Integration des Petrinetz-Analysators TimeNET in die Modellanalyseumgebung MOSEL

Diplomarbeit im Fach Informatik

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Kurzfassung

MOSEL (Modelling, Specification and Evaluation Language) ist eine textuelle Computersprache für die Beschreibung von stochastischen dynamischen Modellen und aus diesen Modellen resultierenden Leistungsmaßen; außerdem ist es der Name einer Modellierungsumgebung, mit der solche Beschreibungen analysiert und die angegebenen Leistungsmaße berechnet werden. Mit MOSEL können komplexe Systeme modelliert werden, wie Kommunikationsnetzwerke, Produktionsanlagen, Computersysteme, und viele weitere. Wie stochastische Petrinetze basiert es auf *Stellen* (die in MOSEL "Knoten" genannt werden) und *Transitionen* (die "Regeln" heißen). Für die eigentliche Auswertung ruft das MOSEL-Programm ein externes Tool auf, nachdem es die MOSEL-Beschreibung in das Beschreibungsformat des jeweiligen Tools übersetzt hat. Bisher konnten zu diesem Zweck das Petrinetz-Analyse-Tool SPNP und das Markov-Analyse-Tool MOSES verwendet werden. In der vorliegenden Arbeit beschreibe ich, wie ich TimeNET, ein weiteres Petri-Netz-Analysetool, in die MOSEL-Umgebung eingebunden habe. Der Hauptvorteil von TimeNET gegenüber den bisherigen Tools ist seine Unterstützung für nicht-markovsche stochastische Modelle.

Die ursprüngliche MOSEL-Sprache enthält einige Sprachelemente, wie Variablen und Funktionen im Format der Programmiersprache C, die durch die Schnittstellen-Sprache von TimeNET nicht unterstützt werden. Deswegen habe ich die Sprache MOSEL stark überarbeitet. Die überarbeitete Fassung trägt den Namen "MOSEL-2". Die Semantik von MOSEL-2 habe ich formal definiert, indem ich ein Verfahren angebe, das ein MOSEL-2-Modell in einen stochastischen Prozess mit endlichem Zustandsraum und stetiger Zeitbasis abbildet.

Die vorliegende Arbeit enthält eine praktische Einführung in die Modellierung mit MOSEL-2, die sich vor allem an Personen ohne Erfahrung in der Erstellung stochastischer Modelle richtet. Für Personen, die bereits mit MOSEL modelliert haben, werden in einem Kapitel die Unterschiede zwischen MOSEL und MOSEL-2 dargestellt, und es werden Vorschläge gemacht, wie bestimmte nicht mehr unterstützte Sprachelemente von MOSEL in MOSEL-2 umgesetzt werden können. In einer exemplarischen Anwendung von MOSEL-2 wird der Energieverbrauch einer Festplatte bei variierender Last modelliert. Schließlich wird MOSEL-2 mit den textuellen stochastischen Modellbeschreibungssprachen CSPL und SHARPE verglichen.

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Diploma Thesis in Computer Science

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Abstract

MOSEL (Modelling, Specification and Evaluation Language) is a textual computer language for the description of stochastic dynamic models and performance measures that result from such models, and it is the name of a modelling environment by which such descriptions can be analysed and their given performance measures can be computed. With MOSEL, complex systems can be modelled, like communication networks, production lines, computer systems, and many more. Like stochastic Petri Nets, it is based on *places* (which are called "nodes" in MOSEL) and *transitions* (which are called "rules"). For actual evaluation, the MOSEL environment calls an external tool after having translated the MOSEL description into the respective tool's description format. Until now, the Petri Net analysis tool SPNP and the state analysis tool MOSES can be used for this purpose. In the present thesis, I describe how I have integrated TimeNET, a Petri Net analysis tool, into the MOSEL environment. The main advantage of TimeNET compared with the present tools is its support of non-Markovian stochastic models.

The original MOSEL language contains some language features, like variables and functions in the style of the C programming language, which are not supported by TimeNET's interface language. Therefore I have revised the MOSEL language; the revised language is called MOSEL-2. I have defined the semantics of MOSEL-2 formally by detailing a procedure that maps a MOSEL-2 description onto a continuous-time stochastic process with finite state space.

The present thesis contains a practical introduction into modelling with MOSEL-2, which primarily addresses users with little experience in the specification of formal models. For people which have already used MOSEL for modelling, the differences between MOSEL and MOSEL-2 are detailed in a chapter of its own, and for many of the obsolete MOSEL language features, equivalent MOSEL-2 constructs are suggested. As a real-world example, it is shown how MOSEL-2 can by used to model the power consumption of a hard disk. Finally, MOSEL-2 is compared to two other textual description languages for stochastic modelling, CSPL and SHARPE.

Contents

Chapter 1

Introduction

The subject of this thesis is the integration of the Petri Net analysis and simulation tool TimeNET (see [TimeNET]) into the modelling environment MOSEL (see [BBH]). This work is located in the area of stochastic modelling and evaluation for the purpose of performance and reliability analysis; therefore this chapter contains a short overview over that area in Section 1.1. The MOSEL environment will be described (in Section 1.2), as well as the TimeNET tool (in Section 1.3). The MOSEL description is rather short, since the complete description of the revised MOSEL language will be the subject of later chapters. In Section 1.4, the overall structure of the present thesis will be sketched.

1.1 Stochastic Modelling and Evaluation

The theory of probabilities is a helpful tool to evaluate complex dynamic systems like computer architectures, communication networks, production lines, and many more. Typically, we know, or can estimate, certain values for *components* of such systems, like the expected lifetime of an individual computer in a redundant high-security computer system, or the average number of parts that a station in a production line can produce per hour. We also know how those components depend on each other, for example, how the reliability of a redundant computer system depends on the reliabilities of the individual computers it is built of, or which other stations are connected to a certain station in a production line.

The following methods, taken from [BBH], page 1, can be used to calculate certain quantitative measures for the system as a whole, like the life time of the whole computer system or the number of parts that can be manufactured by the production line:

- Build a prototype whose architecture is identical to the system to be modelled. The relevant parameters of the prototype's components used should be close to the parameters of the actual system's components. The behaviour of that prototype, especially the measures of interest, can be measured by observation.
- Simulate the behaviour of the system in a computer model. Stochastic models are usually simulated using *discrete event simulation* (DES), which is based on the Monte Carlo method: The probabilistic quantities of the model's components are replaced by random quantities with the same probabilistic distribution. The simulation is repeated for many runs (typically several thousand times) or for very long runs, so that the random quantities will approximate the probabilistic quantities. DES can model a wide range of models, but the number of repetitions that are needed to gain acceptable accuracy may be very high.

- Create a mathematical model of the system and do a computer-based numerical analysis on it. Approximative analysis methods are used for models that are intractable by exact methods or whose exact solution would consume too much time and space. Even if exact solution methods are used, instabilities of the numerical algorithms may have a great influence on the quality of the results in practice. Analytical methods are only known for a limited subset of stochastic models, although research is going on to develop analytical methods for more general model types.

In the following, we will only deal with simulative and analytical methods.

Stochastic models can be used to gain the following types of result measures ([BBH], pages 63–64):

Performance Measures: These are values like system throughput, response time or utilization of components or the whole system, under the assumption that the system does not fail.

Reliability: This is the probability that the system will work without failure during a certain time period. Also of interest is the mean time span until the first failure happens.

Availability: This is the probability that the system is working at a certain time point.

Performability Measures: These are measures that take temporary performance degradations into account. Performance may be reduced by the failure of parts of the system. Performability measures may be seen as a combination of performance measures and availability.

Stochastic modelling needs a sound mathematical basis. For virtually all model types, the methods used for stochastic analysis and simulation are formalised in terms of *stochastic processes* and *Markov chains*, so I'll give a brief informal sketch of them. For more information, refer to [BBH], chapter 2.

- A *stochastic process* is a family of random variables that share a common value space, which is called the process' *state space*. The random variables are indexed by a discrete or continuous parameter. Since we want to model dynamic systems, we will always use time as the process' parameter; the random variable that is indexed by a specific time point gives the *state* of the process at this time point. If the time parameter is continuous, we speak of a *continuous-time stochastic process*; if the values of the time parameter have a constant step width, we speak of a *discrete-time stochastic process*.
- A stochastic process with discrete state space is called a *stochastic chain*.
- A *Markov chain* is a stochastic chain which is memoryless, i.e., the future behaviour of the process only depends on its current state, not on the past behaviour.
- A Markov chain is *homogeneous* if the probabilistic behaviour of the process at time $t + \Delta t$ only depends on the state at time t and on Δt, but not on t itself. For a homogeneous discrete-time Markov chain (DTMC), this means that the transition probabilities from any state to any state in one time step are time-independent constants. The transition probability from one state to another is then geometrically distributed over Δt. — For a homogeneous continuous-time Markov chain (CTMC), the time-derivatives of the transition probabilities are time-independent constant as well. As is well-known from calculus, the transition probabilities have exponential distributions over Δt. In both

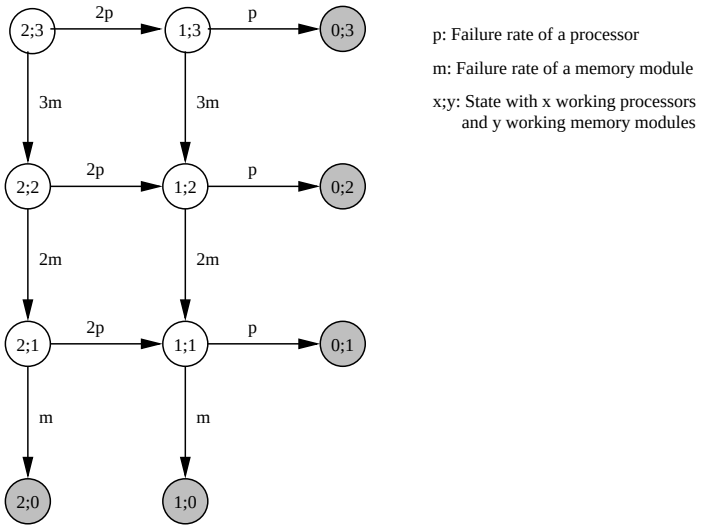


Figure 1.1: An example of a continuous-time Markov chain, taken from [BBH], page 73.

cases, the transition probabilities between any two states and for any time range can be computed from these values. Indeed, such computations actually play an important role in numerical analysis algorithms for many stochastic modelling languages.

For practical stochastical modelling, the following model types have gained wide-spread use, as explained in [BBH], chapter 3:

Markov Chains: Markov Chains, when used as a model type, are strongly connected to the mathematical term which has been explained earlier, but for practical reasons they must be homogeneous and are limited to finite state spaces (since each state has to be specified explicitly).

Usually, such a Markov Chain has a graphical representation, in which each circle represents a state and each arc represents a transition between two states. Each arc is labelled by the transition probability in one time step (for DTMCs) or by the time-derivative of the transition probabilities (for CTMCs). For an example, see Figure 1.1.

Markov Chains "are usually larger and difficult to analyze, but they can also model situations that cannot be represented using non-state-space-models" [BBH, page 72]. As soon as the models get more complex, Markov Chains are usually difficult to create, maintain and understand. To overcome the need to specify each state explicitly, high-level modelling types like *queuing networks* and *stochastic Petri nets* can be used, which are mapped onto DTMCs or CTMCs for analysis. More about Markov Chains can be found, for example, in [STP].

Queuing Networks:

A queuing network consists of service centers and customers (often called *jobs*). A service center consists of one or more servers and one or more queues to hold customers waiting for service. When a customer arrives at a service center, it enters one of the servers or one of the queues. If there are customers waiting when a busy server becomes idle, the next customer to be served is selected according to a *scheduling discipline* (sometimes also called *queueing discipline*). The *queueing delay* is the time period a customer waits in a service center before it enters one

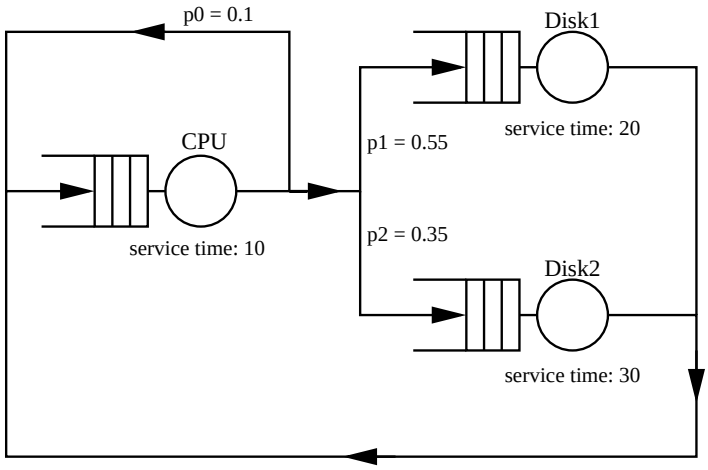


Figure 1.2: An example of a queueing model, taken from [BBH], page 67.

> of the servers. The *response time* is the amount of time a customer spends at the service center, including the queueing delay and the service time. [...]
> A queueing network in which customers arrive from an external source, spend time in the network, and depart is said to be *open*. A queuing network in which there is no eternal source of customers and no departures is said to be *closed*. [BBH, page 64]

Among the queueing disciplines that are usually supported are *First-Come-First-Served*, *Last-Come-First-Served* and *Infinite Server*. Figure 1.2 shows a closed queuing model. Queues are represented by open rectangles, servers are represented by circles.

Queuing networks were among the first modelling formalisms for dynamic stochastic models, but the are only of limited expressive power, since they cannot express dependencies among individual customers in the system.

Stochastic Petri Nets: A stochastic Petri net is also a state-based model type, but its descriptive level is higher than that of Markov Chains. They are based on (pure) Petri nets, which allow to model the dynamic behaviour of processes, like concurrency and synchronisiations, but which do not allow for quantitative analysis.

A *Petri net* consists of *places* and *transitions*, which are connected by *arcs*. A place may contain a variable number of indistinguishable tokens. The current number of tokens in each place determines the current state of the Petri net, which is called the net's *marking*. The *initial marking* is part of a Petri net definition.

A transition may have any number of input arcs, which are arrows that go from the transition's *input places* to the transition, and any number of output arcs, which are arrows that go from the transition to its *output places*. If each input place of a transition contains at least one token, we say the transition is *enabled* and may *fire*, i.e., be executed. When a transition fires, it removes a single token from each of its input places, and adds a single token to each of its output places.

If several transitions are enabled in a certain marking, then *any* of these transitions may fire. This introduces some non-determinism into the model, which is needed to model concurrency. If no transition is enabled in a certain marking, then that marking is called *absorbing*.

The directed *reachability graph* of a Petri net represents all possible markings as graph nodes. If a transition can lead from one marking to another, then these nodes are

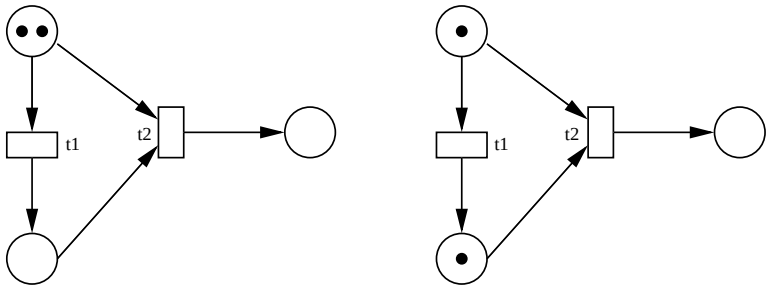


Figure 1.3: A simple Petri net before and after firing $t1$, taken from [BBH], page 74.

connected by an edge in the graph. The reachability graph is usually constructed by depth-first or breadth-first exploration of the state space, starting with the initial marking. It is useful for the examination of a Petri net's structural properties.

Figure 1.3 shows a Petri net, before and after a transition has fired, respectively. Places are represented by circles, tokens are shown as black dots in the circles, and transitions are displayed as rectangles.

A *Stochastic Petri Net* (SPN) adds time to a Petri net: each transition has a probabilistic delay which starts when the transition has been enabled. When the delay has passed and the transition is still enabled, then it actually fires. The delays are exponentially distributed, which allows the Petri net to be converted to a Markov chain for analysis (by *state-space generation*). Usually, not the expected value of the delay is given, but the expected value of its reciprocal, the *firing rate*. If several transitions are enabled at the same time, the rule whose delay has passed first will fire.

> Generalized Stochastic Petri Nets (GSPN) proposed by Ajmone Marsan et al. [ABC] are the extension of Stochastic Petri nets obtained by allowing the transitions of the underlying PN to be immediate as well as timed. Immediate transitions (graphically represented by thin black bars) are assumed to fire in zero time as soon as they are enabled. Timed transitions (represented by rectangular boxes or thick bars) are all associated exponentially distributed firing times with rates just as in SPNs.
>
> When both immediate and timed transitions are enabled in a marking, only the immediate transitions can fire; the timed transitions behave as they are not enabled. When marking m enables more than one immediate transition, it becomes necessary to specify a probability mass function according to which the first transition to fire is chosen. The marking of a GSPN can be classified to *vanishing* marking in which at least one immediate transition is enabled, and *tangible* marking in which only timed transitions [or none] are enabled. The reachability graph of a GSPN can be converted to a Continuous-time Markov chain by eliminating the vanishing markings [which yields a Reduced Reachability Graph (RRG)] and can be solved using different solution methods [...]. [BBH, page 76]

The probabilistic behaviour of a stochastic Petri net can be evaluated at a given time point after it has been started with its initial marking; this is called a *transient* evaluation. The long-time behaviour of a stochastic Petri net can be studied by a so-called *stationary* or *steady-state* evaluation.

Figure 1.4 shows an example of a GSPN.

> Many extensions to Petri nets [and GSPNs] have been proposed in order to increase either the *modeling convenience* or the *modeling power*. Structural extensions that effect only the modelling convenience provide a powerful way to improve the ability of Petri nets to model real problems. Some accepted extensions of this type are:

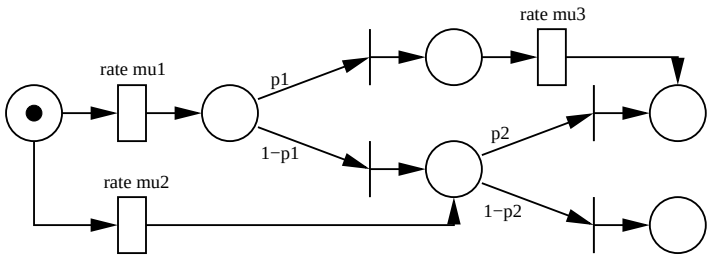


Figure 1.4: A GSPN, taken from [STP], page 136.

Arc multiplicity representing the case when more than one token is to be removed from or to a place in case of firing.

Inhibitor arc from place p to transition t disables t in all markings in which p is not empty. [If the inhibitor arc has a multiplicity m, it disables t in all markings in which p has less than m tokens.]

Transition priorities are integer priority levels assigned to each transition. A transition is enabled only if no other higher priority transition is enabled.

Marking dependent arc multiplicity allows the multiplicity of an arc to vary according to the marking of the net.

[BBH, page 75]

Another extension are *guards*. A guard is a condition in textual form that belongs to a transition. This condition must be met by the marking in order to enable the transition. Guards are useful to express relations between distant places, and they do not change the current marking. Guards are well-fitted for many purposes where the enabling of a transition is difficult to be controlled by arcs.

For the analysis of performability measures, so-called *stochastic reward networks* (SRN) have been introduced, which are based on GSPNs. In an SRN, *rewards* may be specified for some places, which are real-valued functions that depend on the number of tokens in that place. They are used to compute the model's result measures.

GSPNs have a high expressive power, compared with queuing networks, and they allow more concise descriptions than Markov Chain tools. Recent extensions of GSPNs, like MRSPNs (Markov Regenerative Stochastic Petri Net) and DSPNs (Deterministic and Stochastic Petri Net) [German1], allow to use other firing distributions for timed transitions besides the exponential distribution.

Stochastic Process Algebras:

Process algebras are abstract languages used for the specification and design of concurrent systems. [...] In the process algebra approach systems are modeled as collections of entities, called *agents*, which execute atomic *actions*. These actions are the building blocks of the language and they are used to describe sequential behaviors which may run concurrently, and synchronisations or communications between them. [...]
In CCS [Milner's *Calculus of Communicating Systems*, a form of PA's] two agents communicate when one performs an action, a say, while the other performs the complementary action $\bar{a}$. [...] The grammar of the language makes it possible to construct an agent which has a designated first action (prefix); has a choice over alternatives (choice); or has concurrent possibilities (composition). [...] In CSP [Hoare's *Communicating Sequential Processes*, another form of PA's] two agents communicate by simultaneously executing actions with the same label. [...]

$$Mem \stackrel{\text{def}}{=} (get, \top).(use, \mu).(rel, \top).Mem$$
$$Proc \stackrel{\text{def}}{=} (think, p_1\lambda).(local, m).Proc + (think, p_2\lambda).(get, g).(use.\mu).(rel, r).Proc$$
$$Sys_1 \stackrel{\text{def}}{=} (Proc \parallel Proc) \bowtie_L Mem \qquad L = \{get, use, rel\}$$

Figure 1.5: An example PEPA model from [HR], page 238

> Performance Evaluation Process Algebra (PEPA) extends classical process algebra by associating a random variable, representing duration, with every action. These random variables are assumed to be exponentially distributed and this leads to a clear relationship between the process algebra model and a continuous time Markov chain (CTMC).
> PEPA models are described as interactions of *components*. Each component can perform a set of actions: an action [...] is described as a pair (α, r) [...], where α [...] is the *type* of the action and r [...] is the parameter of the negative exponential distribution governing its duration. [HR]

Figure 1.5 shows a simple PEPA model. Besides PEPA, there exist some other SPA formalisms and tools, like TIPP (Timed Process for Performance Evaluation [GHR]), MPA (Markovian Process Algebra [Buchholz]) and EMPA (Extended Markovian Process Algebra [BDG]).

Stochastic process algebras have inherent compositional features, so they are well-fitted for compositional modelling. But the algebraic notation is rather mathematical and unfamiliar for practicians without the necessary background in computer-science.

Other models: Some other graphical model types especially for reliability analysis are also frequently used, such as Fault Trees and Reliability Graphs. In contrast to the four presented model types, they are not state-based. Instead, they use the combinatorial laws of probability for evaluation. Therefore, they can only model events that are stochastically independent. For details, refer to [BBH].

For all presented model types, with the exception of stochastic process algebras, models are typically built using graphical notations. These notations are intuitive and easy to debug if the models are not too big, but they require specialised graphical input tools. Furthermore, graphical representations of bigger models are hard to construct, to read and to debug. Therefore, some graphical and textual modelling languages, like the Stochastic Petri-Net Language SPNL [German2], which is a graphical-textual hybrid, allow the composition of bigger models from smaller parts with well-defined interfaces.

1.2 The Modelling Environment MOSEL

MOSEL [BBH] has been developed by Helmut Herold at *Universität Erlangen-Nürnberg*, Germany. Its name stands for "**Mo**delling, **S**pecification and **E**valuation **L**anguage".

MOSEL is a modelling language targeted at the description and quantitative evaluation of stochastic dynamic models. Using MOSEL, complex systems can be modelled, like communication networks, production lines, computer systems, and many more. The models that are described in MOSEL will be evaluated by a modelling environment that is also called "MOSEL", using numeric analysis methods.

