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## CD++: a toolkit to develop DEVS models



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### SUMMARY

5 **The features of a toolkit for modeling and simulation based on the DEVS formalism are presented. The tool is built as a set of independent software pieces running on different platforms. Not only are the main characteristics of the environment presented, a focus on its use is also considered by inclusion of application examples for a variety of problems. Many models can be defined in an automated fashion, simplifying the**  
10 **construction of new models and easing their verification. The use of this formal approach has allowed the development of safe and cost-effective simulations, significantly reducing development time. Copyright © 2002 John Wiley & Sons, Ltd.**

15 **KEY WORDS:** discrete event modeling and simulation; modeling methodologies; DEVS formalism; Cell-DEVS; modeling and simulation tools

### INTRODUCTION

In recent years, a number of modeling techniques have been introduced in order to improve the definition and analysis of complex dynamic systems. The development of simulation tools has often been closely related to the execution of these models. A considerable effort has been put into the  
20 development of formal modeling techniques, which proved to be useful thanks to their ability to define executable models. Several of these methodologies were created with the purpose of analyzing discrete-event systems; that is, systems that can be represented using continuous time and discrete state variables [1].

The use of a continuous time base enables accurate timing definitions, which improves model  
25 precision. Continuous time representations avoid small discrete time segments, thus reducing processing requirements. A discrete-event formalism that has gained popularity in recent years is called DEVS (discrete event systems specification). It allows a modular description of models that can be integrated using a hierarchical approach [2,3]. It was developed as a theory for discrete event models,

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but recent extensions allow the inclusion of continuous variable systems [4–6]. Using these approaches, quantized or generalized DEVS can be applied to define arbitrary ordinary differential equations. The Cell-DEVS formalism [7] is a combination of DEVS and cellular automata [8] formalisms with timing delays. The idea is to permit a complex physical system to be described as a space composed by cells, in which each element in the grid is defined as a DEVS model using explicit timing.

We have built a toolkit to develop models based on DEVS and Cell-DEVS. The core of the toolkit is the CD++ environment [9], which implements DEVS and Cell-DEVS theory (including quantized systems). The toolkit has been built as a set of independent software pieces. Each tool runs in different operating environments (Windows 95/NT, Linux, AIX, IRIX, HP-UX and Solaris). Graphical interfaces were built as independent front-ends and current versions use Java and VRML to insure platform-independent execution. This approach lets the user, for instance, debug the models in a workstation, execute them in a high-performance environment and visualize the results on a personal computer. The visualization of the execution results can be done locally or remotely, as we have included facilities for Web-based simulation. In this paper, we present the main features of the toolkit and its use in the development of simulation models, focusing on the development process. After reviewing the basic concepts related to DEVS and Cell-DEVS theory, we introduce the main features of the toolkit and show how to define new models. Then, we show how to execute models and present some simulation results.

## THE DEVS FORMALISM

DEVS was originally defined in the 1970s as a discrete-event modeling specification mechanism. It was derived from systems theory and allows hierarchical modular models that can be easily reused to be defined. A real system modeled with DEVS is described as a composite of submodels, each of them being behavioral (atomic) or structural (coupled). Closure under coupling allows coupled models to be integrated into a model hierarchy. Consequently, the security of the simulations is enhanced, testing time is reduced and productivity is improved.

Each model is defined by a time base, inputs, states, outputs and functions to compute the next states and outputs. A DEVS atomic model is formally described by

$$M = \langle X, S, Y, \delta_{\text{int}}, \delta_{\text{ext}}, \lambda, ta \rangle$$

where  $X$  is the input events set,  $S$  is the state set,  $Y$  is the output events set,  $\delta_{\text{int}}$  is the internal transition function,  $\delta_{\text{ext}}$  is the external transition function,  $\lambda$  is the output function and  $ta$  is the time advance function.

Each model is seen as having input and output ports to communicate with other models. The input and output events determine the values to appear in those ports. The input external events are received in input ports and the specification of the external transition function defines the behavior under such inputs. The internal transition function is activated after the lifetime of the present state has been consumed, which is defined by the time advance function. Its goal is to produce an internal event, which leads to a state change. The desired results are spread through output ports by the output function, which executes before the internal transition.

A DEVS coupled model is composed of several atomic or coupled submodels. They are formally defined as

$$CM = \langle X, Y, D, \{M_i\}, \{I_i\}, \{Z_{ij}\} \rangle$$

where  $X$  is the set of input events,  $Y$  is the set of output events,  $D$  is an index for the components of the coupled model and, for all  $i \in D$ ,  $M_i$  is a basic DEVS (that is, an atomic or coupled model).  $I_i$  is the set of influencees of model  $i$  (that is, models that can be influenced by outputs of model  $i$ ) and, for all  $j \in I_i$ ,  $Z_{ij}$  is the  $i$  to  $j$  translation function.

- 5 We can see that coupled models are defined as a set of basic components (atomic or coupled), which are interconnected. The influencees of a model define to which model outputs must be sent. The translation function is in charge of converting the outputs of a model into inputs for the others. To do so, an index of influencees is created for each model ( $I_i$ ). This index defines that the outputs of the model  $M_i$  are connected to inputs in the model  $M_j$ , where  $j$  is an element of  $I_i$ .

Cell-DEVS [10] is an extension to the DEVS formalism, which allows the implementation of cellular models with timing delays. A cellular model can be defined as an infinite  $n$ -dimensional lattice with cells whose values are updated according to a local rule. This is done using the present cell state and those of a finite set of nearby cells (called its neighborhood). The goal of Cell-DEVS is to improve the execution performance of cellular models by using a discrete-event approach and to enhance timing definition by making it more expressive. Here, each cell is defined as an atomic model using timing delays and it can be later integrated to a coupled model representing the cell space. Cell-DEVS atomic models can be specified as

$$TDC = \langle X, Y, S, N, delay, d, \delta_{int}, \delta_{ext}, \tau, \lambda, ta \rangle$$

- 10 where  $X$  defines external input events,  $Y$  is the set of external output events,  $S$  is the set of sequential states for the cell,  $N$  is the set of input events,  $delay$  defines the kind of delay for the cell,  $d$  defines the delay's length,  $\delta_{int}$  is the internal transition function,  $\delta_{ext}$  the external transition function,  $\tau$  is a local computing function,  $\lambda$  the output function and  $ta$  is the time advance function.

- 15 Each cell uses  $N$  inputs to compute its next state. These inputs, which are received through the model interface, activate the local computing function. A delay can be associated with each cell, allowing the deferral of the computed result to be transmitted to other models. *Transport* delays model a variable commuting time. On the other hand, *inertial* delays have pre-emptive semantics (some scheduled events can be avoided). The model advances through the activation of the internal, external, output and state's duration functions, as in other DEVS models.

Once the cell behavior is defined, they can be put together to form a coupled model:

$$GCC = \langle Xlist, Ylist, X, Y, n, \{t_1, \dots, t_n\}, N, C, B, Z \rangle$$

- 20 where  $Xlist$  is an input coupling list,  $Ylist$  is an output coupling list,  $X$  is the set of external input events,  $Y$  is the set of external output events,  $n$  defines the dimension of the cell space,  $\{t_1, \dots, t_n\}$  is the number of cells in each dimension,  $N$  is the neighborhood set,  $C$  is the cell space state set,  $B$  is the set of border cells and  $Z$  is the translation function.

- 25 This specification defines a coupled model for an  $n$ -dimensional array of atomic cells. Each of them is connected to its neighborhood, whose shape must be defined. In order to define the cell space within finite boundaries, the border cells should be provided with a different behavior than the rest of the space. Otherwise, it is considered that the cells in a border are connected with those in the opposite

one. Finally, the  $Z$  function defines the external couplings using the  $Xlist$  and the  $Ylist$  and internal coupling using the neighborhood definition.

As explained above, both formalisms provide the advantages of being discrete-event approaches in terms of execution performance. Discrete event models evolve in continuous time, represented by the occurrence of instantaneous events that can occur asynchronously at unpredictable times. The hierarchical and modular organization allows multiple layers of a given application to be described. DEVS models are closed under coupling, therefore a coupled model is equivalent to an atomic one, improving reuse. This organization makes the definition of submodels easier, which in turn makes the definition of different levels of abstraction easier. The existence of an internal transition function eases the definition of certain properties. Internal state changes can be captured, describing complex internal interactions in a simple and natural way.

Both DEVS and Cell-DEVS provide the advantages of being a formal approach. Formal specification mechanisms are useful to improve the security and development costs of a simulation. DEVS supplies facilities to translate the formal specifications into executable models. In this way, the behavior of a conceptual model can be validated against the real system and the response of the executable model can be verified against the conceptual specification. The formal specification of the models makes the verification of the simulators easier, as they should mimic the behavior of the models in a homomorphic fashion. In [11], a mechanism for achieving this goal was proposed and we have used a simulation approach based on this strategy. Simulation engines are independent from the models and a modeler only has to focus on defining the model correctly following the previous specifications.

DEVS has also been shown to be a general formalism, such that several other existing formalisms can be expressed as DEVS models (including Petri nets, FSM, cellular automata, VHDL or timed graphs). Consequently, a modeler can express different properties in an adequate formalism and use DEVS hierarchical coupling as an integration mechanism.

The hierarchical nature of the formalism makes the reuse of previously defined models easy. Therefore, model databases can be created and models included in these repositories can be integrated to new hierarchies if their input/output trajectories have equivalent semantics. A related advantage is that the learning curve for DEVS tools is short enough to enable new modelers to learn the basics of the formalism without going into details about the underlying theories. In the following, we will exemplify these issues, showing how to develop new models and analyze several examples focusing on the mentioned advantages.

#### DEVS MODEL DEFINITION IN CD++

CD++ [12,13] allows the definition of models following the specifications introduced in the previous section. The tool is built as a hierarchy of models, each of them related to a simulation entity. Atomic models can be programmed and incorporated into a basic class hierarchy programmed in C++.

This class hierarchy implements the model theoretical definition presented in the previous section. New atomic models must be incorporated into the class hierarchy as subclasses of the atomic model class. The hierarchical nature of the formalism made the implementation of the tool in an object-oriented language straightforward. We can see the tool as a modeling environment that complements the programming capabilities of C++.



The use of C++ also enabled us to obtain good performance in terms of model execution. Our models executed one order of magnitude faster than current existing Java environments [14]. The use of an object-oriented implementation reduced the time spent in testing, as reported in [15]. The formal definition permits the focus of the model to develop, whereas the object-oriented approach makes it much easier to find related errors. A specification language allows the definition of coupled and Cell-DEVS models. This language provides a textual representation independent from any tool and chosen development environment.

The abstract simulation mechanism provided enables the modeler to focus on the definition of the models. The only relationship between the models and the simulation engine is defined by the manipulation of a variable containing the time of the next scheduled event, called *sigma*. This variable is used to implement the time advance function: it stores the time remaining until the next scheduled. The internal transition function is activated when  $\sigma = 0$ , and *sigma* must be recomputed every time a model is activated, as each state has an associated lifetime. Every model also includes a ‘phase’ variable (whose basic states are active/passive), which can be used to verify the correctness of the functions defined. For instance, a model in the passive phase cannot have an internally scheduled event. Likewise, an active model cannot have an infinite value for *sigma*. The expression of these constraints is straightforward. In the following, we explain how to incorporate atomic and coupled models to be simulated.

#### Atomic model definition



A new atomic model is created by including a new class derived from *Atomic*. In doing so, the following methods may be overloaded.

- *initFunction*. This method is invoked when the simulation starts. It allows one to define initial values and to execute setup functions for the model.
- *externalFunction*. This method is invoked when an external event arrives from an input port.
- *internalFunction*. This method is started when an internal event occurs (that is, the value of *sigma* is zero).
- *outputFunction*. This method executes before the internal function in order to generate outputs for the model.

These functions are equivalent to those defined in the formal specifications for atomic models. Consequently, different properties may be verified: inconsistent states (i.e. an internal transition function is activated before the scheduled internal events, external functions are activated before/after the proper timeslots, inconsistent states or values are received via input ports, etc.). The newly defined models can be incorporated into the modeling class hierarchy. The following primitives can be used when defining an atomic model.

- *holdIn(state, time)*. A model executing this sentence remains in *state* during  $time(\sigma = time)$ . When the time is consumed ( $\sigma = 0$ ), the model executes the internal transition. This macro was included to make the definition of the duration function easy.
- *passivate()*. The model enters in passive mode ( $phase = passive; \sigma = infinite$ ) and it is only reactivated by an external event.

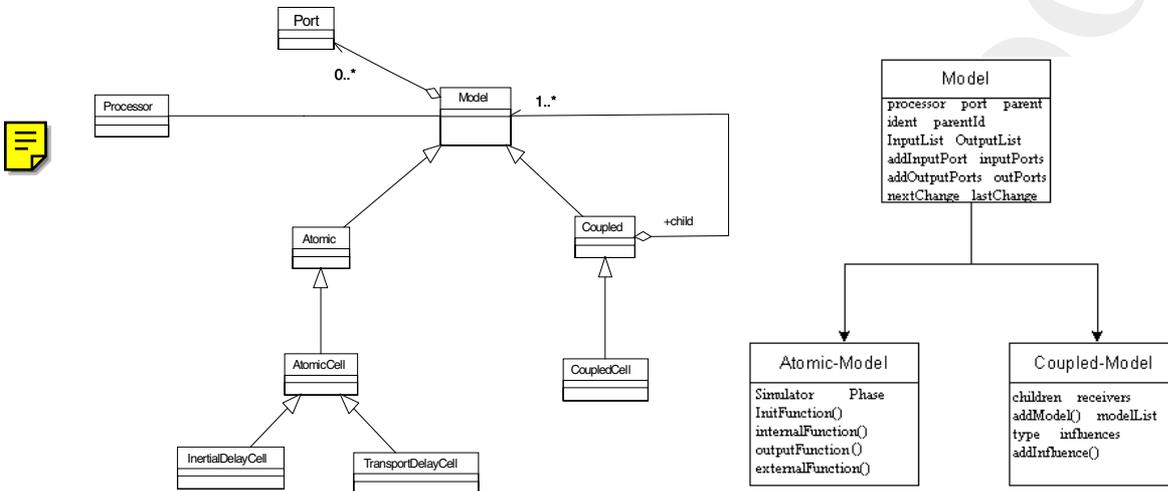


Figure 1. Cell-DEVS models and processors.

