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INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

*Modèle de synchronisation de l'approche AA4MM et  
spécification event-B*

Julien Siebert — Joris Rehm — Vincent Chevrier — Laurent Ciarletta — Dominique Mery

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## Modèle de synchronisation de l'approche AA4MM et spécification event-B

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Theme : Knowledge and Data Representation and Management  
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**Résumé :** Agent and Artefact for Multiple Models coordination (AA4MM)\* est un logiciel développé par Julien Siebert durant sa thèse. Le but de cet outil est de rendre la conception et l'implémentation de simulations de systèmes complexes modulaires et décentralisées. Le but principal est de pouvoir réutiliser des outils (modèles et simulateurs) existants et de les faire interagir afin de simuler des phénomènes à des niveaux d'abstraction différents. La contrainte principale est que les personnes impliquées dans la conception et l'implémentation de telles simulations ne sont pas obligatoirement des experts en théorie de la modélisation et de la simulation. En conséquence, les défis liés à la coordination (synchronisation, respect des contraintes de causalité) sont du ressort du logiciel AA4MM. Ce rapport présente la spécification du modèle de synchronisation. Celle-ci est faite en Event-B et son but est de vérifier que le modèle de synchronisation ne conduit pas à des deadlocks (cas dans lesquels les simulateurs en interaction s'attendent les uns les autres indéfiniment).

**Mots-clés :** Interactions de modèles, co-evolution, spécification formelle, event-b, synchronisation

Ce travail a donné lieu à une collaboration entre Julien Siebert et Joris Rehm

\* <http://www.loria.fr/~siebertj/aa4mm/aa4mm.html>

## AA4MM synchronization model and event-B specification

**Abstract:** Agent and Artefact for Multiple Models coordination (AA4MM)<sup>†</sup> is a framework developed by Julien Siebert during its PhD. It is intended to make the design and the implementation of complex systems simulation modular and decentralized. The main goal is to reuse existing models and simulators and to make them interact in order to simulate different levels of abstraction. The main constraint is that people involved into the design process do not have to care about anything else but modelling. Coordination challenges remain to the framework. This report presents the event-B specification of the synchronization model proposed in [SCC10]. Its goal is to check that the system is never blocked (no deadlock): no simulator is waiting for another indefinitely.

**Key-words:** Models interactions, coevolution, formal specification, event-b, synchronization

<sup>†</sup> <http://www.loria.fr/~siebertj/aa4mm/aa4mm.html>

## 1 Introduction

This document describes and corresponds to the proof of properties of the AA4MM coordination model. It is not intended to argue this model. For these aspects see [SCC10].

### 1.1 Brief description of AA4MM

The Agent and Artefact for Multiple Models and simulators co-evolution (AA4MM) framework is a meta-model based upon the Agent and Artefact paradigm [RVO07]. It has been developed in order to couple heterogeneous models and simulators. Its implementation purpose is to build a society of interacting and co-evolving (existing) models and simulators. Since this society is composed by already existing modeling and simulation tools, some constraints and issues appear [SCC10]. The purpose of this report is not to present all of them. However, for the sake of understanding, some of the issues are presented hereafter.

### 1.2 Issues

1. **Data coherence between models** Scales or dimensions in which a piece of data is represented could be different from a model to another. For example, a position  $pos_1 = \langle x, y, z \rangle$  (with  $x, y$  and  $z$  expressed in *meters*) in a first model can be represented only in two dimensions in a second one :  $pos_2 = \langle x', y' \rangle$  (with  $x'$  and  $y'$  expressed in *kilometers*). A solution proposed in [BRC07] is to define operations (projection, discretisation, reduction) in order to achieve this coherence.
2. **Data compatibility between simulators** Each simulator could implement a single piece of data in its own way (integer, float...) or some simulators may not implement all aspects of a given model. These challenges are discussed in [RAF<sup>+</sup>04]. A solution is to add an entity (a program) between the simulators. Its role is to translate the data in order to respect the compatibility between simulation tools.
3. **Time coherence between models** Each model could have its own time representation. We need to assure, for example, that a time value  $t_1 \in \mathbb{R}^+$  in a first model correspond to a time value  $t_2 \in \mathbb{N}$  in a second one. A possible solution is to express an operation that makes the correspondence between both time values.
4. **Coordination** Each simulator process its own time execution (discrete events, time steps). We must beware of coordination between them. That is, if a simulator needs some data from another one, they must be synchronized in order to respect simulation time consistency.

We choose to use Agent and Artefacts paradigm in order to deal with coherence and compatibility issues (as in [BRC07]). The coordination process can either be done by a central scheduler or by a decentralized protocol. The originality of our model is its decentralized coordination. This raises the question to ensure the synchronization and to respect the causality constraint.

## 2 Coordination of multiple simulators

The goal of time management in distributed simulation is to ensure that local causality constraint is respected [Fuj01]. The next sections present the causality issues and the solution adopted by AA4MM approach.

### 2.1 Introduction

Let  $S \subseteq \mathbb{N}$  be the finite set representing the indices of simulators. Let  $s_i$  ( $i \in S$ ) be the simulator in charge of the model  $m_i$  (we assume that one simulator  $s_i$  is in charge of only one model  $m_i$ ). Let  $m_i$  have  $X_i$  input ports and  $Y_i$  output ports.

### 2.2 Model execution process

Let  $d_i$  be the data produced by an execution of  $m_i$ . When a model  $m_i$  is executed, the simulator  $s_i$  reads input data  $d_j$  from other simulators ( $j \in S$ ) and sets them into the input ports  $X_i$ . Then

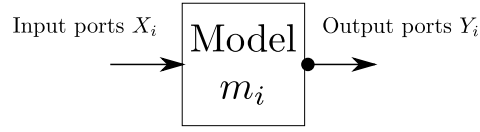


FIG. 1: Model representation, as defined in [ZPK00]

$s_i$  executes the model  $m_i$ , increases its local simulation time from (current)  $t_i$  to (next)  $t_i + \Delta t_i$  and finally proposes output data  $d_i$  to other simulators ( $d_i$  come from the output ports  $Y_i$ ).