The basic modelling primitives of a MOSEL model are nodes and rules. Functionally, they are like the places and transitions, respectively, of a stochastic Petri Net. The state of a

```
/*********** M/E2/1 server  and  M/M/1 server ==============*/

/*---------------- NODES -------------------------------------*/
NODE  N1[K; Phase1[1]; Phase2[1]]=K;
NODE  N2[K]=0;

/*---------------- NOT ---------------------------------------*/
NOT  N1+Phase1+Phase2+N2 != K;

/*---------------- Rules -------------------------------------*/
FROM  N1      TO  Phase1  IF Phase1+Phase2==0;
FROM  Phase1  TO  Phase2  WITH mue11;
FROM  Phase2  TO  N2      WITH mue12;
FROM  N2      TO  N1      WITH mue2;

/*---------------- RESULTs -----------------------------------*/
RESULT  IF (N2!=0) rho2 += PROB;
RESULT  MEAN N1;
RESULT  DIST N2;

RESULT>>  lambda2 = rho2*mue2;
```

Figure 1.6: An example of a MOSEL description

MOSEL model is determined by the values of all its nodes; the rules describe the possible transitions between these states. Each rule fires either immediately when its conditions are met, or it has a stochastic delay that is exponentially distributed. To get an impression how a MOSEL model description looks like, see Figure 1.6, which is presented without any further explanation.

The real evaluation will not be done by MOSEL itself; instead, the MOSEL model will be analysed by an external analysis tool. For this purpose, the MOSEL model description will be translated into the format that is used by the respective tool. This tool is invoked automatically by the MOSEL environment, its results are read in and written to the MOSEL result file. Optionally, the results may be displayed is graphs. The graph description(s), in the proprietary IGL format ("**I**ntermediate **G**raphics **L**anguage"), are written to a separate file. The graphs can be displayed, printed or changed using the IGL interpreter, which is part of the MOSEL program suite.

So far, the following stochastic analysis tools are supported:

- The stochastic Markov analysis tool MOSES [BGJZ], developed at *Universität Erlangen-Nürnberg*, Germany.
- The Petri Net analysis tool SPNP [SPNP], developed at Duke University, USA.

The MOSEL environment is already prepared for the integration of other stochastic analysis or simulation tools, due to its modular structure.

1.3 The Petri Net Tool TimeNET

The Petri Net Tool TimeNET [TimeNET] [ZFGH1] [ZFGH2] is actually a collection of tools that support the creation, testing, and evaluation (analysis and simulation) of stochastic Petri nets. "The development of TimeNET has been influenced by other software tools like GreatSPN, SPNP and UltraSAN. The first version of TimeNET was a major revision of the tool DSPNexpress, which had been developed at TU Berlin since 1991" [ZFGH2].

TimeNET supports the following types of Petri net models:

Hierarchical Coloured Petri Nets (HCPN): Coloured Petri Nets can contain ordinary tokens, which are all undistinguishable, as well as coloured tokens, which can be distinguished by their different colours. Coloured Petri Nets are useful to model manufacturing systems where different parts must be distinguished. Complex manufacturing systems can be managed by hierarchical decomposition of the net.

Fluid Stochastic Petri Nets (FSPN): The FSPN formalism is an extension of the GSPN formalism. It does not only know places that contain a number of tokens, but it also allows places that contain a continuous amount of fluid, represented by a non-negative real number. That fluid can "flow" along through fluid arcs, in a constant flow, as long as the corresponding transition is enabled. Alternatively, a certain amount of fluid can be removed or deposited at once. *Second Order FSPNs* can also model a stochastic variation of the flow. FSPNs are useful for performance and dependability analysis of systems containing continuous components such as time, liquid, temperatures, or others. For more information, see [Wolter].

Extended Deterministic and Stochastic Petri Nets (eDSPN): This Petri Net type is an extension of the GSPN type. Transitions in eDSPNs are not limited to immediate and exponential firing distributions:

> The firing delay of transitions in eDSPNs can either be zero (immediate), exponentially distributed, deterministic, or belong to a class of general distributions called *expolynomial*. Such a distribution function can be piecewise defined by exponential polynomials and has finite support. It can even contain jumps, making it possible to mix discrete and continuous components. Many known distributions (uniform, triangular, truncated exponential, finite discrete) belong to this class. [ZFGH2]

An eDSPN is also referred to as a MRSPN (Markov Regenerative Stochastic Petri Net). This name stems from an analysis method for such nets which is used by TimeNET for stationary analysis. An eDSPN whose general distributions are all deterministic is called a DSPN (Deterministic and Stochastic Petri Net).

All those Petri net types can be created and modelled using the graphical user interface *Agnes* (**A** **g**eneric **n**et **e**diting **s**ystem). Figure 1.7 shows an eDSPN that is just being edited in Agnes. Agnes has an interface to each analysis tool and simulation tool: It can ask the user for evaluation options using a dialog window, run the tool, read in the computed result values, and display the results. For all Petri net types, evaluation by simulation is possible as well as numeric analysis for certain subtypes.

In the present thesis, we will only consider eDSPNs, since they fit naturally into the existing MOSEL language. The MOSEL language just has to be extended by adding means to specify other distributions besides the exponential and immediate distributions.

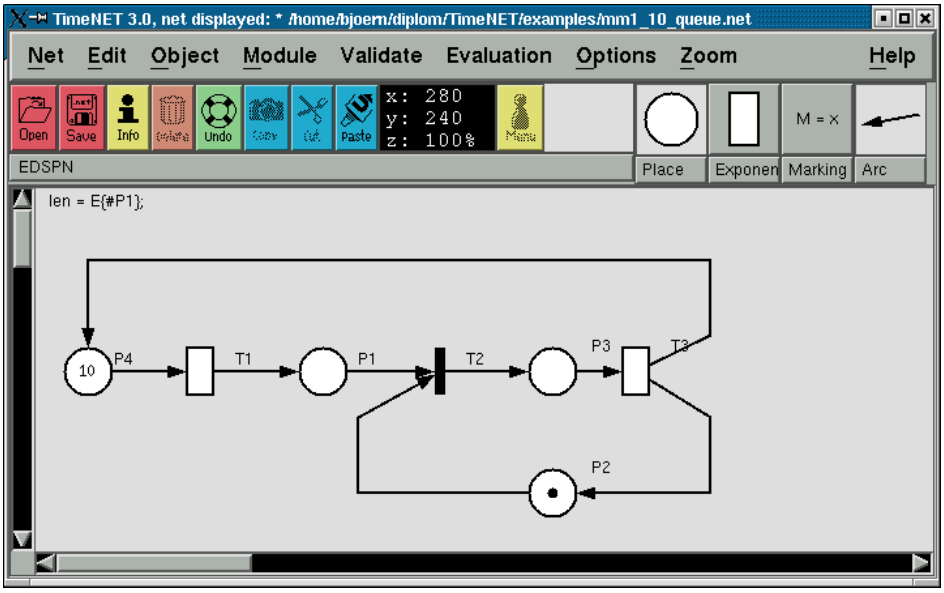


Figure 1.7: Agnes, the graphical user interface of TimeNET.

Figure 1.8 contains the description of a TimeNET model in the TimeNET interface format `.TN`, which is used by TimeNET's eDSPN tools. More about this format can be found in [TimeNET].

Analysis of eDSPNs requires more sophisticated numerical methods than analysis of GSPNs. TimeNET contains five evaluation tools for eDSPNs:

1. continuous-time stationary analysis;
2. continuous-time transient analysis;
3. approximative stationary analysis;
4. discrete-time analysis;
5. continuous-time simulation.

Continuous-time stationary analysis

For the continuous-time steady-state (or *stationary*) analysis, at most one non-exponential timed transition may be enabled at any time point. For the computation of the solution, an algorithm based on *Markov renewal theory* [Kulkarni] is used:

> For a steady-state [...] analysis of a stochastic Petri net model of any kind, the reachability graph is computed next. [...] Subnets of immediate transitions are evaluated in isolation [...] . The reduced reachability graph of a GSPN is isomorphic to a continuous-time Markov chain, because of memoryless state changes. Only the corresponding linear system of equations has to be solved. In case of an eDSPN (and DSPNs as a special case), an additional step is required. The underlying stochastic process is only memoryless at some instants of time, called *regeneration points*. If a transition with non-exponentially distributed firing delay is enabled in a marking, the next regeneration point is chosen after firing or disabling this transition. The time of firing the next exponential transition is taken otherwise.

```
-- FILE erlang4phases.TN CONTAINING STRUCTURAL DESCRIPTION OF A NET

NET_TYPE:               DSPN
DESCRIPTION:            ?
PLACES:                 5
TRANSITIONS:            4
DELAY_PARAMETERS:       2
MARKING_PARAMETERS:     1
REWARD_MEASURES:        1

-- LIST OF MARKING PARAMETERS (NAME, VALUE, (X,Y)-POSITION):

MARKPAR K 20 1.39 4.22

-- LIST OF PLACES (NAME, MARKING, (X,Y)-POSITION (PLACE & TAG)):

PLACE P1 K 2.5 1.06 2.44 0.88
PLACE P2 0 2.48 2.58 2.4 2.86
PLACE P3 0 3.78 2.58 3.7 2.88
PLACE P4 0 5.4 2.58 5.36 2.86
PLACE P5 1 2.5 3.58 2.46 3.4

-- LIST OF DELAY PARAMETERS (NAME, VALUE, (X,Y)-POSITION):

DELAYPAR service 0.1 1.39 4.59
DELAYPAR arrival 0.125 1.39 4.82

-- LIST OF TRANSITIONS
--      (NAME, DELAY, ENABLING DEPENDENCE, KIND, FIRING POLICY,
--       PRIORITY, ORIENTATION, PHASE, GROUP, GROUP_WEIGHT,
--      (X,Y)-POSITION (TRANSITION, TAG & DELAY), ARCS)

TRANSITION t1 1 SS IM RE 1 0 1 0 1.000000 1.7 2.5 1.7 2.8 0 0
INPARCS 2
1 P1 0
1 P5 0
OUTPARCS 2
4 P2 0
1 P1 0
INHARCS 0

TRANSITION T2 arrival SS EXP RE 0 0 1 0 1.000000 3.2 2.5 3.0 2.8 0 0
INPARCS 1
1 P2 0
OUTPARCS 1
1 P3 0
INHARCS 0

TRANSITION T3 arrival SS EXP RE 0 0 1 0 1.000000 4.5 2.5 4.5 2.8 0 0
INPARCS 2
4 P3 0
1 P1 0
OUTPARCS 2
1 P4 0
1 P5 0
INHARCS 0

TRANSITION T4 service SS DET RE 0 0 1 0 1.000000 6.6 2.5 6.6 2.8 0 0
INPARCS 1
1 P4 0
OUTPARCS 1
1 P1 0
INHARCS 0

-- DEFINITION OF PARAMETERS:

-- MARKING DEPENDENT FIRING DELAYS FOR EXP. TRANSITIONS:

-- MARKING DEPENDENT FIRING DELAYS FOR DET. TRANSITIONS:

-- PROBABILITY MASS FUNCTION DEFINITIONS FOR GEN. TRANSITIONS:

-- MARKING DEPENDENT WEIGHTS FOR IMMEDIATE TRANSITIONS:

-- ENABLING FUNCTIONS FOR IMMEDIATE TRANSITIONS:

-- MARKING DEPENDENT ARC CARDINALITIES:

-- REWARD MEASURES:

MEASURE Server1
E{#P1};

-- END OF SPECIFICATION FILE
```

Figure 1.8: Example `.TN` file for TimeNET.

> By taking only the regeneration points into account, a discrete-time Markov chain is embedded. [...] The evolution of the stochastic process during the enabling of a transition with non-exponentially distributed firing delay is analysed. At most one transition of this type can be enabled per marking for this type of analysis. Therefore only exponential transitions may fire during the enabling period, resulting in a continuous-time subordinated Markov chain (SMC) of the non-exponential transition. The transient and cumulative transient solution of this Markov chain computes [the one-step transition probabilities between two regeneration points and the average sojourn times in the states of the SMC until regeneration, respectively]. [...]
>
> [For the embedded DTMC,] a linear system of equations based on the [one-step transition probabilities between two regeneration points] has to be solved [...]. The state probabilities of the actual stochastic process can then be obtained as the mean sojourn time in each state between two regeneration points. Finally, [...] the user-defined performance measures are calculated from the state probabilities. [ZFGH2]

More about Markov renewal theory can be found in [Kulkarni], more about its application for the stationary evaluation of eDSPNs in [CGL].

Continuous-time transient analysis

Continuous-time transient analysis requires that non exponential timed transitions must be deterministic (so only DSPNs can be analysed in a transient state), and that at most one deterministic transition may be enabled at any time point.

> The method is based on supplementary variables, which capture the elapsed enabling time of transitions with non-exponentially distributed firing delays. State equations can be

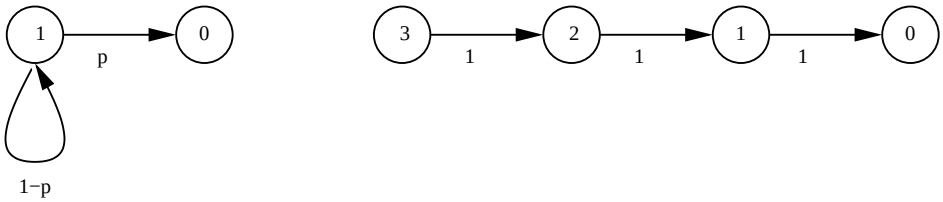


Figure 1.9: DTP representations of a geometric and a deterministic distribution, respectively.

> derived for the description of the dynamic behaviour of DSPNs, consisting of partial and ordinary differential equations which are combined with initial and boundary conditions. [...] During the transient analysis, TimeNET shows the evolution of the performance measures from the initial marking up to the transient time graphically. [ZFGH2]

More about the method of supplementary variables can be found in [German1] and [German3].

Approximative stationary analysis

For approximative stationary analysis, all general transition distributions must be deterministic, but several deterministic transitions may be enabled at the same time. The technique is based on the approximation of the deterministic delays by phase-type distributed stochastic delays which are modified Cox distributions [ZFGH2]. A Cox distribution is the combination of exponential distributions. It is represented by a sequence of exponential phases with possibly complex probabilities and complex rates [BBH]. The number of phases used to approximate the deterministic distributions may be set by the user. Higher numbers lead to more accuracy, but also to a bigger state space. More about the approximation technique used can be found in [German4].

Discrete-time analysis

For the discrete-time stationary and transient analysis, all general transition distributions must be deterministic, but several deterministic transitions may be enabled at the same time. Exponential transition distributions are replaced by geometric distributions, their natural counterparts for discrete model time. The expected delay of a geometric delay must be higher than the time base scale, and the deterministic fire delays must be integer multiples of the time base scale. This solution method is well-suited for clocked activities like in a clocked network or in a processor system.

The evaluation algorithm is based on the *Discrete Deterministic and Stochastic Petri Net* formalism (DDSPN) [ZCH]. In DDSPNs, arbitrary firing times can be represented as the time to absorption in a finite absorbing DTMC with an underlying constant time step. The geometric distribution that approximates the exponential distribution is represented by a two-phase DTMC, while the deterministic distribution is represented by a DTMC whose number of phases depends on the number of time steps that are contained in the deterministic delay, as show in Figure 1.9. A transition will fire in phase 0. Since several transitions may go to phase 0 at the same instant, conflicts and confusions may arise, which must be resolved by priorities and weights.

For the analysis of a DDSPN, the markings and the phases of each transition are part of the state space of the underlying DTMC.

Continuous-time simulation

For the stationary and transient simulation, any general transition distribution can be used, and several generally distributed transitions may be enabled at the same time.

> The simulation can be executed in a *sequential* or *distributed* manner, i.e. multiple simulation replications run on multiple hosts in a workstation cluster, using a master/slave concept. [...] Since samples from the transient phase do not represent the steady-state behavior of the model, the length of this phase is detected automatically by the simulation component and the samples from this phase are discarded. [...] Usually a TimeNET simulation run stops after a user-specified accuracy of the results has been achieved, which is checked statistically. The accuracy can be controlled [...]. The standard simulation allows two types of variance estimation, which is necessary to detect the already reached accuracy. The normal case is the application of variance estimation based on *spectral variance* analysis. In many cases, a variance reduction technique based on *control variates* can be applied successfully. [TimeNET]

1.4 Thesis Overview

During my work on the integration of TimeNET into the MOSEL environment, I had to realize that some important language features of MOSEL cannot be properly translated into the description language used by TimeNET. Also, some language characteristics of MOSEL were quite irregular and/or hard to understand for newcomers. Therefore, I revised the MOSEL language and called the revised form "MOSEL-2".

Chapter 2 contains the complete language definition of MOSEL-2. Its semantics is described by explaining how to convert a MOSEL-2 description into a stochastic process and how to gain result measures from that process.

Chapter 3 explains how to invoke the MOSEL-2 environment in order to evaluate a model. Since each analysis tool that can be used by MOSEL-2 has its own command line options, a large number of command line options are available for MOSEL-2.

Chapter 4 gives a practical introduction into modelling with MOSEL-2 for people who are not acquainted with MOSEL.

Chapter 5 shows a practical real-world example of evaluation with MOSEL-2: the power comsumption of a hard disk will be modelled.

Chapter 6 explains the differences between MOSEL and MOSEL-2. For most MOSEL language constructs that have been changed or eliminated, we suggest how to translate them into equivalent MOSEL-2 constructs.

Chapter 7 explains the internal steps of the MOSEL-2 evaluation environment, and also some implementation aspects that might be of interest.

Chapter 8 categorizes the MOSEL-2 language in terms of specification languages and software ergonomy; MOSEL-2 will be compared with the stochastic modelling languages CSPL and SHARPE.

Chapter 9 summarizes the present thesis and suggests some future work.

Chapter 2

Definition of the MOSEL-2 Modelling Language

In this chapter, we will define the syntax and semantics of MOSEL-2. The name "MOSEL-2" stands for "**Mo**delling, **S**pecification and **E**valuation **L**anguage", revised definition. MOSEL-2 is based on the original MOSEL definition, as described in [BBH]. A revision was needed since the original MOSEL definition contained language elements that are not supported by the TimeNET tool, but which were needed for the convenient description of larger models, as C-like functions and variables. The differences between the original version and the revised version are described in Chapter 6.

The purpose of MOSEL-2 is to model complex systems, like computer systems, communication networks or production systems, in order to evaluate their performance, reliability, or similar measures. Parts of the model may be defined stochastically, like the processing time of an individual component or the successor of a station in a production system. The given model may be analysed numerically or it may be simulated, yielding the desired result measures.

Nodes are used to describe the model's state. In a specific state, each node has a certain value, which is an integer number in the range from 0 to a node-dependent maximum. This maximum is called the node's *capacity*. The node's *value range* is the set of its possible values.

The state space is the cartesian product of the nodes' value ranges. It is bounded (i.e. finite), since the value ranges are all finite. At time $t = 0$, the process is in its initial state. This initial state is composed of the initial node values, which have to be stated explicitly or implicitly in the model description.

Rules are used to describe how the system may change from one state to another. A rule may change the model's state by setting some nodes to specific values and/or by incrementing or decrementing the values of some nodes. A rule is generally appliable to a set of states. This set is specified by the rule's explicit conditions, and implicitly by some of the rule's actions; for example, a rule may not set a node to a negative value or to a value that exceeds its capacity. If the rule is appliable in the current state, we say it is *enabled*. Several rules may be enabled at the same time.

Each rule is given a probabilistic firing time distribution. This firing time distribution specifies how much time will pass from the point when the rule has been enabled up to the point when the rule will be actually executed. Special subcases are deterministic firing times and rules that will fire immediately.

Not every state in the state space may be reachable; which states are actually reachable depends on the initial state and on the rules that lead from one state to the next.

We will define the semantics of a MOSEL-2 description by describing how it can be converted into a stochastic chain, that means, a stochastic process with finite state space. This stochastic chain is reached in three steps:

1. The MOSEL-2 description is translated into a mathematical model called the *Explicit State Model* (ESM).
2. The Explicit State Model is converted to a process with mixed continuous/discrete state space and continuous time base. The state space of the Markov process consists of the states of the ESM, but supplementary real numbers have been added to each state, which indicate the remaining firing times for each rule. Since the remaining firing times are part of the process' state space, we can predict the probabilistic behaviour in the future from the current behaviour and do not need to examine past states. In other words, the process is Markovian. (This technique has been inspired by [German1], chapter 6.)
3. From that Markov process, we can derive a stochastic chain with finite state space by dropping the remaining firing times in the states. This new process is generally not Markovian. It *is* Markovian, indeed, if the MOSEL-2 description from which it has been derived only contains immediate rules and exponentially distributed rules.

It is easier to define the semantics on a subset of the MOSEL-2 language only, which we call *Core MOSEL-2*. The semantics of the full MOSEL-2 language can then be explained in terms of Core MOSEL-2. So this chapter is divided into the following sections:

Section 2.1 Definition of Core MOSEL-2.

Section 2.2 Definition of Full MOSEL-2. The meanings of additional elements of MOSEL-2 are defined in terms of Core MOSEL-2.

Section 2.3 Definition of the semantics of Core MOSEL-2. This shows how a MOSEL-2 description can be formally translated into a stochastic process.

The syntax formalism EBNF

The syntax of MOSEL-2 will be formally described by means of the Extended Backus-Naur Formalism (EBNF) [Wirth]. Its descriptive power is equivalent to context-free grammars, but EBNF grammars are usually more concise. Aspects of the MOSEL-2 language that cannot be expressed by context-free grammars are explained in plain English. An EBNF production looks like

a ::= b "OR" c .

The syntactic symbol a in this example denotes the syntactic unit to be defined. The part to the right of the "`::=`" shows how the symbol a can be constructed as a sequence of the symbols b, the keyword "OR" and the symbol c. The full stop indicates the end of the production. MOSEL-2 keywords and other characters that are part of MOSEL-2, like "`+`" and "`..`", must be enclosed in quotes ("") when used in an EBNF production.

If there are several productions that define a, they are all valid as alternatives. The EBNF operator "|" can be used as an abbreviation for such alternatives:

a ::= *b* (OR | AND) *c* .

This is equivalent to

a ::= *b* OR *c* .
a ::= *b* AND *c* .

Normally, the concatenation of subsequent symbols takes precedence over "|", so we need parentheses here to change the precedence.

The EBNF operator "[]" can be used to denote that the enclosed expression is optional:

a ::= ["-"] *b* .

This is equivalent to:

a ::= *b* .
a ::= "-" *b* .

The EBNF operator "{}" can be used to denote that the enclosed expression is optional and can be repeated:

a ::= *b* {"+" *c*} .

This is equivalent to the recursive definition:

a ::= *b* *x* .
x ::= "+" *c* *x* .
x ::= .

The EBNF productions of the MOSEL-2 syntax are embedded in the MOSEL-2 definition of this chapter; they are also listed alphabetically in Appendix A.

2.1 Core MOSEL-2

We will first define elementary constructs, and go up later to the top-level constructs of Core MOSEL-2, namely nodes, rules and results.

2.1.1 Lexical items

MOSEL-2 is a format-free language, which means that indentation and line breaks have no special meaning. Any sequence of spaces, tabulator stops and new-line characters is called *whitespace* and is ignored. (Actually, there are three exceptions: (1) in strings, spaces and tabulator stops are copied literally, (2) a "//" comment must be ended by a new-line character, and (3) two consecutive names have to be separated by whitespace).

comment ::= "//" *line*
| "/*" *text* "*/" .

A comment in a MOSEL-2 description is ignored. There are two forms of comments, both known from C/C++, namely a one-line comment that starts with "`//`" and ends at the end of the current line, and a free form that starts with "`/*`", may contain any text including line breaks, and ends with "`*/`". Such comments may not be nested.

number ::= *digits* ["`.`" *digits*] [("`e`" | "`E`") ["`+`"| "`-`"] *digits*] .
digit ::= "`0`" | ...| "`9`" .
digits ::= *digit* {*digit*} .