- *sendOutput(time, port, value)*. Sends an output message through the given port.
- *state()*. Returns the present model phase.

Let us consider the modeling of the activities in a small airport. The environment to be modeled includes several planes arriving and leaving the airport, a control tower, the runway and a hangar where planes needing service can be sent to. For instance, we can define an atomic model for the control tower as follows:

$$\begin{aligned}
 \text{Control} &= \langle X, S, Y, \delta_{\text{int}}, \delta_{\text{ext}}, \lambda, ta \rangle \\
 X &\in \{in\_d \in N, in\_a \in N\}; \\
 S &\in \{rnwy\_use\_time, preparation\_time \in R^+\} \\
 &\cup \{pl\_queue \in \{fl\_number \in N \times arr\_time \in R + rnwy\_use\_time \in R^+ \times port\_name \in I\}^*\} \\
 &\cup \{which \in N\} \cup \{phase \in passive, rnwy\_use, prep\_rnwy\_use\}; \\
 Y &\in \{rnwy\_use/rnwy\_use \in N\} \cup \{departing/departing \in N\} \cup \{done\_a, done\_d \in boolean\} \\
 &\cup \{stop\_a, stop\_d \in boolean\}.
 \end{aligned}$$

A formal specification for the transition functions can be found in [16]. Here, we show how to implement the transition functions using the tool. This model uses two input ports ( $X$ ) and four output ports ( $Y$ ). The *rnwy-use\_time* variable stores the landing or departure time for the following plane. The *preparation\_time* is related to the delay of the control tower controller to decide the next plane to be authorized. We use a plane queue, containing instances of (*flight number, arrival time, rnwy-use time, use of the runway*), which includes the basic information of each flight received by the control tower.

Two different port names are used in order to recognize if it is a landing or departing flight. The *which* variable stores a pointer to the plane chosen to use the runway.

The transition functions for this model define the activities carried out by the control tower. New requests for landing and departures are received at any moment, thus they are implemented in the external transition function. Whenever a new plane needs to use the runway, it sends a request to the control tower and the request is queued. We use two input ports (landing or departing) to define the type of use for the runway. We also detect emergencies here. If the model phase is *rnwy-use*, this means that the runway is being used. During this time, the planes do not send new requests to the control tower, unless they are in an emergency state. In this case, we use the *elapsed time* variable to decide how to react. If half of the time needed to depart/land has been elapsed, the control tower lets the present plane finish using the runway. Otherwise, the plane is pre-empted and queued again, letting the emergency plane land first.

The operator needs some time to do the related work (*preparation\_time*). During this time, the control tower remains in the *prep\_rnwy-use* state. Then, a plane must be chosen. When this has been decided, the control tower remains in the state *rnwy-use* during the use of the runway. During the use, other waiting planes are informed and they do not request to use the runway. The *query\_time* function analyzes the flight number and computes the time it takes the plane to depart/land, according to the kind of aircraft, weather conditions, etc. When this time is consumed, the output function is executed. If the model was in *prep\_rnwy-use* phase, this means that the control tower is prepared to let a new plane use the runway. Hence, we send a 'STOP' signal in order to avoid new planes being sent. Instead, if the present phase is *rnwy-use*, this means that a plane has finished using the runway and the model can receive new planes. Therefore, a 'GO' signal is sent to other models. When an airplane departs, its number is sent to other models through the 'departing' port. When the plane is landing, its information is sent through the 'landing' port. This information could be used to collect statistics, or to interact with other models.

As we can see, the formal specification provides a clear separation between input, output and internal functions. It also facilitates verifying the model behavior. The occurrence of different states is automatically informed. For instance, if a phase different than those programmed is detected, an error is raised. If a message arrives in the wrong port or its associated time is wrong, the tool automatically raises an error. This procedure reduces the possibility of errors and makes the testing phase easy, as the user only has to focus on the behavior of the corresponding function. In addition, the user only has to focus on the modeling activities (as we can see, there is no relationship with the simulation code at all).

These facilities enabled us to build an independent tool that facilitates model verification [17]. Once an atomic model has been built and incorporated into the modeling hierarchy, we can control if the model being verified returns the expected results at a given time. An experimental framework composed of a generator and an acceptor can be coupled to a base model to be verified. The generator recognizes the input ports of the base model and connects its outputs to the inputs of the model. The acceptor recognizes output ports to be analyzed.

The generator verification data are provided by the modeler, who should write an entry table indicating the testing values and their corresponding correct results. The data corresponding to external transitions are sent by the generator to the base model in order to be processed. Data corresponding to internal transitions are sent to the acceptor, which stores this information and later compares it with the real values issued by the model. Consequently, output error messages are issued. The results file

```

control::control( const string &name ) : Atomic( name ),
in_a(this->addInputPort("in_a")), in_d(this->addInputPort("in_d")),
done_a(this->addOutputPort("done_a")), done_d(this->addOutputPort("done_d")),
stop_a(this->addOutputPort("stop_a")), stop_d(this->addOutputPort("stop_d")),
rnwy-use(this->addOutputPort("rnwy-use")), departing(this->addOutputPort("departing")) {
}

Model &control::initFunction() {
    Preparation_time = control_tower_preparation();
    fl_number=0 ;
    return *this ;
}

Model &control::externalFunction( const ExternalMessage &msg ) {
    fl_number = msg.value();
    rnwy-use_time = query_time();
    if(port() == in_a ) // The chosen plane lands
        rnwy-use = "landing";
    if(port() == in_d ) // The chosen plane departs
        rnwy-use = "departing";

    // Only emergency planes are accepted while the runway is being used
    if (state() == rnwy-use) {
        // If the previous plane is finishing rnwy-use, continue
        if (elapsed_time < rnwy-use_time/2) { // Otherwise, empty the runway
            queue(fl_number, msg.time(), rnwy-use_time, "emergency");
            holdIn(emergency, preparation_time);
            return (*this);
        }
    }

    // A new plane wants to use the runway. Queue its information.
    queue(fl_number, msg.time(), rnwy-use_time, rnwy-use);
    if (state() != rnwy-use)
        this->holdIn( prep_rnwy-use, preparation_time );
    return *this;
}

Model &control::internalFunction( const InternalMessage & ) {
    if (state() == rnwy-use or state()==emergency)

        if (queue == EMPTY)
            this->passivate();
        else
            this->holdIn( prep_rnwy-use, preparation_time );
    if (state() == prep_rnwy-use) {
        // Choose the first plane to be landed in the queue.
        which = schedule(queue);
        tail(queue); // Delete the first element in the queue, that was chosen
        this->holdIn(rnwy-use, rnwy-use_time );
    }
    return *this ;
}

```

Figure 2. Control tower transition functions.

```

Model &control::outputFunction( const InternalMessage &msg ) {
    if (state() == emergency) {
        this->sendOutput( msg.time(), rnwy-use , RNWY-USE_CANCEL);

    if (state() == rnwy-use) {
        this->sendOutput( msg.time(), done_a , GO) ;
        this->sendOutput( msg.time(), done_d , GO) ;

    if ( use == "landing") { // The chosen plane lands
        // Record the landing
        this->sendOutput( msg.time(), "landing" , fl_number) ;
    }
    if ( use == "departing" ) { // The chosen plane departs
        // Record the departure
        this->sendOutput( msg.time(), "departing" , fl_number) ;
    }
    }
    if (state() == prep_rnwy-use) {
        // While using the runway stop receiving new requests
        this->sendOutput( msg.time(), stop_a , STOP);
        this->sendOutput( msg.time(), stop_d , STOP);
    }
    return *this ;
}

```

Figure 2. Continued.

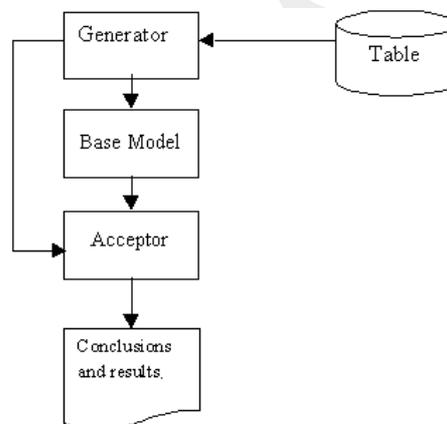


Figure 3. Format for the verification framework.

allows the differences between the expected data and the outputs issued by the model to be checked. In addition, differences in timing can be analyzed.

For instance, the runway model definition was tested using the data shown in Figure 4. We have injected different types of inputs to show the possible errors that can be obtained. The transition type

E 00:01:08:000 2	Output file:
I 00:05:11:000 2	
E 00:10:10:000 15	00:05:08:003 out 2
I 00:15:13:000 15	00:15:13:000 out 15
E 00:20:12:000 40	00:25:17:000 out 20
I 00:25:17:000 40	00:35:18:000 out 60
E 00:30:15:000 60	00:45:19:000 out 70
I 00:35:18:000 60	
E 00:40:19:000 70	
I 00:45:22:000 70	

Figure 4. Input/output data for the runway model.

```

Verification results file:
Invalid result:
  Expecting: 2.000000 At: 00:05:11:000
  Getting: 2.000000 At: 00:05:08:003

Invalid result:
  Expecting: 40.000000 At: 00:20:17:000
  Getting: 20.000000 At: 00:20:17:000

Invalid result:
  Expecting: 70.000000 At: 00:45:22:000
  Getting: 70.000000 At: 00:45:19:000

```

Figure 5. Output data for the runway model.

might be *I* or *E*, indicating if it refers to an internal or external transition, respectively. For an *E*-type transition, data in the table should be interpreted as ‘value *X* enters the model at time *T*’. Taking line number 1 in the example as a reference, we should interpret it as ‘value 2 enters the model at 00:01:08:000’. Likewise, for an *I*-type transition, data in the table should be interpreted as ‘model must output value *Y* at time *T*’. Line 4 of the example should be read as ‘model must output value 15 at 00:15:13:00’.

The behavior of the runway model is to receive planes. Every time a plane leaving or departing is received, it uses the runway for a period, after which an output (representing the flight number) is generated. When we run the verification frame in this model, we obtain the results presented in Figure 5. We first inject the flight number 2 and expect the runway to be ready at 5:11:000. Nevertheless, the runway outputs the plane 2 only 4 min and 0.003 s after the input. This execution results in an output error. Then we inject flight 15, whose output is expected at 15:13:000. As we can see, no errors were raised in this case. The following error shows that, after injecting a value 20 at 20:12:000, the model returns a 20 at 25:17:000, which is an unexpected value according to the input definition. The final error shows another timing problem according to the inputs specified.

The verification mechanism highly enhances the testing procedures. The user can provide a set of test cases, whose definition can be done simultaneously with the model specification.

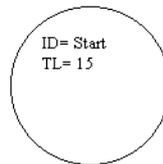


Figure 6. Graphical notation for a state: identifier and time length.

### Graphical definition of atomic models

Coding in C++ allows the user great flexibility in defining model behavior. Nevertheless, non-experienced users can have difficulties in defining models using this approach. The provision of a graphical notation to specify the model behavior can provide the modeler with a powerful tool to define models. Graph-based notations have the advantage of allowing the user to think about the problem in a more abstract way. Therefore, we have used an extended graph to allow the user to define atomic model behavior [18].

Each graph defines the state changes according to internal and external transition functions and each is translated into a textual definition. In this way, the users do not need to compile the new added models, which are interpreted by the modeling tool. The graphical notation of a model is just a frame with the model name. The corresponding textual notation has the syntax `[idModel]`. This identifier declares a DEVS model that can be used subsequently.

The graph-based specification for atomic models represents their state changes. Each state is represented by a bubble including an identifier and the duration for the state. This allows one to define the pair (state, duration) associated with internal transition functions. Figure 6 shows a state called 'Start', whose duration is 15 time units.

The text representation for states uses the following syntax:

```
state : stateId1 ... stateIdn
stateIdj : lifetimej
```

We first enumerate all the states present in the model and associate each of them with their corresponding lifetime. When the lifetime is consumed, the model changes the state by executing an internal transition function.

As explained earlier, each model includes an interface with input/output ports. We represent them as arrowheads associated to a model definition. The text specification for the ports includes their name and a type, based on the formal specification for DEVS models, as follows:

```
in  : portId:type  portId:type ...
out : portId:type  portId:type ...
```

For instance, the model in Figure 7 is specified as

```
in  : p2:integer , p1; /* integer default values */
out : q1:float , q2: integer;
```



Figure 7. Graphical notation for input/output ports.

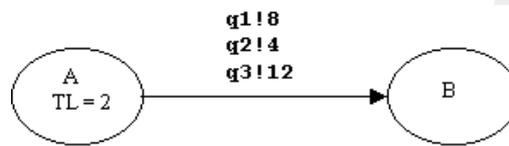


Figure 8. Definition of an internal transition function.

Internal transition functions are represented by arrows connecting two states. Each of them can be associated to pairs of ports with values  $(p, v)$  corresponding to the output function. The syntax for the output function values is  $\mathbf{p!v}$ . For instance, Figure 8 represents that the model changes from state A to state B after 2 time units. First, the output function sends the value 8 through the port q1, 4 through the port q2 and 12 through the port q3.

The syntax for the internal transition function construction is

```
int : startState endState [outPort!value]+
```

Here we indicate the origin and destination states, and a port list with the corresponding values. For instance, the model in Figure 8 can be described as

```
10 int : A B q1!8 q2!4 q3!12
```

External transition functions are represented graphically by a dashed arrow connecting two states. The notation used to represent ports and expected values is similar to the one used for external transition, but replacing the exclamation mark by a question mark:  $\mathbf{p?v [t_i \dots t_f]}$ . Here,  $t_i \dots t_f$  represent the initial and final expected simulated times for the external transitions. These values allow the verification of the timing of the models, raising an error if an external transition comes out of time. The syntax for this construction is

```
ext : startState endState inPort value timeRange
```

This syntax describes the origin and destination states, an input port and a time range counted since the instance of arriving at the start state. All these constructions can be combined to define the behavior of atomic models. For instance, Figure 9 represents a simple model using all the constructions.