**Remark 2.2.1** *Note that  $\Delta t_i$  is not fixed and depends on the execution policy (discrete events or step-by-step).*

The data  $d_i$  produced by the execution of  $m_i$  at simulation time  $t_i$  are timestamped with a time value  $t_i$ . A timestamped data is denoted  $d_i^{t_i}$ . However, since this notation is quite heavy, in this document, it is sometimes simplified in  $d_i$  for the sake of clarity.

### 2.3 Coordination issues

The goal of time management in distributed simulation is to ensure that all the models are executed in the correct order and that the causality constraint is respected [Fuj01]. It means that, if a simulator  $s_i$  depends on output data  $d_j$  produced by  $s_j$ ,  $s_i$  cannot execute its model  $m_i$  until  $s_j$  has produced *valid* data (see definition 2.3.1).

**Definition 2.3.1** *Data are said to be valid (in the point of view of  $s_i$  at simulation time  $t_i$ ) on two conditions. On the one hand,  $d_j^{t_j}$  are produced by  $s_j$  at a simulation time  $t_j < t_i$ . On the other hand, the next data  $d_j^{t_j^{next}}$  produced by  $s_j$  are produced at a simulation time value  $t_j^{next} = (t_j + \Delta t_j) \geq t_i$ .*

When all the input data for the model  $m_i$  are valid in the sense of  $s_i$ , the model execution is said to be *safe* and its execution will not provoke causality constraint violation (see definition 2.3.2, citation 2.3.1 and figure 2).

**Definition 2.3.2** *For a simulator  $s_i$  ( $i \in S$ ), a model execution associated with the current simulation time  $t_i$  is said to be safe to process if all the input data  $d_j$  ( $j \in S$ ) received after this event execution are timestamped with a time value  $\geq t_i$ .*

**Citation 2.3.1** *[...] if a process contains an unprocessed event  $E_{10}$  with a time stamp  $T_{10}$  (and no other with smaller time stamp)<sup>1</sup>, and that process can determine that it is impossible for it to later receive another event with time stamp smaller than  $T_{10}$ , then  $E_{10}$  is said to be safe because one can guarantee that processing the event will not later result in violation of local causality constraint. (Section 3.1 in [Fuj01])*

<sup>1</sup>It means  $s_i$  is going to executes  $m_i$  at simulation time  $t_i = 10$

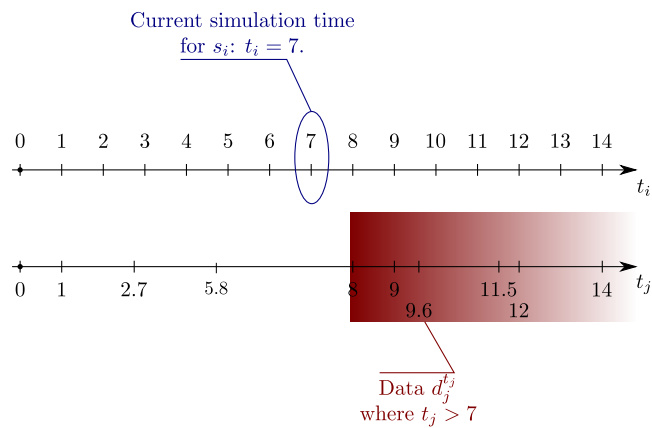
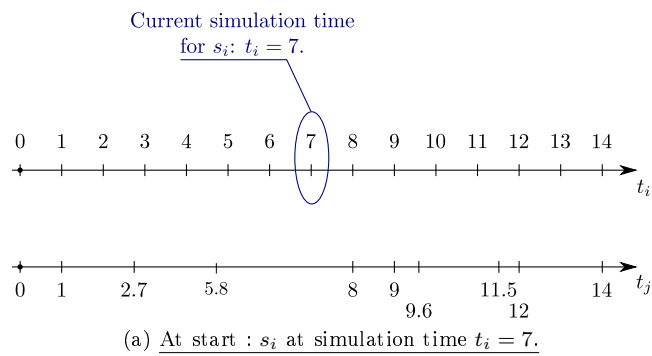
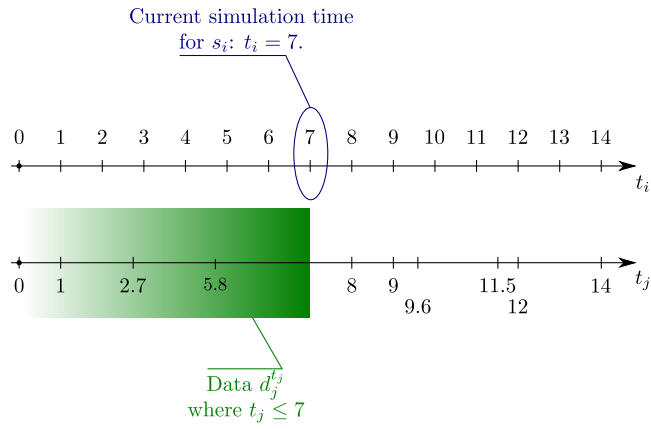
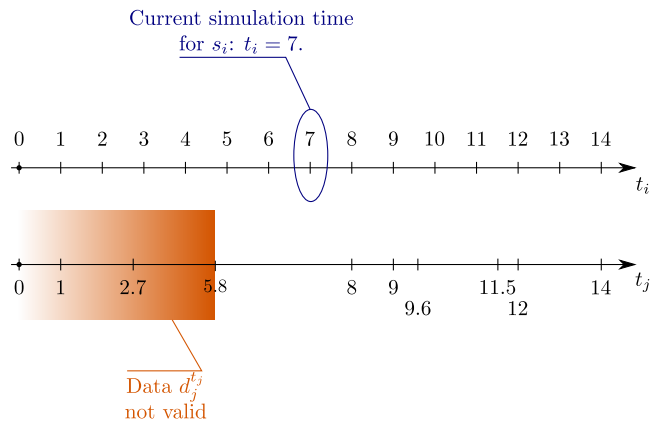