MOSEL-2 does not distinguish integer values and floating point values; integer values are just a subset of the floating point values.

identifier ::= (*letter* | "_") {*letter* | *digit* | "_"} .
letter ::= "`A`" | ...| "`Z`" | "`a`" | ...| "`z`" .

An identifier may be used as the name of a node, a result, or a duration. In Full MOSEL-2, it may also be the name of a constant, an enumeration, a function, or a named condition. Each identifier can only denote *one* of those types. It must have a single definition in the source text. Each use of the identifier must follow that definition.

The following names are reserved keywords with special meanings; they may not be used as identifiers:

AFTER	AND	ASSERT	AVG	COND	CONST	CUM
CURVE	DIST	ELIF	ELSE	ENUM	EXTERN	FIXED
FLOOR	FROM	FUNC	IF	MEAN	NODE	NOT
OR	PARAMETER	PICTURE	PRD	PRINT	PRIO	PROB
PRS	RATE	RESULT	SIN	SQRT	STEP	THEN
TIME	TO	UTIL	WEIGHT	WITH	XLABEL	YLABEL

Two successive names, i.e. identifiers or reserved keywords, in a MOSEL-2 description must be separated by whitespace. Capital letters are different from small letters, so "`node`", "`NODE`" and "`Node`" are all different names.

2.1.2 Expressions

A MOSEL-2 expression yields a floating point value.

expr ::= *simple-expr*
| "IF" *condition* "THEN" *simple-expr*
{"ELIF" *condition* "THEN" *simple-expr*}
"ELSE" *simple-expr* .

A *conditional expression* starts with an "IF", and yields the value of the first *simple-expr* for which the associated *condition* holds. If no *condition* holds, it yields the value of the final *simple-expr*.

simple-expr ::= *term* {("`+`" | "`-`") *term*} .
term ::= *factor* {("`*`" | "`/`") *factor*} .

The arithmetic operators "+", "-", "*" and "/" are supported. Division by zero is forbidden and yields an error. The arithmetic operators are left-associative. The operators "*" and "/" have higher priority, unless the evaluation order is changed by parentheses.

factor ::= *atom* {"^" *atom*} .

The operator "^" is right-associative and used for exponentiation. The exponentiation base (the left operand of an exponentiation) must be positive.

atom ::= "(" *expr* ")" .

Parentheses can be used to express and/or change the evaluation order.

atom ::= ("SIN" | "SQRT" | "FLOOR") "(" *expr* ")" .

"SIN(*expr*)" yields the sine of *expr*, where *expr* is measured in radians.

"SQRT(*expr*)" yields the non-negative square root of *expr*, which must be non-negative.

"FLOOR(*expr*)" yields the largest integer value that is not greater than *expr*.

atom ::= *number* | *result* | *node* .
result ::= *identifier* .
node ::= *identifier* .

A result name (see Section 2.1.8) in an expression yields the value of the respective result. A node name (see Section 2.1.5) in an expression yields its state-dependent value.

atom ::= ["AVG"] "PROB" "(" *condition* ")"
| ["CUM" | "AVG"] "MEAN" "(" *state-expr* ")"

Conditions and expressions in a PROB or MEAN construct are evaluated for each state. A node name in such a construct evaluates to the node's value in that state. A PROB construct yields the overall probability of all states where *condition* holds. A MEAN construct yields the expectation value of *state-expr*, i.e. the sum of *state-expr* evaluated for all states, each term weighed by the probability of its state.

The keywords PROB and MEAN may be prefixed by AVG if the analysis is transient, which computes the time-averaged probability or expectation value, i.e., the values are evaluated and integrated in the time span from $t = 0$ up to the evaluation time point and divided by the length of the time span. The keyword MEAN may be prefixed by CUM if the analysis is transient, computing the cumulated expectation value, i.e., the expectation value is evaluated and integrated in the time span from $t = 0$ up to the evaluation time point.

This definition of MOSEL-2 expressions is very general. There exist several subtypes of MOSEL-2 expressions, which have certain limitations:

- **Probability Expressions**

p-expr ::= *expr* .

A *p-expr* (for *probability expression*) is an expression that defines the value of a result (see Section 2.1.8). It may not contain any conditional expressions, node names, and functions (see Section 2.2), except those who are part of PROB or MEAN constructs.

A result name in a *p-expr* yields the value of that result.

- **State Expressions**

  state-expr ::= *expr* .

  A *state-expr* is a state-dependent expression. It can be used in a MEAN, RATE or WEIGHT construct, in a *condition* (see Section 2.1.3), or in a function definition (see Section 2.2.6). It may contain conditional expressions, node names, and functions, but no PROB or MEAN constructs, and no result names.

- **Constant Expressions**

  const-expr ::= *expr* .

  A *const-expr* is an expression that is used to define a constant (see Section 2.2.3). It may not contain any conditional expressions, PROB or MEAN constructs and no functions, named conditions, results, and nodes, either. A constant expression can be used in an AFTER rule part (see Section 2.1.7) and in a constant definition.

- **Integer Expressions**

  int-expr ::= *const-expr* .

  An *int-expr* is a constant expression that must yield a non-negative integer value.

2.1.3 Conditions

A condition is defined as follows:

condition ::= *and-condition* {"OR" *and-condition*} .
and-condition ::= *not-condition* {"AND" *not-condition*} .
not-condition ::= ["NOT"] *simple-condition* .
simple-condition ::= *state-expr compare-oper state-expr*
| "(" *condition* ")" .
compare-oper ::= "=" | "/=" | "<=" | ">=" | "<" | ">" .

A condition is state-specific. It is used in PROB constructs and in IF rule parts. OR-ed and AND-ed conditions are shortcut-evaluated, so "*node* `> 0 AND 1/`*node* `= 1`" is a valid expression, although "`1/`*node* `= 1`" is illegal if *node* = 0.

2.1.4 MOSEL-2 File Structure

mosel-file ::= {*const-def*}
node-def {*node-def*}
{*assertion*}
{*func-def* | *cond-def*}
rule-def {*rule-def*}
results
{*picture-def*}

A Core MOSEL-2 file consists of node definitions, assertions, rule definitions, result definitions, and picture definitions, in that order. Constant definitions (*const-def*), function definitions (*func-def* and *cond-def*) and picture definitions (*picture-def*) are part of Full MOSEL-2 and are defined in Section 2.2.

2.1.5 Nodes

A node is associated with a name and a value range. The values are integer numbers ranging from 0 to a node-specific maximum, called the node's *capacity*.

node-def ::= "NODE" *node* "`[`" *max-value* "`]`" ["`:=`" *initial-value*] "`;`" .
max-value ::= *int-expr* .
initial-value ::= *int-expr* .

node-def defines a node with name *node* and a value range $\{0, \ldots, max\text{-}value\}$. The node's initial value will be *initial-value* or 0, if *initial-value* is omitted. *initial-value* must be an integer number in $\{0, \ldots, max\text{-}value\}$.

In this chapter, $\max_{node}$ will stand for *node*'s *max-value*.

2.1.6 Assertions

assertion ::= "ASSERT" *condition* "`;`" .

An assertion contains a condition that must hold in every reachable state. This construct is useful to debug a MOSEL-2 description. When the analyzer finds a reachable state for which *condition* does not hold, it reports an error.

2.1.7 Rules

A rule is composed of the following parts:

- A precondition, which describes the subspace of states in which the rule is enabled.
- One or more actions, which describe the changes of the current state that take place when the rule fires.
- A firing distribution. When the rule gets enabled, it may fire immediately, after a fixed time interval, with exponentially distributed probability, or with (discrete) uniform distribution.

- A re-enabling policy. When a rule gets disabled, it may remember or forget the time that has elapsed while the rule was enabled. This has impact on the time until the remaining firing delay when the rule gets re-enabled.
- A priority and a weight. If several rules are enabled and may fire at the same time, only one of the rules with maximum priority will do so. Let S be the set of all rules that are enabled, may fire at a certain time point, and have maximum priority. Let t be the sum of weights of all those rules. Then each rule of S fires with a probability w/t, where w is the rule's weight. Timed rules always have a weight of 1 and a priority of 0. Immediate rules have a default priority of 1, but they can be assigned higher priorities.

The syntax definition of a rule is:

rule-def ::= *rule-parts* "`;`" .
rule-parts ::= *rule-part* {*rule-part*} .

A rule definition may be composed of the following parts, in any order:

- **IF part**

  rule-part ::= "IF" *condition* .

  An IF part specifies that *condition* is a guard for the current rule, i.e. a precondition that must be true in order to enable the rule. IF parts may occur more several times in a rule definition.

- **FROM part**

  rule-part ::= "FROM" *node* ["`(`" *arity* "`)`"] .
  arity ::= *int-expr* | *node* .

  The first variant of a FROM part is a combination of a precondition and an action. In the pre-firing state, the value of *node* must be $\geq$ *arity*. In the post-firing state, the value of *node* is decreased by *arity*. If *arity* is omitted, it is assumed to be 1. If *arity* is a node name, the state-dependent node value will be taken as arity. If *arity* is constant, it must be positive.

  rule-part ::= "FROM" *node* "`[`" *node-value* "`]`" .
  node-value ::= *int-expr* .

  The second variant is a precondition and may only be used if the rule also contains a part "TO *node*[*value*]". In the pre-firing state, the condition *node* = *node-value* must hold in order to enable the rule.

  FROM parts may occur several times in a rule definition.

- **TO part**

  rule-part ::= "TO" *node* ["`(`" *arity* "`)`"] .

  The first variant of a TO part is a combination of a precondition and an action. In the pre-firing state, the condition *node* $\leq \max_{node} - arity$ must hold. If the same rule also contains a rule part "FROM *node*($arity_2$, then the condition $node - arity_2 \leq \max_{node} - arity$ must hold instead. In the post-firing state, the value of *node* is increased by *arity*. If *arity* is omitted, it is assumed to be 1.

rule-part ::= "TO" *node* "[" *node-value* "]" .

The second variant is an action. In the post-firing state, the value of *node* will be set to *node-value*.

TO parts may occur several times in a rule definition.

- **RATE part**

  rule-part ::= "RATE" *rate* .
  rate ::= *state-expr* .

  This part specifies that the rule has an exponential firing time distribution with mean *rate*, which must be a positive floating point value. A RATE part may only occur once in a rule definition.

- **AFTER part**

  rule-part ::= "AFTER" *delay* .
  delay ::= *const-expr* .

  The first variant of an AFTER part specifies that the rule has a deterministic firing time and fires *delay* time units after enabling. The *delay* must be positive.

  rule-part ::= "AFTER" *start* ".." *end* .
  start ::= *const-expr* .
  end ::= *const-expr* .

  The second variant specifies that the rule has a uniform firing time distribution and fires in the interval from *start* to *end* time units after enabling. The inequality $0 \leq start < end$ must hold.

  rule-part ::= "AFTER" *start* ".." *end* "STEP" *step* .
  step ::= *const-expr* .

  The third variant is used in a rule that has a discrete uniform firing time distribution , i.e., it fires with uniform probability at one of the time points $start$, $start + step$, $start + 2 \cdot step$, ..., end. The inequality $0 \leq start < end$ must hold, *step* must be positive and $(end - start)/step$ must be an integer number.

  A rule definition may contain at most one AFTER part.

- **PRIO part**

  rule-part ::= "PRIO" *priority* .
  priority ::= *int-expr* .

  This sets the rule's priority to *priority*. A PRIO part may only occur once in a rule definition and it can only be used in an immediate rule; if it is omitted in an immediate rule, a priority 1 will be assumed. A timed rule always has a priority of 0.

- **WEIGHT part**

  rule-part ::= "WEIGHT" *weight* .
  weight ::= *state-expr* .

This part sets the rule's weight to *weight*, which must evaluate to a positive floating point value. This part may only occur once in a rule and it can only be used in an immediate rule; if it is omitted, a weight of 1 will be assumed.

- **Policy part**

  rule-part ::= "PRD" | "PRS" .

  This part sets the rule's re-enabling policy to *pre-emptive different* (PRD) or *pre-emptive resume* (PRS), respectively. A rule with policy PRD forgets the elapsed enabling time when it gets disabled. A rule with policy PRS remembers the elapsed enabling time when disabled; this will influence the firing time distribution when the rule gets re-enabled.

  This part may only occur once in a rule definition. If it is omitted, the PRD policy will be assumed.

The parts RATE and AFTER exclude each other in a rule. If none of them is used, the rule fires immediately after enabling. The PRIO and WEIGHT parts may only be used if the rule is immediate.

No node may be used in several FROM parts or several TO parts of a rule. If a node contains a part "TO *node*[*new_value*]", then an (optional) FROM part using that node must have the form "FROM *node*[*old_value*]".

2.1.8 Results

results ::= [*time-def*] {*result-def*} .

time-def ::= "TIME" *number* ";"
| "TIME" *start* ".." *end* "STEP" *step-width* ";" .

start ::= *number* .

end ::= *number* .

step-width ::= *number* .

Normally, a MOSEL-2 model is evaluated in its stationary state, but the result part can be preceded by a time definition, which causes a transient evaluation of the MOSEL-2 model. A time definition can give a single, non-negative time point, or a set of equidistant time points, ranging from a *start* time point to an *end* time point, where the distance between two evaluation points is *step-width*. The inequations $0 \leq start < end$ and $step\text{-}width > 0$ must hold.

In Core MOSEL-2, there are two types of result definitions:

1. Proper results:

   result-def ::= ("PRINT" | "RESULT") *result* ":=" *p-expr* ";" .

   Such a result definition defines *result* and assigns the value of *p-expr* to it. The value of *result* can be used in subsequent result definitions. If the keyword PRINT is used, the value of the result will be written into the result file and can be used in picture definitions that may follow (see Section 2.2.9).

2. Durations:

   result-def ::= "PRINT" *duration* "`:=`" "TIME" "TO" *condition* "`;`" .
   duration ::= *identifier* .

   Such a result definition prints a *duration*, i.e. the expected time span until *condition* holds for the first time. The *duration* can be used in picture definitions (see Section 2.2.9). It must not be used in subsequent result definitions.

2.2 Full MOSEL-2

Full MOSEL-2 is an extension of Core MOSEL-2. The additional language constructs do not increase the expressiveness of MOSEL-2, they only improve its usability for the concise and readable description of stochastic models by adding "syntactic sugar". The following language constructs are defined in terms of Core MOSEL-2, which implicitly defines their semantics.

2.2.1 MOSEL Compatibility

For compatibility with the original MOSEL language, you can use "`=`" (instead of "`:=`") as assignment operator , you can use "`==`" (instead of "`=`") to test for equality , and you can use "WITH" (instead of "RATE")for exponential distributions . The old and new forms may be mixed.

2.2.2 Strings

string ::= "`"`" sequence of printable chars "`"`" .

Full MOSEL-2 is equipped with an additional lexical element, namely the *string*. A string may contain any sequence of printable chars, including spaces, but it must not contain double quotes "`"`" and it must not exceed line boundaries. Strings are used to define labels in picture definitions.

2.2.3 Constants

const-def ::= "CONST" *constant* "`:=`" *const-expr* "`;`" .

atom ::= *constant* .

constant ::= *identifier* .

A CONST definition defines a floating point constant. In all following places in the MOSEL-2 source text where *constant* is used in an expression, it will yield the value of *const-expr*.

const-def ::= "PARAMETER" *constant* "`:=`" *range* {"`,`" *range*} "`;`" .

range ::= *const-expr*
| *const-expr* "`..`" *const-expr* ["STEP" *const-expr*] .

A PARAMETER definition specifies that the model description actually specifies multiple models that differ in the value of this parameter. For each parameter value that is listed, a model will be analysed where the parameter is assigned this value:

PARAMETER *parameter* := $range_1, \ldots, range_n$

In all places further down in the MOSEL-2 source text where *parameter* is used in an expression, it will yield the value in $range_1, \ldots range_n$ that is assigned to *parameter* in the current model. There are two types of ranges:

1. A range may be of the form "*const-expr*", which represents the value of that expression.
2. A range may be of type "*start*..*end* STEP *step*", where $start \leq end$ and $step > 0$. This represents the values $start, start + step, start + 2 \cdot step, \ldots, end$. If "STEP *step*" is omitted, the value 1 will be assumed for *step*.

If there is a total of n PARAMETER definitions in a MOSEL-2 file, where for $i \in \{1, \ldots, n\}$, $name_i$ is assigned num_i values, then a total of $num_1 \times \cdots \times num_n$ models will be analysed, with all possible combinations of values assigned to $name_1, \ldots, name_n$.

2.2.4 Enumerations

const-def ::= "ENUM" *enum* "`:=`" "`{`" *constant* {"`,`" *constant*} "`}`" "`;`" .
enum ::= *identifier*.

An enumeration definition defines an enumeration name together with integer constants, counting from 0, that belong to that enumeration:

ENUM *enum* := {$name_0$, ..., $name_n$};

This defines integer constants $name_0, \ldots, name_n$ with values $0, \ldots, n$, respectively.

atom ::= *enum* .

When used in an expression, *enum* evaluates to n.

2.2.5 Nodes with Implicit Capacity

node-def ::= "NODE" *node* ["`:=`" *initial-value*] "`;`" .

In many models, the maximum value of a node is implicitly given by the initial state and the rules of the model that might change the node's value. (Example: If, for a given node, all rules in a model can only decrease the node's value, then the maximum value of the node is equal to its initial value.) In such a case, the explicit capacity can be omitted in the node definition and will be determined by the analysis tool. Such a node has an *implicit capacity*.

2.2.6 Functions

Sometimes, state-dependent expressions or conditions are used repeatedly in rule and/or result definitions. *Functions* can be used as placeholders for such expressions or conditions. They can help making the MOSEL-2 description shorter and easier to read. MOSEL-2 offers two subtypes of functions: the *FUNC*, which evaluates to a numerical value, and the *COND*, which is a placeholder for a logical condition.

func-def ::= "FUNC" *function* [*formal-args*] "`:=`" *state-expr* "`;`" .
function ::= *identifier* .
cond-def ::= "COND" *named-cond* [*formal-args*] "`:=`" *condition* "`;`" .
named-cond ::= *identifier* .

A FUNC definition *func-def* associates the identifier *function* with *state-expr*. A COND definition *cond-def* associates the identifier *named-cond* with *condition*. When subsequently used, a function evaluates to *state-expr* or *condition*, respectively. Node names are allowed in *state-expr* and *condition*, i.e. the function gets the current state as an implicit argument. Explicit arguments are also allowed:

formal-args ::= "`(`" *formal-arg* {"`,`" *formal-arg*} "`)`" .
formal-arg := *identifier* .

In the definition of a function, the defined name may be followed by a list of identifiers, called the *formal arguments*, which must be enclosed in parentheses.

atom ::= *formal-arg* .

The formal arguments may be used in the expression that defines the function. They will be replaced by actual values when the function is *called*, i.e., evaluated as part of an expression.

atom ::= *function* [*actual-args*] .
actual-args ::= "`(`" *state-expr* {"`,`" *state-expr*} "`)`" .

A FUNC is evaluated when its name is part of an expression. If that function has been defined using formal arguments, then actual arguments must be given and the number of actual arguments and the number of formal arguments must match. When *function* is evaluated, the i-th formal argument is replaced by the value of the i-th actual argument.

simple-condition ::= *named-cond* [*actual-args*] .

A COND is evaluated when its name is part of a condition. Actual arguments are treated in the same way as for functions.

2.2.7 Rule Extensions

- A rule may have variants:

  rule-def ::= *rule-parts* "`{`" *rule-parts* "`;`" {*rule-parts* "`;`"} "`}`" .

  Imagine a rule with variants like:

  $rule\text{-}parts_0$ { $rule\text{-}parts_1$; $rule\text{-}parts_2$; $rule\text{-}parts_3$; }

  This is equivalent to the rules:

  $rule\text{-}parts_0$ $rule\text{-}parts_1$;
  $rule\text{-}parts_0$ $rule\text{-}parts_2$;
  $rule\text{-}parts_0$ $rule\text{-}parts_3$;

  The $rule\text{-}parts_1$, $rule\text{-}parts_2$, $rule\text{-}parts_3$ are called *local rules*.

- A rule may have local rules that can only be enabled when the global rule has fired:

  rule-def ::= *rule-parts* "THEN" "`{`" *rule-parts* "`;`" {*rule-parts* "`;`"} "`}`" .

  Imagine a rule with local rules like:

  $rule\text{-}parts_0$ THEN { $rule\text{-}parts_1$; $rule\text{-}parts_2$; $rule\text{-}parts_3$; }

  This is equivalent to:

  NODE implicit_node[1];
  ...
  $rule\text{-}parts_0$ TO implicit_node;
  FROM implicit_node $rule\text{-}parts_1$;
  FROM implicit_node $rule\text{-}parts_2$;
  FROM implicit_node $rule\text{-}parts_3$;

  The $rule\text{-}parts_1$, $rule\text{-}parts_2$, and $rule\text{-}parts_3$ are called *local rules*.

- FROM and TO rule parts may contain a pseudo node "EXTERN":

  from-or-to-part ::= "EXTERN" .

  A rule part "FROM EXTERN" may be used to mark a rule that models an "import" of items from the exterior, while a rule part "TO EXTERN" may be used to mark a rule that models an "export" of items to the exterior. These rule parts are ignored when the model is evaluated.

- Multiple FROM rule parts may be combined:

  ```
  FROM node1 FROM node2(5) FROM node3
  ```

  is equivalent to

  ```
  FROM node1, node2(5), node3
  ```

- Multiple TO rule parts may be combined:

  ```
  TO node1 TO node2(5) TO node3[down]
  ```

  is equivalent to

  ```
  TO node1, node2(5), node3[down]
  ```

2.2.8 Result Extensions

atom ::= [“AVG”] “UTIL” “(“ node “)” .

The expression “UTIL(*node*)” is an abbreviation for “PROB(*node* > 0)”, while the expression “AVG UTIL(*node*)” is an abbreviation for “AVG PROB(*node* > 0)”. “UTIL” stands for “utilization”.

result-def ::= “PRINT” [“AVG”] DIST *node* “;” .

Such a result definition prints the distribution of *node*, i.e. the probabilities of each node value. If the analysis is transient and AVG is used, the probabilities will be time-averaged. The given definition would be equivalent to the following result definitions ($n := \max_{node}$), if result names could be arbitrary strings:

PRINT “P{*node* = 0}” := [AVG] PROB(*node* = 0);
...
PRINT “P{*node* = *n*}” := [AVG] PROB(*node* = *n*);

If the capacity of *node* has been defined by giving an enumeration name, the constants of that enumeration will be used to denote the possible values of *node*.

For each node, only one such result definition is allowed, so you can either print the current distribution or the time-averaged distribution of a node. For a *node* with implicit capacity, the result definitions “PRINT DIST *node*” and “PRINT AVG DIST *node*” are not allowed.

2.2.9 Pictures

MOSEL-2 may optionally generate a file with plot graphs. This file is produced in IGL format (**I**ntermediate **G**raphics **L**anguage) and the graphs contained herein can be viewed, printed and edited using the IGL interpreter written by Helmut Herold. The individual graphs are called *pictures* in MOSEL-2, and their shapes are described in the picture definitions, which make an optional part of a MOSEL-2 file.

picture ::= “PICTURE” [*pic-title*] {*pic-element*} [“;”] .
pic-title ::= *string* .

A picture definition can contain an optional picture title, which will be displayed on the top of the picture graph. The picture description is a sequence of elements that may appear in any order.

pic-element ::= “PARAMETER” *pic-param* .
pic-param ::= “TIME” | *parameter* .

A picture's parameter may be a MOSEL-2 parameter or the parameter TIME (if transient analysis of a time range has been selected). The values of that parameter are displayed along the x-axis. If there are too many values for the parameter (more than about ten), then the x-axis gets subdivided in a scale with regular intervals. A picture can only have one parameter.

pic-element ::= "CURVE" *curve* {"," *curve*} .

curve ::= (*result* | *duration*) [*label*] .

label ::= *string* .