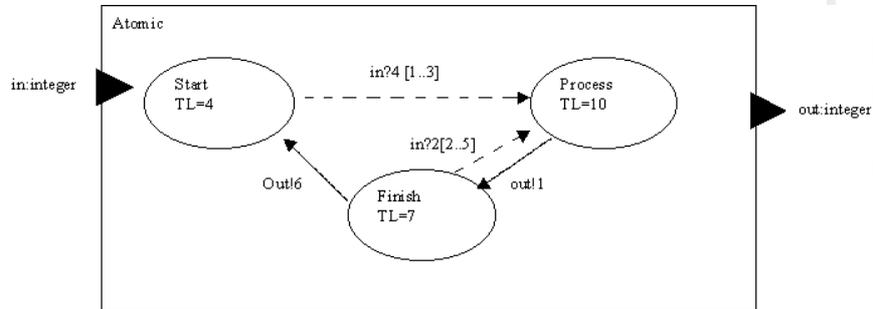


Figure 9. Definition of an atomic model.

This model can be formally specified as

$Simple\_Proc = \langle X, S, Y, \delta_{int}, \delta_{ext}, \lambda, ta \rangle$

$X = \{("in", integer)\}; Y = \{("out", integer)\};$

$S = \{Start, Process, Finish\};$

$\delta_{ext}(s, e, x)\{$

*case port (in){*

    4:     *if (e < 1 or e > 3) error();*

*phase = Process;  $\sigma = 10$ ;*

    2:     *if (e < 2 or e > 5) error();*

*if (phase != finish)*

*phase = Process;  $\sigma = 10$ ;*

  }

}

$\lambda()\{$

*case (phase){*

*Finish: send(out, 6);*

*Process: send(out, 1);*

  }

}

$\delta_{int}()\{$

*case (phase):*

*Finish: passivate();*

*Process: hold\_in(Finish, 7);*

}

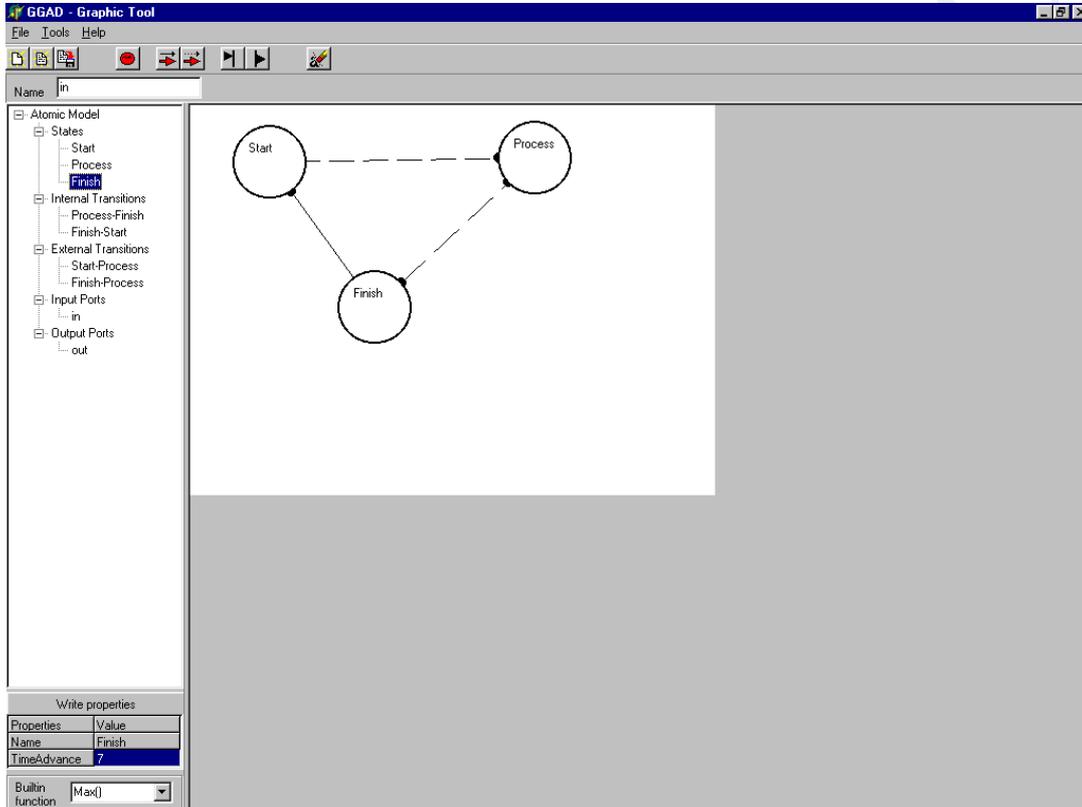


Figure 10. Graphical specification of a simple problem.

In the following, we show the definition of this model using the tool, and the intermediate code generated.

The tool uses the graphical specification shown in Figure 10 to generate the text specification that is used by CD++ (Figure 11). The behavior generated when this specification is read is that explained previously.

This notation enables a clear and clean graphical representation for DEVS atomic models, enabling non-expert users to define models using the toolkit. It also enables a faster learning curve. The core of the tool remains unchanged; therefore, the verification mechanisms mentioned earlier are still valid. It is even easier to detect ambiguous states or timing errors thanks to the reduction in expressivity of the associated language. This simple notation enables the user to develop complex applications thanks to the hierarchical nature of the formalism. If the model states are too complex to be defined in a certain level of abstraction, several simpler submodels can be created and combined together. Nevertheless, in many cases, state machines are not powerful enough to solve complex problems in which one cannot

```
[exampleGG]
in: in
out: out
state: Start Process Finish
int: Process Finish out!1
int: Finish Start out!6
ext: Start Process in 10
ext: Finish Process in 2
Start:0
Process:10
Finish:7
```

Figure 11. Textual definition of the problem.

simply analyze state changes (as in FSM or Petri nets). To attack these cases we have allowed the transition functions to invoke user-defined routines written in C++. They can be associated to the links representing the transition functions. In addition, if models that are more complex are needed, the user can directly define them in C++ as explained earlier. This variety of ways to express atomic models, combined with libraries of existing models, lets each user attack the problem solving tasks at an adequate level of complexity. For instance, graph-based notations can be used for educational purposes, or for problems well-suited to state-based approaches (such as communication protocols), whereas C++ coding can be used for defining complex hybrid systems.

### Coupled model definition

After defining the atomic models for a given application, they can be combined into a multicomponent model. Coupled models are defined using a specification language specially defined with this purpose in mind. The language was built following the formal definitions for DEVS coupled models. Therefore, each of the components defined formally for DEVS coupled models can be included. Optionally, configuration values for the atomic models can be included.

The **[top]** model always defines the coupled model at the top level. As shown in the formal specifications presented earlier, four properties must be configured: components, output ports, input ports and links between models. The following syntax is used.

- **Components.** This describes the models integrating a coupled model. The syntax is `model_name@class_name`, allowing more than one instance of the same model using different names. The class name reference to either atomic or coupled models (which should be defined in the same configuration file).
- **Out.** This defines the names of output ports.
- **In.** This defines the names of input ports.
- **Link.** This describes the internal and external coupling scheme. The syntax is: `source_port[@model] destination_port[@model]`. The name of the model is optional and, if it is not indicated, the coupled model being defined is used.

Let us consider the coupled model representing the airport example of the previous section (Figure 12).

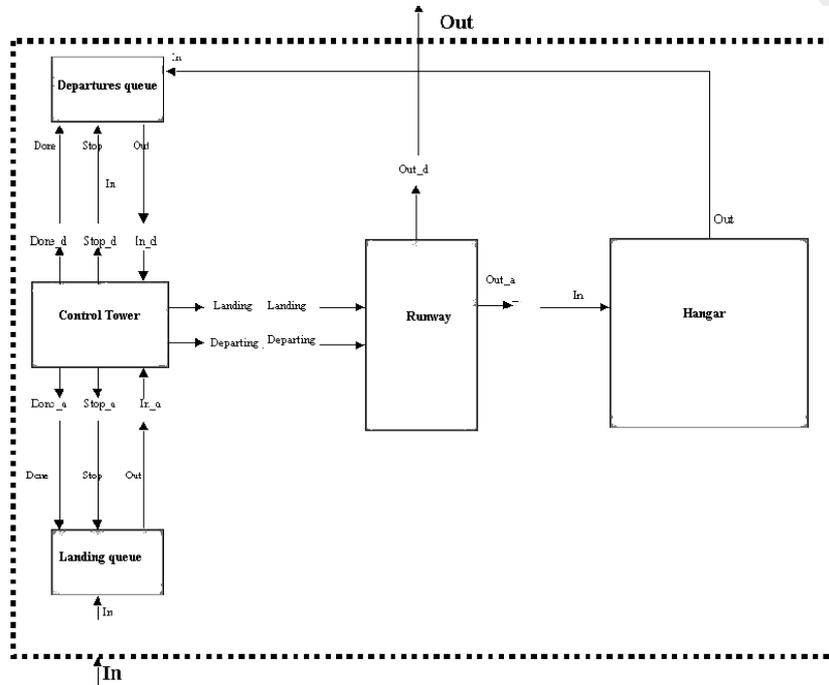


Figure 12. Model interconnection for the airport coupled model.

We can see that the control tower is connected to two queues: one for departures and the other for arrivals. These queues are used to model the time employed by planes to enter or leave the airport area. The control tower is also connected to a model representing the runway. Every time a plane is authorized to depart or land, the runway model is activated. Finally, all landed planes go to a hangar for maintenance. A plane can only leave after service. The hangar can be defined as another atomic model or as a coupled model with different service stations for the planes. The airport coupled model can be formally specified as

$$\begin{aligned}
 \text{Airport} &= \langle X, Y, D, \{M_i\}, \{I_i\}, \{Z_{ij}\} \rangle \\
 X &= \{("In", \text{unsigned int})\}; \quad Y = \{("Out", \text{unsigned int})\}; \\
 D &= \{\text{DeparturesQ}, \text{Control Tower}, \text{RunwayQ}, \text{Runway}, \text{Hangar}\}; \\
 I_{\text{Self}} &= \{\text{RunwayQ}\}; \\
 I_{\text{RunwayQ}} &= \{\text{Control Tower}\}; \\
 I_{\text{Control Tower}} &= \{\text{RunwayQ}, \text{DeparturesQ}, \text{Runway}\};
 \end{aligned}$$

```

[top]
components: DeparturesQ@StoppableQueue Rnwy-useQ@StoppableQueue Runway@Runway Hangar
components: ControlTower@ControlTower
in : In          out : Out
link : out@DeparturesQ In_d@ControlTower
link : out@RunwayQ In_a@ControlTower
link : In in@RunwayQ
link : Out_a@Runway In@Hangar
link : Out_d@Runway Out
link : Done_a@ControlTower in@RunwayQ
link : Stop_a@ControlTower stop@RunwayQ
link : Departing@ControlTower Departing@Runway
link : Rnwy-use@ControlTower Runway@Runway
link : Done_d@ControlTower in@DeparturesQ
link : Stop_d@ControlTower stop@DeparturesQ
link : Out@Hangar in@DeparturesQ

[Hangar]
components : selector@selector deposit1@queue deposit4@queue deposit3@queue Chosen@DeMux
components : deposit2@queue
in : In          out : Out
link : out1@selector in@deposit1
link : out2@selector in@deposit2
link : out3@selector in@deposit3
link : out4@selector in@deposit4
link : out@deposit1 in1@Chosen
link : out@deposit4 in4@Chosen
link : out@deposit3 in3@Chosen
link : out@deposit2 in2@Chosen
link : In in@selector
link : out@Chosen Out

```

Figure 13. Coupled model definition.

$$I_{Runway} = \{Self, Hangar\};$$

$$I_{Hangar} = \{DeparturesQ\};$$

Figure 13 shows the definition of this formal description using the coupling specification language of the tool. In this case, the hangar was also defined as a coupled model, which is included in the specification.

The tool uses this information to generate instances of previously defined atomic models or creates  
5 new instances of coupled models that can later be reused to form other multicomponent models.

Coupled models can be defined using a graphical specification that maps the representation for  
coupled models explained earlier. In this case, squares represent submodels (atomic or coupled)  
and circles the model's input/output ports. Internal links are represented using arrows connecting  
the components. The previous specification can be graphically defined as shown in Figure 14. The  
10 tool translates each graphical construct into the corresponding syntax element (for instance, the  
previous text specification was generated using the tool). Both ways of specifying coupled models  
are straightforward and easy to learn by new users. The modeler does not need to learn a programming  
language to define new coupled models.



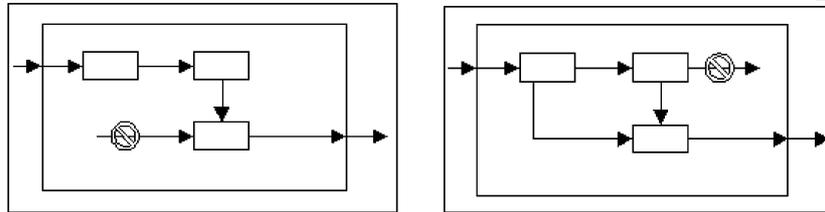


Figure 15. Unlinked input/output ports.

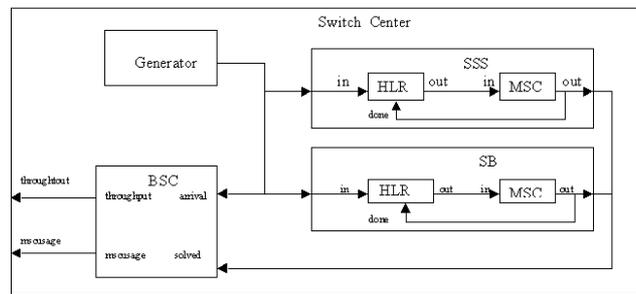


Figure 16. Switching station coupled model.

check every output port, analyzing their influencee lists for every model. An empty list means that the output port is not linked to any input port in the simulation. In addition, a global influencee's list is built using all the input ports that are linked to any output port. This list must contain all the input ports defined in the coupled model. If a port does not belong to it, no output port is linked to it.

- 5 In both cases, CD++ raises an error message, enabling the analysis of the problem. In some cases, the modeler does not want to use an existing port, but in others this can result in complex undesirable errors being discovered. No other couplings are verified, as this is not needed. We have followed the DEVS specifications for couplings and the tool uses this constructive approach. Therefore, we know that the links built from the specifications are correct. The tool includes type validation, ensuring compatibility
- 10 of the data shared through input/output ports.

A coupled model representing a switching station for mobile phones was verified using the services of the tool (Figure 16).

The HLR model is in charge of managing the call flow. When it receives a request, it queues it and advances the switching time associated to the call. When the call is sent, it receives an ACK signal.

- 15 When the coupled model was verified, we found the errors in Figure 17.