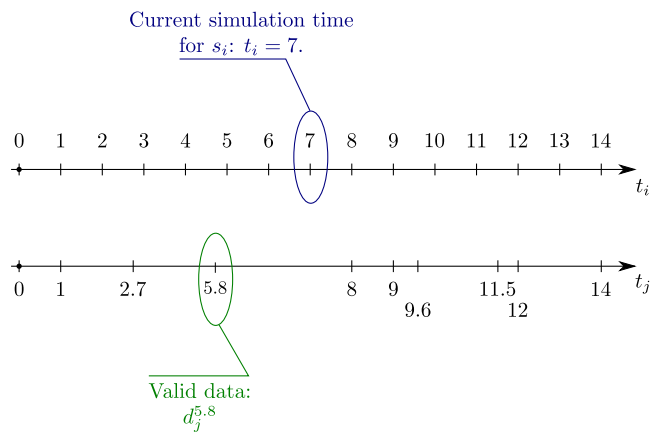
FIG. 2: Valid data example. Simulator  $s_i$  (upper time line) is waiting for *valid* data  $d_j^{t_j}$  produced by the simulator  $s_j$  (lower time line)



(c) Data that fulfil the first condition to be valid  $t_i < t_j$  (see definition 2.3.1).



(d) Data that fulfil the first condition to be valid ( $t_i < t_j$ ) but not the second  $t_j^{next} = (t_j + \Delta t_j) \geq t_i$  (see definition 2.3.1).



(e) Data  $d_j^{5.8}$  is valid in the sense of  $s_i$  for the simulation time  $t_i = 7$ .

FIG. 2: Valid data example. Simulator  $s_i$  (upper time line) is waiting for *valid* data  $d_j^{t_j}$  produced by the simulator  $s_j$  (lower time line)

## 2.4 Validity time interval

In the previous example (figure 2), the problem for the simulator  $s_i$  at simulation time  $t_i = 7$ , is to know that data  $d_j^{5.8}$  is valid. In other sense, that no data are going to be produced between local simulation time values  $t_j = 5.8$  and  $t_j = 7$ . This useful information is only known by the simulator  $s_j$  as it executes its model  $m_j$ .

The principle of our coordination model is to assign a validity interval (denoted by  $\Gamma_j, \forall j \in S$ ) to the exchanged data  $d_j$ . This interval is proposed by the simulator  $s_j$  that produces the data  $d_j$  to be exchanged. Consequently, when a simulator  $s_i$  needs to read input data  $d_j$  ( $j \in S$ ), it just has to check  $\Gamma_j$  to know if  $d_j$  is valid. Since  $s_i$  knows that whether the input data it needs are valid or not,  $s_i$  can wait for valid data or process the model execution (if all input data  $d_j$  are valid). A direct consequence is that the simulators stay synchronized (see section 2.7) and respect causality constraint. The coordination model is said to be correct (see citation 2.4.1).

**Citation 2.4.1** *From the standpoint of synchronization, "correctness" only goes so far as to say that the parallel execution will produce identical results as a sequential execution of the same program. Also it should be pointed out that the adherence of this constraint is sufficient, but not always necessary, to guaranty that no causality errors occurs.* (Section 3.1 in [Fuj01])

### 2.4.1 Definition

The validity interval comes from the valid data definition (definition 2.3.1). It is defined, for every simulator  $s_i$  that executes a model  $m_i$  and increments its local simulation time  $t_i$  by a finite quantity of simulation time  $\Delta_i \geq 0$ , by the equation 1 :

$$\forall i \in S, \Gamma_i = ]t_i; t_i + \Delta_i] \quad (1)$$

The validity interval  $\Gamma_i$  means that, when a piece of data is produced at simulation time  $t_i$ , then this piece of data is valid until the next time the model will be executed (i.e. at simulation time  $t_i + \Delta_i$ ). In other words, the data  $d_i^{t_i}$  is not modified for the simulation time interval  $\Gamma_i = ]t_i; t_i + \Delta_i]$ .

## 2.5 Simulation algorithm

The following algorithm (see algorithm 1) represents one model execution *step* for  $s_i$ . One model execution *step* depends on the execution policy implemented by the simulator. That is,  $s_i$  executes  $m_i$  for one simulation step (if step-by-step simulation) or one simulation event (if discrete event simulation). The whole simulation process for  $s_i$  is a loop on this algorithm until the simulation ends.

**Remark 2.5.1** *The process of waiting for valid input data (lines 2 to 8 in algorithm 1) can either be implemented in a sequential or a concurrent manner.*

## Algorithm 1: One model execution step

MODEL EXECUTION STEP( $I, s_i$ )

**Description:**  $s_i$  executes its own model  $m_i$  for one simulation step (if step-by-step simulation) or one simulation event (if discrete event simulation). Let  $j \in S$  represent the indices of external simulators  $s_j$  interacting with  $s_i$ .

**Input:** A finite set of input data  $d_j^{t_j}$  (associated with their validity interval  $\Gamma_j$ ) called I

**Output:** A finite set of output data  $O$

```

(1)    $ct_i \leftarrow \text{CurrentSimulationTime}(s_i)$ 
(2)   foreach input data  $(d_j, \Gamma_j)$  in  $I$ 
(3)     if  $ct_i \in \Gamma_j$ 
(4)       set  $d_j$  to the right input port  $x_i \in X_i$  of  $m_i$ 
(5)     else
(6)       wait for a new input data  $(d_j, \Gamma_j)$ 
(7)     end if
(8)   end for
(9)    $s_i$  executes  $m_i$ 
(10)   $s_i$  increases its local simulation time
(11)   $nt_i \leftarrow \text{CurrentSimulationTime}(s_i)$ 
(12)   $\Gamma_i \leftarrow ]ct_i, nt_i]$ 
(13)  foreach output data  $d_i$  in  $Y_i$ 
(14)     $O \leftarrow \text{add}(O, (d_i, \Gamma_i))$ 
(15)  end for
(16)  return  $O$ 

```

## 2.5.1 Remark on simultaneous simulation events

In discrete event simulation, in the case of simultaneous events, the simulation algorithm 1 can be either applied as it is (the simulator  $s_i$  executes events in a sequential manner) or the simulator  $s_i$  can execute all the simultaneous events during one *step*.