A picture may contain one or more curve definitions. A curve is a set of values of a result or a duration, one for each value of the picture's parameter. Only results in a PRINT result definition can be used in a picture definition. In the graph, the values are marked by automatically selected symbols, like circles and triangles, and connected by solid lines. If there are free parameters in the model description, i.e. parameters than the picture's parameter, a set of curves will be created for each curve definition, one curve for each combination of the free parameter's values.

A curve definition may get an optional label, which will be displayed to the right of the rightmost point of that curve and, additionally, in the picture's legend. In a curve's label, a substring "$*pic-param*" will be replaced by the value of *pic-param*. If the curve label is omitted in a curve definition, a standard curve label will be used, which consists of the result or duration name, followed by the values of the free parameters in parentheses.

pic-element ::= "CURVE" ["AVG"] "DIST" *node* [*label*] .

To show the distribution of a node, i.e. the probabilities of all node values, you may use this alternative curve definition. The picture's parameter is implicitly set to the node's value range, so you must not explicitly define it. If the node's capacity is an enumeration, the x-axis will be labeled by the values of that enumeration. The curve label is treated the same as described for ordinary curve definitions. If you use this type of curve definition, you must not define other curves for the same picture.

If you want to use a node's distribution in a picture definition, you must have a "PRINT DIST *node*;" result definition in your MOSEL-2 file; if you want to show its time-averaged distribution, you must have a "PRINT AVG DIST *node*;" result definition.

pic-element ::= "FIXED" *fixed-param* {"," *fixed-param*} .

fixed-param ::= *pic-param* "=" *const-expr* .

To reduce the number of free parameters in a picture, each parameter (except the picture's parameter) may be fixed to one of its possible values. A parameter may not be fixed to two or more values in the same picture definition.

pic-element ::= "XLABEL" *string*
| "YLABEL" *string* .

The picture's x-axis or y-axis can be assigned a label using the XLABEL or YLABEL construct, respectively. Each construct may only be used once in a picture definition.

2.2.10 Loops

loop ::= "@" *range-list* {*range-list*} "{" *body* "}" .

range-list ::= "<" *loop-range* {"," *loop-range*} ">" ["" "" *link* "" ""] .

An "@" character in a MOSEL-2 source text introduces a loop. A loop is a preprocessor expression and can be used anywhere in a MOSEL-2 source text. When the MOSEL-2 description is parsed, the loop is *expanded* and the expansion is re-fed into the input of the parser. In the simple case – if we only have one range list in our loop – the loop is *expanded* by repeating the *body* as many times as specified by the range list of *body*.

The replacement *body* can be any text with balanced curly brackets ("{}"). That means, the number of opening brackets must match the number of closing brackets and no prefix of *body* may have more closing brackets than opening ones. The *body* may span multiple source lines.

The optional concatenation *link* may contain any text, but no newline or """. The *link* is inserted between repetitive expansions of the loop.

The *body* gets expanded for each loop range in the range list, as described for the following individual cases:

Numbers:

loop-range ::= *loop-value*
| *loop-value* ".." *loop-value* .

A loop range may be a single number, or a sequence of integer values, given by its lower and the upper limits, which must be integer values.

loop-value ::= (*number* | *constant* | "#"[*cardinal*]) [("+" | "-") *cardinal*] .
cardinal ::= *digits* .

A loop value may be denoted as a literal, as the name of a constant, or as a loop index starting with "#" (see below). If the value is integer, an integer displacement may be added to that value, or subtracted from that value. A constant used as a loop value must not depend on a parameter.

Enumerations:

loop-range ::= *enum* .

A loop range may be an enumeration name. In this case, the loop body will be expanded for each constant that belongs to *enum*.

Parameters:

loop-range ::= *parameter* .

A loop range may be a parameter name. In this case, the loop body will be expanded for each value of *parameter*.

Evaluation time points:

loop-range ::= "TIME" .

If transient evaluation of the model is selected, then a loop range may be "TIME". In this case, the loop body will be expanded for each time point for which the model will be evaluated.

Identifiers:

loop-range ::= *identifier* .

If the loop range is a single identifier and does not fit into any of the above categories, the loop body will be expanded once for this identifier.

For example,"`@<1..3>"*"{(a-b)}`" would expand to "`(a-b) * (a-b) * (a-b)`".

The form of a loop with multiple range lists will be treated as multiple nested single loops. For example:

```
@<1..3>"+"<1..2>"*"{c}
```

is equivalent to

```
@<1..3>"+"{@<1..2>"*"{c}}
```

and expands to

```
@<1..2>"*"{c} + @<1..2>"*"{c} + @<1..2>"*"{c}
```

which in turn expands to

```
c * c + c * c + c * c
```

The value for which the loop body is expanded is called the *loop index*. It can be referenced anywhere in the loop body by the following construct:

loop-index ::= "`#`" | "`##`" | "`<#`" [*cardinal*] [("`+`" | "`-`") *cardinal*] "`>`" .

A "`#`" or a "`<#>`" will be replaced by the current loop index. If the current loop index is an integer number, an integer displacement may be added or subtracted. Example: "`<# + 2>`" will be replaced by the current loop index + 2.

If loops are nested, a "`##`" in a loop body will stand for the combined loop index, which consists of the indexes of all surrounding loops, concatenated by "_". To access the index of an individual loop, put the loop number (1 for the outmost loop) behind an "`#`" and put angle brackets around it. For example, to access the index of the 2nd loop, use "`<#2>`".

An example: The loop

```
@<1..3><2,3,5>{CONST A## := <#2 + 2>;}
```

will be expanded to the definitions

```
CONST A1_2 := 4;
CONST A1_3 := 5;
CONST A1_5 := 7;
CONST A2_2 := 4;
CONST A2_3 := 5;
CONST A2_5 := 7;
CONST A3_2 := 4;
CONST A3_3 := 5;
CONST A3_5 := 7;
```

2.3 Core MOSEL-2 semantics

This section describes how a Core MOSEL-2 description can be translated into a stochastic process with continuous time parameter and finite state space, i.e. a stochastic chain. This will be done in the following three steps:

1. We describe the translation process from MOSEL-2 to the Explicit State Model (ESM).
2. We define a Markov process that is based on the ESM. We do so by adding the remaining firing times of all rules to each state of the explicit state model, which gives us enough information to predict the probabilistic behaviour of the process in the future from the current state only, without regarding any past states.
3. From that Markov process, we derive a stochastic chain that does not necessarily need to be Markovian, but which has the same state space as the ESM.

Finally, we show how the results measures can be computed from the transient or steady-state probabilities of the stochastic chain.

The Explicit State Model

To simplify the definition of the stochastic process, we will first translate a MOSEL-2 description into a static mathematical model which has an explicit state space. This model is called *Explicit State Model* (ESM). In this section, we will define the structure of an ESM. The translation process from MOSEL-2 to the ESM will be described in the next section.

Let N be the set of nodes in a MOSEL-2 description, identified by their names.

Every node $n \in N$ is associated with its value range, which is the set of integer values which the node can assume: $VR_n := \{0, \ldots, \max_n\}$.

The global state space GS is the cartesian product of all nodes' value ranges:

$$GS := \prod_{n \in N} VR_n.$$

Any order of the value ranges can be used. For a global state s and a node $n \in N$, we denote n's corresponding value as s_n.

In a MOSEL-2 description, every node n is given an initial value $is_n \in VR_n$. This defines the initial state $is \in GS$.

Let R be the set of rules in a MOSEL-2 description. Every rule $r \in R$ is associated with the following attributes:

- An *enabling set*, $EN_r \subset GS$. The rule r is enabled in every state $s \in EN_r$, and disabled in all other states.
- A *state transition*, $tr_r : EN_r \mapsto GS$. If r fires, the state changes from $s \in EN_r$ to $tr_r(s)$.
- An accumulative probabilistic *firing distribution* $fd_r : [0, \infty) \mapsto [0, 1]$. Assume r gets enabled at $t_0 = 0$, and X be the random variable for r's firing time. Then $fd_r(t) := \mathrm{P}\{X \leq t\}$, for any $t \geq 0$. This function must be isotonic and $fd_r(t) \to 1$ for $t \to \infty$.

- A re-enabling *policy* $pol_r \in \{\text{prd}, \text{prs}\}$. If $pol_r = \text{prs}$, the rule will "remember" the time span for which it has been enabled, even after disabling. If $pol_r = \text{prd}$, the rule will "forget" that time span. This makes a difference for timed non-exponentional firing distributions.
- A *priority* $pr_r \in$ Integer. If several rules are enabled and may fire at the same time, only the rules with the highest priority will really fire.
- A state-dependent *weight function* $w_r : EN_r \mapsto (0, \infty)$. If several rules with maximum priority and total weight tw may fire at the same time in state $s \in EN_r$, the rule that is actually firing will be chosen probabilistically. Rule r will be chosen with probability $w_r(s)/tw$.

So the explicit state model consist of the following parts:

- The global state space GS.
- The initial state $is \in GS$.
- The rule set R.

And for each $r \in R$:

- An enabling set $EN_r \subset GS$.
- A state transition $tr_r : EN_r \mapsto GS$.
- A firing distribution $fd_r : [0, \infty] \mapsto [0, 1]$.
- A re-enabling policy $pol_r \in \{\text{prd}, \text{prs}\}$.
- A priority pr_r.
- A weight function $w_r : EN_r \mapsto (0, \infty)$.

Translating a MOSEL-2 description into an Explicit State Model

Every MOSEL-2 node has a corresponding ESM node, $nodeinN$, with the same name and $VR_{node} := \{0, \ldots, \max_{node}\}$.

Every MOSEL-2 rule is translated into an ESM rule $r \in R$ by the following procedure:

Preconditions:

- A part "IF *condition*" is translated into the set of all states $s \in GS$ for which *condition* holds.
- A part "FROM $node(arity)$" is translated into the set of all states $s \in GS$ for which $s_{node} \geq arity$.
- A part "TO $node(arity)$" is translated into the set of all states $s \in GS$ for which $s_{node} \leq \max_{node} - arity$.
- A part "FROM $node[value]$" is translated into the set of all states $s \in GS$ for which $s_{node} = value$.

The enabling set EN_r is defined as the intersection of all those sets.

Actions:

For each enabling state $s \in EN_r$, we define a state $s' \in GS$, which is the current state after r has fired in state s:

- If r contains a part "FROM $node(arity_1)$" and a part "TO $node(arity_2)$", then $s'_{node} := (s_{node} - arity_1) + arity_2$.
- If r contains a part "FROM $node(arity)$", then $s'_{node} := s_{node} - arity$.
- If r contains a part "TO $node(arity)$", then $s'_{node} := s_{node} + arity$.
- If r contains a part "TO $node[value]$", then $s'_{node} := value$.
- For each other $node$, define $s'_{node} := s_{node}$.

State s' is well-defined since every node may only occur in a single FROM part and/or in a single TO part. Since s' is the successor state of s if r has fired, we set $tr_r(s) := s'$. This defines tr_r, the state transition of r.

Firing distributions:

If r contains a part "RATE $rate$", then $rate$ may be a state-dependent firing rate, so r fires with exponential distribution whose actual rate is $rate(s) \in (0, \infty)$ for $s \in EN_r$. For each possible rate $\lambda \in rate(EN_r)$, we have to create a separate rule whose enabling set is confined to $rate^{-1}(\{\lambda\})$ and whose firing distribution is $fd_r(t) := 1 - e^{-\lambda t}$ for $t \geq 0$.

All other distributions are state independent:

If r contains a part "AFTER $time$", then r fires deterministically, i.e.:

$$fd_r(t) := \begin{cases} 0 & \text{if } t < time \\ 1 & \text{if } t \geq time \end{cases}$$

If r contains a part "AFTER $start..end$", then r fires with uniform distribution, i.e.:

$$fd_r(t) := \begin{cases} 0 & \text{if } t < start \\ (t - start)/(end - start) & \text{if } start \leq t \leq end \\ 1 & \text{if } t > end \end{cases}$$

If r contains a part "AFTER $start..end$ STEP $step$", then r fires with discrete uniform distribution, i.e.:

$$fd_r(t) := \begin{cases} 0 & \text{if } t < start \\ (i+1)/(n+1) & \text{if } i := \lfloor (t - start)/step \rfloor \in \{0, \ldots, n\} \\ 1 & \text{if } t \geq end \end{cases}$$

where $n := (end - start)/step$.

If r contains no RATE or AFTER part, then r fires immediately, i.e. $fd_r(t) := 1$ for $t \geq 0$.

Re-enabling policies:

If r contains the part "PRS", then set the policy of r to $pol_r :=$ PRS, i.e., r will remember the elapsed enabling time even after disabling.

If r contains the part "PRD" or no policy part at all, then set the policy of r to $pol_r :=$ prd, i.e., r will forget the elapsed enabling time when disabled.

Priorities:

If r contains a part "PRIO *prio*", then define the priority of r as $pr_r := prio$. If r contains no PRIO part, set $pr_r := 0$.

Weights:

If r contains a part "WEIGHT *weight*" (which is only allowed for immediate rules), then set the weight function of r to $w_r(s) := weight$ for each $s \in EN_r$.

Note that *weight* might be state-dependent, so the values of $w_r(s)$ may vary for different $s \in EN_r$. (The actual firing probability of an enabled immediate rule is equal to its relative weight and depends on the priorities and weights of the other enabled rules, as explained below.)

If r contains no WEIGHT part, set $w_r(s) := 1$ for each $s \in EN_r$.

The Markov Process

Assume we have an Explicit State Model, as previously defined. Then we can derive a Markov process from it that describes the temporal, dynamic behaviour which is governed by the firing distributions and weights of the model's rules. Recall that the ESM consists of the following parts:

- The global state space GS.
- The initial state $is \in GS$.
- The rule set R.

And for each $r \in R$:

- An enabling set $EN_r \subset GS$.
- A state transition $tr_r : EN_r \mapsto GS$.
- A firing distribution $fd_r : [0, \infty] \mapsto [0, 1]$.
- A re-enabling policy $pol_r \in \{\text{prd}, \text{prs}\}$.
- A priority pr_r.
- A weight function $w_r : EN_r \mapsto (0, \infty)$.

A Markov process is a family $(X_t)_{t \geq 0}$ of random variables, where t is the time parameter. A Markov process is memory-less, which means, that for any $t_0, \Delta t \geq 0$, any Borel set S and any family of Borel sets $(S_t)_{0 \leq t \leq t_0}$ with $\mathrm{P}\{X_t \subset S_t \ ; \ 0 \leq t \leq t_0\} > 0$, we have

$$\mathrm{P}\{X_{t+\Delta t} \subset S \mid X_t \subset S_t \ ; \ 0 \leq t \leq t_0\} = \mathrm{P}\{X_{t_0+\Delta t} \subset S \mid X_{t_0} \subset S_{t_0}\}.$$

We will only deal with time-homogeneous Markov processes, i.e. processes with

$$\mathrm{P}\{X_{t+\Delta t} \subset S \mid X_t \subset S_0\} = \mathrm{P}\{X_{\Delta t} \subset S \mid X_0 \subset S_0\}$$

for all $t, \Delta t \geq 0$ and all Borel sets S, S_0.

In the class of Markov processes that we need, the random variables have values in the *Markov space* $MS := GS \times \underbrace{[0,\infty] \times \ldots \times [0,\infty]}_{|R| \text{ factors}}$, where $[0,\infty] = [0,\infty) \cup \{\infty\}$. The Markov space is composed of the global space and of the *remaining firing time* (RFT) for each rule $r \in R$. An element of the Markov space is called a *Markov state*. (The additional RFTs are called *supplementary variables*; this technique has been inspired by [German1], chapter 6.)

For each Markov state $s \in MS$, $gs(s) \in GS$ denotes its corresponding global space.

For each Markov state $s \in MS$ and each rule $r \in R$, the *remaining firing time* $rft_r(s) \in [0,\infty]$ is part of s. If $0 < rft_r(s) < \infty$, then r will fire if it is enabled for $rft_r(s)$ time units.

For $t \geq 0$, the random variable X_t may not sojourn in any Markov state $m \in MS$ with $rft_r(m) = 0$ for any enabled rule $r \in R$, since this would mean that r could fire at time t, and consequently, that X_t would change to another Markov state, so X_t would be ambiguous. Such Markov states are called *vanishing states*, since they are not visible in the Markov process. Markov states with $rft_r(m) > 0$ for every enabled $r \in R$ are called *tangible states*.

The Tangible Hull

For a vanishing Markov state $m \in MS$, we define its *tangible hull* as follows: Set $m_0 := m$. Then we iteratively compute the sequence of successor states $m_1, m_2, \ldots \in MS$ until we reach a tangible state. This computation has to take the firing probabilities into account, so we might actually reach several tangible states, where their probabilities sum up to 1. The successor states are computed as follows:

Be $i \in \{1,2,\ldots\}$, and $F \subset R$ the non-empty set of rules that may fire immediately in state m_i, i.e., $rft_r(m_i) = 0$ and $m_i \in \mathrm{EN}_r$ for $r \in F$. Of all those rules, only consider the set of rules P with maximum priority:

$$P := \Big\{ r \in F \;\Big|\; pr_r \geq \max_{r' \in F}(pr_{r'}) \Big\}.$$

The total weight $tw := \sum_{r' \in P} w_{r'}(gs(m_i))$ is the sum of the weights of all rules in P. Each rule $r \in P$ will fire with the probability $w_r(gs(m_i))/tw$ that equals the relative weight of r.

If rule r fires in state m_{i-1}, we compute its successor state m_i as follows:

- Set the new global state $gs(m_i) := tr_r(gs(m_{i-1}))$.
- For each rule $r' \in R$ that is enabled in $gs(m_i)$, and whose remaining firing time is ∞, choose a new remaining firing time according to its firing time distribution $fd_{r'}$. Do this also for r (which has just fired) if it is still enabled:

  $$rft_{r'}(m_i) \in [0,\infty) \quad \text{for } r' \in R \text{ with } gs(m_i) \in EN_{r'} \text{ and } (rft_{r'}(m_{i-1}) = \infty \text{ or } r' = r)$$

- For each rule with policy PRD that is disabled in $gs(m_i)$, set its remaining firing time to ∞. Do this also for r if it is now disabled:

  $$rft_{r'}(m_i) := \infty \quad \text{for each } r' \in R \text{ with } gs(m_i) \notin EN_{r'} \text{ and } (pol_{r'} = \text{prd or } r' = r)$$

- For each other rule, leave its remaining firing time:

  $$rft_{r'}(m_i) := rft_{r'}(m_{i-1}) \quad \text{for each other } r' \in R$$

Setting a remaining firing time *rft* according to a firing distribution *fd* implies:

1. $\mathrm{P}\{rft \in (a, b]\} = fd(b) - fd(a)$ for each a, b with $0 \leq a < b$,
2. $\mathrm{P}\{rft = b\} = fd(b) - \sup_{a<b} fd(a)$ for each $b > 0$, and
3. $\mathrm{P}\{rft = 0\} = fd(0)$.

We repeat to compute $m_1, m_2, \ldots$ until we have a tangible state m_i. If we never reach a tangible state, we have a vanishing loop. The probability to get into a vanishing loop from m must not be > 0. (Such vanishing loops cannot be detected by examining the ESM model alone; the flow in the model has to be checked, for example by generating the reduced reachability graph.)

The set of all tangible states that can be reached from m, together with their respective probabilities, is the tangible hull of m.

Deriving the Markov Process

The initial state X_0 of the Markov process must contain the remaining firing times of all rules, and it must not be a vanishing state. So we will construct the initial Markov state in two steps: we add the RFTs and we compute its tangible hull:

1. Define $m \in MS$ as follows:
   - $gs(m) := is$.
   - $rft_r(m) \in [0, \infty)$ for each $r \in R$ with $m \in EN_r$.
     Choose $rft_r(m)$ probabilistically according to the rule's firing time distribution fd_r.
   - $rft_r(m) := \infty$ for each $r \in R$ with $m \notin EN_r$.
2. Set X_0 to the tangible hull of m. As a consequence, X_0 may contain multiple states whose probabilities sum up to 1.

The states $(X_t)_{t>0}$ probabilistically depend on X_0 as follows:

Let us assume that, at time $t_0 \geq 0$, X_{t_0} is in a certain state $m \in MS$. We know that m is a tangible state, because the Markov process only contains tangible states. So the next rule will fire at $t_1 > t_0$, where $t_1 := t_0 + \min\{rft_r(m) | r \in R \text{ with } m \in \mathrm{EN}_r\}$. Thus, the family $(X_t)_{t_0 \leq t < t_1}$ will behave deterministically if $X_{t_0} = m$, and we can define the future states $m_t \in MS$ for $t \in [t_0, t_1]$ as follows:

- $gs(m_t) := gs(m)$.
- $rft_r(m_t) := rft_r(m) - (t - t_0)$ for each $r \in R$ with $m \in EN_r$.
- $rft_r(m_t) := rft_r(m)$ for each $r \in R$ with $m \notin EN_r$.

For $t \in [t_0, t_1)$, m_t is a tangible state, and we have $X_t = m_t$. But m_{t_1} is a vanishing state, and X_{t_1} probabilistically assumes the states of the tangible hull of m_{t_1}. Therefore, the stochastic process $(X_t)_{t \geq 0}$ does not contain any vanishing states.

The Stochastic Process

The stochastic process $(Y_t)_{t\geq 0}$ with $Y_t = gs(X_t)$ has a finite state space, so it is a stochastic chain, but not necessarily Markovian. If the firing distribution of all rules is immediate or exponential, then it is well-known that $(Y_t)_{t\geq 0}$ *is* a continuous-time Markov chain (CTMC), since immediate and exponential firing-distributions are memoryless.

Result Measures

The values of the result measures of a Core MOSEL-2 model description can be derived from the stochastic chain $(Y_t)_{t\geq 0}$, which has been defined above.

Stationary Analysis: If no time definition is given (neither in the MOSEL-2 model nor in the command line), the result measures will be evaluated in the stationary state of the Markov process. For many processes, including all continuous-time Markov models, the stationary state can be defined as

$$Y_\infty := \lim_{t\to\infty} Y_t.$$

If $(Y_t)_{t\geq 0}$ is not Markovian, then that limit need not exist, since the process may be periodic. So we need a more general definition of the stationary state in this case:

$$Y_\infty := \lim_{t\to\infty} \frac{1}{t}\int_0^t Y_u\, du.$$

An expression "PROB (*condition*)" will be evaluated as

$$P\{y \in Y_\infty \mid \textit{condition} \text{ holds in } y\}.$$

An expression "MEAN (*state-expr*)" will be evaluated as

$$E\{\textit{state-expr}(Y_\infty)\}$$

(Remember that a *state-expr* is state-dependent and can therefore be understood as a real-valued function.)

Transient Analysis: If a time definition is given, then the MOSEL-2 model will be evaluated at time points $t_1, \ldots, t_n$ for $n \geq 1$. Be $t \in \{t_1, \ldots, t_n\}$.