In this case, the *HLR* class includes an input port named *stop*; therefore, the user is informed about this situation enabling them to solve the problem, if needed.

```

CD++
-----
Version 2.0-R.43

Starting simulation. Stop at time: Infinity

Exception thrown!
Model Name: HLR1
Input Port Name: stop, is not influenced.
Description: Input Ports without Influences!

Model Name: HLR2
Input Port Name: stop, is not influenced.
Description: Input Ports without Influences!

Aborting simulation...

```

Figure 17. Error detected: unlinked ports.

```

Rule: 1 10 { (0,0) = 1 and ( truecount = 3 or truecount = 4 ) }
Rule: 1 10 { (0,0) = 0 and truecount = 3 }
Rule: 0 10 { t }

```

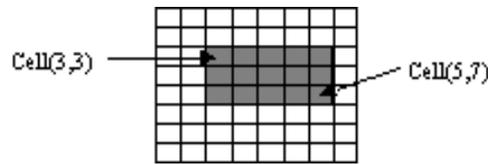
Figure 18. Rule definition for the Life game.

### Cell-DEVS model definition

The tool includes a specification language allowing the description of Cell-DEVS models. These definitions are based on the formal specifications defined earlier and can be completed by considering a few parameters: size, influencees, neighborhood and borders. These are used to generate the complete cell space. The behavior of the local computing function is defined using a set of rules of the form *VALUE DELAY {CONDITION}*. These indicate that when the *CONDITION* is satisfied, the state of the cell changes to the designated *VALUE*, and it is *DELAY*ed for the specified time. If the condition is false, the next rule in the list is evaluated until a rule is satisfied or there are no more rules. In the latter case, an error is raised, indicating that the model specification is incomplete. The existence of two or more rules with the same condition but with different state values or delays is also detected, avoiding the creation of ambiguous models. In these situations, the simulation is aborted.

Figure 18 shows the rules for the ‘Life’ game [19]. This model represents a cell space with entities that evolve according to the neighbors’ states. A cell remains active when the number of active neighbors is three or four (*truecount* indicates the number of active cells) using a transport delay of 10 ms. If the cell is inactive and the neighborhood has three active cells, the cell activates. In every other case, the cell remains inactive (*t* indicates that whenever the rule is evaluated, a true value is returned).

Several useful operations are included: Boolean (*AND*, *OR*, *NOT*, *XOR*, *IMP* and *EQV*), comparison (*=*, *! =*, *<*, *>*, *<=* and *>=*) and arithmetic (*+*, *-*, *\** and */*). In addition, different types of functions are

Figure 19. A zone defined by the range  $\{(3, 3) \dots (5, 7)\}$ .

available: trigonometric, roots, power, rounding and truncation, module, logarithmic, absolute value, minimum, maximum, greatest common denominator and lowest common multiple. Other existing functions allow one to check if a number is an integer, even, odd or prime. Some of the functions allow one to query the cell state of the neighborhood, e.g. *truecount*, *falsecount*, *undefcount* and *statecount*(*n*).

The *Time* function returns the model simulated time. Functions *RadToDeg* and *DegToRad* are used for angle conversion. There are also conversions for polar and rectangular coordinates and temperatures in Celsius, Fahrenheit or Kelvin degrees. Other functions allow the evaluation of certain conditions. The function *IF*(*c*, *t*, *f*) returns *t* if *c* evaluates to true and *f* otherwise. On the other hand, *IFU*(*c*, *t*, *f*, *u*) evaluates *c* and, if it is true, it returns the *t* value. If it is false it returns *f* and *u* if it is undefined.

Some common constants are predefined:  $\pi$ , *e*, gravitational constant, light speed, Planck constant, etc. Finally, pseudorandom number generation is included. Different probability distributions are considered, including uniform, chi-square, Beta, exponential,  $\Phi$ , Gamma, Gaussian, binomial and Poisson.

The cells can use integer or real values. Undefined values can be used, allowing one to apply three-valued logic. The undefined value is also useful for other purposes. For example, in the rule

$$10 \ 100 \ \{random \geq 0.4\}$$

the condition is evaluated to true in some cases and to false in others. Therefore, a model using this rule could return all the rules evaluated as false, which occurs when a model is incomplete. Nevertheless, in this case the model is well-specified but the use of a random number produces this result for the present state. The tool automatically identifies these cases and assigns the undefined value to the cell, informing the user of this situation and continuing with the simulation.

The language permits the manipulation of *n*-dimensional references. Likewise, a neighborhood can be composed of non-adjacent cells and the neighborhood's dimension can be similar or inferior to the dimension of the model. *n*-dimensional space *zones*, defined by a cell range, can be associated with a set of rules different from the rest of the cell space.

Several applications of the formalism can be found in [12,20,21]. We show the definition of a well-known model for fire propagation in forest fires [22]. This model uses environmental and vegetation conditions to infer the fire spread ratio and the intensity. Three parameter groups determine the fire spread ratio: vegetation type, fuel properties (vegetation classified according to its size) and environmental parameters (wind speed, fuel humidity and field slope).

```

Wind direction = 45.000000 (bearing)      Wind speed = 8.045000 [kph]
NFFL model = 1                            Cell Width = 15.240000 [m] (E-W)
Cell Height = 15.240000 [m] (N-S)
Max. Spread = 17.967136 [mpm] ( in the direction of the wind)
0° Spread = 5.106976 [mpm]                Distance = 15.240000 [m]
45° Spread = 17.967136 [mpm]             Distance = 21.552615 [m]
90° Spread = 5.106976 [mpm]              Distance = 15.240000 [m]
135° Spread = 1.872060 [mpm]             Distance = 21.552615 [m]
180° Spread = 1.146091 [mpm]             Distance = 15.240000 [m]
225° Spread = 0.987474 [mpm]             Distance = 21.552615 [m]
270° Spread = 1.146091 [mpm]             Distance = 15.240000 [m]
315° Spread = 1.872060 [mpm]             Distance = 21.552615 [m]

```

Figure 20. Parameter definition for a Rothermel fire model.

```

[ForestFire]
type : cell                                dim : (20,20)
delay : inertial                           border : nowrapped
neighbors : (-1,-1) (-1,0) (-1,1) (0,-1) (0,0) (0,1) (1,-1) (1,0) (1,1)
localtransition : FireBehavior

[FireBehavior]
rule : { (1,-1)+(21.552615/17.967136) } { (21.552615/17.967136)*60000 } { (0,0)=0 and 0<(1,-1) }
rule : { (1,0)+(15.24/5.106976) } { (15.24/5.106976)*60000 } { (0,0)=0 and 0<(1,0) }
rule : { (0,-1)+(15.24/5.106976) } { (15.24/5.106976)*60000 } { (0,0)=0 and 0<(0,-1) }
rule : { (-1,-1)+(21.552615/1.872060) } { (21.552615/1.872060)*60000 } { (0,0)=0 and 0<(-1,-1) }
rule : { (1,1)+(21.552615/1.872060) } { (21.552615/1.872060)*60000 } { (0,0)=0 and 0<(1,1) }
rule : { (-1,0)+(15.24/1.146091) } { (15.24/1.146091)*60000 } { (0,0)=0 and 0<(-1,0) }
rule : { (0,1)+(15.24/1.146091) } { (15.24/1.146091)*60000 } { (0,0)=0 and 0<(0,1) }
rule : { (-1,1)+(21.552615/0.987474) } { (21.552615/0.987474)*60000 } { (0,0)=0 and 0<(-1,1) }
rule : { (0,0) } 0 { t }

```

Figure 21. Definition of a fire forest model.

The fuel model, the speed and direction of the wind, terrain topology and dimensions of a cell are used to get the spread ratio in each direction. For instance, Figure 20 shows the values obtained for a fuel model group number 9, a SE wind of 24.135 km per hour and a cell size of  $15.24 \times 15.24 \text{ m}^2$ .

In CD++, this model can be defined as a  $20 \times 20$  cellular model representing the terrain and vegetation. A cell value of 0 indicates the absence of fire and other values indicate the time the fire has started on that cell. We use a non-wrapped border, a  $3 \times 3$  neighborhood and inertial delays.

The local computing function is called *FireBehavior* and the rules are devoted to the detection of the presence of fire in the eight neighboring cells. If there is fire in one of the them, the cell can burn. For instance, the first rule checks if the current cell is not burning ( $(0,0) = 0$ ) or the SW neighbor has started to burn ( $0 < (1,-1)$ ). If this condition is met, the value for the cell is set to the result of the expression  $(1,-1) + (21.552615/17.967136)$ , which is the time the fire starts in the cell, using the values previously computed. As the spread ratio for the fire in the NE direction is  $17.967136 \text{ m min}^{-1}$  (mpm) and a cell has a diagonal of 21.552615 m, it takes  $(21.552615/17.967136) \text{ min}$  for the fire to reach the cell once it has started in its SW neighbor. The delay component of the rule says this value is

```
[new-life-rule]
rule : 2 100 { (0,0) = 1 }
rule : 1 100 { (0,0) = 0 }
```

Figure 22. Redefinition of the Life game.

set after  $(21.552615/17.967136) \times 60\,000$  ms. The remaining rules represent the behavior associated with the remaining neighbors.

We could use inertial delays to model other behavior. For instance, if rain is considered, wet cells do not burn and if any of the cells scheduled to start burning get wet before the fire starts, they do not burn either. Inertial delays pre-empt any scheduled change if it receives an event from a neighbor cell before the scheduled time, causing the present state to acquire a different value.

As we can see, the burn time for each cell depends on the spread ratio in the direction of the burning cell. It is important to notice that the cells are updated at different times, as set by a rule's delay component. This is a clear departure from the classical approach to cellular automata where all active cells are updated at the same time. A non-burning cell in the direction of the fire spread is updated in a shorter period than a non-burning cell in the opposite direction. Another advantage is that the expression of a timing delay is done in a natural fashion (compared, for instance, with the timing control defined in the airport model). In this way, the modeler can reduce the development time related to timing control programming.

We also have included verification facilities that can be applied when executing Cell-DEVS models. The simplest ones include checks on the number of cells in each dimension, initialization of each of the cells, the positions of the border cells and zones and the positions of the cells representing the *Xlist* and *Ylist*. The most complex verification aids are related to the definition of the local computing function rules. These aids allow the detection of some inconsistencies in the model definition:

- ambiguous models—a cell with the same precondition (state and neighbors) can produce different results;
- incomplete models—no result exists for a certain precondition;
- non-deterministic models—different preconditions are valid simultaneously. If they produce the same result, the simulation can continue, but the modeler must be notified. Otherwise, if different results are found, the simulation should stop because the future state of the cell cannot be determined.

Figure 22 shows a modification of the Life game model (using 0, 1 or 2 as cell values), in which the rules are not completely defined. Here, we can find cases in which all the preconditions are false (i.e. if the cell being evaluated has a value of 2).

In these situations an error is raised, as shown in Figure 23. The message describes the event that has occurred and shows the state values for the neighboring cells.

The error describes the fact that the rules are not complete (in the absence of this verification the simulation would crash, as there are no rules to be executed). In this case, the origin cell has a value of 2 and there is no rule whose precondition is valid for this case.

```

CD++
-----
Version 2.0-R.43

Starting simulation. Stop at time: 00:00:05:000

Exception thrown!
Description: None of the rules evaluates TRUE!
Model used is: new-life-rule
The state of the Neighbors is:
+-----+
| 0.00000  1.00000  2.00000 |
| 1.00000  2.00000  1.00000 |
| 0.00000  1.00000  2.00000 |
+-----+
Aborting simulation...

```

Figure 23. Error detected: no valid rule.

```

[new-life-rule2]
rule : 2 100 { (0,0) = 1 and (0,1) = ? }
rule : 1 100 { (0,0) = 0 }
rule : 0 100 { (0,0) = 2 }

```

Figure 24. Life game with undefined values.

```

CD++
-----
Version 2.0-R.43

Starting simulation. Stop at time: 00:00:05:000

Warning! - None of the rules evaluate to True, but any evaluates to undefined
...

```

Figure 25. Warning: undefined state for a cell.

The tool includes rule definitions using three-valued logic. Therefore, when a set of rules is being defined, the values true, false or undefined can be obtained. If any of the rules result in an undefined value, the cell state is undefined. In this case, a warning is issued. Figure 24 shows a redefinition of the previous example.

- 5 When the state value for the cell is 1 and the neighbor (0, 1) is not undefined (?), the first rule results in an undefined state. In that case, when we evaluate  $(0, 1) = ?$ , the result is ? and the result of the AND operation is undefined. When the rest of the rules are evaluated, no valid precondition is found. In this case, the value of the cell is set to undefined and the warning message shown in Figure 25 is issued.

```
[new-life-rule3]
rule : 2 100 { (0,0) = 1 }
rule : 1 100 { (0,0) = 0 or (0,0) = 1 }
rule : 0 100 { (0,0) = 2 }
```

Figure 26. Life game with ambiguous rules.

```
CD++
-----
Version 2.0-R.43

Starting simulation. Stop at time: 00:00:05:000

Exception thrown!
Description: Two rules evaluate to TRUE and the result is different!
Model used is: new-life-rule3
The state of the Neighbors is:
+-----+
| 1.00000  0.00000  0.00000 |
| 1.00000  0.00000  1.00000 |
| 1.00000  0.00000  0.00000 |
+-----+
Aborting simulation...
```

Figure 27. Error detected: ambiguous rules.

If there are two or more rules whose condition evaluate to true, and their postconditions or delays are different, an error is raised. In this case, the model is ambiguous and the simulation is aborted, avoiding the execution of models running in a non-deterministic fashion. In Figure 26, we show a set of ambiguous rules for the Life game.

5 In this case, if a cell has a value of 1, the first and second rules are valid, but the results are different. Figure 27 shows the execution when these rules are evaluated. When two different rules are valid, but their results are the same, a warning is raised, but the simulation continues. In this case, although two rules are valid simultaneously, the simulation results would be the same if any of them is executed. The warning enables the modeler to check possible ambiguities.

10 There are a few special cases to consider: if a stochastic model is used, it might happen that either multiple rules are valid or that none of them are. For the first case, the first valid rule is considered. For the second case, the cells have an undefined value (?) and the delay time is the default delay time specified for the model. In any case, the simulator notifies this situation to the user, showing a warning message on standard output, but the simulation is not aborted.