Indeed, it is worth noting that the lower boundary  $ct_i$  in  $\Gamma_i$  is excluded. It means that at current simulation time  $t_i$ , the simulator  $s_i$  can only read input data produced before that simulation time. It is useful to avoid incoherence problems with simultaneous simulation events. For example, consider one standalone simulator  $s_i$ . Its input data  $d_i$  correspond to its output data. Consider that it produces a set of output data made of three different pieces of data :  $d_i^{t_i} = (\alpha, \beta, \gamma)$  (as described in figure 3).

1.  $s_i$  reads input data  $d_i^{t_i} = (\alpha, \beta, \gamma)$
2.  $s_i$  executes  $m_i$
3.  $s_i$  produces output data  $d_i^{t_i + \Delta_i} = (\alpha_{new}, \beta_{new}, \gamma_{new})$  associated with  $\Gamma_i = ]ct_i, nt_i] = ]t_i, t_i + \Delta_i]$

FIG. 3: Execution process

Assume that, each piece of data  $\alpha, \beta, \gamma$  is produced by one simultaneous simulation event  $e_\alpha, e_\beta$  and  $e_\gamma$ . Furthermore, each simulation event  $e_\alpha, e_\beta$  and  $e_\gamma$  needs the three pieces of data values  $\alpha, \beta, \gamma$  to be executed. In this case, the expected execution process is the following (see figure 4) :

1. at  $t_i$ ,  $s_i$  reads  $d_i^{t_i} = (\alpha, \beta, \gamma)$ ,
2.  $s_i$  executes  $e_\alpha, e_\beta$  and  $e_\gamma$ ,
3.  $s_i$  increases  $t_i$  by  $\Delta_i$ ,
4.  $s_i$  produces output data  $d_i^{t_i+\Delta_i} = (\alpha_{new}, \beta_{new}, \gamma_{new})$

$$\left\{ \begin{array}{l} e_\alpha(\alpha, \beta, \gamma) \rightarrow \alpha_{new} \\ e_\beta(\alpha, \beta, \gamma) \rightarrow \beta_{new} \\ e_\gamma(\alpha, \beta, \gamma) \rightarrow \gamma_{new} \end{array} \right\}$$

FIG. 4: Expected execution process (concurrent) : each event depends on the original value  $\alpha, \beta, \gamma$

However, a problem can happen if, instead of executing all the simultaneous simulation events together in one simulation *step*, they are executed sequentially. That is (see figure 5) :

1. at  $t_i$ ,  $s_i$  reads  $d_i^{t_i} = (\alpha, \beta, \gamma)$ ,
  - (a)  $s_i$  executes  $e_\alpha$ ,
  - (b)  $s_i$  produces output data  $d_i^{t_i} = (\alpha_{new}, \beta, \gamma)$
2. Then,  $s_i$  reads input data  $d_i^{t_i} = (\alpha_{new}, \beta, \gamma)$ ,
  - (a)  $s_i$  executes  $e_\beta$ ,
  - (b)  $s_i$  produces output data  $d_i^{t_i} = (\alpha_{new}, \beta_{new}^*, \gamma)$
3. Finally,  $s_i$  reads input data  $d_i^{t_i} = (\alpha_{new}, \beta_{new}^*, \gamma)$ ,
  - (a)  $s_i$  executes  $e_\gamma$ ,
  - (b)  $s_i$  increases  $t_i$  by  $\Delta_i$
  - (c)  $s_i$  produces output data  $d_i^{t_i+\Delta_i} = (\alpha_{new}, \beta_{new}^*, \gamma_{new}^*)$ .

$$\left\{ \begin{array}{l} e_\alpha(\alpha, \beta, \gamma) \rightarrow \alpha_{new} \\ e_\beta(\alpha_{new}, \beta, \gamma) \rightarrow \beta_{new}^* \\ e_\gamma(\alpha_{new}, \beta_{new}^*, \gamma) \rightarrow \gamma_{new}^* \end{array} \right\}$$

FIG. 5: Execution process to avoid (sequential) : each event does not depend on the original value  $\alpha, \beta, \gamma$  but on the intermediate values

Whatever the execution policy chosen, the previously defined validity interval  $\Gamma_i$  avoids this kind of problem. Indeed, in the second case example, the data  $d_i = (\alpha_{new}, \beta, \gamma)$  cannot be read by  $s_i$  because it is associated with a validity interval  $\Gamma_i = ]t_i, t_i] = \emptyset$ . As a consequence,  $s_i$  always reads input data  $d_i^{t_i} = (\alpha, \beta, \gamma)$  before executing the simultaneous events  $e_\alpha, e_\beta$  and  $e_\gamma$ .

## 2.6 Example

The figure 6 describes the execution of the *model execution step* algorithm 1 for one model  $m_i$ . In this example, the exchanged data ( $d_i, \Gamma_i$ ) are symbolized by colored rectangles (the green, blue, orange and red ones). The horizontal axis (denoted  $t_i$ ) represents the simulation time axis of simulator  $s_i$  (graduations are only present for the sake of the visibility).