An expression "PROB (*condition*)" will be evaluated as

$$P\{y \in Y_t \mid \textit{condition} \text{ holds in } y\}.$$

An expression "AVG PROB (*condition*)" will be evaluated as

$$\frac{1}{t}\int_0^t P\{y \in Y_u \mid \textit{condition} \text{ holds in } y\}\, du.$$

An expression "MEAN (*state-expr*)" will be evaluated as

$$E\{\textit{state-expr}(Y_t)\}$$

An expression "AVG MEAN (*state-expr*)" will be evaluated as

$$\frac{1}{t}\int_0^t E\{\textit{state-expr}(Y_u)\}\,du$$

An expression "CUM MEAN (*state-expr*)" will be evaluated as

$$\int_0^t E\{\textit{state-expr}(Y_u)\}\,du$$

Durations: An expression "TIME TO *condition*" will be evaluated as

$$\int_0^\infty E\{Z_t\}\,dt$$

where for $t \in [0, \infty)$:

$$Z_t := \begin{cases} 0 & \text{if } \textit{condition} \text{ holds for } Y_u, \text{with } u \in [0,t] \\ 1 & \text{else} \end{cases}$$

Chapter 3

The MOSEL-2 Evaluation Environment

Currently, there exists no analysis or simulation tool that can immediately evaluate a MOSEL-2 description, but the modelling environment "MOSEL-2" can translate a MOSEL-2 description into a description for a Markov analyser (MOSES) or one of two Petri Net Analyzers (SPNP and TimeNET). The program MOSEL-2 has been developed as part of this thesis and is based on the program MOSEL by Helmut Herold, who also designed the original version of the MOSEL language [BBH].

In this chapter, the calling syntax for the MOSEL-2 environment and the restrictions for the specific analysis tools are described.

The MOSEL-2 environment has been written in standard ISO C90. A few POSIX extensions have been used, but the program should be easily portable to other operating systems, like Microsoft Windows. For the generation of the lexical scanner, the GNU program "flex" is used. The syntactic parser is generated by the GNU program "bison". Both programs are available from "`http://www.gnu.org`". For evaluation purposes, at least one of the tools MOSES [BGJZ], SPNP (version 6 or later) [SPNP], or TimeNET (version 3.0) [TimeNET], has to be installed on the computer system.

3.1 Command line options

The MOSEL-2 environment is called from a shell using the following command line syntax:

mosel2 *options input-file*

The parameter *input-file* is the name of a MOSEL-2 description file, which usually has the suffix "`.mos`". This MOSEL-2 file is read in, parsed and checked for errors.

The options are prefixed by a dash "`-`". Each option is denoted by a single letter, like "`-s`". Multiple options can follow a single dash, like "`-Ts`", which has the same meaning as "`-T -s`". Some options need an argument; this argument must immediately follow the option, separated by whitespace.

MOSEL-2 knows the following options:

"`-c`"
: Creates a CSPL output file from the input file. It may be processed by the SPNP tool.

A CSPL file has the suffix "`.c`".

"`-m`"
Creates a MOSLANG output file from the input file. It may be processed by the MOSES tool. A MOSLANG file has the suffix "`.spec`".

"`-T`"
Creates a TimeNET output file from the input file. It may be processed by one of the TimeNET tools. A TimeNET file has the suffix "`.TN`".

"`-s`"
Causes MOSEL-2 to start the selected tool, to read in the results and to create a result file. If the input file contains picture definitions, an IGL file will also be created. The tool-specific output file and all intermediate files created by the selected tool are deleted.

"`-o` *option*"
Passes an option on to the selected tool. The options that can be used are tool-specific; they are described in detail in the following sections.

"`-t`*start*"
Selects a transient evaluation at time point *start*. This option is not allowed if the input file already contains a time definition. Note that the arguments must immediately follow the "-t", without any intervening whitespace.

"`-t`*start*,*end*,*step-width*"
Selects a transient evaluation in the time span from *start* to *end*, in steps of *step-width*. This option is not allowed if the input file already contains a time definition. Note that the arguments must immediately follow the "-t", without any intervening whitespace.

"`-r` *result-file*"
Normally the name of the result file is derived from the name of the input file by replacing its suffix by "`.res`". By using this option, you can give an arbitrary name to the result file.

"`-i` *igl-file*"
Normally the name of the IGL file is derived from the name of the input file by replacing its suffix by "`.igl`". By using this option, you can give an arbitrary name to the IGL file.

"`-k`"
Causes MOSEL-2 to keep the tool-specific output file and the intermediate files created by the selected tool. This is helpful for debugging.

"`-v`"
Normally, the terminal output of the evaluation tool is not shown. This option evaluates "verbosely": the output of the selected tool is written to the terminal.

"`-d`"
Dumps the internal MOSEL-2 model after parsing the input file.

"`-h`"
Prints some help information about the calling syntax of MOSEL-2.

Only one tool can be used in a single evaluation run of the MOSEL-2 environment. The name of the tool-specific output file is equal to the input file name, but the suffix of the input file will be replaced by the tool-specific suffix, e.g., the call "`mosel2 -c example.mos`" will create a CSPL file named "example.c". If the input file contains parameters, multiple output files have to be created, each one with a different combination of parameter values. In this case, the output files contain an additional number in their names: "example_1.c", "example_2.c", etc.

The meaning of the arguments behind the option "`-o`" depends on the selected tool. Since the MOSEL-2 options are evaluated from left to right, the tool selection ("`-c`", "`-m`" or "`-T`") must preceed any tool-specific options.

3.1.1 CSPL options

A CSPL option may be set in one of the following ways from the MOSEL-2 command line:

"`-o` *option*`=`*value*"
The CSPL *option* will be set to *value*.

"`-o +`*option*"
The CSPL *option* will be set to "yes".

"`-o -`*option*"
The CSPL *option* will be set to "no".

The case of *option* and *value* does not matter, so "PR_DOT" and "pr_dot" are equivalent. Any number of CSPL options may be given in the MOSEL-2 command line. The possible options and their values are shown in Figure 3.1. For the meaning of these options, refer to [SPNP], pages 50–60. In CSPL, the option names are written in capital letters and prefixed by "IOP_" or "FOP_", and the values are prefixed by "VAL_".

3.1.2 MOSES options

If the MOSES tool is selected, only one option may be passed on to MOSES. It consists of a method name and an optional iteration count:

"`-o` *method*"
The direct MOSES analysis *method* will be used. The direct methods are "crout", "grassmann", "lpu" and "multilevel".

"`-o` *method*`,`*count*"
The iterative MOSES analysis *method* will be used with *count* iterations. The iterative methods are "power" (Jacobi method) and "power2" (Gauss-Seidel method).

The default method is "lpu". For details concerning the methods, refer to [BGJZ].

3.1.3 TimeNET options

TimeNET offers a number of tools for analysis and simulation. The actual TimeNET tool is selected by the kind of evaluation (stationary or transient) and by one of the options

Option	Values	Default Value
pr_rset	yes, no, tan	no
pr_rgraph	yes, no	no
pr_mark_order	canonic, lexical, matrix	canonic
pr_merg_mark	yes, no	yes
pr_full_mark	yes, no	no
usename	yes, no	no
pr_mc	yes, no	no
pr_dermc	yes, no	no
pr_mc_order	fromto, tofrom	fromto
pr_prob	yes, no	no
pr_probdtmc	yes, no	no
pr_dot	yes, no	no
mc	ctmc, dtmc	ctmc
ssmethod	sssor, gasei, power	sssor
ssdetect	yes, no	yes
sspres	*non-negative real number*	0.25
tsmethod	tsunif, foxunif	foxunif
cumulative	yes, no	yes
sensitivity	yes, no	no
iterations	*non-negative integer number*	2000
precision	*non-negative real number*	1E-6
elimination	redonthefly, redafterrg, rednever	redonthefly
ok_absmark	yes, no	no
ok_vanloop	yes, no	no
ok_trans_m0	yes, no	yes
ok_van_m0	yes, no	yes
abs_ret_m0	*non-negative real number*	0.0
debug	yes, no	no

Figure 3.1: The analysis options of the SPNP tool.

"`-o analysis`" (this is the default), "`-o approx`", "`-o discrete`" and "`-o simulation`". All TimeNET tools can take additional options which can be passed via the MOSEL-2 option "`-o "`*options*`"`". What *options* are actually allowed depends on the specific TimeNET tool. A summary of these options follows below; for more information about the meaning of those options, please refer to [TimeNET], pages 27–42.

"`-o analysis`"
Selects continuous-time analysis. In every state of the model, only one non-exponential, non-immediate rule may be enabled. If the model is analysed in its stationary state, the rules may have any MOSEL-2 firing distributions. If the model is analysed in a transient state, the rules may have immediate, exponential or deterministic firing distributions.

The following options can be given to the analysis tool:

- If stationary analysis is selected, you may pass the following options (in the given order) to use the slower, but stable EMC explicit solution method:

  `-E` (`-s`|`-p`) (`-d`|`-i` *count*) [`-a` *count*]

  The meaning of the individual options is:

"`-s`"
Select sequential execution.

"`-p`"
Select parallel distributed execution.

"`-d`"
Solve the linear equation system directly.

"`-i` *count*"
Solve the system iteratively in *count* iterations.

"`-a` *count*"
Select high-precision arithmetic with *count* bits.

The default options for stationary analysis are "`-E -s -d`".

- If stationary analysis has been selected, you may pass the following options (in the given order) to use the faster, but instable fill-in avoidance solution method:

  `-I` (`-s`|`-p`) (`-u`|`-l`|`-r` *seed*) [`-v`] [`-a` *count*]

  The meaning of the individual options is:

  "`-s`"
  Select sequential execution.

  "`-p`"
  Select parallel distributed execution.

  "`-u`"
  Start with a uniform state probability vector.

  "`-l`"
  Start with a state probability vector loaded from a file.

  "`-r` *seed*"
  Start with a random probability vector with random *seed*.

  "`-v`"
  Save the final state probability vector to a file.

  "`-a` *count*"
  Select high-precision arithmetic with *count* bits.

- If transient analysis has been selected, the following options can be passed to the analysis tool, in any order:

  "`-p` *real-number*"
  Set the general precision to *real-number*. The default is 1E-7.

  "`-s` *real-number*"
  Set the step size of the iterative calculation to *real-number*. The default is 0.1.

  "`-c` *integer-number*"
  Set the cluster size to *integer-number*. The default is 10.

  "`-a`"
  Use alternative algorithm. Try this option if the default algorithm fails.

  "`-x`"
  Show result curves graphically.

"`-o approx`"
Selects continuous-time approximative analysis. Only stationary analysis is available. Rules may have immediate, exponential or deterministic firing distributions. Multiple deterministic rules may be enabled at the same time.

The following options can be passed to the approximative analysis tool in any order:

"`-m` (`automatic`|`iterate`|`stable`|`direct`)"
Set the solution method for the linear equation system. The default is "`direct`".

"`-p` *real-number*"
Set the general precision to *real-number*. The default is 1E-10.

"`-i` *integer*"
Set the number of iterations to *integer*. The default is 1000.

"`-t` *real-number*"
Set the largest value that is dropped to zero ("drop tolerance"). The default is 0.

"`-r` *integer*"
Set the real number of phases for the Cox distribution to *integer*. The default is 10.

"`-c` *integer*"
Set the virtual number of phases for the Cox distribution to *integer*. The default is the real number of phases.

"`-o discrete`"
Selects discrete-time analysis. Rules may have immediate, exponential or deterministic firing distributions. Multiple deterministic rules may be enabled at the same time. The mean firing delays of exponential rules must be greater than the discrete time base, while the firing delays of deterministic rules must be a multiple of the discrete time base.

The following options can be passed to the approximative analysis tool, in the given order:

(`-en`|`-em`|`-et`) (`-a`|`-i`) *iterations scale precision*

Any number of trailing options may be omitted. The meaning of the individual options is:

"`-en`"
Select normal computation of the state space. This is the default.

"`-em`"
Select method "memo" for the computation of the state space. This is more efficient than "`-en`" in many cases.

"`-et`"
Select method "time" for the computation of the state space. This is more efficient than "`-en`" in many cases.

"`-a`"
Solve the linear equation system directly. This is the default.

"`-i`"
Solve the linear equation system iteratively.

"*iterations*"
Set the maximum number of iterations for the iterative solution method. The default is 1000.

"*scale*"
Set the discrete time base to $1/scale$ time units. The default is 1.

"*precision*"
Set the general arithmetic precision. The default is 1E-7.

"`-o simulation`"
Select continuous-time simulation. Rules may have any MOSEL-2 distribution. Multiple rules with non-exponential, non-immediate distribution may be enabled at the same time.

- If stationary simulation has been selected, the following options can be passed to the simulation tool, in the given order:

  (`-S`|`-C`|`-RS`) (`-Ton`|`-Toff`) *confidence-level* *error-percentage* *epsilon* *random-seed* *samples-max* *firings-min* *model-time-max* *real-time-max* (`-Voff`|`-Von`)

  Any number of trailing options may be omitted. The meaning of the individual options is:

  "`-S`"
  Estimate the variance using the *spectral variance* analysis. This is the default.

  "`-C`"
  Estimate the variance using the *control variates* technique. This requires a minimum number of five concurrent simulation processes.

  "`-RS`"
  Select the RESTART simulation method. Use this method if you have some very unlikely events in your model.

  "`-Ton`"
  Use automatic detection of the initial transient period. This is the default.

  "`-Toff`"
  Don't use automatic detection of the initial transient period.

  "*confidence-level*"
  Set the confidence level in percent. The default is 95.

  "*error-percentage*"
  Set the permitted difference at the confidence level for probability measures in percent. The default is 50.

  "*epsilon*"
  Set the maximum relative error in percent. The default is 10.

  "*random-seed*"
  Set the seed for the random generator. The default is 1.

  "*samples-max*"
  Set the maximum number of samples for a measure. The default is 0, which means the number is unlimited.

  "*firings-min*"
  Set the minimum number of firings for each transition. The default is 50.

  "*model-time-max*"
  Set the maximum length of a simulation run in model time units. The default is 0.0, which means the length is unlimited.

  "*real-time-max*"
  Set the maximum duration of the simulation in seconds. The default is 0.0, which means the duration is unlimited.

  "-*Von*"
  Show a visualisation of the simulation progress.

  "-*Voff*"
  Don't show a visualisation of the simulation progress. This is the default.

- If transient simulation has been selected, the following options can be passed to the simulation tool, in the given order:

  samples-max confidence-level epsilon random-seed real-time-max

  Any number of trailing options may be omitted. The meaning of the individual options is:

  "*samples-max*"
  Set the maximum number of samples for a measure. The default is 0, which means the number is unlimited.

  "*confidence-level*"
  Set the confidence level in percent. The default is 95.

  "*epsilon*"
  Set the maximum relative error in percent. The default is 10.

  "*random-seed*"
  Set the seed for the random generator. The default is 1.

  "*real-time-max*"
  Set the maximum duration of the simulation in seconds. The default is 0.0, which means the duration is unlimited.

3.2 Tool-specific restrictions

The analysis and simulation tools that are currently supported by MOSEL-2, namely MOSES, SPNP and TimeNET, all impose certain restrictions on the models they are able to evaluate.

MOSES restrictions

The following restrictions must be obeyed for a MOSEL-2 model that is to be analysed by the MOSES tool:

- The boolean operators "OR" and "NOT" may not be used in conditions. There is one exception: a MOSEL-2 assertion *needs* a NOT operator, but only on the top-level of the asserted expression.
- In comparisons, the left side must only contain nodes, while the right side must be constant.
- FLOOR, SIN, SQRT and "^" (exponentiation) may not be used in state-dependent expressions.
- Nodes must have explicit capacities.
- Functions (FUNCs and CONDs) may not be used.
- Assertions must contain a "NOT" on the top-level of the asserted expression.
- Only rules with immediate or exponential firing distributions may be used.
- A rule's PRIO part is ignored.
- A rule's policy (PRD or PRS) is ignored.

- Only stationary analysis is possible.
- Durations cannot be evaluated.
- A rule's FROM/TO parts may not have node-dependent arities.

TimeNET restrictions

The following restrictions must be obeyed for a MOSEL-2 model that is to be analysed or simulated by one of the TimeNET tools:

- A FLOOR, SIN, or SQRT is only allowed in a state-dependent expression if its argument is constant.
- Assertions are ignored.
- Durations are not allowed.
- Cumulative (CUM) and time-averaged (AVG) measures are not allowed.
- A state-dependent expression in a result measure or in a rule's IF part will only be evaluated with integer precision. As a consequence, all constants in such expressions must be integer constants, and division rounds down to the next integer (e.g. 3/2 yields 1).
- For approximation, only stationary analysis is possible.
- For transient simulation, only basic measures are possible, i.e., PROB and MEAN expressions cannot be used as operands in arithmetic expressions.

SPNP restrictions

The following restrictions must be obeyed for a MOSEL-2 model that is to be analysed by the SPNP tool:

- Only rules with immediate or exponential firing distributions may be used.

Chapter 4

Introduction to Modelling and Evaluation with MOSEL-2

This chapter contains a tutorial for the creation and evaluation of stochastic models using the modelling environment MOSEL-2.

A First Example

To get a feeling what a MOSEL-2 description looks like, we will start by a simple model of a border crossing for trucks. Imagine that tracks are arriving at an average rate of five trucks per hour (so we have a rather small border crossing), regardless of the time of day. The border is open 16 hours a day. We want to know how many trucks have to be checked per hour in order to keep the waiting queue short.

We may estimate that the clearance rate must be somewhere in the range of five to ten trucks per hour, so we will check the behaviour for these rates. We do not know the exact probabilistic distribution of the trucks' arrival times, so we assume the time span between two trucks' arrivals is exponentially distributed. Finally, we must have an upper limit of the waiting queue, since models with an infinite number of states are not supported by MOSEL-2. So we set this limit to 100. The MOSEL-2 model of the border crossing may look like this:

```
 (1) CONST arrival_rate := 5;
 (2) CONST hours_open := 16;
 (3) CONST max_length := 100; // maximum length of the queue
 (4) PARAMETER clearance_rate := 5..10;
 (5) ENUM state := {open, closed};

 (6) NODE queue[max_length] := 0;
 (7) NODE border[state] := open;

 (8) FROM EXTERN TO queue RATE arrival_rate;
 (9) IF border = open FROM queue TO EXTERN RATE clearance_rate;
(10) FROM border[open] TO border[closed] AFTER hours_open;
(11) FROM border[closed] TO border[open] AFTER 24 - hours_open;

(12) PRINT mean_queue_length := MEAN(queue);
(13) PRINT prob_queue_full := PROB(queue = max_length);
```

The numbers at the beginning of each line are not part of the MOSEL-2 file, they are added for referencing.

We will now look at the model line by line.

```
(1) CONST arrival_rate := 5;
(2) CONST hours_open := 16;
(3) CONST max_length := 100; // maximum length of the queue
```

In MOSEL-2, numeric constants can be given symbolic names by the CONST definition, as demonstrated in lines (1), (2), and (3). The characters "`//`" introduce a comment which extends to the end of the line (like in C++) and which is ignored. MOSEL-2 also allows comments that start with "`/*`" and end with "`*/`" and may exceed line boundaries (like C comments).

```
(4) PARAMETER clearance_rate := 5..10;
```

In line (4), a *parameter* is defined, which may have the values 5, 6, 7, 8, 9, and 10. The model will be evaluated for each of those values assigned to `clearance_rate`. So this MOSEL-2 description actually describes six models. If a MOSEL-2 description contains more than one parameter, then the model will evaluated for each possible combinations of the parameter values.

```
(5) ENUM state := {open, closed};
```

In line (5), an *enumeration* named `state` is defined, which consists of two symbolic constants: `open`, which has value 0, and `closed`, which has value 1. Such enumerations are useful to define symbolic names for different states of the model, e.g. the opening state of the border.

In lines (6) and (7) two nodes are defined, namely `border` and `queue`:

```
(6) NODE queue[max_length] := 0;
```

The node `queue` shall contain the length of the waiting queue. It is given a maximum value that it can assume, called the *capacity* of that node, which is `max_length` for `queue`. The minimum value of a node is always 0, and a node can only assume integer values. (So we cannot have partial trucks in our queue.) Each node must have an initial value, which is 0 for `queue` in our case. If the initial value is omitted, 0 is assumed for it, so we could have left the expression "`:= 0`".

```
(7) NODE border[state] := open;
```

The node `border` shall contain the state of the border, i.e., whether it is opened or closed. The expression "`[state]`" means that the node `border` can assume all values of the enumeration `state`: `open` (which is 0), and `closed` (which is 1), so the capacity of `border` is 1, and its initial value is 0.

Lines (8)–(11) contain the rules that describe the the dynamic behaviour of the model.

```
(8) FROM EXTERN TO queue RATE arrival_rate;
```

Line (8) models the arrival of a new truck: It increments the value of the node `queue` by 1, which is expressed by the rule part "`TO queue`". The part "`FROM EXTERN`" is ignored by the analysis tool, it is merely a hint for the (human) creator or reader of the model, that the MOSEL-2 description is an *open* model, which may "get" items from the exterior (e.g. trucks). The part "`RATE arrival_rate`" tells us (and MOSEL-2) that the rule will *fire*, i.e. be executed, with exponential distribution and with an average rate of *arrival_rate*.

```
(9) IF border = open FROM queue TO EXTERN RATE clearance_rate;
```

Line (9) models the clearance of a truck in the queue: It decrements the value of `queue` by 1, which implies that the rule can only be executed if `queue` > 0. The rule has another necessary condition, namely "`border = open`", so the trucks are only checked if the border is open. We say a rule is *enabled* if all its conditions are met. The rule part "`TO EXTERN`" is the counterpart to "`FROM EXTERN`" and it is ignored as well.

```
(10) FROM border[open] TO border[closed] AFTER hours_open;
```

Line (10) models the change of the border's state from `open` to `closed`. The rule fires when a fixed time interval, namely `hours_open`, has passed since the rule has been enabled. Such a distribution is called *deterministic*.

```
(11) FROM border[closed] TO border[open] AFTER 24 - hours_open;
```

In the next morning, the border has to be re-opened. This is modeled by line (11).

```
(12) PRINT mean_queue_length := MEAN(queue);
```

Line (12) defines a *result measure*: `mean_queue_length` will be assigned the average value of the node `queue`, and it will be printed to the result file.

```
(13) PRINT prob_queue_full := PROB(queue = max_length);
```

Line (13) defines another result measure: `prob_queue_full` will be assigned the probability that the condition "`queue = max_length`" is met, and it will also be printed to the result file.

This model can be analysed by the MOSEL-2 environment using the TimeNET analysis tool. If the MOSEL-2 description has been saved as a file "border.mos", the following command line will start MOSEL-2:

```
mosel2 -Ts border.mos
```

The option "`-Ts`" tells MOSEL-2 to translate the model to TimeNET format (`T`) and to start the TimeNET analysis tool (`s`). TimeNET is needed here since it is the only tool for which MOSEL-2 supports deterministic distributions at the moment. The results of the analysis will be stored in a file "border.res".

A MOSEL-2 description is subdivided into seven sections which must occur in the following order:

1. The optional *constant definition section*, which contains constant definitions, parameter definitions and enumeration definitions. In the present example, this part comprises lines (1)–(5).

```
Stationary analysis of "border.mos" by TimeNET

Parameters:
  clearance_rate = 5

Results:
  mean_queue_length = 95.1663
  prob_queue_full = 0.333333
=======================================
...
...
=======================================
Parameters:
  clearance_rate = 10

Results:
  mean_queue_length = 15.0283
  prob_queue_full = 0
=======================================
```

Figure 4.1: Result file "border.res"

2. The *node definition section*, which contains the node definitions (lines (6)–(7) in the present example).
3. The optional *function definition section*, which contains the function definitions. The present example contains no functions.
4. The optional *assertion section*, which contains *assertions*, i.e. logical-arithmetical conditions that must hold for each of the reachable states. The present example contains no assertions.
5. The *rule section*, which contains the MOSEL-2 rules (lines (8)–(11) in the present example).
6. The optional *result section*, which contains the result measure definitions (lines (12)–(13) in the present example).
7. The optional *picture section*, which contains the picture definitions that create graphs of the result measures. The present example contains no picture definitions.

Results and Pictures

If we evaluate the example file "border.mos", we get a result file "border.res", which contains all result measures for each value of the parameter `clearance_rate`. It is shown in Figure 4.1.