15 As we can see, Cell-DEVS formal specifications were directly mapped into CD++. These specifications allowed us to define formal verification mechanisms and to prove properties of the model. Likewise, they make the definition of a cellular model easier. These models can be defined using very simple rules and a few parameters. The delay functions enable the simple definition of timing relations. Therefore, a very simple set of procedures is needed to define complex models, thus improving the development process. The following section shows other extensions that make the

20

```

[3dl]
type : cell                      dim : (7,7,3)
delay : transport                 border : wrapped
neighbors: (-1,-1,-1) (-1,0,-1) (-1,1,-1) (0,-1,-1) (0,0,-1) (0,1,-1)
neighbors: (1,-1,-1) (1,0,-1) (1,1,-1) (-1,-1,0) (-1,0,0) (-1,1,0) (0,1,1)
neighbors: (0,-1,0) (0,0,0) (0,1,0) (1,-1,0) (1,0,0) (1,1,0) (0,0,1)
neighbors: (-1,-1,1) (-1,0,1) (-1,1,1) (0,-1,1) (1,-1,1) (1,0,1) (1,1,1)
localtransition: 3dl-rule

[3dl-rule]
rule : 1 100 { (0,0,0) = 1 and (truecount = 8 or truecount = 10) }
rule : 1 100 { (0,0,0) = 0 and truecount >= 10 }
rule : 0 100 { t }

```

Figure 28. Definition of the 3D Life game.

definition of complex models easier (including  $n$ -dimensional models or alternative topologies for the meshes). Moreover, important improvements in the development times can be obtained when expert users of the tool are compared with experienced programmers in other environments.

### $n$ -dimensional model definition

Cell-shaped real systems are usually modeled using two-dimensional representations. Nevertheless, several theoretical problems can be defined as cellular models with three or more dimensions. Therefore, provisions for the inclusion of  $n$ -dimensional models were included in the tool. Two-dimensional models are stored in an array of  $t_1 \cdot t_2$  cells, where the element  $(x_1, x_2)$ ,  $x_i \in [0, t_i - 1]$ , is in the position  $x_1 + x_2 \cdot t_1$ . Likewise, we use an array of  $\prod_{i=1..n} t_i$  cells to store the states for the cellular automata with dimensions  $(t_1, t_2, \dots, t_n)$ . In this case  $(x_1, x_2, \dots, x_n)$  occupies the position

$$\sum_{i=1..n} x_i \cdot \left( \prod_{k=1..i-1} t_k \right).$$

- 5 We show the use of multidimensional models presenting a simple variation of the ‘Life’ game. We consider a population of active cells represented by ‘1’ values, distributed in an area of  $7 \times 7 \times 3$  cells. The neighborhood has  $3 \times 3 \times 3$  cells. Inactive cells have a ‘0’ value. An inactive cell activates when it has over 10 living neighbors. In addition, a cell remains active when the neighborhood contains 8 or 10 active neighbors. Otherwise, the cell is deactivated. Figure 28 shows a description for this model using the cell description language.

10 The first lines define the dimension parameters of the cell space. The kind of delay and the shape of the neighborhood are also included. Finally, we include the local computing function. Models of higher dimensions are defined in the same way.

### Coupling DEVS and Cell-DEVS models

- 15 Cellular models can be coupled with other DEVS and can be integrated into the model hierarchy using a standard interface. The *portInTransition* directive is used by a cell to query the value of a message

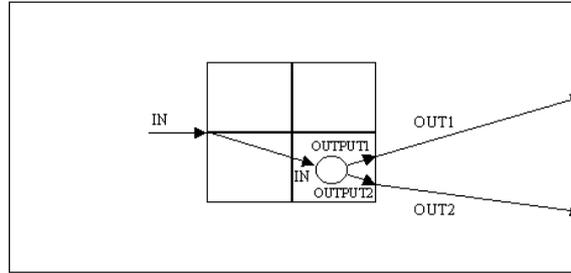


Figure 29. Coupling scheme of the previous example.

```
[EX]
type : cell                dim = (2, 2)
delay : transport          border : wrapped
neighbors : (-1,-1) (-1,0) (-1,1) (0,-1) (0,0) (0,1) (1,-1) (1,0) (1,1)
in : in
out : out1 out2
link : in in@(1,1)
link : output1@1(1,1) out1
link : output2@1(1,1) out2
portInTransition : in@(1,1) specialRule
localtransition : nothing-rule
zone : generateOut { (1,1) }

[nothing-rule]
rule : { (0,0) } 1 { t }

[specialRule]
rule: { portValue(thisPort) } 1 { t }

[generateOut]
rule : { (0,0)+send(output1,9.9999) } 1 { (0,0)>=10 }
rule : { (0,0)+send(output2,3.3333) } 1 { (0,0)<10 }
```

Figure 30. Example of use of the new features.

arriving at a different input port to those connected to the neighbors. On the other hand, output ports are activated using the *send* function.

Figure 29 [13] presents a simple cellular model to show the use of these directives. It is a  $2 \times 2$  Cell-DEVS receiving inputs in the cell (1, 1). It also uses the values of cell (1, 1) to send outputs to other models using two output ports.

First, we define the Cell-DEVS coupled model values. In this case, it is a  $2 \times 2$  cell space with transport delays. The borders are wrapped and all the adjacent cells form the neighborhood. We use the link directive to define the internal and external coupling. In this case, the coupled model input port 'in' is connected to the 'in' port of the cell (1, 1). Then we can see that two output ports are defined for cell (1, 1) (*output1* and *output2*). They are linked to the coupled model output ports. Then, the

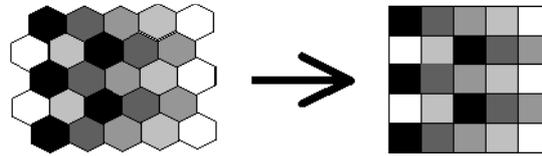


Figure 31. Mapping a hexagonal geometry into a square lattice.

*portInTransition* directive allows the definition of the name of the function to be used when a message arrives through the specified port. In this case, the *specialRule* is executed when an input arrives at the *in* port in cell (1, 1). When this rule is activated, the function *portValue(x)* gets the value of the last message which arrived through the port *x* of the cell (*thisPort* returns the name of the port where the message has arrived).

The local computing function, called *nothingRule*, just keeps the present value of the cell. The cell (1, 1) is also defined as a special zone (*generateOut*) with different behavior. In this case, when the cell is activated it checks the present cell value. If it is smaller than 10, the value 3.3333 is sent through the port *output2*. Otherwise, the value 9.9999 is sent through the port *output1*.

#### 10 Cell-DEVS lattice translator

Most existing cellular models use grids with *square* geometry. They are simple to define and visualize, but have poor *isotropy* capacities (the capacity of a phenomenon to be expanded in every direction in an homogeneous fashion). Certain phenomena cannot even be modeled accurately if square grids are used. The provision of other topologies can solve these problems. For instance, *triangular* grids use a reduced number of neighbors and reduce the number of states to be evaluated. *Hexagonal* cells have the highest isotropy, making the models more natural to develop. The difficulties with any of these geometries are related to the model visualization.

CD++ was developed considering square geometry. Therefore, to include other geometrical shapes it was necessary to extend the original definitions. In [23], some mappings between different geometries have been proposed. Some of these functions are easy to implement, but the visualization of results is difficult. Neighborhood definition is also complex. Figure 31 shows a possible mapping of hexagonal meshes into square lattices.

This transformation is carried out by analyzing the parity of the row where a cell is located. If we consider that a cell is in the position  $(x, y)$ , where  $x$  is the row and  $y$  the column, the position is translated as shown in Figure 32.

The mapping results in a correspondence that differs according to the original row position. Therefore, the translated cellular model is inhomogeneous. The case for triangular meshes is similar. Here, each cell is also provided with a different orientation than those of the neighboring cells. These ideas can be seen in Figure 33.

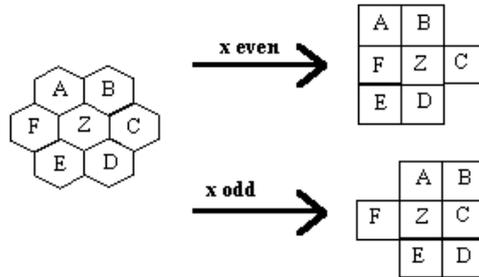


Figure 32. Distribution of close neighbors in the mapping.

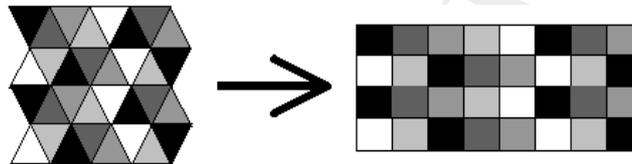


Figure 33. Mapping a hexagonal geometry into a square lattice.

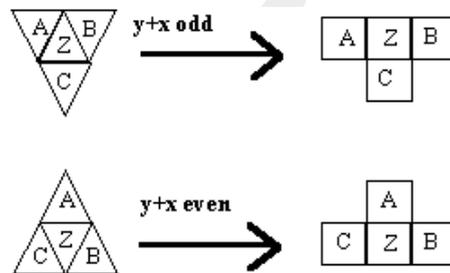


Figure 34. Distribution of close neighbors in the mapping.

Using this function, each row of triangles is mapped into a row of squares, providing a non-homogeneous set of rules. In this case, the position depends on the parity of  $x + y$ ; that is, the parity of adding row and column positions, as shown in Figure 34.

5 These procedures were used to build a lattice translator. The translator allows the user to define rules using triangular or hexagonal meshes. Then, it translates them to the original syntax using square rules that can be executed by CD++. The specification language was extended to provide a different way of referencing the neighboring cells. The new specification syntax is depicted in Figure 35.



Figure 35. Relative positions of the neighbors in the different geometries.

```

Rule: 1 10 {[3]=1 and statecount(9.99)=3}

Rule: 1 10 {(((0,1)=1) and (if((statecount(9.99) - (if((-1,1)=9.99,1,0)) -
(if((1,1)=9.99,1,0))) < 0, 0, (statecount(9.99) - (if((-1,1)=9.99,1,0)) - (if((1,1)=9.99,1,0)))) = 3))
and even(cellpos(0))}

Rule: 1 10 {(((0,1)=1) and (if((statecount(9.99) - (if((-1,-1)=9.99,1,0)) -
(if((1,-1)=9.99,1,0))) < 0, 0, (statecount(9.99) - (if((-1,-1)=9.99,1,0)) - (if((1,-1)=9.99,1,0)))) = 3))
and odd(cellpos(0))}
    
```

Figure 36. Example of a rule in an hexagonal geometry with the corresponding translation.

Each rule in a hexagonal or triangular lattice is translated into two different square rules, each of them considering the parity of rows and columns, as explained earlier. The translation procedures must know which row we are translating. The *cellpos* function returns the value of the *i*th position of a tuple referenced by the cell where the rule is being executed. Figure 36 shows the translation of a simple rule into a hexagonal geometry.

This example shows a rule saying that, if the value in the neighbor called [3] is 1, and there are three cells in the neighborhood whose value is 9.99, the cell has a future value of 1. This value is sent to the neighboring cells using a transport delay after 10 time units. The following two rules represent the translation of that rule into a square mesh, using the definition shown in the previous figures.

In a square lattice, we use eight neighbors, against six used in the hexagonal mesh. Therefore, when we translate the rules from one topology to the other, we should not count those neighbors that should not be included. The function *statecount*(*n*), which returns the number of cells whose values are *n*, is used for this purpose. We can see that we compute *statecount*(9.99), as in the previous case, and then in the even rows we subtract the values of cells (-1, 1) and (1, 1). The following rule is evaluated only in odd rows. The function *cellpos*(*n*), which returns the *n*th value of the tuple referencing a cell, is used to check the cell row used.

Figure 37 shows the result obtained when the same procedure is applied to a triangular geometry. The main difference in this rule is that we have more neighbors. Therefore, we have to control the values corresponding to even and odd rows/columns.

```

Rule: 1 10 {[3]=1 and statecount(9.99)=3}

Rule: 1 10 {((0,-1)=1) and (if((statecount(9.99)-(if((-1,-1)=9.99,1,0))-
(if((-1,0)=9.99,1,0))-if((-1,1)=9.99,1,0))-if((1,-1)=9.99,1,0))-
(if((1,1)=9.99,1,0)))<0,0,(statecount(9.99)-(if((-1,-1)=9.99,1,0))-if((-1,0)=9.99,1,0))-
(if((-1,1)=9.99,1,0))-if((1,-1)=9.99,1,0))-if((1,1)=9.99,1,0)))=3)) and
even(cellpos(0)+cellpos(1))}

rule: 1 10 {((1,0)=1) and (if((statecount(9.99)-(if((-1,-1)=9.99,1,0))-if((-1,1)=9.99,1,0))-
(if((1,-1)=9.99,1,0))-if((1,0)=9.99,1,0))-if((1,1)=9.99,1,0)))<0,0,(statecount(9.99)-
(if((-1,-1)=9.99,1,0))-if((-1,1)=9.99,1,0))-if((1,-1)=9.99,1,0))-if((1,0)=9.99,1,0))-
(if((1,1)=9.99,1,0)))=3)) and odd(cellpos(0) + cellpos(1))}

```

Figure 37. Example of a rule in an triangular geometry with the corresponding translation.

## SIMULATION MODELS

As we could see in the previous sections, the main advantage of the DEVS formalism is that the models can be specified independently of the simulation mechanism. At present, we have implemented a number of different simulation techniques; namely, hierarchical [13], flat [24], real-time [25] and parallel [26]. In every case, the model specifications remained untouched and they could be reused, even after changing a simulation technique completely. CD++ was defined using the abstract simulation mechanisms presented in [11]. DEVS simulators can be seen as hierarchical schedulers of events that activate the corresponding submodels. The schedules allow the skipping of periods of inactivity in the simulation.

The basic idea is to provide independent basic abstract classes: models and processors. The first is used to represent the behavior of the atomic and coupled models and they were presented in the previous section. The second implements the simulation mechanisms associated with the models. Figure 38 shows a detailed class hierarchy including all the modeling and simulation entities.

Each modeling entity is associated with a processor that is in charge of activating the model, which is in charge of defining the behavior to be implemented. Each kind of model is associated with a different processor. Simulators and coordinators are built to manage atomic and coupled models. The root coordinator drives the simulation in its global aspects. It keeps the global time and it is in charge of the start and finish of the simulation. It also collects the output results. It is related to the highest level coupled model and its corresponding coordinator.