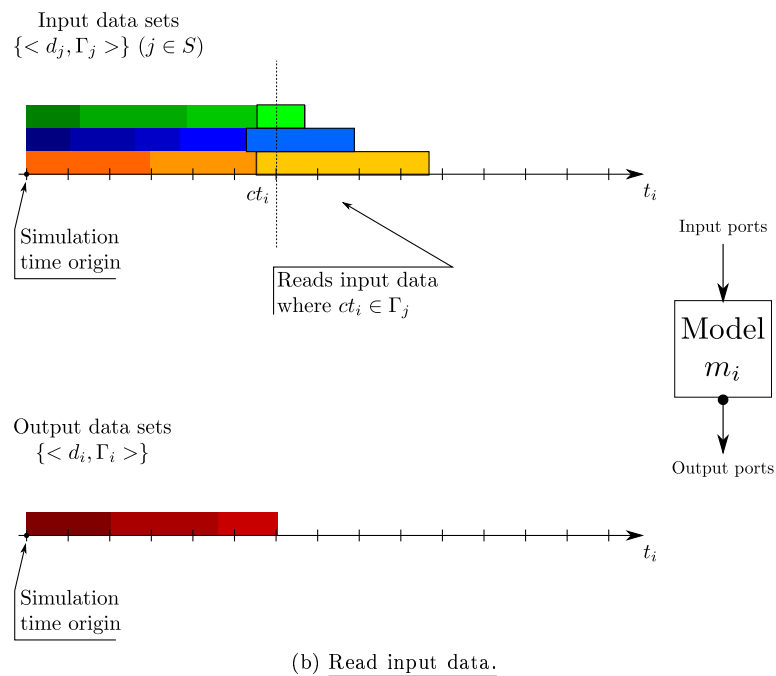
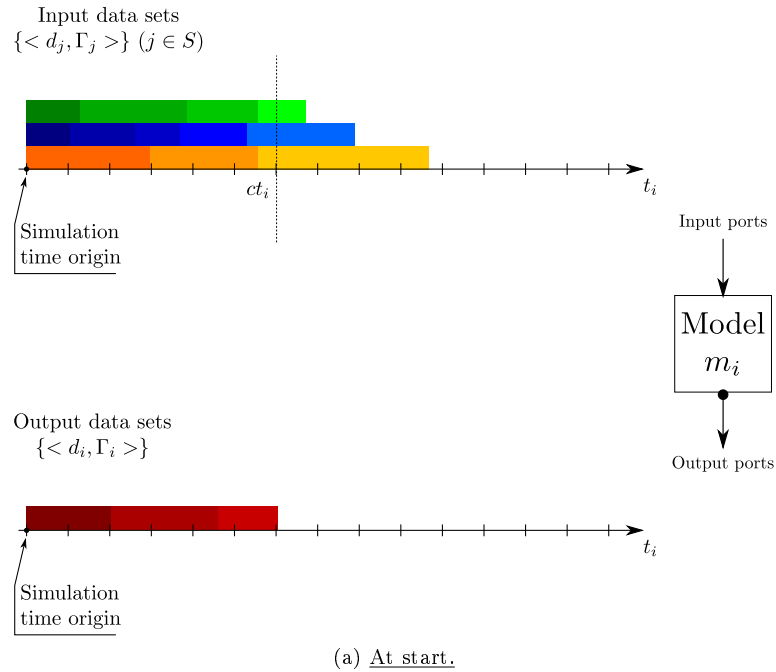


FIG. 6: Algorithm 1 by the example : from the starting state (6a), input data are read (6b) (algorithm 1 lines 2 to 8). The model is then executed (6c) (algorithm 1 lines 9 to 11). Finally, output data are posted (6d) (algorithm 1 lines 13 to 15).

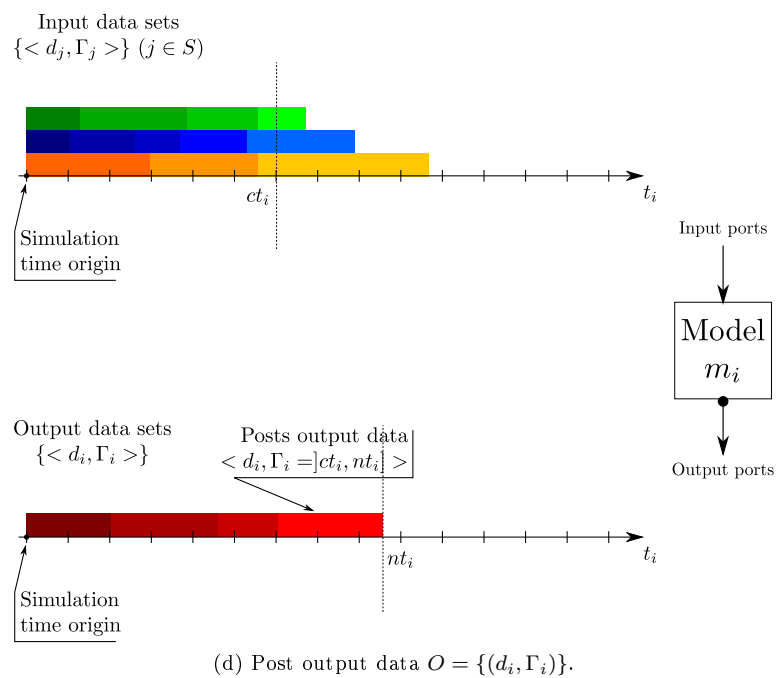
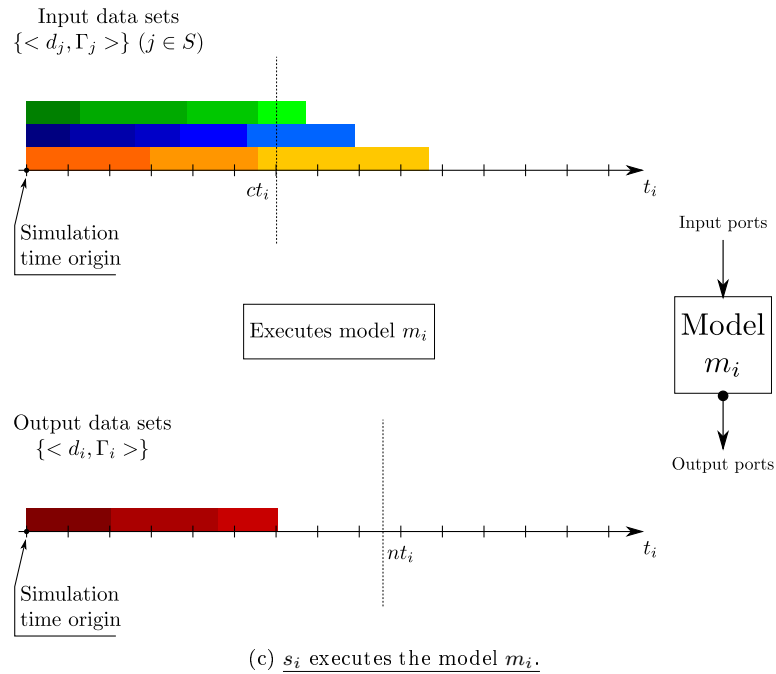


FIG. 6: Algorithm 1 by the example : from the starting state 6a, input data are read 6b (algorithm 1 lines 2 to 8). Then, the model is executed 6c (algorithm 1 lines 9 to 11). Finally, output data are posted 6d (algorithm 1 lines 13 to 15).