Often, it is easier to interprete the result measures when they are displayed as a graph. MOSEL-2 supports the generation of such graphs via the PICTURE definition. If we want to create a picture that shows how the `mean_queue_length` depends on the `clearance_rate`, we add the following lines to the file "border.mos":

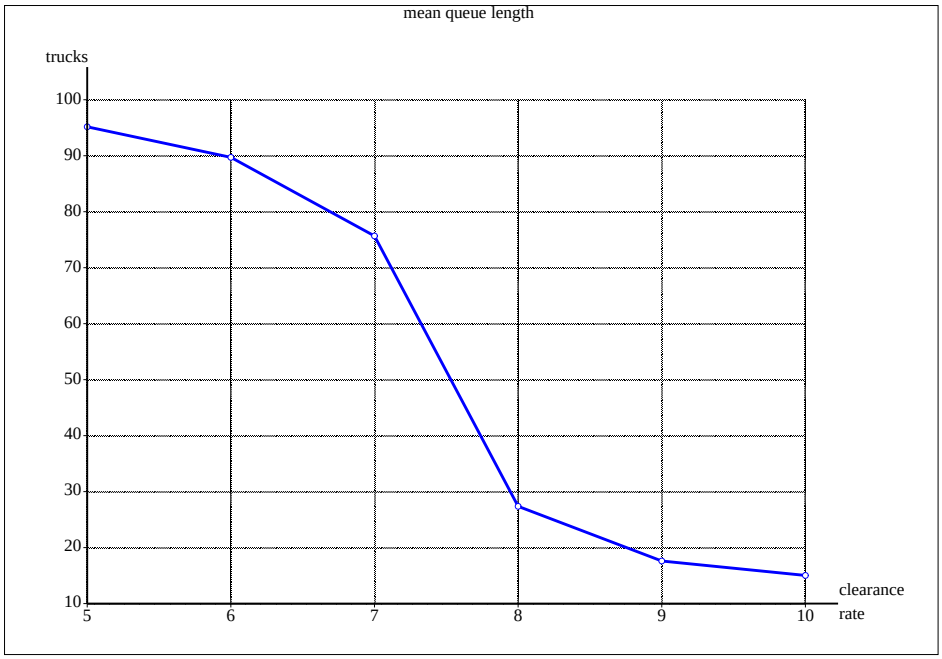


Figure 4.2: IGL picture generated from "border.mos".

```
PICTURE "mean queue length"
PARAMETER clearance_rate
CURVE mean_queue_length
XLABEL "clearance rate"
YLABEL "trucks";
```

This defines a picture titled "mean queue length", which shows how the values of the result measures `mean_queue_length` depend on the values of the parameter `clearance_rate`. The x-axis is labeled "clearance rate", and the x-axis is labeled "trucks". The order of all lines but the first one is arbitrary.

When MOSEL-2 is started again, it creates an additional file "border.igl". IGL is an acronym for **I**ntermediate **G**raphics **L**anguage, which is the proprietary format of MOSEL and MOSEL-2 for result graphs. The pictures contained in an IGL file can be viewed by the IGL interpreter, as shown in Figure 4.2. The IGL interpreter is described in [BBH]. It also allows to save a picture as an Embedded PostScript (EPS) file, and to change several features of the pictures, like the font, the title, the scales, and many more.

In MOSEL-2, time measures like rates and delays have no dimension. In the present model, we have used an hour as the base time unit, so the rule part "`AFTER 16`" actually means "after 16 hours". But this decision is arbitrary, we could have also selected a second as the base time unit. The only restriction is that the base time unit must be consistent within the whole model.

The values have been evaluated for the *stationary state*, which can be imagined as the probabilistic behaviour of the model for $t \to \infty$. For most models, the values of all result measures converge in this case. (The present model is an exception, since the length of the queue oscillates between daytime and night. Here the stationary state is actually the time-averaged limit for $t \to \infty$, as described in Section 2.3.)

Transient Evaluation

It would be interesting how the result measures behave in specific time instants. This type of evaluation is called *transient evaluation*.

MOSEL-2 offers two ways to initiate transient evaluation:

By command line option: You may evaluate the above description using the command line

```
mosel2 -Ts -t0,72,2 border.mos
```

This will evaluate the result measures for $t = 0, 2, 4 \ldots, 72$, where $t = 0$ is the time instant where the model is in the deterministic state described by the initial values of its nodes.

In the source file: You achieve the same effect if you insert the line

```
TIME 0..72 STEP 2;
```

between line (11) and line (12) of the file "border.mos".

For this model, we get $6 \cdot 37 = 222$ values for `mean_queue_length`, namely the number of parameters times the number of time instants. So the interpretation of the results will be easier if we have a result graph. To display how the values in depend on the time, we might use the following picture definition:

```
PICTURE "mean queue length"
PARAMETER TIME
CURVE mean_queue_length "$clearance_rate trucks/h"
XLABEL "time [h]"
YLABEL "trucks";
```

This picture definition will create a bunch of curves, one for each value of the parameter `clearance_rate`. The string `"$clearance_rate trucks/h"` labels each of these curves, "`$clearance_rate`" being replaced by the actual value of that parameter.

The picture definition will generate the graph shown in Figure 4.3. In this graph, you can see the different behaviour of the queue length during daytime and night.

Loops

If we like to have a separate graph for each value of `clearance_rate`, we must write a separate PICTURE definition for each graph. For the value "5", the definition would look as follows:

```
PICTURE "mean queue length for 5 trucks/h"
PARAMETER TIME
FIXED clearance_rate = 5
CURVE mean_queue_length;
```

The line "`FIXED clearance_rate = 5`" sets the parameter `clearance_rate` to 5, so we only get one curve in this graph. For the other values, similar picture definitions have to be written.

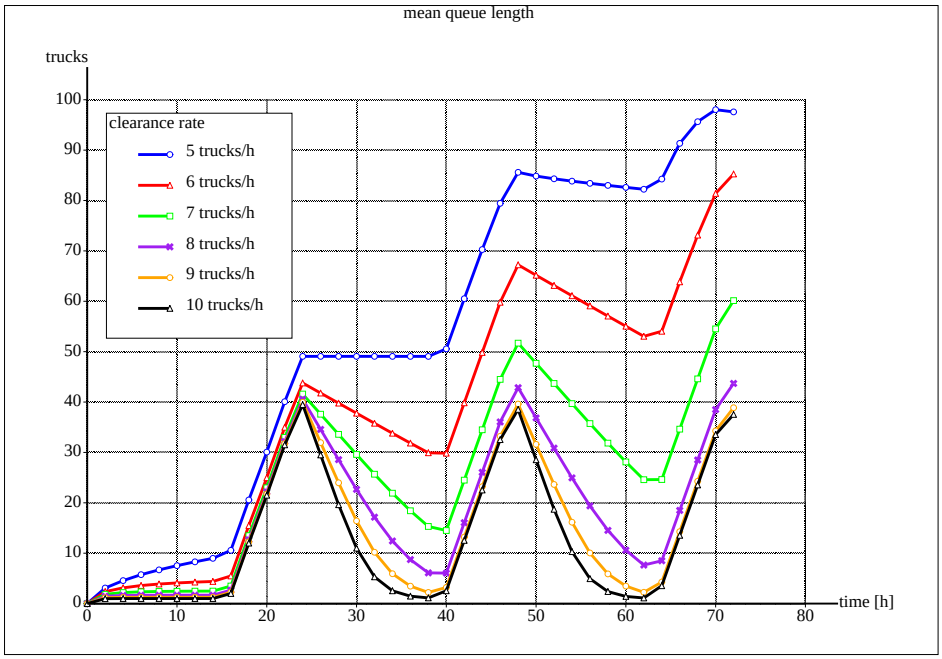


Figure 4.3: IGL picture generated from "border.mos", transient analysis.

To abbreviate the tedious repetition of picture definitions, MOSEL-2 offers the possibility to generate them by using the *loop* preprocessor construct:

```
@<clearance_rate>{ PICTURE "mean queue length for # trucks/h"
                   PARAMETER TIME
                   FIXED clearance_rate = #
                   CURVE mean_queue_length; }
```

The character "`@`" starts a loop. The part in angle brackets ("`<>`") is called the *loop range*. The part in braces ("`{}`") is called the *loop body*. The loop body gets *expanded*, i.e., it will be treated as if it were inserted several times in the source text, the number of repetitions being determined by the loop range. In the present example, the loop range comprises all six values of the parameter `clearance_rate`, so the loop body will be expanded six times, creating six picture definitions.

For each expansion, the current value of the loop range is called the *loop index*. It can be referenced in the loop body by the special character "`#`". In the present example, "`#`" would expand to "5", "6", "7", "8", "9" and "10", respectively, since these are the values of the parameter `clearance_rate`. So we would get a picture definition for each of the parameter values.

If we like to have a separate picture for every time point at which the model is evaluated, we would write:

```
@<TIME>{ PICTURE "mean queue length after # hours"
         PARAMETER clearance_rate
         FIXED TIME = #
         CURVE mean_queue_length; }
```

Here, the roles of the parameter `clearance_rate` and the special parameter TIME have been swapped.

Since the loop is a preprocessor construct, it can be used anywhere in a MOSEL-2 definition. For example, a finite sum in any MOSEL-2 expression can be expressed by a loop. Look at the following MOSEL-2 line:

```
IF @<1..4>"+"{node_#} = 0 TO node_1 RATE 1;
```

This will be expanded to

```
IF node_1 + node_2 + node_3 + node_4 = 0 TO node_1 RATE 1;
```

The loop range in this example is an *explicit range* that comprises all integer values from 1 to 4. The lower bound and/or the upper bound of that range may be constant names as well. An explicit range can also be an enumeration of values, like "`<1,2,3,4>`", or a combination of both, like "`<1..3,5>`", which is equivalent to "`<1,2,3,5>`".

The "`"+"`" in the above loop is called a *link*. A link is placed between two expansions of the loop body. It can be used to put anything between the loop expansions, for example logical operators, as in

```
CONST n := 3;
...
IF @<1..n>"AND"{node_# = 0} TO node_1 RATE 1;
```

which expands to

```
IF node_1 = 0 AND node_2 = 0 AND node_3 = 0 TO node_1 RATE 1;
```

If you have defined a constant, e.g. "`CONST k := 5;`", and you want to use its value as part of an identifier, you cannot use a construct like "`node_k[10]`", but you may use a loop with a single-valued range: The lines

```
NODE @<k>{node_#}[10];
@<k>{ NODE node_#[10]; }
```

will both be expanded to "`NODE node_5[10];`". (So you can choose your favourite line.)

Imagine you want to define a series of identical nodes, but the last one should be the only one with a non-zero initial value. This can be written as follows:

```
CONST n := 4;

@<1..n-1>{ NODE node_#[20] := 0;  }
     @<n>{ NODE node_#[20] := 20; }
...
```

The explicit range "`<1..n-1>`" contains a number that is subtracted from its upper bound. This is a so-called *displacement*. Displacements can be added to or subtracted from any number in an explicit range. They can also be used in loop index references. For example, the MOSEL-2 line

```
@<1..n-1>{ FROM node_# TO node_<#+1> RATE 1/10;  }
```

defines $n-1$ rules, each of which decrements the value of a node and increments the value of the next node. The index reference "`<#+1>`" has to be in angle brackets to make clear that the displacement is part of the reference.

Even an enumeration can be used as a loop range. In that case, the loop indexes will be the names of the corresponding values in the enumeration. For example,

```
ENUM cpu_states := {down, slow, fast};
NODE cpu[cpu_states];
...
@<cpu_states>{ PRINT cpu_# := PROB(cpu = #); }
```

expands to:

```
ENUM cpu_states := {down, slow, fast};
NODE cpu[cpu_states] := down;
...
PRINT cpu_down := PROB(cpu = down);
PRINT cpu_slow := PROB(cpu = slow);
PRINT cpu_fast := PROB(cpu = fast);
```

Finally, an identifier in a loop range that is neither a parameter, nor a constant, nor an enumeration, can also be used as a loop index. For example, the following lines

```
@<io,cpu,disk>{ NODE #[10]; }
...
@<io,cpu,disk>{ PRINT mean_# := MEAN(#); }
```

would expand to

```
NODE io[10];
NODE cpu[10];
NODE disk[10];
...
PRINT mean_io := MEAN(io);
PRINT mean_cpu := MEAN(cpu);
PRINT mean_disk := MEAN(disk);
```

Functions (FUNCs and CONDs)

Let us look at a model for reliability analysis: We have a high-security system, for example in an aircraft, that consists of redundant components, namely three sensors and five computers. The system is considered to be operational if at least two sensors and two computers are working. A single sensor has a mean time to failure of 60 000 hours, while a single computer has only a mean time to failure of 2 000 hours. We assume that the actual lifetimes are exponentially distributed. We want to know the mean time to failure of the whole system, and the probability that the system is still working at a fixed time point. An appropriate MOSEL-2 model "aircraft.mos" might look as follows:

```
 (1) CONST sensor_count := 3;
 (2) CONST computer_count := 5;
 (3) ENUM state = {down, up};

 (4) CONST sensor_lifetime := 60000;
 (5) CONST computer_lifetime := 2000;

 (6) @<1..sensor_count>{ NODE sensor_#[state] := up; }
 (7) @<1..computer_count>{ NODE computer_#[state] := up; }

 (8) FUNC sensors := @<1..sensor_count>"+"{sensor_#};
 (9) FUNC computers := @<1..computer_count>"+"{IF computer_# = up
                                                THEN 1 ELSE 0};
(10) COND system_down := sensors < 2 OR computers < 2;

(11) @<1..sensor_count>{ FROM sensor_#[up] TO sensor_#[down]
                         RATE 1 / sensor_lifetime; }
(12) @<1..computer_count>{ FROM computer_#[up] TO computer_#[down]
                           RATE 1 / computer_lifetime; }

(13) TIME 0..3000 STEP 100;
(14) PRINT prop_sys_up := PROB(NOT system_down);
(15) PRINT time_sys_down := TIME TO system_down;
```

In lines (6) and (7), we define one node for each sensor and computer, using loops.

In line (8), we define a FUNC named "`sensors`", whose value is the number of working sensors. A FUNC might be thought of as a named expression. In contrast to a constant, nodes (whose values are state-dependent) might be used in the FUNC's definition. In the FUNC `sensors`, we add the values of all nodes. Since the value of the constant `down` is 0 and the value of the constant `up` is 1, we achieve the desired result.

Line (9) is similar to line (8), but here we do not sum up the values of the nodes directly. Instead, we add 1 if the node's value is `up` and 0 else. The "IF... THEN... ELSE..." expression is also called a *conditional expression*. This construct would also work if we had used "`ENUM state = {up, down};`" in line (3), while the construct in line (8) would not.

Line (10) defines a COND `system_down`, which is similar to a FUNC, but it defines a condition, not an expression. In its definition, the FUNCs `sensors` and `computers` are called. Note that in a MOSEL-2 function call, unlike in many other programming languages, no parentheses are following the function name (unless the function has explicit parameters, which are explained below).

In lines (11) and (12), a rule is defined for each component of the system, which changes from state `up` to `down` with the appropriate rate.

Line (13) states for which instants a transient analysis should be performed.

Line (15) defines a *duration* named `time_sys_down`. A duration is the mean time interval until a certain condition holds.

Durations are only supported by the analysis tool SPNP, so we must use this tool when running MOSEL-2:

```
mosel2 -cs aircraft.mos
```

FUNCs and CONDs are both called *functions*. They can be used to define complex expressions that would look ugly in the place where that definition is needed. For example, if a firing rate of a rule depends on a node's value in a non-regular fashion, we could define the firing rate by a FUNC, as we do in the following example:

```
FUNC mue_io := IF io = 1 THEN 1 / 28
               ELIF io = 2 THEN 1 / 18.667
               ELIF io = 3 THEN 1 / 15.5553
               ELIF io = 4 THEN 1 / 13.998
               ELIF io = 5 THEN 1 / 13.0668
               ELIF io = 6 THEN 1 / 12.4443
               ELIF io = 7 THEN 1 / 11.99991
               ELIF io = 8 THEN 1 / 11.6669
               ELSE             0;
...
FROM io TO cpu RATE mue_io;
```

The "IF... THEN... ELSE" expression in this example is extended by several "ELIF..." parts. "ELIF" is an abbreviation for "ELSE IF". The value of the whole expression is the value of the first expression whose condition holds. If no condition holds, the expression after the keyword "ELSE" is used.

A function may have *explicit arguments* which are placeholders in the function's definition for an expression that is passed to it when the function is called, as in the following example:

```
FUNC min(a,b) := IF a <= b THEN a ELSE b;
...
FROM n1, n2 TO n3 RATE mue * min(n1, n2);
```

This is equivalent to

```
FROM n1, n2 TO n3 RATE mue * (IF n1 <= n2 THEN n1 ELSE n2);
```

We notice that `n1` and `n2` (the *actual arguments*) take the positions of `a` and `b` (the *formal arguments*) in the definition of `min`. As we can also see, explicit parameters must be enclosed in parameters, in the function definition as well as in the function call. Since arguments are always numeric values, we do not need to give an explicit type in the function definition, unlike in most programming languages.

An alternative aircraft model

We can write an alternative version of the "aircraft.mos" model in which we do not create a node for each component of the system, but use two nodes instead that keep the number of working sensors and computers, respectively:

```
(1) CONST sensor_count := 3;
(2) CONST comp_count := 5;

(3) CONST sensor_lifetime := 60000;
(4) CONST computer_lifetime := 2000;
```

```
(5) NODE sensors := sensor_count;
(6) NODE computers := computer_count;

(7) COND system_down := sensors < 2 OR computers < 2;

(8) FROM sensors RATE sensors / sensor_lifetime;
(9) FROM computers RATE computers / computer_lifetime;

(10) TIME 0..3000 STEP 100;
(11) PRINT prop_sys_up := PROB(NOT system_down);
(12) PRINT time_sys_down := TIME TO system_down;
```

The node definitions in lines (5) and (6) have no explicit capacities (which would be enclosed in brackets), so we say they have *implicit capacities*. Their actual maximum values are determined by their initial values and by the rules that may change the nodes' values. Since both values may only be decremented, we know that `sensor_count` and `computer_count` are the implicit capacities of `sensors` and `nodes`, respectively. The analysis tools SPNP and TimeNET use the following method to determine the node's capacities: they explore the state space starting with the initial state and record each state that is reachable. If states are found in which a node exceeds a certain hard-coded limit, an error will reported. For SPNP, this limit is 200, while TimeNET can deal with values of up to 65535.

The node `sensors` may represent multiple sensors, so we must adapt the failure rate to that number: in line (8), the failure rate is *state dependent*: If n sensors are still working, the failure rate is n times as high as the failure rate for one sensor. – The same holds for the rule in line (9).

Assertions

MOSEL-2 can check that each of the reachable states holds certain conditions, called *assertions*, as in the following example:

```
(1) CONST k := 10;
(2) CONST n := 4;
(3) NODE N1[k] := k;
(4) @<2..n>{ NODE N#[k]; }
(5) ASSERT N1 + N2 + N3 + N4 = k;
(6) @<2..n>{ FROM N1 TO N# RATE mue * N1; }
(7) @<2..n>{ FROM N# TO N1 RATE mue * N#; }
```

The assertion "`ASSERT N1 + N2 + N3 + N4 = k;`" requires that all nodes' values always sum up to `k`. If a state can be reached in which this condition does not hold, an error will reported by the analysis tool, and the analysis fails. Assertions are not needed for simple models like the one above, but bigger models are more error-prone, and assertions are a valuable debugging aid for them.

By the way: in line (4), the initial values of the nodes `N2`, `N3` and `N4` are omitted. Therefore, MOSEL-2 uses the default initial value 0 for these nodes.

Normally, the output of the analysis tool will not be shown, but this can be changed by the MOSEL-2 option "`-v`", so you should use this option when using assertions in your model in

order to see any error messages. Unfortunately, the TimeNET analysis tool does not support assertions, so they will be ignored if TimeNET is being used.

Immediate Rules

So far, we have met rules with exponentially distributed firing times, which are specified by the rule part "`RATE` *expr*", and rules with deterministic firing times, which are specified by "`AFTER` *expr*". But many models can be described easier if we can assume that certain model states are vanishing, i.e., they will change to another state immediately.

For example, consider a computer which gets new jobs in exponentially distributed time intervals with a mean rate of 0.2 jobs per second. Up to 10 jobs may be queued, and the processor can process one job at a time, which takes 4 seconds. In one of five cases, the job must be processed again, so it will be re-entered into the queue. We are interested in the processors' mean utilization and in the distribution of the queue's length.

The following model "computer.mos" describes our computer:

```
(1) NODE queue[10] := 0;
(2) NODE processed[1] := 0;

(3) FROM EXTERN TO queue RATE 0.2;

(4) FROM queue TO processed AFTER 4;
(5) FROM processed TO EXTERN WEIGHT 4;
(6) FROM processed TO queue WEIGHT 1;

(7) PRINT utilization := UTIL(queue);
(8) PRINT DIST queue;
```

The rules in lines (5) and (6) are *immediate rules*, because they have no explicit distribution rate. They may both fire immediately if the value of node `processed` is non-zero. If several rules may fire at the same time instant, the rule that will actually fire will be selected probabilistically. The rule part "WEIGHT" can give a rule a bigger or smaller weight. The rule in line (5) with "WEIGHT 4" will be selected four times as often as the rule in line (6) with "WEIGHT 1". If a rule has no explicit weight, it will get a default weight of 1.

In line (7) of the above model, we compute the utilization of `queue`, i.e. the probability that `queue` > 0. In line (8), the *node distribution* of `queue`, i.e. the probabilities of all its possible values, is printed.

The order in which immediate rules may fire may also be determined by the rule part "PRIO *number*". If several immediate rules are enabled at the same time, only the rule that has the highest priority assigned will fire. If several rules have maximum priority, the rule that will actually fire will be probabilistically selected by the rules' weights, as explained above. Priorities must be non-negative integer numbers. If the "PRIO" keyword is missing in a rule, then an immediate rule will get the default priority 1, while a non-immediate rule will get the default priority 0.

All states of the model in which `processed` is non-zero will change immediately. Therefore such states are called *vanishing states*. An immediate rule may lead from one vanishing state to another vanishing state. This is legal, as far as the system will eventually return to a *tangible* (non-vanishing) state, i.e. a state in which no immediate rule is enabled.

Subrules

In the example "computer.mos" of the previous section, we could have written the rules in lines (4)–(6) as a single rule with *subrules*:

```
FROM queue AFTER 4 THEN { TO EXTERN WEIGHT 4;
                          TO queue  WEIGHT 1; }
```

This rule is equivalent to the rules in lines (4)–(6). The node `processed` is not used here, so it can be eliminated. Instead, MOSEL-2 creates an implicit node that will be set to 1 by the *global rule* "`FROM queue AFTER 4`", and reset to 0 by one of the *local rules* "`TO EXTERN WEIGHT 4;`" and "`TO queue WEIGHT 1;`". The implicit rule is not accessible to the user, although it is part of the MOSEL-2 model.

Although a rule with subrules seems to be a unit, it actually consists of several rules that may fire at different times. Imagine that the global rule already has fired and set the implicit node to 1. If the local rules are not immediate, or if they are all blocked, then no local rule may fire. This has to be taken into consideration when using local rules. Take a look at the following excerpt of a MOSEL-2 model:

```
ASSERT node_1 + node_2 + node_3 = 10;
...
FROM node_1 RATE 1
THEN { TO node_2 WEIGHT 4;
       TO node_3 WEIGHT 1; }
```

If the global rule fires and `node_2` and `node_3` have already reached their maximum capacities, none of the local rules may fire and the sum of the nodes' values will evaluate to 9, causing the assertion to fail.