### 20 Hierarchical processors

As previously explained, different simulation processors are used: simulators, coordinators and root coordinators. They are related to different models: simulators are associated with atomic models and coordinators with coupled ones.

The coupling relationship is recorded in the instance variables *devs-component* and *processor* of the processor and model, respectively. The *parent* variable indicates the parent processor in the simulators'

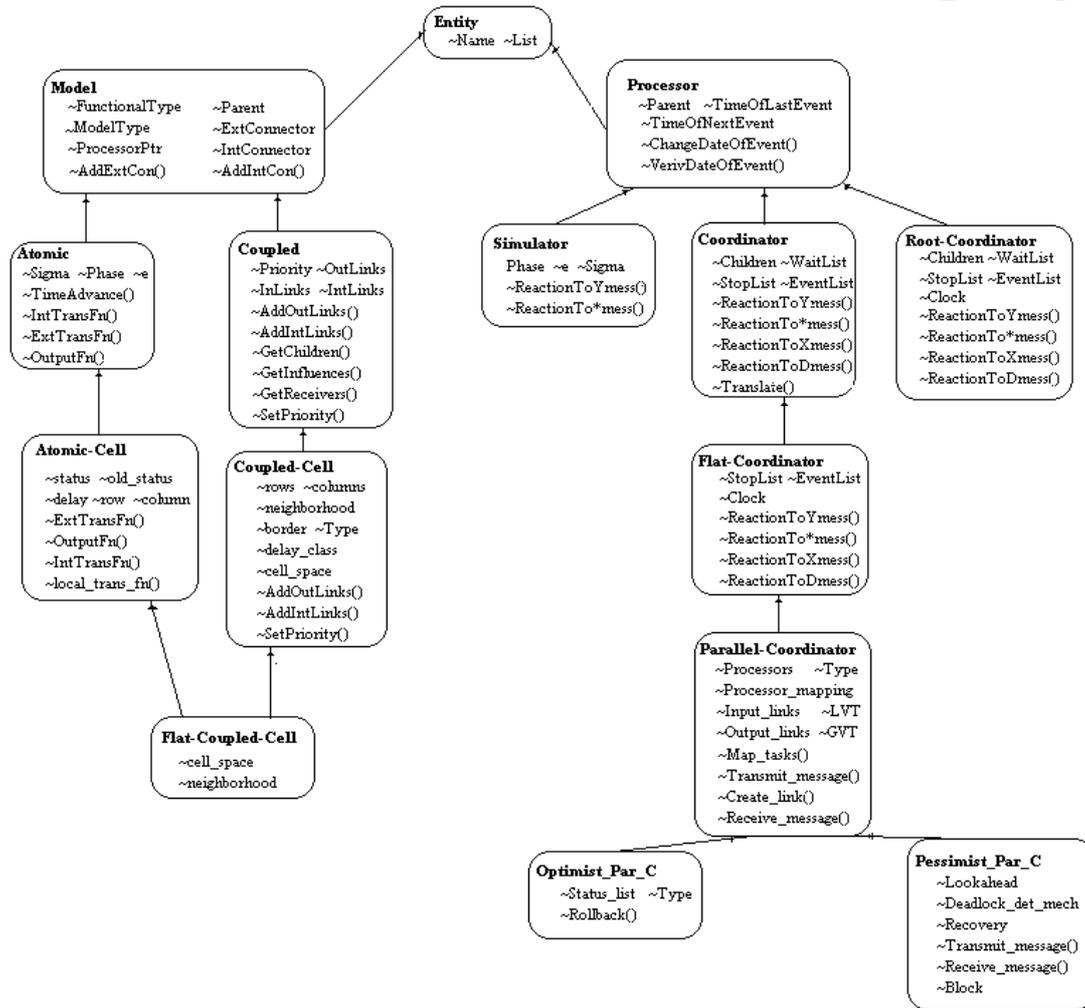


Figure 38. Basic class hierarchy.

hierarchy. The times of the last event and the next event are recorded to identify the imminent children and to verify correctness in the message’s simulated times.

The simulation process is driven by message passing between the processors. The messages include information related to the message’s origin, the time of the related event and a content consisting of a port and a value. There are four types of messages: \* (used to signal a state change due to an internal event), X (used when an external event arrives), Y (the model’s output) and *done* (indicating that a model has finished its task).

The submodel with the smaller scheduled internal event in the hierarchy is called *imminent*. When this model must execute, a \*-message is sent to its simulator. The message passes through the middle level coordinators, provided with a list of imminent children for this purpose. When an external message arrives, an *X*-message is consumed and the external transition function executed. The simulators return done-messages and *Y*-messages that are converted to new \*-messages and *X*-messages, respectively. *Y*-messages carry the results to be transmitted to other models. *done*-messages are used to inform that each model has finished the task given by its higher level coordinator.

If a basic model receives an external event  $x \in X$ , the model executes the external transition function  $\delta_{\text{ext}}$ . Consequently, the next internal event (that is, that produced by the consumption of time in the model) is rescheduled. *X*-messages are also transmitted to the lower levels in the hierarchy using the coupling scheme, up to the moment where it arrives in an atomic model.

The abstract simulator analyzes the external events and the scheduled internal transitions for all its children and chooses the imminent child. These procedures are repeated up to the moment when a simulator is chosen. This is the simulator related to the imminent model, which must be activated. The imminent model starts by executing the output function  $\lambda$  to generate an output event  $y \in Y$ . Each output is sent to the parent coordinator, which checks the influencees and translates it into new inputs, using the  $Z_{ij}$  translation function. Then, the internal transition function  $\delta_{\text{int}}$  executes, resulting in a state change and the scheduling of a new internal transition. Every activation of a model finishes with a *done*-message used to update the future activation time of the model. The *done*-message with the earlier future time is transmitted to the upper level coordinator, allowing the local time of the particular coupled models to be maintained.

The *SimLoader* class is in charge of parsing the model specification, providing an interface to load the simulator configuration. Once the models are loaded, there are two possible procedures to start the simulation. The first is by using the class *StandAloneLoader*, responsible for loading the parameters. The *NetworkLoader* class is responsible for getting the same parameters by using TCP/IP services. In this way, the simulator can be executed as a simulation server and the parameters can be loaded remotely, getting the results in a remote fashion. Finally, the *Simulator* class is responsible for the creation of the model tree and for the establishment of the links between ports using the specification. Once the hierarchy of the model is built, the simulation can begin. To do so, the external events are added, an event list created and the stop time initialized.

### Flat processors

The overhead that results from the exchange of messages between processors could be minimized if the hierarchy is properly flattened. Therefore, the number of messages can be reduced accordingly [27]. It is important to conserve the usual model definition, execution and the separation between models and processors. We extended the flat simulators to introduce flat simulation in CD++. This new processor is unique across all the processors' hierarchy and replaces all the usual coordinators and simulators existing in a hierarchical approach.

The processor hierarchy corresponding to a hierarchical simulator is shown in Figure 39. Whenever the root coordinator has to schedule an event to lower-most simulators (simulators #4 and #5), the overhead incurred by message passing can be considerable. The same phenomenon is produced if the

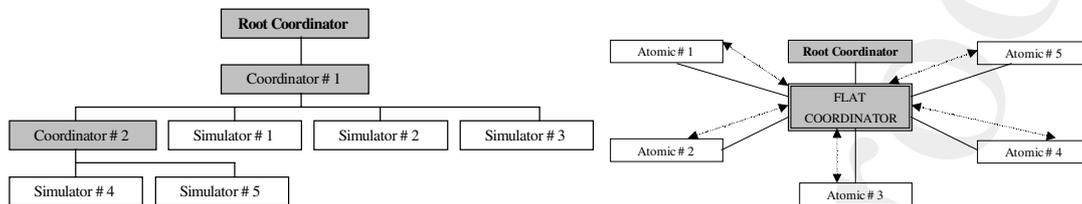


Figure 39. Processors' hierarchy (hierarchical and flat approaches).

simulator #5 sends an output through a port connected to simulator #3. The number of intermediate coordinators can be arbitrarily high depending on the model studied.

If we simulate the model shown using a flat simulator, the resulting hierarchy is remarkably simplified and the overhead incurred by message passing is significantly reduced. The flat coordinator stores information concerning the atomic models it handles. Information about ports, links, time of next event, time of the last event processed as well as the queue of pending events must be saved.

### Real-time processors

We developed several modifications to the original simulation engines in order to provide real-time responses. A real-time simulator must handle events in a timely fashion, where time constraints can be stated and validated. These new features would allow interaction between the simulator and the surrounding environment. Therefore, inputs could be received by ports connected to real input or even data collected from human interaction. Similarly, outputs could be sent through output ports connected to specialized devices.

In this case, the root coordinator manages the advance of time along the simulation. This coordinator must wait until the physical time reaches the next event time to initiate the new cycle. Periods of inactivity are not skipped; instead, the root coordinator expects the scheduled time to be reached and only then starts the new simulation cycle.

### Parallel processors

When a simulation is run in a distributed fashion, each machine runs one logical process which hosts one or more DEVS processors. Under these assumptions, a coordinator's children need not be executing on the same logical process. If the correspondence between models and DEVS processors is one-to-one, then every coupled model is associated to only one coordinator. Then every message sent to child processors running on different CPUs requires inter-process communication. Figure 40(a) illustrates this case. It shows a coordinator sending a message to its eight children distributed on two CPUs. Four inter-process messages are required for the four children running on processor 1.

To reduce inter-process messages, coupled models use a coordinator on each logical process where a child processor is running. Children processors send messages to the local coordinator, which decides how to handle the received messages. Upon receiving a message from a child, a coordinator

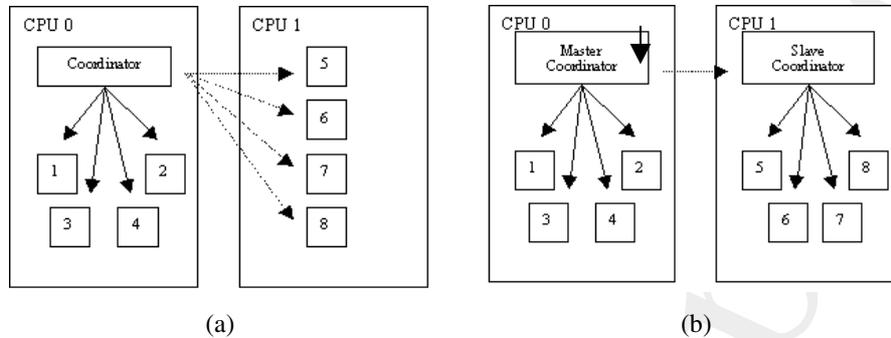


Figure 40. (a) Coordinator sending messages; (b) slave–master pair (dashed lines are inter-process messages).

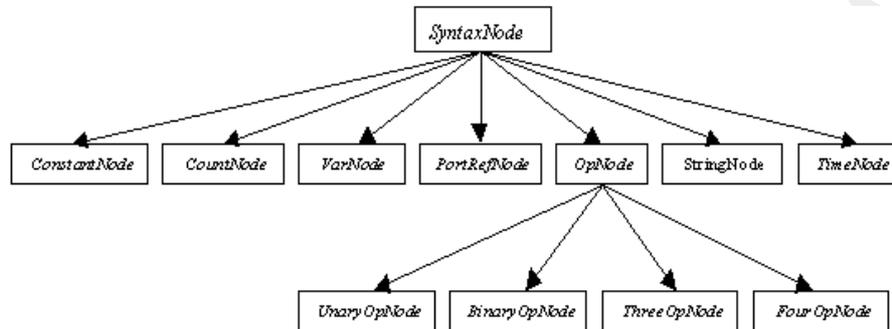
could forward this message to all the coordinators for the model. This organization would require all coordinators to know about each other. For instance, if coupled model *A* is a child of coupled model *B*, then *B*'s coordinators would have to interact with *A*'s coordinators. If not handled carefully, this communication can turn out to produce a large number of inter-process messages. In such a scenario, a way of keeping the number of inter-process messages to a minimum is to have only one of the coordinators receiving messages from or routing messages to the parent model coordinator. This specialized coordinator is known as a *master coordinator*, and all other coordinators are *slaves* (Figure 40(b)). The master coordinator for model *A* is the only one that can receive or send messages to *B*'s local coordinator.

When master and slave coordinators are used, DEVS processors are organized in a hierarchy, which does not have a one-to-one correspondence with the model hierarchy. Therefore a parent–child relationship that takes into account the existence of master and slave coordinators must be defined:

- (a) for each *simulator*, the parent coordinator is the parent's model local processor (it is guaranteed that this one exists);
- (b) for each *slave coordinator*, the parent coordinator is the master coordinator of the model;
- (c) for each *master coordinator*, the parent coordinator is the parent's model local processor—just as if it were a *simulator*.

The simulation advances as a result of the exchange of messages between parent and child DEVS processors. Every message is a pair of the form  $(type, time)$  and can belong to one of two categories: synchronization messages and content messages. The synchronization messages are  $(@, t)$ ,  $(*, t)$  and  $(done, t)$ , and the contents messages are  $(y, t)$  and  $(q, t)$ .

The synchronization messages  $(@, t)$ ,  $(*, t)$  are sent from a parent DEVS processor to its imminent children.  $(@, t)$  is used to tell the children to send their outputs and  $(*, t)$  tells the children to invoke their transition function (whether it corresponds to executing an external, internal or confluent transition). All outputs produced by a model are translated to  $(y, t)$  messages between a child DEVS processor and its parent. Finally, those external messages that arrive from outside the system or that are generated as a result of an output message being sent to an influencee are sent as  $(q, t)$  messages.

Figure 41. Subclasses of *SyntaxNode*.

### Implementation of the Cell-DEVS specification language

The rules defining the model coupling and those related to the behavior of a cell should be translated into an executable definition. We show how rules for cellular models are evaluated (those used for coupled models and analytical specifications for atomic models are handled similarly). The rules' specifications are associated with a function's identifier, which is registered by each cell. When the models to be simulated are loaded, if the definition of a transition function is not registered, then it is added to a table. In this table, the function name acts as an identifier and each one of the rules is represented with a tuple (value, delay, condition). Each element of the tuple is represented by a tree. Figure 41 shows such a rule definition tree.

The *SyntaxNode* class is an abstract class that allows the description of a node in the rule evaluation tree. It is composed of the following.