## 2.7 Formalisation : no deadlock

We have developed a formal specification in event-B of this coordination model (see section 3). The goal of this formalisation is to ensure that synchronization always occurs between simulators. That is, the system is alive and deadlock free with  $n$  simulators ( $n \in \mathbf{N}$ ). A sketch of the proof, using *reductio ad absurdum* is presented in the next section.

### 2.7.1 Notations

Let  $S \subseteq \mathbf{N}$  be the finite set representing the indices of the simulators. Let  $s_i$  ( $i \in S$ ) be the simulator in charge of the model  $m_i$ . Let  $B \subseteq S$  be the finite set representing the indices of the blocked simulators. That is, simulators that cannot execute their own models because some input data are missing.

### 2.7.2 Hypothesis

Consider that the set of blocked simulators  $B \neq \emptyset$ . I.e. there exists at least one simulator that is blocked : simulator  $s_i$  ( $i \in B$ ) is stopped at time  $t_i = t_i^{stop}$  (see figure 7a). Our initial hypothesis is that  $s_i$  has executed  $m_i$  and produced output data  $(d_i, \Gamma_i)$  (the red rectangles in figure 7a) until it is stopped ( $t_i = t_i^{stop}$ ).

Considering our coordination model (see algorithm 1 and figure 6), there exists a partial order relation between the time values of every blocked simulators (see an example in section 2.8.1). As a consequence, we propose the following lemma (used to derive the examples in sections 2.8.2 and 2.8.3) :

**Lemma 2.7.1** *A simulator  $s_i$  is said to be blocked ( $i \in B$ ) if and only if :*

1. *it depends of data  $d_j$  provided by a finite subset of simulators  $j \in S^* \subseteq S$ ,*
2. *there exists at least one simulator  $s_k$  blocked :  $\exists k \in (S^* \cap B) \neq \emptyset$ ,*
3.  *$t_k^{stop} < t_i^{stop}$ .*

### 2.7.3 No simulator can be blocked

In the finite set of blocked simulators  $s_i (i \in B)$ , the partial order relation between the time values  $t_i^{stop}$  implies that there exists one blocked simulator  $s_j$  with a minimum time value :

$$\forall i \in B, \exists j \in B \text{ such as } t_j^{stop} = \min_i(t_i^{stop})$$

The contradiction appears with the blocked simulator  $s_j$  described previously. Indeed, considering the lemma 2.7.1 if  $s_j$  is blocked, then there must exist a simulator  $s_k$  that is blocked and that possesses a time value  $t_k^{stop} < t_j^{stop}$ , which is not possible ( $t_j^{stop}$  being the minimum value). It means that, if  $s_j$  is blocked, then  $s_j$  is stop at time  $t_j^{stop} = 0$ . Either  $s_j$  is not running at all (maybe, it has not been initiated properly), or  $s_j$  is currently processing its first execution step and as a consequence, is not blocked.

We can reconsider this reasoning for all the blocked simulators and come to the same conclusion that in this coordination model, simulators cannot be blocked by waiting for each other (there is no deadlock). Next section give, as an example, a sketch of this proof.

## 2.8 Sketch of proof

### 2.8.1 Simulator $s_i$ is blocked

It is waiting for input data  $(d_j, \Gamma_j)$  from another simulator  $s_j$  (where  $i \neq j$  and  $i, j \in S$ ). This simulator cannot send data because it is also stopped but at a time  $t_j < t_i$  (see figure 7b).

### 2.8.2 First case : simulator $s_j$ is blocked but is waiting for $s_i$

$s_j$  also waits for input data. Two cases appear. Either the simulator  $s_j$  is waiting for input data from  $s_i$ . This is impossible since our first assumption was that  $s_i$  is blocked at simulation time  $t_i = t_i^{stop}$  and has produced all output data  $d_i$  until then. As a consequence, applying our coordination model means that  $s_j$  must be able to process the execution of  $m_j$  until  $t_j = t_i^{stop}$  (see figure 7c).

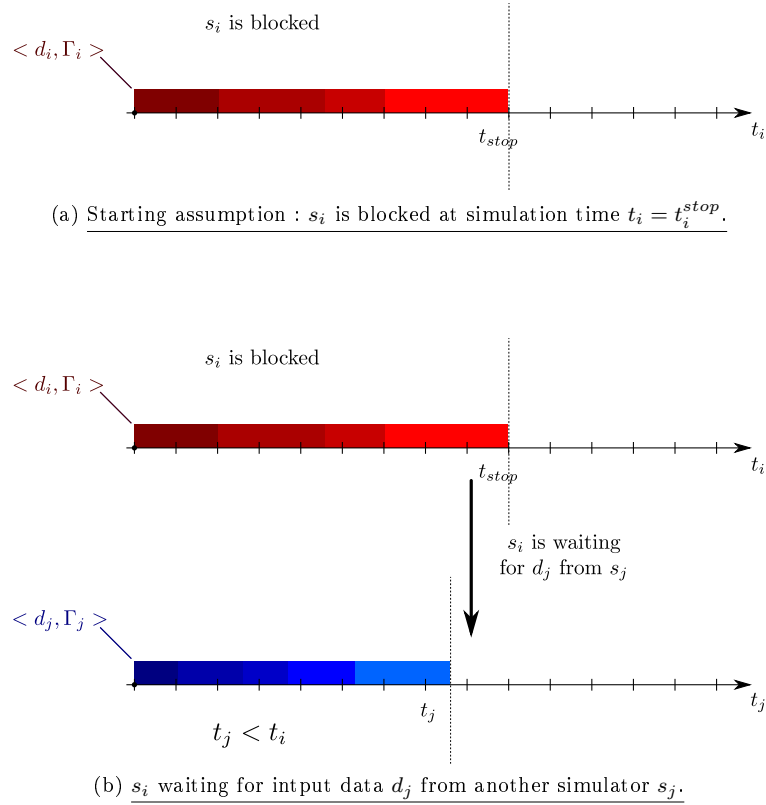


FIG. 7: Sketch of proof

### 2.8.3 Second case : simulator $s_j$ is blocked and is waiting for $s_k$

In the second case, the simulator  $s_j$  is waiting for input data  $(d_k, \Gamma_k)$  from another simulator  $s_k$  at time  $t_k < t_j < t_i$  (where  $i \neq j \neq k$  and  $i, j, k \in S$ . see figure 7d). It is worth noticing that this case is similar to the very state where  $s_i$  is blocked. So we can have the same reasoning to know why  $s_k$  is blocked, and by iteration on every simulator.