MOSEL-2 offers another type of subrules: If you have a condition that should be part of several rules, you can use that condition as a global rule and the individual rules – without the condition – as local rules:

```
IF CPU = up AND mode = idle
{
                                  FROM driverq TO mode[driver];
  IF driverq = 0                  FROM kernelq TO mode[kernel];
  IF driverq = 0 AND kernelq = 0 FROM userq   TO mode[user];
}
```

(Please note that the opening brace is *not* preceded by the keyword "THEN". This distinguishes the present subrule type and the subrule type with implicit nodes.) This rule definition is equivalent to:

```
IF CPU = up AND mode = idle
FROM driverq TO mode[driver];

IF CPU = up AND mode = idle AND driverq = 0
FROM kernelq TO mode[kernel];
```

```
IF CPU = up AND mode = idle AND driverq = 0 AND kernelq = 0
FROM userq TO mode[user];
```

In general, the global rule part of a subrule without THEN may contain any rule part or any combination of rule parts, as long as they can be combined with each of the local rules. For example, you may not have a RATE in a global rule and in one of its local rules, since a rule may only contain one RATE.

Re-Enabling Policies

Immediate rules and rules with exponential distribution are memory-less: their probabilistic behaviours depend only on the current state, not on the past. This does not hold for deterministic rules: It makes a difference how long a deterministic rule has already been enabled, since that determines the time when it will fire.

Imagine a multi-tasking computer that runs batch jobs of equal lengths, but who might be interrupted at irregular intervals to run an interactive task. When the computer has finished the interactive task and resumes the current batch job, it will continue at the point where it has been interrupted. Let's write a MOSEL-2 model for it, using a base time unit of one second:

```
(1) ENUM states := {interactive, batch};

(2) NODE queue[20];
(3) NODE state[states] := batch;

(4) FROM state[batch] TO state[interactive] RATE 1/50;
(5) FROM state[interactive] TO state[batch] RATE 1/10;
(6) FROM EXTERN TO queue RATE 1/10;
(7) IF state = batch FROM queue TO EXTERN AFTER 8 PRS;

(8) PRINT DIST queue;
```

In line (2), MOSEL-2 initializes the node `queue` to the default value 0.

Lines (4) and (5) model the interruption by an interactive task; line (6) adds batch jobs to the queue.

In line (7), batch jobs are removed from the queue. The keyword "PRS", which stands for "**P**re-emptive **Re**sume", causes the rule to take the passed enabling time into account, even when the rule has been disabled and re-enabled again. This is just what we want.

If we had a poor multi-tasking system that does not allow to resume a pre-empted job, we would restart the current batch job after each interruption. This can be modelled if "PRS" is replaced by the keyword "PRD", which stands for "**P**re-emptive **R**epeat **D**ifferent". The policy PRD is the default policy if neither keyword is used.

Arities

Sometimes a rule in a MOSEL-2 model should decrement or increment a value by an amount greater than one, for example in the following production (or bottling) system:

A bottling factory might be have three stations:

1. Four bottling stations. Each bottling station needs two seconds to fill a bottle.
2. A packaging station where the bottles are put into cases. Twelve bottles fit into one case, three from each bottling station. After all bottles have arrived, the packaging station needs 3 seconds to do its work.
3. The control station, where a worker checks the cases for glass damages, missing bottles etc. A check takes 4–8 second for one case, with uniform distribution.

The queues between the bottling stations and the packaging station can take 30 bottles each, the queue between the packaging station and the control station can take ten cases. The resulting MOSEL-2 model "bottling.mos" looks as follows:

```
(1) CONST n := 4; // Number of bottling stations.
(2) CONST bottles_per_case := 12;

    // Bottles of *one* station that go into a case.
(3) CONST row := bottles_per_case/n;

    // Waiting queues from bottling stations to packing station.
(4) @<1..n>{ NODE bottle_queue_#[30]; }

    // Waiting queue from packing station to control station.
(5)          NODE case_queue[10];

(6) @<1..n>{ FROM EXTERN TO bottle_queue_# AFTER 2; }
(7) @<1..n>{ FROM bottle_queue_#(row) } TO case_queue AFTER 3;
(8) FROM case_queue TO EXTERN AFTER 4..8;

(9) PRINT mean_bottle_queue := MEAN(bottle_queue_1);
(10) PRINT mean_case_queue := MEAN(case_queue);
```

In line (7), the rule parts "`FROM bottle_queue_#(row)`" decrement the value of `bottle_queue_#` by the value of `row` (which is three) for each bottling station. The rule will only be enabled if the nodes can be decremented by that amount. The expression "`(row)`" is called the *arity* of the FROM rule part.

In line (8), the rule part "`AFTER 4..8`" specifies a uniform firing distribution in the time interval of 4–8 time units after that rule has been enabled.

In the model "bottling.mos", several timed rules with non-exponential distribution may be enabled in the same state. This cannot be handled by the analysis component of TimeNET, so we must use the simulation tool to evaluate that model:

```
mosel -Ts -o simulation bottling.mos
```

The option "`-o simulation`" selects the TimeNET simulation tool. See Section 3.1.3 for more information.

An arity can by used in a FROM rule part as well as in a TO rule part; their meanings are analogous. An arity expression may be a constant expression, as above, or a node name. A node name as arity can be used to set a node's value to zero:

```
...FROM node(node)...
```

This can also be accomplished by the following rule part:

```
...TO node[0]...
```

Which method is actually used is a matter of taste.

Nested Loops

Let us consider the following example: A communication network may be a chain of point-to-point connections. The transmission delays between two adjacent stations are known, but in our model, we need the transmission delays of any pair of stations, adjacent or not. In MOSEL-2, we could compute the transmission delays as in the following extract of a model file:

```
(1) CONST k := 5; // Number of stations
(2) CONST d1 := 12.3; // Delay between stations 1 and 2 in milliseconds
(3) CONST d2 := 5.2;  // Delay between stations 2 and 3 in milliseconds
(4) CONST d3 := 9.5;  // Delay between stations 3 and 4 in milliseconds
(5) CONST d4 := 7.8;  // Delay between stations 4 and 5 in milliseconds

(6) @<1..k>{ CONST delay_#_# := 0; }
(7) @<1..k-1><#+1..k>{ CONST delay_<#1>_<#2> := @<#1..#2-1>"+"{d<#3>}; }
(8) @<2..k><1..#-1>{ CONST delay_<#1>_<#2> := @<#2..#1-1>"+"{d<#3>}; }
```

The constants `delay_`m`_`n, for $m, n \in \{1, \ldots, 5\}$, is the transmission delay between stations m and n in milliseconds. For $m = n$, they are set to zero in line (6).

For $m < n$, the transmission delays are computed in line (7). This line contains three nested loops. The outer loop has the range "`<1..k-1>`". It has no explicit body, but is followed by the range of the middle loop. This is an abbreviation for

```
@<1..k-1>{ @<#+1..k>{ CONST ...; } }
```

The middle loop's range is "`<#+1..k>`". Its lower bound, "`#+1`", is the index of the outer loop, incremented by one. The loop body of the middle loop is

```
CONST delay_<#1>_<#2> := @<#1..#2-1>"+"{d<#3>};
```

Since this body is part of two nested loops, the loop index is no longer unambiguous, so we have to add the number of the loop to each loop index reference, like "`<#1>`" for the index of the outer loop and "`<#2>`" for the index of the middle loop. The body again contains an inner loop, whose range depends on the indexes of the outer and middle loop. The inner loop expands to the finite sum of the distances between `#1` and `#2`.

For $m > n$, the transmission delays are computed in line (8), which is analogous to line (7).

You may have noticed that the index references "`#1`" and "`#2`" are surrounded by angle brackets in the loop body, but not if they are used as part of a loop range. The angle brackets "`<>`" are needed to make clear that the loop number is part of the index reference. Without the angle brackets, the loop reference "`#1`" would be read as "`#`" (which is ambiguous), followed by a "`1`".

Expressions and Conditions

So far, we have used lots of arithmetical expressions in our examples without any explicit explanation. Now it is time to learn a little bit more about them.

MOSEL-2 expressions can use the arithmetic operators "`+`", "`-`", "`*`", "`/`", and "`^`" (exponentiation). Evaluation is done with floating-point precision, so "`3/2`" evaluates to 1.5, not to 1. Integer values are just a subset of the floating point values, so there is no difference between "`1`" and "`1.0`" .

The exponentiation operator has the highest priority and is right-associative, i.e. "`x ^ y ^ z`" is equivalent to "`x ^ (y ^ z)`". All other operators are left-associative, so "`x - y - z`" is equivalent to "`(x - y) - z`", for example.

Additionally, MOSEL-2 offers the following arithmetical functions:

FLOOR: The expression "`FLOOR(`x`)`" yields the largest integer number that is not larger than x.

SIN: The expression "`SIN(`x`)`" yields the sine of x, where x is measured in radians.

SQRT: The expression "`SQRT(`x`)`" returns the non-negative square root of x.

Finally, the conditional expression "IF... THEN... ELSE..." can be used in MOSEL-2 expressions. If it is used as a subexpression, it has to be enclosed in parentheses.

A MOSEL-2 condition may use the comparison operators "`<`", "`>`", "`=`", "`<=`" ($\leq$), "`>=`" ($\geq$) and "`/=`" ($\neq$) to compare two numeric values. For C enthusiasts, "`==`" can be used as an alias for "`=`", and "`!=`" can be used as an alternative for "`/=`".

Subconditions may be negated by the logical operator "NOT" or connected by the logical operators "AND" and "OR". The logical operator "AND" has higher priority than the logical operator "OR", so the condition

```
a < b OR c = d AND e > f
```

is equivalent to

```
a < b OR (c = d AND e > f)
```

MOSEL-2 uses short-circuit evaluation for the logical operators "AND" and "OR". That means, if the first operand of an "AND" operator evaluates to "FALSE", then the second operand will not be evaluated at all. This can be used to prevent division by zero: The condition "`a = 0 OR 1 / a < 10`" will *not* report an error message if `a` is zero.

Result Measures Revisited

In transient analyses, the result expressions MEAN(*expression*) and PROB(*condition*) yield the mean value and the probability, respectively, at a certain instant. Sometimes time-averaged result measures might be of more interest, especially in performability analyses.

For example, a generator in a power station is constructed for a use of twenty years. Major damages occur with a mean rate of one damage in five years. The generator's power will

decrease linearly by 1/20 of the initial power with every damage, but after ten damages, the generator will be shut down. Also, the generator may break fatally with a mean delay of thirty years. For simplicity, we assume that all distributions are exponential. We want to know the total amount of electrical energy that is being generated during these twenty years. For this evaluation, we can write the following MOSEL-2 model, using a year as the base time unit:

```
 (1) CONST initial_power := 100; // in MW
 (2) CONST hours_per_year := 24 * 365.25; // approximately
 (3) ENUM bool := {yes, no};

 (4) NODE damages[9] := 0;
 (5) NODE working[bool] := yes;

 (6) COND power := IF working = yes
 (7)               THEN initial_power * (1 - damages / 20);
 (8)               ELSE 0;

 (9) TO damages RATE 1/5;
(10) IF damages = 9 TO working[no] RATE 1/5;

(11) FROM working[yes] TO working[no] RATE 1/30;

(12) TIME 20;
     // Result measures are in MWh
(13) PRINT average_energy := AVG MEAN(power * hours_per_year);
(14) PRINT total_energy := CUM MEAN(power * hours_per_year);
```

We increment the number of damages in lines (9) and (10), and derive the current power from it in lines (6)–(8). Fatal breaks are modelled by line (11). We evaluate the model at the end of the usage time, as specified by line (12). Line (13) computes the average amount of energy that has been generated per year, while line (14) computes the total amount for all twenty years.

In a transient evaluation, the expression "AVG MEAN(*expression*)" yields the time-averaged mean value of *expression*, evaluated in the time span from $t = 0$ up to the evaluation time point. The expression "CUM MEAN(*expression*) yields the accumulated mean value for that time span. Time-averaged probabilities can be evaluated by "AVG PROB(*condition*)". Time-averaged and cumulative result measures are only supported by SPNP.

Until now, we have only seen so-called *basic measures*, which consist of a single MEAN, PROB or UTIL expression. But MOSEL-2 allows such basic measures to be operands in arithmetic expressions that are called *complex measures*, like:

```
PRINT mean_total := MEAN(zone_1) + MEAN(zone_2) + MEAN(zone_3);
RESULT prob_blocks_1 := UTIL(blocks_1);
RESULT prob_blocks_2 := UTIL(blocks_2);
RESULT prob_blocks_3 := UTIL(blocks_3);
PRINT prob_blocks := @<1..3>"+"{alpha_# * prob_blocks_#};
```

If a result definition starts with "RESULT" instead of "PRINT", then the result will not be printed in the result file, nevertheless it can be used in subsequent result definitions.

Chapter 5

Example: Power Dissipation of a Hard Disk

In this chapter, we will examine a real-word example, namely a model for the power dissipation of a notebook hard disk for a specific operating system strategy and varying I/O traffic.

Modern hard disks make use of several operating modes that are associated with different levels of consumption. In the present example, we will model the IBM DCRA 22160 hard disk (a 2.5" notebook drive with ATA interface), which can assume the following operating modes [Beutel]:

Reading, Writing: When the hard disk reads from the disks or writes to them, it has a typical power dissipation of 3.5 W.

Seeking: The drive is in seek mode when the read/write heads are positioned on a new cylinder. The typical power dissipation in this mode is about 3.5 W.

Performance Idle: When no more read or write requests are waiting, the hard disk changes to performance idle mode immediately. "In performance idle mode, all electronic components remain powered and full frequency servo remains operational" [IBM]. The average power consumption in this mode is 2.1 W.

Low Power Idle: When the disk has remained in performance idle mode for a certain period, it automatically changes to low power idle mode. "In low power idle mode, additional electronics are powered off, and the head is parked near the mid-diameter of the disk without servoing. [...] The transition time is dynamically managed by user's recent access pattern, instead of fixed times" [IBM]. According to [Beutel], the period spent in performance idle mode before switching to low power idle mode varies from 0 to 4 seconds, with an average of 2 seconds. Typically, 0.75 Watts are dissipated in this mode.

Standby: The operating system may initiate a change to standby mode, in which the hard disk spindle motor is switched off. This mode should only be used if no I/O requests are expected in the near future. Power dissipation in this mode is 0.275 W.

Switching from standby mode to any other mode (and vice versa) is relatively costly, concerning energy and time, since the drive's spindle motor has to be started (or stopped). A *shutdown*, i.e. a switch from low power idle mode to standby mode, takes 12.8 seconds and

consumes 16.8 Joules. A *wakeup*, i.e. a switch from standby mode to performance idle mode, takes 2.5 seconds and consumes 8.0 Joules [Beutel]. The drive's I/O transfer rate is in the range of 1 MByte per second (the drive has been built in 1996).

In our model, the operating system will buffer write requests; up to 1 MBytes will be buffered. The buffered blocks will be written to disk if the buffer is full; if any block in the buffer is older than 60 seconds, the whole buffer will be written back even if the buffer is not full yet.

The OS will switch from low power idle mode to standby mode after a predefined delay. We will parametrise this standby delay in the range from 2–40 in order to examine the effects of its variation. If the disk is in standby mode, it will spin up only when an I/O request is going to be processed.

The arrival pattern of I/O requests depends on the applications that are running on a computer. We assume that read requests and write requests arrive at the OS kernel in bundles. The lengths of the bundles are geometrically distributed with parameter $p = 0.2$: if a bundle arrives, it has length n with probability $(1-p)^{n-1} \cdot p$. We assume the time between the arrival of I/O requests bundles to be exponentially distributed; we will use a mean rate of 0.1 write requests bundles per second, and vary the mean rate of read requests between 0.01 and 0.5 bundles per second.

The actual MOSEL-2 description "harddisk.mos" is given in Figure 5.1 and Figure 5.2. Power measures are given in Watts, energy measures are given in Joules, and time measures are given in seconds.

Normally, single disk blocks can be written to a write buffer. Since our write buffer has a size of 1 MBytes, and a disk block contains 512 Bytes, we could have up to 2000 blocks in our write buffer. Modelling such a buffer would lead to a state explosion. To reduce the state space of our model, we divide the write buffer in relatively large chunks of 50 KB. This size will also be used as the base unit of single read/write requests, since the comsumption of time and energy of such a chunk is not much higher than for a single block.

The constant definitions in lines (1)–(17) should be clear, as we have already described the characteristics of the drive and the operating system. The `read_write_delay` in line (10) is derived from the I/O transfer rate. The constants `bundle_prob_write` and `bundle_prob_read` are the parameters for the geometric distribution of the I/O request bundle lengths.

The nodes that are defined in lines (20)–(24) have the following meanings:

`disk` represents the current state of the disk; the possible states are defined in line (18), where `lp_idle` stands for "low power idle mode" and "`perf_idle` stands for "performance idle mode";

`buffer` represents the number of chunks (of 50 KBytes each) that are currently in the write buffer;

`fill_buffer` has the value "`yes`" when the write buffer is currently filled by a write request bundle;

`write` signals whether the write buffer should be written to the disk now;

`read` signals whether a read request bundle is currently arriving.

The function `power`, which is defined in lines (25)–(30), yields the current power consumption, which depends on the disk's mode.

```
     // Disk characteristics.
 (1) CONST perf_idle_power := 2.1;
 (2) CONST lp_idle_power := 0.945;
 (3) CONST standby_power := 0.275;
 (4) CONST shutdown_delay := 12.8;
 (5) CONST shutdown_energy := 16.8;
 (6) CONST wakeup_delay := 2.5;
 (7) CONST wakeup_energy := 8.0;
 (8) CONST active_power := 3.5;
 (9) CONST lp_idle_delay := 2;
(10) CONST read_write_delay := 0.05; // in seconds per 50 KB

     // OS characteristics.
(11) PARAMETER standby_delay := 2..40 STEP 2;
(12) CONST buffer_size := 20; // in units of 50 KB
(13) CONST max_buffer_age := 60;

     // Assumed I/O traffic.
(14) CONST write_request_rate := 0.1;
(15) PARAMETER read_request_rate := 0.5, 0.2, 0.1, 0.04, 0.02, 0.01;
(16) CONST bundle_prob_write := 0.2;
(17) CONST bundle_prob_read := 0.2;

(18) ENUM disk_states := {lp_idle, perf_idle, standby, shutdown, wakeup,
                          reading, writing};
(19) ENUM bool := {no, yes};

(20) NODE disk[disk_states] := lp_idle;
(21) NODE buffer[buffer_size] := 0;
(22) NODE fill_buffer[bool] := no;
(23) NODE write[bool] := no;
(24) NODE read[bool] := no;

(25) FUNC power := IF disk = lp_idle   THEN lp_idle_power
(26)               ELIF disk = perf_idle THEN perf_idle_power
(27)               ELIF disk = standby   THEN standby_power
(28)               ELIF disk = shutdown  THEN shutdown_energy / shutdown_delay
(29)               ELIF disk = wakeup    THEN wakeup_energy / wakeup_delay
(30)                                     ELSE active_power;

(31) COND disk_ready := (disk = lp_idle OR disk = perf_idle);
(32) COND disk_down := (disk = standby OR disk = shutdown);
(33) COND io_requested := (read = yes OR write = yes);

     // Disk power saving mechanism.
(34) FROM disk[perf_idle] TO disk[lp_idle] AFTER lp_idle_delay;
(35) FROM disk[lp_idle] TO disk[shutdown] AFTER standby_delay;
(36) FROM disk[shutdown] TO disk[standby] AFTER shutdown_delay;

     // Spin up disk if it is needed.
(37) IF io_requested AND disk_down TO disk[wakeup];
(38) FROM disk[wakeup] TO disk[perf_idle] AFTER wakeup_delay;
```

Figure 5.1: Description "harddisk.mos" models the power dissipation of a hard disk.

```
     // Incoming read request bundles.
(39) FROM read[no] TO read[yes] RATE read_request_rate;

     // Processing read requests.
(40) IF disk_ready AND read = yes {
(41)  TO disk[reading], read[yes] WEIGHT 1 - bundle_prob_read;
(42)  TO disk[reading], read[no]  WEIGHT bundle_prob_read;
(43) }
(44) FROM disk[reading] TO disk[perf_idle] AFTER read_write_delay;

     // Incoming write request bundles.
(45) FROM fill_buffer[no] TO fill_buffer[yes] RATE write_request_rate;

     // Buffer write requests.
(46) IF fill_buffer = yes TO buffer {
(47)  TO fill_buffer[yes] WEIGHT 1 - bundle_prob_write;
(48)  TO fill_buffer[no]  WEIGHT bundle_prob_write;
(49) }

     // Trigger writing when buffer is full.
(50) IF buffer > 0 FROM write[no] TO write[yes] AFTER max_buffer_age;
(51) IF buffer = buffer_size FROM write[no] TO write[yes];

     // Write from buffer to disk.
(52) IF disk_ready AND write = yes FROM buffer TO disk[writing];
(53) FROM disk[writing] TO disk[perf_idle] AFTER read_write_delay;
(54) IF buffer = 0 FROM write[yes] TO write[no];

     // Result measures.
(55) PRINT mean_power := MEAN(power);
(56) PRINT prob_pending_io := PROB(io_requested AND disk = wakeup);
```

Figure 5.2: Description "harddisk.mos" models the power dissipation of a hard disk (continued).

In lines (37) and (38), we spin up the disk if an I/O request is waiting. A possible shutdown will be aborted.

In lines (40)–(44), incoming read request bundles are processed. The rule in lines (40)–(43) and the rule in line (44) fire alternately until node `read` is reset in line (42). The geometric distribution of the bundle's length is modeled by the weights of the subrules in lines (41) and (42).

The write buffer is filled by write requests in line (46)–(49); the procedure is similar to the read request handling in lines (40)–(44), but does not affect the disk's state.

In line (52), we write to disk if writing has been triggered by line (50) or (51), and the disk is ready. Line (53) terminates writing a single chunk and line (54) terminates writing the whole buffer.

As result measures, we compute the expected power consumption in line (55). Since pending I/O requests may slow down the computer's operation, we are also interested in the probability that an I/O operation is requested but the disk has not recovered from standby mode yet, which is computed in line (56).

Actually, the given model cannot be evaluated by TimeNET: In line (55), the function `power` is used to compute the result measure `mean_power`. It is defined in lines (25)–(30), using

non-integer constants for the power consumption in specific disk states. TimeNET currently computes state-dependent expressions in reward measures with integer precision only, so it complains about the non-integer constants in `power`. We can remedy this situation in two ways: Either we change the constants to integer values by scaling from Watt to milliwatt, or we use an alternative method to compute `mean_power`:

```
PRINT mean_power := PROB(disk = lp_idle) * lp_idle_power
                  + PROB(disk = perf_idle) * perf_idle_power
                  + PROB(disk = standby) * standby_power
                  + PROB(disk = shutdown) * (shutdown_energy / shutdown_delay)
                  + PROB(disk = wakeup) * (wakeup_energy / wakeup_delay)
                  + PROB(disk = reading) * active_power
                  + PROB(disk = writing) * active_power;
```

Here we exploit the fact that TimeNET computes complex result measures from basic result measures with floating point precision.

The rules with deterministic delays that switch the disk's state, in lines (34), (35), (36), (38), (44), and (53), are mutually exclusive, but any of these rules may be concurrently enabled with the deterministic rule in line (50), which checks the write buffer age. Thus we must select an evaluation method that can deal with concurrent deterministic rules, so we can use either simulation, discrete-time analysis, or continuous-time approximative analysis.