- *ConstantNode*—stores a constant value with domain in real numbers, integers or three-valued logic.
- *CountNode*—allows the definition of the functions *TrueCount*, *FalseCount* and *UndefCount*.
- *VarNode*—stores a reference to a neighbor cell, defined as an offset from the present cell.
- *PortDefNode*—defines a reference to an input port of the cell.
- *StringNode*—contains a string of characters representing the name of an input port of the cell. It is used to evaluate the *PortValue* function.
- *TimeNode*—allows the *Time* function to be defined, which returns the present simulated time.
- *OpNode*—an abstract class representing functions with one or more parameters. It has the subclasses *UnaryOpNode*, *BinaryOpNode*, *ThreeOpNode* and *FourOpNode*, which represent the functions with one, two, three or four parameters, respectively.

Each rule defining the behavior of a cell can be represented by a tree structure. For example, the representation of the first rule of the Life game presented in Figure 18 can be represented as shown in Figure 42.

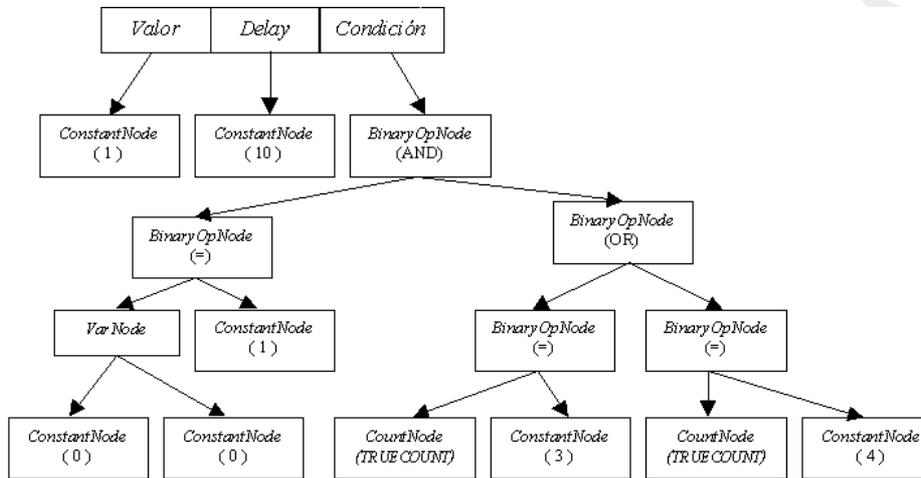


Figure 42. Tree structure used to represent the first rule of the Life game.



Therefore, to evaluate a rule it evaluates in recursive form the tree that represents the condition. If the result of the evaluation is true, it proceeds to evaluate the trees corresponding to the value and the delay, and the result of these evaluations are the values used by the cell.

**Cell-DEVS quantized models**

- 5 Recently, a theory of quantized DEVS models has been developed [4,5]. The theory has been verified when applied to predictive quantization of arbitrary ordinary differential equation models. In this way, continuous variable models can be defined as DEVS. A curve is represented by the crossings of an equal spaced set of boundaries, separated by a *quantum* size. A *quantizer* checks for boundary crossings whenever a change in a model takes place. Only when such a crossing occurs is a new value sent to the receiver. This operation substantially reduces the frequency of message updates, while potentially incurring into error.



The cost/benefit analysis between reduced traffic and increased error was discussed in [28]. It was also shown that the technique is useful when it is applied to Cell-DEVS models [29]. It was found that the number of messages involved in the simulation of Cell-DEVS models presented a reduction in the number of messages involved, as can be seen in Figure 44 (including the results for two different applications). The curves belong to the class of curves  $f(x) = bx^{-a}$  with  $x \in (0, 1]$ . These results approximate the theoretical optimum results presented in [5].

The introduction of quantizers introduces an error factor, whose value is a function of the local computing function, the number of simulation steps and the quantum. The future input values for a cell are dependent on the present results for the cell. This dependence can lead to a nonlinear behavior of the error, depending on the interconnection of the cell. In any case it can be seen that the higher the



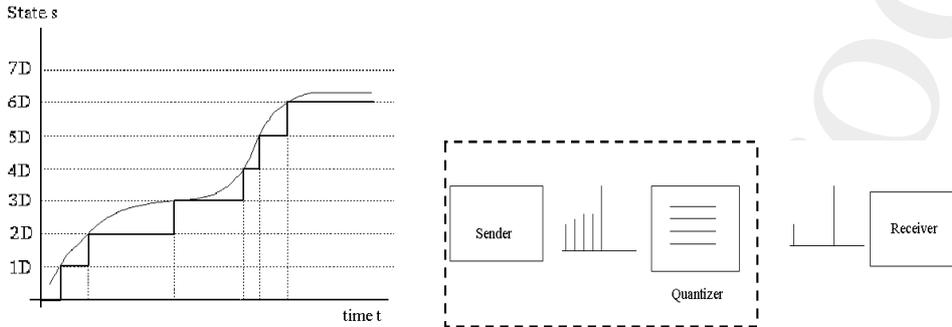


Figure 43. DEVS quantization [5].

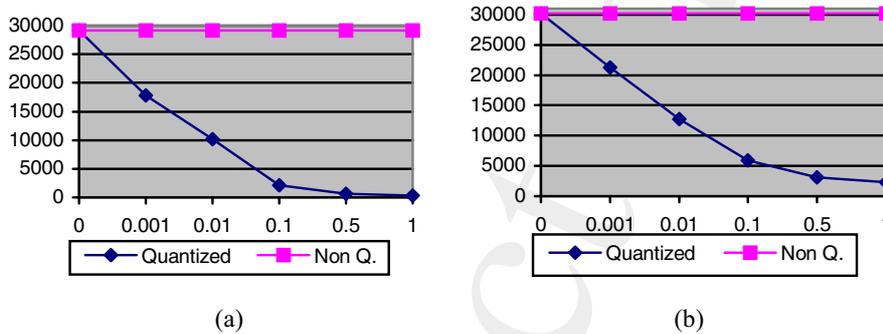


Figure 44. Number of messages involved.

quantum, the worse the error. The use of a higher quantum reduces the number of steps, but each of them has a higher error. The experimental results validate this behavior.



The error grows as  $f(x) = ax^b$  and can be linear when there is no influence between cells. We can see that, in the (a) case, the error hardly increases while the messages go down by approximately 1/10.

5 Considering these factors, the tool has included quantization facilities. The simulators are able to run quantized models in a more efficient fashion.

### SIMULATING MODELS

Once a model has been generated and its description is included in the modeling hierarchy, it can be simulated. As explained earlier, the model interaction is carried out through message passing.

10 The ultimate goal of each model is to receive inputs through the input ports and generate outputs

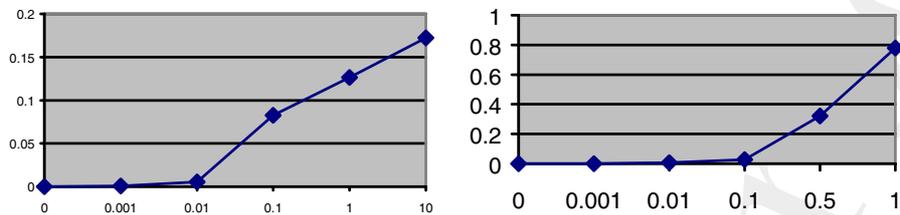


Figure 45. Accumulated error behavior.

in the output ports according to the definitions of the transition functions. The tool provides a way of registering every input and output of individual models. Nevertheless, fully detailed interaction between the models can be registered by analyzing a log output file. Figure 46 shows a printout of the log file generated by the tool when the Life game is simulated.

5 It can be seen that the simulation process begins by sending an initialization (*I*) message to the external model (top), which is in charge of distributing them through the cell space (see Figure 46(a)). Each of the cells replies with a *done* (*D*) message (see Figure 46(b)), telling the time for the next internal event (in this case, 100 ms; that is, the delay defined in the specification).

10 When the top-level coordinator receives all the *done*-messages (Figure 46(c)), it transmits the time of the imminent child to the root coordinator. In this way, the global time of the simulation is updated. The root coordinator replies using a \*-message (see Figure 46(d)), that is sent to the imminent children. They execute and their simulators generate *Y*- and *done*-messages (see Figure 46(e)).

15 Finally, the coordinator analyzes which output of a model should be sent to others (see Figure 46(f)), generating new *X*-messages. The cycle is repeated up to the moment where all the external events are consumed, or when the simulation time is consumed (in this case, 500 ms, as can be seen in Figure 46(g)).

20 Based on the log file, a simple text output interface was defined. It allows the user to see the execution of Cell-DEVS models in a fast way, allowing them to debug executable models. For instance, Figure 47 shows the results obtained when executing the 3D Life game defined earlier (showing the 3D space as three independent planes).

These values can be used to visualize the results using 3D tools. Figure 48 shows the outputs of the 3D Life game in one of our current 3D visualization engines.

25 The values in the log file can be used to provide a generic graphical output. Figure 49 shows its use when executing the control tower model presented earlier (at present, a prototype—all the state variable values have been added by hand to make the description of the model execution clearer).

30 In this case, we show the execution of the control tower when three different requests are demanded. The model is initially in a *passive* state (with no scheduled internal events; that is,  $\sigma = \infty$ ). In simulated time 3, an input request arrives through the port *in\_d*. Checking the model specification, we see that the flight information is stored and an internal event is scheduled. In this case, we need a preparation time of 7 time units. During this time, the model remains in the *prep\_rnwy-use* phase. When the time is consumed ( $\sigma = 0$ ), an internal function is executed. The output function executes first,

```

Message I / 00:00:00:000 / Root(00) for top(01) (a)
Message I / 00:00:00:000 / top(01) for life(02)
Message I / 00:00:00:000 / life(02) for life(0,0) (03)
Message I / 00:00:00:000 / life(02) for life(0,1) (04)
...
Message I / 00:00:00:000 / life(02) for life(19,19) (402)
Message D / 00:00:00:000 / life(0,0) (03) / ... for life(02)
Message D / 00:00:00:000 / life(0,1) (04) / 00:00:00:100 for life(02) (b)
Message D / 00:00:00:000 / life(0,2) (05) / 00:00:00:100 for life(02)
...
Message D / 00:00:00:000 / life(19,19) (402) / ... for life(02)
Message D / 00:00:00:000 / life(02) / 00:00:00:100 for top(01) (c)
Message D / 00:00:00:000 / top(01) / 00:00:00:100 for Root(00)
Message * / 00:00:00:100 / Root(00) for top(01) (d)
Message * / 00:00:00:100 / top(01) for life(02)
Message * / 00:00:00:100 / life(02) for life(0,1) (04)
...
Message * / 00:00:00:100 / life(02) for life(19,17) (400)
Message Y / 00:00:00:100 / life(0,1) (04) / out / 0.000 for life(02) (e)
Message D / 00:00:00:100 / life(0,1) (04) / ... for life(02)
Message Y / 00:00:00:100 / life(0,2) (05) / out / 0.000 for life(02)
...
Message D / 00:00:00:100 / life(19,16) (399) / ... for life(02)
Message Y / 00:00:00:100 / life(19,17) (400) / out / 1.000 for life(02)
Message D / 00:00:00:100 / life(19,17) (400) / ... for life(02)
Message X / 00:00:00:100 / life(02) / neighborchange / 0.000 for life(19,0) (383) (f)
Message X / 00:00:00:100 / life(02) / neighborchange / 0.000 for life(19,1) (384)
...
Message X / 00:00:00:100 / life(02) / neighborchange / 1.000 for life(18,18) (381)
Message D / 00:00:00:100 / life(19,0) (383) / ... for life(02)
Message D / 00:00:00:100 / life(19,1) (384) / ... for life(02)
Message D / 00:00:00:100 / life(19,2) (385) / 00:00:00:100 for life(02)
...
Message D / 00:00:00:100 / life(18,18) (381) / ... for life(02)
Message D / 00:00:00:100 / life(02) / 00:00:00:100 for top(01)
Message D / 00:00:00:100 / top(01) / 00:00:00:100 for Root(00)
Message * / 00:00:00:200 / Root(00) for top(01)
Message * / 00:00:00:200 / top(01) for life(02)
Message * / 00:00:00:200 / life(02) for life(19,2) (385)
...
[The simulation cycle is repeated]
Message D / 00:00:00:500 / life(12,8) (251) / ... for life(02)
Message D / 00:00:00:500 / life(12,9) (252) / ... for life(02)
Message D / 00:00:00:500 / life(02) / ... for top(01) (g)
Message D / 00:00:00:500 / top(01) / ... for Root(00)

```

Figure 46. Message traffic during the execution of the hierarchical model.

sending the STOP signal to other models (represented by a short arrow in the figure). Then the internal transition function is executed, queuing the plane, choosing it (as there is no other plane queued) and putting the model in the *rnwy-use* state during 7 time units. When this time is consumed, the GO signal is sent to the output ports and flight #1 is sent through the corresponding port (in this case, *departing*).

- 5 A second plane arrives and the procedure is repeated. When 3 time units have been consumed, a new external event occurs, indicating an emergency plane (#4). Then, the emergency signal is sent to the landing port, the previous plane is dequeued, letting flight #4 land. When it finishes landing, flight #2

```

Time: 00:00:00:000
0123456 0123456 0123456
+-----+ +-----+ +-----+
0|1      | 0|      | 0|1      |
1|1 1 11 | 1|11 11 | 1| 111  |
2| 1  1  | 2|  11 1 | 2| 1 11  |
3|      | 3| 1 11 | 3|      |
4|  1 11 | 4|  1 1 | 4|  1 11 |
5|  11 1 | 5|  1 1 | 5|  11 1 |
6|1  1 1 | 6|  1  1 | 6| 1 11 1 |
+-----+ +-----+ +-----+
Time: 00:00:00:200
0123456 0123456 0123456
+-----+ +-----+ +-----+
0|1      | 0|1      | 0|1      |
1|1 1 1  | 1| 1 1  | 1|1 1 1 |
2|      | 2|  1  1 | 2|      |
3| 1  1  | 3| 1  11 | 3| 1  11 |
4|      | 4|  11  | 4|      |
5|1  1  | 5| 1  1 1 | 5|1  1 1 |
6|11  11 | 6|11  11 | 6|11  111 |
+-----+ +-----+ +-----+
...
Time: 00:00:00:100
0123456 0123456 0123456
+-----+ +-----+ +-----+
0| 1  1  | 0|11  1 | 0| 1  1  |
1|1 1  1 | 1| 1  1  | 1|1 11 1 |
2|11  1 1 | 2| 1  1  | 2|11  11 |
3|      | 3|  1 1 1 | 3|  1 1  |
4|      | 4|      | 4|      |
5| 1  111 | 5| 1  111 1 | 5| 1  11 1 |
6|      | 6|  1  | 6|  1  1  |
+-----+ +-----+ +-----+
Time: 00:00:00:900
0123456 0123456 0123456
+-----+ +-----+ +-----+
0|      | 0|      | 0|      |
1|      | 1|      | 1|      |
2|      | 2|      | 2|      |
3|      | 3|      | 3|      |
4| 1  1  | 4| 1  11 | 4| 1  1  |
5|      | 5|      | 5|      |
6|      | 6|      | 6|      |
+-----+ +-----+ +-----+

```

Figure 47. Execution results for the 3D Life game.