### 2.8.4 Conclusion

Since the number of simulator  $n$  is finite and since the number of exchanged data  $(d_i, \Gamma_i) (\forall i \in S)$  (i.e. the number of blue, red, green and yellow rectangles in figure 7) is also finite, we can conclude that if  $s_i$  is blocked, it implies two distinct cases. On the one hand, one simulator is waiting for data  $d_i$  that has already been produced (like in our first case in section 2.8.2 and figure 7c). This leads to a contradiction and is not possible. On the other hand, every simulator is blocked. And as a consequence, the simulation process has never begun which is also a contradiction.

We can say that if the simulation process is properly instanciated (see definition 2.9.1), no deadlock could happen because of the coordination model<sup>2</sup>.

## 2.9 Intialisation process

In the previous section, it has been demonstrated that simulators cannot wait for each other indefinitely unless the initialization has not been set properly.

**Definition 2.9.1**  $\forall i \in S$ , at the origin of simulation time, every simulator  $s_i$  has been parametrized and possessed all the input data in order to execute its own model  $m_i$  once.

The initialization process depends mainly on the models interactions network. For example, if all simulators begin at simulation time  $t_i = 0$  ( $\forall i \in S$ ) one way to initialize the whole simulation process is that every simulator  $s_i$  has to post its initial data  $d_i^0$  associated with the validity time interval

<sup>2</sup>Of course it can exist deadlocks caused by a concurrent implementation but this is not the scope of this part.

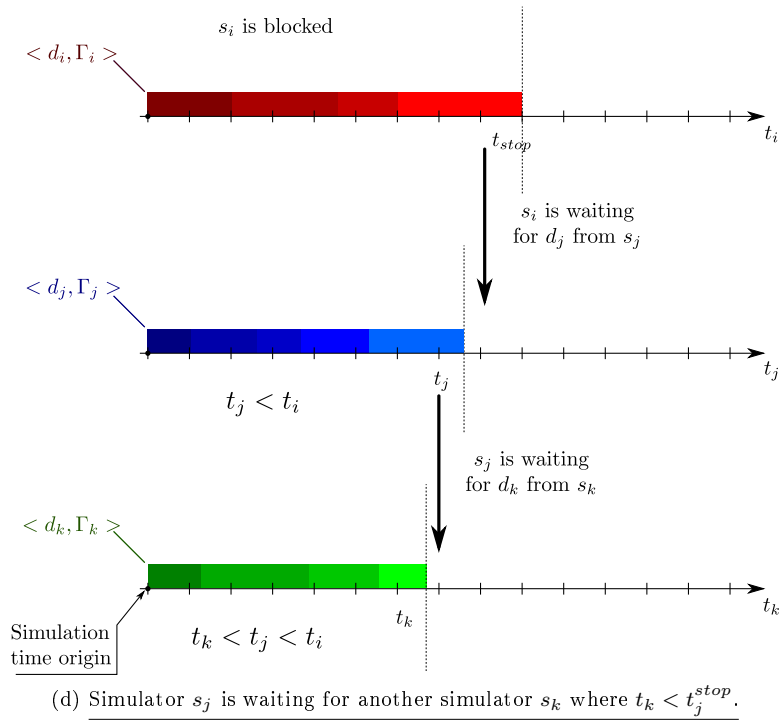
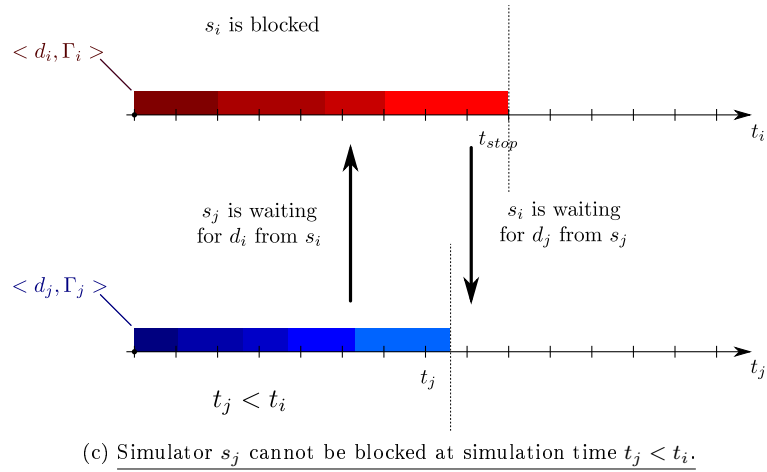


FIG. 7: Sketch of proof

$\Gamma_i = ]x, 0]$  (with  $x < 0$ ). This condition allows every simulator to read its input data set and then, to process the simulation.

### 3 Coordination model specification

We develop a formal specification of the coordination model mentioned before. This specification has been written in Event-B. Its purpose is to check that, implementing the coordination model, no simulator stay blocked.

#### 3.1 Variables and constants used

Each simulator  $s_i$  holds a simulation time value : the current simulation time value  $ct_i \in \mathbb{N}$ . We define a constant  $np$  which is the number of interacting simulators :  $np = \text{card}(S)$ .

In order to know if a simulator is running or waiting, we define a boolean  $r_i$  for each simulator  $s_i$  which takes the value TRUE if the simulator is running and FALSE if the simulator is waiting for some input data.

