Associated Color	Color RGB Definition
Input ports	Dark orange	`ffcd70` / `ff8900`
Output ports	Dark green	`688e68` / `82ae82`
Channels, buses and port-level metadata	Pure blue	`0000ff`
Lines for shapes (ex: units)	Pure black	`000000`
Default background	Pure white	`ffffff`
State-related background	Light purple	`f1e3f1`
Dataflow object	Stronger purple	`cfaecf` / `a13ba1`
Computation-related background	Light blue	`e1ebff`
Dataflow unit	Stronger blue	`96d2e6` / `0000ff`
Scale indication background	Light yellow	`faf8b3`
Probe	Blue	`3838f4`
Post-it like comment	Lighter yellow	`ffffc8`

Buses (i.e. sets of channels) are represented like channels, yet thicker (generally, their line width is to be equal to 0.10 cm times the number of channels they regroup) and barred with a dash (a bit like in electronics), with the channel count being displayed just above.

Both channels and buses may adopt different colors (preferably blueish, though) to help the reader understanding the overall connectivity.

22.4 Annex 4: Credits

Many thanks, among others, go to:

- Samuel Thiriot, for many inspiring comments and ideas
- Omar Benhamid, for rich exchanges about the entry and exit points of a dataflow
- Robin Huart, notably for the mock-up units, the language bindings and the platform integration
- Karel Redon, for thoughts about the buses and their graphical representation, and for the Python workbench