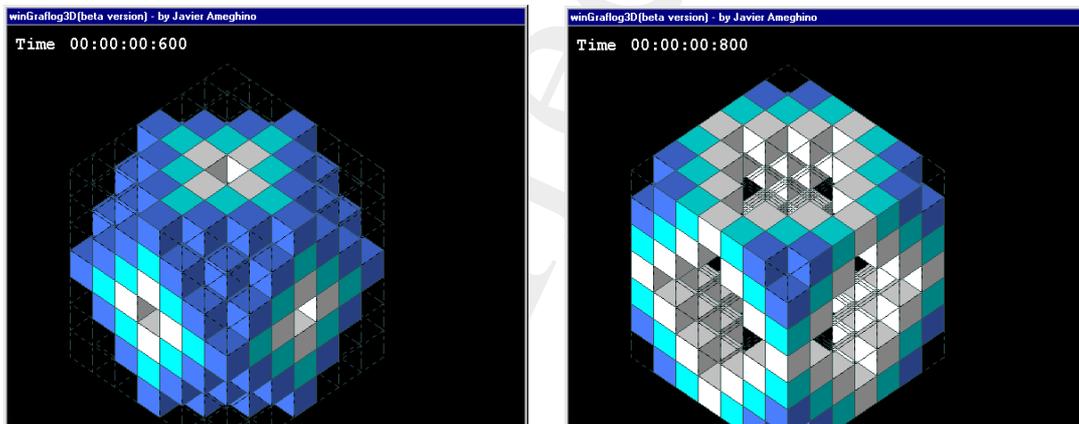


Figure 48. Graphical display for the 3D Life game.

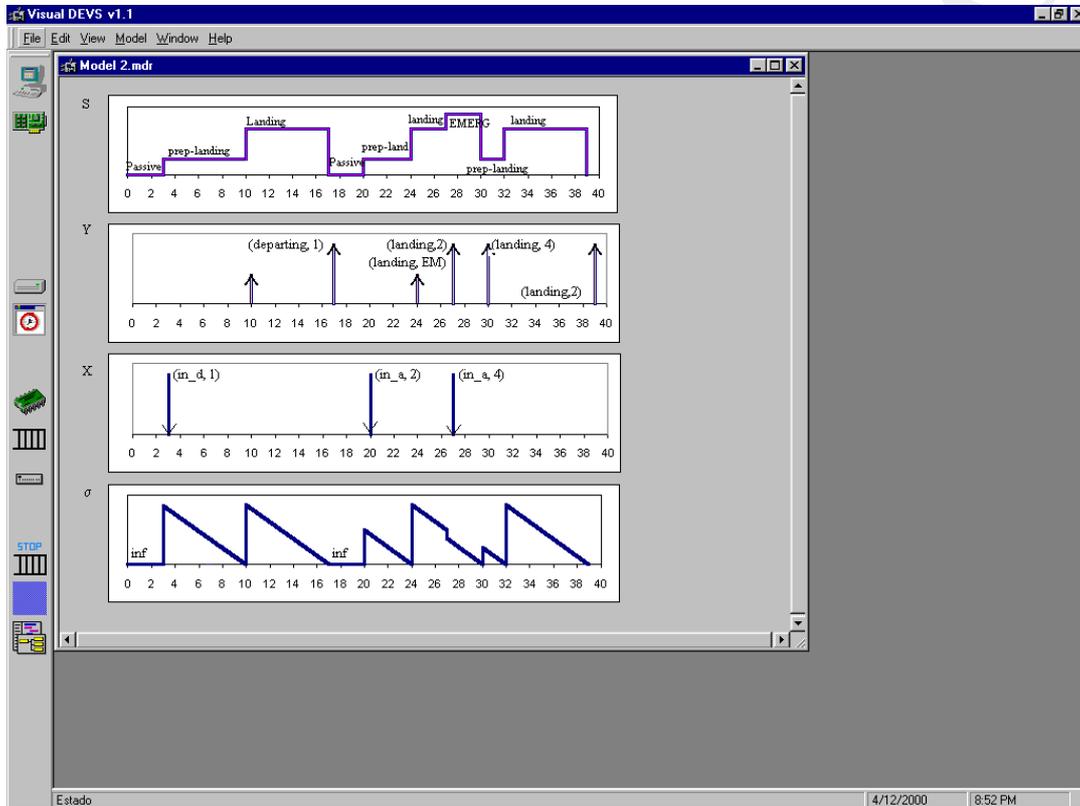


Figure 49. Execution results for the airport model.

is authorized to use the runway and lands (the values related to this flight are kept in the control tower queue).

In addition to these standard graphical outputs, a SCADA tool built with industrial application purposes was modified to receive inputs from the CD++ tool [30]. The SCADA receives inputs from the simulator and reacts to them as if they were real-time data. In this way, complex man-machine interaction can be provided. The user can define what values in a model they want to be analyzed and how. Graphical mimics can be associated with different. It can also associate alarm conditions to the central databases, combine the results, store them as historical data to be analyzed, etc.

Another graphical output included shows the execution results of Cell-DEVS models. For instance, Figure 51 includes the execution results of the original Rothermel model presented earlier.

Each of these graphical tools is independent from the simulation engine. Therefore, different kinds of visualization methods can be employed for the same simulation results. Some of these results can be seen using a centralized tool using Windows. Others were developed in Java and can be embedded in

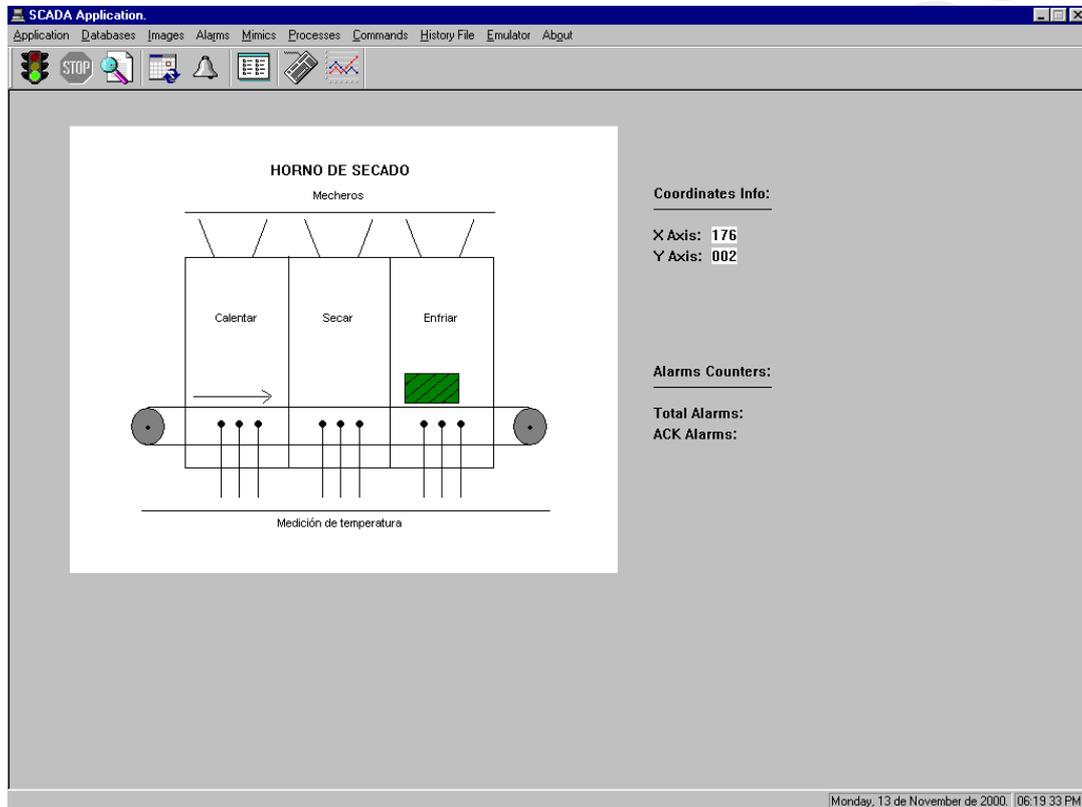


Figure 50. Output visualization using IGNATIUS.

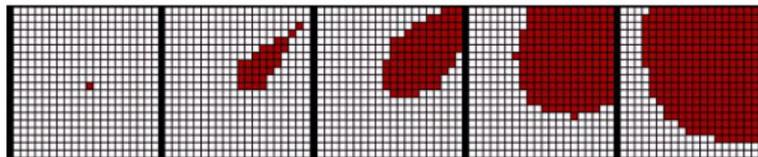


Figure 51. Fire propagation results. The fire originated in cell (11, 11) with wind blowing NE.

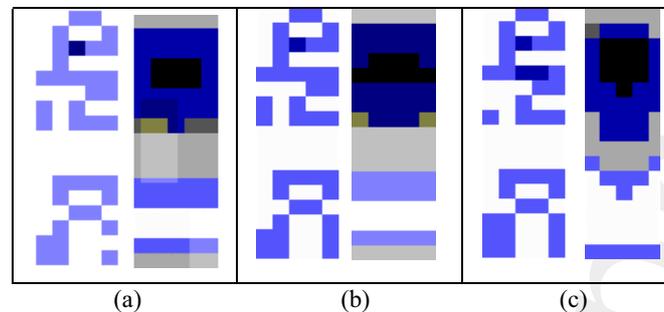


Figure 52. Error behavior for the heat seekers: (a) non-quantized and  $q = 0.001$ ; (b)  $q = 0.1$ ; (c)  $q = 1$ .

a Web front-end that can communicate with the simulation server, providing facilities for Web-based simulation. Recently we have extended these results to provide 3D visualization using VRML. 

Finally, Figure 52 shows the execution results of different quantized versions of a model. It shows that the error introduced by the quantizers can lead to undesired behavior for the execution models.

- 5 We show the behavior of devices seeking heat sources in a diffusion model. This 3D model uses one plane for the heat diffusion and a second one for the heat field. The seekers move in the plane looking for the heat maxima in the second plane. In Figure 52, the left-hand side of each part shows the behavior of the heat seekers and the right-hand side shows the heat surface for a given simulated time (using a different quantum in each case). We can see that the use of a high quantum produces
- 10 much higher errors, producing a result completely different from that desired in both fields. The use of a smaller quantum also introduces errors, but most seekers can reach the local maximum. Therefore, several orders of improvement in execution times can be achieved using small quanta, preserving the behavior of the model. In this case, a speedup of almost 40% was achieved with almost no error.

## CONCLUSIONS

- 15 We have introduced several features of CD++, a toolkit for DEVS modeling and simulation. The tool was built using the DEVS formal modeling technique, improving the safety and development times of the simulations. The tool executes in a stand-alone mode or as a simulation server that can be executed remotely. It executes on different platforms, from low-priced personal computers up to high-performance multiprocessors or distributed systems. The separation of visualization tools from the
- 20 simulation engines makes the development of new improvements in visualization easier, improving its use for Web-based simulation.

- We have shown that the abstract simulation mechanism enables different simulation techniques to be defined without the need to change the models developed, as they follow the formal specifications of the DEVS formalism. The models are easily reusable thanks to their hierarchical construction.
- 25 Consequently, the costs of development are reduced, the quality of the models improves and non-

expert users are able to start developing new applications with a fast learning curve. Several types of models can be integrated in an efficient fashion, allowing multiple points of view to be analyzed using the same model. The formalism allows improvement in the security and cost in the development of the simulations. Experimental results of applications have shown improvements for expert developers. The main gains have been reported in the testing and maintenance phases, the more expensive phases for these systems [14].

The tool was used to develop several kinds of application examples, which allowed us to show the flexibility of the toolkit. Some of them include:

- Alfa-1—a complete simulated processor emulating the SPARC CPU (used for educational purposes);
- ATLAS—a high-level specification language for traffic models (mapped in DEVS and Cell-DEVS);
- a watershed model;
- Rothermel fire spread analysis;
- a robot moving in a manufacturing plan;
- diverse physical problems—heat diffusion, crystal growth, excitable media, particle collision, heat seekers, surface tension, etc.;
- an airport model (and a 3D model of planes coming to the airport);
- a model of a manufacturing plant;
- a library of network performance analysis (based on client/server applications for Web servers);
- cryptkey generation;
- ant foraging models and other ecological systems.

At present, some other applications are being developed, including analysis of PCS systems, behavior of the heart tissue, a flow injection model and an extended library for modeling network systems.

The tools are public domain and can be obtained at <http://www.sce.carleton.ca/faculty/wainer/celldevs>. The developed models are publicly available and will be incorporated into a Web-based environment that can be applied to the development of DEVS models.



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## Annotations from spe482.pdf

### Page 5

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*Annotation 1*

Au: lines 1-7

Please check sense here.

*Annotation 2*

Au: line 21

`overloaded' OK?

### Page 6

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*Annotation 1*

Au:

Please cite all figures in text.

### Page 27

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*Annotation 1*

Au: Figure 29

Please clarify `the previous example'?

### Page 37

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*Annotation 1*

Au: line 1

Please clarify `it'?

*Annotation 2*

Au: line 11

Sense OK?

*Annotation 3*

Au: line 21

Do you mean `In all cases'?

### Page 38

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*Annotation 1*

Au: line 4

Please clarify `in the (a) case'?

### Page 39

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*Annotation 1*

Au: line 6

Please clarify `them'?

### Page 42

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*Annotation 1*

Au: line 7

Missing text?

### Page 44

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*Annotation 1*

Au: line 2

Define VRML?

**Page 45**

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*Annotation 1*

Au:

Please supply page numbers for reference [1].

Please supply volume and page numbers for references [9,15].

Please supply publisher and town for all Proceedings.