#### CONSTANTS

$np$  The number of simulator (or processes )

#### VARIABLES

$t$  Current Simulation Time

$r$  is a process Running?

#### INVARIANTS

$inv1 : t \in 1 .. np \rightarrow \mathbb{N}$

Current simulation time

$inv2 : r \in 1 .. np \rightarrow \text{BOOL}$

#### 3.2 Initialisation

The initialization process is the following : every simulator  $s_i$  begin with a current simulation time equal to zero.

$$\forall i \in \mathbb{N}, i \leq np : t_i = 0$$

At the beginning of the simulation, every simulator is waiting for input data.

$$\forall i \in \mathbb{N}, i \leq np : r_i = \text{FALSE}$$

#### EVENTS

##### Initialisation

**begin**

$act1 : t := 1 .. np \times \{0\}$

$act2 : r := 1 .. np \times \{\text{FALSE}\}$

**end**

#### 3.3 Actions

The actions describe the sequence of event for each simulator  $s_i$ . It can be broke into two distinct actions. In the first one, called  $begin\_p$ , the simulator  $s_i$  is waiting for input events from the other simulators  $s_j$  which satisfy the guard condition enunciated in section 2 :

$$\forall j \neq i : ct_i \in \Gamma_j \text{ (see grd3)}$$

Since we only focus on deadlock, we only cares about the current simulation time values. Once all the input events have been read, the simulator can execute the model for one simulation event (or step) :  $r_i \leftarrow \text{TRUE}$  (act1).

#### EVENTS

**Event**  $begin\_p \hat{=}$

**any**

*i*

**where**

**grd1** :  $i \in 1 .. np$

**grd2** :  $r(i) = FALSE$

**grd3** :  $\forall j \cdot j \in 1 .. np \setminus \{i\} \Rightarrow t(i) \leq t(j)$   
 A process *i* can be proceed if every other processes have a current time value  $t(j)$  greater or equal than its own current time value  $t(i)$

**then**

**act1** :  $r(i) := TRUE$

**end**

In the second action, called *end\_p*, the simulator  $s_i$  has processed its model ( $r_i = TRUE$  (grd2)) and updates its simulation time values  $t_i$ .

$$t_i \leftarrow t_i + \delta \text{ (act2)}$$

Finally,  $s_i$  send the output data to the other simulators (through the artefacts see [SCC10]) and  $s_i$  now start to wait for new input events  $r_i \leftarrow FALSE$  (see act1).

### EVENTS

**Event** *end\_p*  $\hat{=}$

**any**

*i*

*delta*

**where**

**grd1** :  $i \in 1 .. np$

**grd2** :  $delta > 0$

**grd3** :  $r(i) = TRUE$

**then**

**act1** :  $r(i) := FALSE$

**act2** :  $t(i) := t(i) + delta$

**end**

### 3.4 Theorem

In event-B, a theorem is a predicate which has been demonstrated from the invariants. In our case, the theorem shows that either the action *begin\_p* or the action *end\_p* can always start. It means that no simulator stay blocked and that they synchronized themselves.

#### THEOREMS

$$\text{thm1} : (\exists i \cdot i \in 1 .. np \wedge r(i) = FALSE \wedge (\forall j \cdot j \in 1 .. np \setminus \{i\} \Rightarrow t(i) \leq t(j))) \vee (\exists k, delta \cdot k \in 1 .. np \wedge r(k) = TRUE \wedge delta > 0)$$

The first part of the theorem means that it always exists a simulator  $s_i$  that can go from the event *begin\_p* from the event *end\_p* because all the guards in event *begin\_p* are valid.

$$\text{thm1 (left part)} : \exists i \cdot i \in 1 .. np \wedge r(i) = FALSE \wedge (\forall j \cdot j \in 1 .. np \setminus \{i\} \Rightarrow t(i) \leq t(j))$$

The second part of the theorem (after the Or statement :  $\vee$ ) means that there always exists a simulator  $s_i$  that can go from the event *end\_p* to the event *begin\_p* because all the in event *end\_p* guards are valid.

$$\text{thm1 (right part)} : \exists k, delta \cdot k \in 1 .. np \wedge r(k) = TRUE \wedge delta > 0$$

## 4 Specification

An Event-B Specification of machine0  
Generated Date: 23 Mar 2010 @ 03 :00 :05 PM

**MACHINE** machine0

**SEES** context0

**VARIABLES**

t

r

**INVARIANTS**

**inv1** :  $t \in 1 .. np \rightarrow \mathbb{N}$

Current simulation time

**inv2** :  $r \in 1 .. np \rightarrow \text{BOOL}$

**thm1** :  $(\exists i \cdot i \in 1 .. np \wedge r(i) = \text{FALSE} \wedge (\forall j \cdot j \in 1 .. np \setminus \{i\} \Rightarrow t(i) \leq t(j)))$   
 $\vee (\exists k, \text{delta} \cdot k \in 1 .. np \wedge r(k) = \text{TRUE} \wedge \text{delta} > 0)$

**EVENTS**

**Initialisation**

**begin**

**act1** :  $t := 1 .. np \times \{0\}$

**act3** :  $r := 1 .. np \times \{\text{FALSE}\}$

**end**

**Event** *begin\_p*  $\hat{=}$

**any**

*i*

**where**

**grd1** :  $i \in 1 .. np$

**grd2** :  $r(i) = \text{FALSE}$

**grd3** :  $\forall j \cdot j \in 1 .. np \setminus \{i\} \Rightarrow t(i) \leq t(j)$

A process *i* can be proceed if every other processes have a current time value *t(j)* greater or equal than its own current time value *t(i)*

**then**

**act1** :  $r(i) := \text{TRUE}$

**end**

**Event** *end\_p*  $\hat{=}$

**any**

*i*

*delta*

**where**

**grd1** :  $i \in 1 .. np$

**grd2** :  $\text{delta} > 0$

**grd3** :  $r(i) = \text{TRUE}$

**then**

**act1** :  $r(i) := \text{FALSE}$

**act2** :  $t(i) := t(i) + \text{delta}$

**end**

**END**

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