The simulation component of TimeNET has problems when estimating the variance of certain result measures, like "`PROB(disk = shutdown)`", since it may be constant for a longer model time period during the simulation. Therefore, the result measures gained by simulation are inexact, even when a low error rate has been specified. For discrete-time analysis, we would have to select a time resolution of 0.05 sec, since this is the time needed for a read or write, as specified in line (10). For this time resolution, the state-space of the discrete-time analysis gets unacceptably large. So we may only use continuous-time approximative analysis, which is started by:

```
mosel2 -Tsv -o approx harddisk.mos
```

The analysis of all 120 models takes about five hours on a PC equipped with an AMD Athlon with 1.5 GHz and 256 MBytes of main memory. The analysis consumes up to 150 MBytes of main memory. The computed mean power consumption is shown in Figure 5.3, and the computed probability of pending I/O caused by the wake-up delay is shown in Figure 5.4.

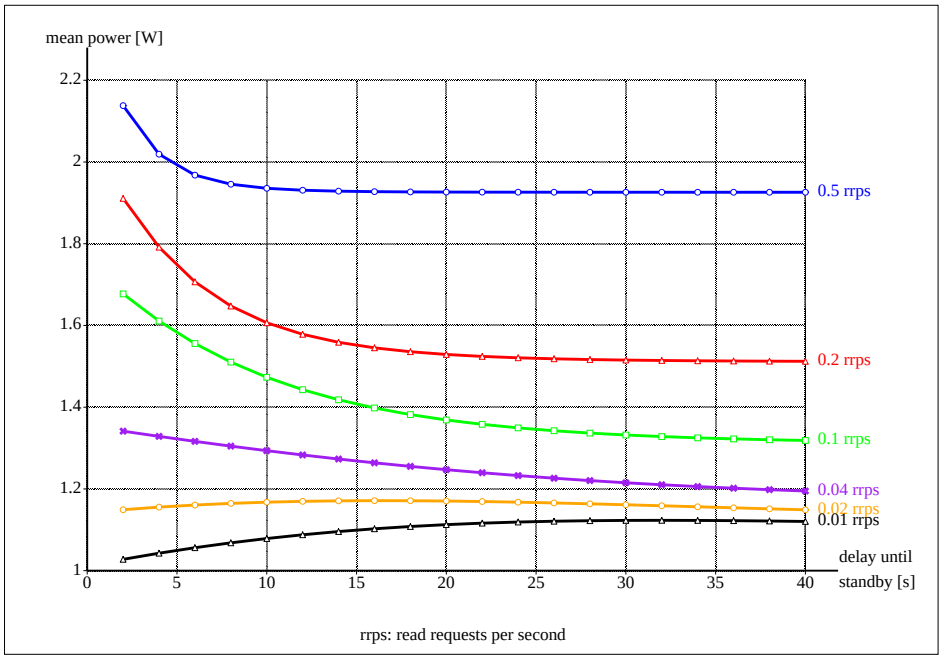


Figure 5.3: Mean power consumption, as computed by "harddisk.mos".

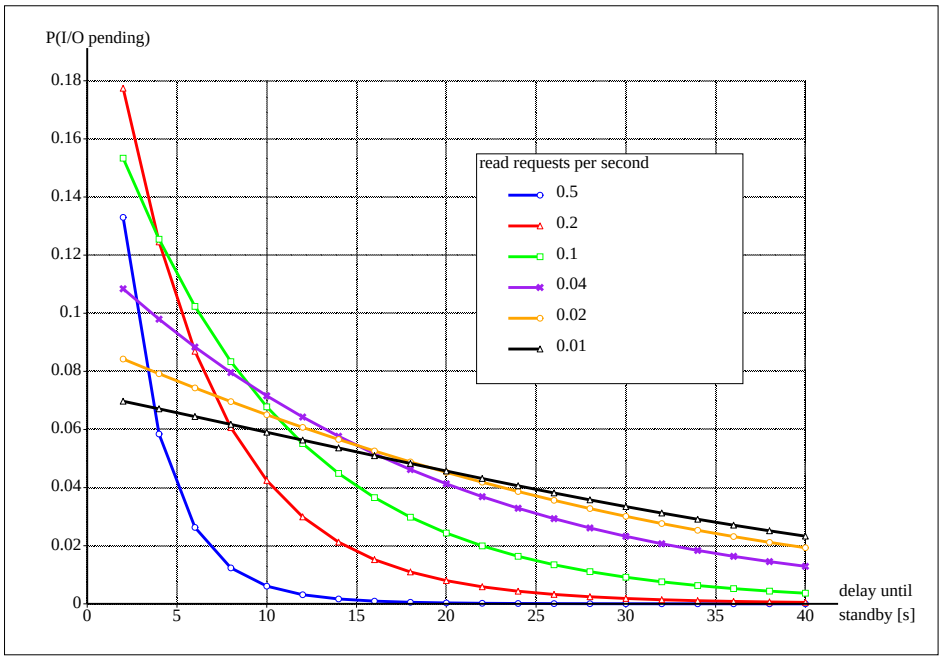


Figure 5.4: Probability of pending I/O, as computed by "harddisk.mos".

Chapter 6

Porting Models from MOSEL to MOSEL-2

This chapter deals with the differences between the original MOSEL language, as described in [BBH], and MOSEL-2. I will also give hints how an existing MOSEL description can be translated into a MOSEL-2 description.

Section 6.1 deals with features of MOSEL that have been abolished or changed in MOSEL-2, and how to translate them into equivalent MOSEL-2 constructs. A short summary of all constructs that have been introduced in MOSEL-2 is given in Section 6.2.

6.1 MOSEL Constructs Changed or Missing in MOSEL-2

The following language constructs of MOSEL do not exist in MOSEL-2, so they must be expressed by other language constructs of MOSEL-2:

Constant definitions

"#define *constant const-expr*" in MOSEL should be translated into "CONST *constant* := *const-expr*;" in MOSEL-2 . Besides, a CONST definition can evaluate arithmetic expressions, including "^" (exponentiation), "SQRT" (square root), "SIN" (sine), and "FLOOR" (round down to nearest integer).

A "#define" with multiple values can be translated into a parameter definition:

#define *name* $value_1$ $value_2$ $value_3..value_4$

should be translated into

PARAMETER *name* := $value_1, value_2, value_3..value_4$;

A parameter range can have an explicit step width, like

```
PARAMETER mu := 0.1..0.9 STEP 0.1;
```

This is an abbreviation for

```
PARAMETER mu := 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9;
```

Enumerations

The syntax of the enumeration definition has changed in MOSEL-2, in order to have a more regular syntax (upper-case keywords only). An old-style definition

```
enum state {down, up, idle};
```

has to be rewritten as

```
ENUM state := {down, up, idle};
```

Assignments to constants within an enumeration, like

```
enum state = {down = 1, up = 2, idle = 3};
```

are not allowed in MOSEL-2. In this case, define the individual constants in MOSEL-2 using CONST.

Variable declarations

HELP, INPUT, and OUTPUT variables are not allowed in MOSEL-2 since they are not supported by the TimeNET analysis tool. INPUT variables of a MOSEL model must be changed to CONST definitions in MOSEL-2. They have been abolished since a model with INPUT variables is underspecified and therefore incomplete. HELP variables may be replaced by CONST definitions, which can contain arithmetic operators. OUTPUT variables should be replaced by results in MOSEL-2.

Function definitions

General C function definitions are not allowed in MOSEL-2. They must be replaced either by a FUNC, which yields a numeric value, or a COND, which yields a boolean value and can be used in place of a condition.

MOSEL-2 functions (FUNCs and CONDs) may be state-dependent, i.e., their values may depend on the current values of the model's nodes: A node name in a function definition yields the current value of that node when that function is called. Since the model's nodes are only known to the MOSEL-2 environment after parsing the node definitions, functions may only be defined *after* the node definition part.

Functions may get explicit arguments, like

```
FUNC min(a,b) := IF a < b THEN a ELSE b;
```

Since they are always numeric, no explicit type has to be given for them. A function without explicit arguments is written without parentheses.

The NODE part

In MOSEL-2, a node with a capacity given as an enumeration name is treated like an ordinary node. Unlike in MOSEL-2, there will be no subnodes created for that node.

A node definition without an explicit capacity is treated differently in MOSEL and MOSEL-2. In MOSEL-2, such nodes have implicit capacities, which means that the analysis tool has to derivate the maximum value of that node by exploring the reachable state space, starting from the initial state and using the model's rules.

Multidimensional nodes and subnodes have been eliminated in MOSEL-2, since they were practically never used. Definitions of multidimensional nodes or nodes with subnodes in MOSEL must be resolved into multiple ordinary node definitions in MOSEL-2.

The START part

A START part, which is used in MOSEL to define the initial values of all nodes, has been eliminated since the positional matching of the nodes and their initial values is error-prone and sensitive to model changes. Define the initial values in the nodes' definitions, like:

NODE foo[10] := 5;

The NOT part

A NOT construct in MOSEL is called *assertion* in MOSEL-2, and its syntax is different. Therefore, a MOSEL assertion

NOT *condition* ;

has to be translated into

ASSERT NOT *condition* ;

The keyword "NOT" is now used to express negation in conditions, so a new keyword for assertions seems more natural.

Rules

- The keywords "W" and "WITH", which denote an exponential firing rate in a MOSEL rule, should be translated into "RATE" for MOSEL-2. Currently, you can still use "WITH", for compatibility reasons.
- The keywords FROMC, FROMM, FROME, TOC, TOM, and TOE are not allowed in MOSEL-2. The FROMC and TOC constructs of MOSEL only check the current state, but do not change it, so their names are misleading. The FROMM and TOM do not check the current state, which is error-prone.
  - FROMC and TOC should be replaced by appropriate IF rule parts;
  - FROMM and TOM should be replaced by FROM and TO, respectively.
  - FROME should be replaced by "FROM EXTERN", and TOE should be replaced by "TO EXTERN".
- The following construct is legal in MOSEL:

```
enum state = {idle, up, down};
...
NODE cpu[state];
...
FROM idle TO up WITH 0.1;
```

If no other node has capacity "state", then the line "FROM idle TO up WITH 0.1;" is an abbreviation for "FROM cpu[idle] TO cpu[up] WITH 0.1;". In MOSEL-2, this is not allowed. The long form has to be used.

- The keyword "P", which denotes a probability of a MOSEL rule, has been changed to "WEIGHT" in MOSEL-2. A "WEIGHT" is only allowed for immediate rules, and the sum of weights of all immediate rules that are enabled at any time does *not* need to be 1. For example, consider the following rules:

```
FROM a TO b WEIGHT 1;
FROM a TO c WEIGHT 2;
FROM a TO d WEIGHT 3;
```

If node a is non-zero, all three rules are enabled. The three rules fire with probabilities 1/6, 2/6, and 3/6, respectively, which yields a total probability of 1.

- A MOSEL rule with subrules must be translated into one of two forms that are offered by MOSEL-2:

1. Consider the MOSEL example

```
IF cpu == up {
  FROM idle        TO busy IF n1 >= b;
  FROM cpu[busy]   TO cpu[wait] WITH mue_1;
  FROM wait, n1(b) TO n2(b), idle;
}
```

This means that the global rule part should be part of every local rule. So this rule is equivalent to

```
IF cpu == up FROM idle        TO busy IF n1 >= b;
IF cpu == up FROM cpu[busy]   TO cpu[wait] WITH mue_1;
IF cpu == up FROM wait, n1(b) TO n2(b), idle;
```

The global rule is integrated as a part of each local rule. For this application of local rules, you can use the same syntax in MOSEL-2, too.

2. Consider the MOSEL example

```
FROM kernel WITH 1.0 / kerneltime IF state_CPU == up_CPU {
  TO user          P 1.0 - pio - pdone;
  TO driver        P pio;
  TO idle, kernelq P pdone;
}
```

This defines a global rule whose firing is a necessary condition for the enabling of the immediate local rules. So this rule is equivalent to

```
NODE temp[1] = 0;
...
FROM kernel WITH 1.0/kerneltime IF state_CPU == up_CPU TO temp;
FROM temp TO user          P 1.0 - pio - pdone;
```

```
FROM temp TO driver         P pio;
FROM temp TO idle, kernelq  P pdone;
```

In MOSEL-2, such a rule type must be expressed by putting a "THEN" in front of the opening brace:

```
FROM kernel RATE 1 / kerneltime IF state_CPU = up_CPU
THEN {
  TO user           WEIGHT 1.0 - pio - pdone;
  TO driver         WEIGHT pio;
  TO idle, kernelq  WEIGHT pdone;
}
```

- Conditional expressions, which might be used in firing rates, have a new syntax that is easier to parse:

```
FROM io TO driverq WITH io == 1 ? 1.0 / 28.00,
                        io == 2 ? 1.0 / 18.667,
                        ...
                        io == 9 ? 1.0 / 11.4037,
                                  1.0 / 11.20
```

  In MOSEL-2, this would be

```
FROM io TO driverq RATE (IF   io = 1 THEN 1 / 28
                         ELIF io = 2 THEN 1 / 18.667
                         ...
                         ELIF io = 9 THEN 1 / 11.4037,
                         ELSE             1 / 11.20);
```

  The parentheses are optional here, but they are useful to distinguish the conditional firing rate from an IF rule part. In this example, you may also note that integer literals and floating-point literals are not distinguished, as they are in MOSEL: The expression 1/28 yields 0.0357... in MOSEL-2, not 0, as it would in MOSEL.

- In MOSEL-2, a rule priority may be only given behind the keyword "PRIO", while MOSEL additionally allows rule priorities in brackets after the probability of an immediate transition or after the firing rate of an exponential transition.

- Priorities may be given in MOSEL as well as in MOSEL-2, but their meaning is different if a priority is given to a non-immediate (timed) rule: In MOSEL, an enabled timed rule with a given priority disables all rules with lower priorities. In MOSEL-2, it does not. Instead, if multiple rules are going to fire at the same time instant, the priority will be used to decide which rule will actually fire. This is useful to control the firing order in discrete-time analysis where such conflicts are quite common.

Results

A new, more general scheme of result definitions has been developed, so most MOSEL result definitions must be translated:

1. "RESULT *name* = MEAN *node*;" is written as "RESULT *name* := MEAN(*node*);" in MOSEL-2.

2. "RESULT DIST *node*;" must be changed to "PRINT DIST *node*;".

3. "RESULT *name* = UTIL *node*;" must be changed to "RESULT *name* := UTIL(*node*);".

4. "RESULT MTTA" in MOSEL yields the mean time that has passed until the system runs into an absorbing state. An absorbing state is a state in which no rule is enabled. MOSEL-2 instead offers the more general concept of *durations*: The result definition

   PRINT *duration* := TIME TO *condition*;

   prints the mean time that has passed until a state is reached in which *condition* is true. Such states need not be absorbing. This makes reliability evaluation in MOSEL-2 easier: The rules of the model need not be disabled if the system is in a failure state.

5. "RESULT IF (*condition*) *actions*;" is a conditional result definition. An *action* in such a RESULT definition is a variable assignment. There is no general scheme to translate this into MOSEL-2, but in most cases, such a RESULT definition adds the probabilities of all states in which *condition* holds:

   RESULT IF (*condition*) *result* += PROB;

   This can be translated into the MOSEL-2 construct

   RESULT *result* := PROB(*condition*);

The keyword "RESULT>>" for result measures that should be put into the result file has been changed to "PRINT" in MOSEL-2.

Reward values

In MOSEL, reward values are associated with the possible values of a node. They have been abandoned in MOSEL-2. If you want to associate a numeric reward value with each value of a certain node, use the conditional expression. Take the following MOSEL example:

```
NODE driverq[3] = 0 REWARDS 3.1 2.4 1.3 0.7;
```

This can be expressed in MOSEL-2 as:

```
NODE driverq[3] := 0;
FUNC driverq_reward := IF driverq = 0 THEN 3.1
                       ELIF driverq = 1 THEN 2.4
                       ELIF driverq = 2 THEN 1.3
                       ELIF driverq = 3 THEN 0.7
                                        ELSE 0;
```

The you can use "`driverq_reward`" as a state-dependent reward value in your result definitions.

The reward function

MOSEL's specialised reward measures make use of a user-supplied C function that is named "REWARD_FUNCTION". In MOSEL-2, there is no specific reward function. A MOSEL reward function must be transformed into an expression that is the argument of a MEAN construct. Of course, function calls can be used in that expression. Consider the following MOSEL example:

```
...
double REWARD_FUNCTION(void)
{
  int min, max;
  if (processors_up > memories_up)
    { max = processors_up; min = memories_up; }
  else
    { min = processors_up; max = memories_up; }
  return max * (1 - pow(1 - 1.0/max, min));
}
...
NODE processors_up[3] = 3;
NODE memories_up[5] = 5;
...
RESULT>> MEAN REWARDss;
```

This could be translated into the following MOSEL-2 model:

```
...
NODE processors_up[3] := 3;
NODE memories_up[5] := 5;
...
FUNC helper(a,b) := a * (1 - (1 - 1/a) ^ b);
FUNC reward := IF processors_up > memories_up
               THEN helper(processors_up, memories_up)
               ELSE helper(memories_up, processors_up);
...
PRINT result := MEAN(reward);
```

Reward measures

The reward measures in MOSEL have been replaced by the more regular scheme of the MEAN expression. To translate a reward measure to MOSEL-2, the REWARD_FUNCTION has to be translated into a MOSEL-2 FUNC (which is referenced below as *func*) and the individual reward measure has to be translated as follows:

`RESULT` *name* `= MEAN REWARDat;`

Translate this to "`RESULT` *name* `:= MEAN(`*func*`);`". MOSEL-2 knows that this measure is transient if the whole model is analysed in a transient state.

`RESULT` *name* `= MEAN REWARDss;`

Translate this to "`RESULT` *name* `:= MEAN(`*func*`);`". MOSEL-2 knows that this measure is stationary if the whole model is analysed in its stationary state.

`RESULT` *name* `= MEAN AccREWARDss;`

This reward measure unfortunately has no MOSEL-2 equivalent yet.

`RESULT` *name* `= MEAN AccREWARDuntil;`

Translate this to "`RESULT` *name* `:= CUM MEAN(`*func*`);`". This type can only be used if the whole model is analysed in a transient state.

`RESULT` *name* `= MEAN AccREWARDper;`

Translate this to "`RESULT` *name* `:= AVG MEAN(`*func*`);`". This type can only be used if the whole model is analysed in a transient state.

Pictures

Picture definitions in MOSEL-2 do not have all the possibilities of MOSEL picture specifications, since it has been a goal of the revision to keep the language small and since many features of a picture can be customized after the picture generation, by using the IGL interpreter. Only the following MOSEL picture parameters are supported in MOSEL-2 (the syntax of many of them has changed):

`-TITLE` *string*

In MOSEL-2, a picture's title is optional. If given, it must be enclosed in double quotes and follow the keyword PICTURE that starts a picture definition.

`-NOLOOPPACKUP`

In MOSEL-2, a picture definition always defines only one picture. If you want to have a separate picture for each parameter value, enclose the picture definition in a loop and use the construct "FIXED *parameter* = *value*" to select the parameter value of the picture:

```
PARAMETER mue := 0.1..0.9 STEP 0.1;
...
@<mue>{ PICTURE "utilization for mue = #"
        FIXED mue = #
        PARAMETER TIME
        CURVE util;
      }
```

`XSCALE` *name*

In MOSEL-2, the graph's parameter is determined by "PARAMETER *name*".

`XSCALE -ARROWTEXT` *string*

In MOSEL-2, use "XLABEL *string*".

`YSCALE -ARROWTEXT` *string*

In MOSEL-2, use "YLABEL *string*".

`CURVE` *result*`, ...`

In MOSEL-2, this is unchanged.

`CURVE DIST` *node*

In MOSEL-2, only one node may be part of a "CURVE DIST" picture element.

`CURVE TIME` *name*`, ...`

In MOSEL-2, use "PARAMETER TIME" and "CURVE *name*, ...".

`CURVE -CAPTION` *string*

In MOSEL-2, put the caption string immediately behind the name of the result in a CURVE part: "CURVE *result string*".

Shortcuts and loops

The use of shortcuts in MOSEL was only allowed in front of selected language constructs. In MOSEL-2, shortcuts have been replaced by *loops*. Loops are not handled by the parser itself, but they are preprocessed by the lexical scanner. Therefore, they can appear anywhere in a MOSEL-2 source, but they have to be introduced by a special character, the "`@`". Since the preprocessor does not know about syntactic structures, the part of a loop that should be repeated must be enclosed in braces ("{ }") and is called the *loop body*. So a MOSEL loop definition

```
<1..3> NODE n#[max] = 0;
```

has to be written in MOSEL-2 as

```
@<1..3>{ NODE n#[max] := 0; }
```

For nested loops, MOSEL-2 offers a special abbreviation. The nested loop in MOSEL:

```
<1..3> <down,up> FROM n<#1>[#2] TO n<#1>[idle];
```

can be written in MOSEL-2 as

```
@<1..3><down,up>{ FROM n<#1>[#2] TO n<#1>[idle]; }
```

In MOSEL-2, a simple "`#`" in a nested loop yields an error. To access a single index, e.g. the index of the 2nd loop, use "`<#2>`". To access all indexes, joined by "_", use "`##`".

In MOSEL, a loop index can be used in a simple calculation: "`<#+1>`", "`<#-2>`", "`<#*3>`", "`<#/4>`". In MOSEL-2, only the operators "`+`" and "`-`" are allowed here.

The `#include` statement

The "#include" preprocessor statement has been abolished. This forces the user to write a complete MOSEL-2 description in a single file.

The `#string` statement

The "#string" preprocessor statement has been eliminated. It was mostly used in combination with a loop range:

```
#string sum_x + x# :
...
FROM a TO b WITH x1 $sum_x(<2..3>);
```

This results in a rule

```
FROM a TO b WITH x1 + x2 + x3;
```

In MOSEL-2, you may yield the same result by writing

```
FROM a TO b RATE @<1..3>"+"{x#};
```

6.2 New MOSEL-2 Constructs

The following constructs have been introduced in MOSEL-2 by the language revision:

- A general RESULT/PRINT definition can use closed expressions for arbitrary complex result measures.
- A rule can have a deterministic or (discrete) uniform firing distribution, specified by the AFTER rule part.
- An immediate rule can have a WEIGHT part to control the probability of its firing with respect to other immediate rules that are enabled at the same time. This is a generalization of MOSEL's "P" rule part.
- The NOT operator for boolean negation has been introduced in MOSEL-2.
- FUNC and COND definitions are MOSEL-2 replacements for the full blown C functions in MOSEL.
- MOSEL-2 offers two forms of local rules: In *ordinary local rules*, each local rule is *augmented* by the rule parts of the global rule it belongs to. In *local rules marked by* THEN, the local rules *depend* on the global rule via an implicit node.
- The CONST and PARAMETER constructs are replacements for "#define". Values in those definitions may be arithmetic expressions. This partly compensates the lack of variables.
- A general loop construct, which replaces MOSEL's loops and "#string" construct, has been introduced.
- MOSEL-2 uses a new form of the conditional operator "IF" which is parsable by LL(1) and recursive descent parsers.

Chapter 7

Implementation of MOSEL-2

In this chapter, I will present some implementation aspects of the MOSEL-2 environment that has been developed as part of this thesis. I will concentrate on the conversion to TimeNET, since this tool has been newly integrated into MOSEL-2.

Parsing a MOSEL-2 File

The MOSEL-2 input file is analysed in two phases, which are interwoven:

Scanning: The input file is read in and split into tokens by the lexical *scanner*. A token may be a keyword, a number, a name, a string, a special char (like ";") or a special char sequence (like ":="). Comments and whitespaces are deleted. If a loop is encountered in the source text, it will be read and expanded immediately. The expanded loop will be re-fed to the scanner's input stream and read by the scanner before the following characters are scanned. The scanner is generated by the GNU tool "flex" from the MOSEL-2 source file "scanner.l".

Parsing: The token stream of the scanner is parsed and an internal representation of the input model is built. The parser is generated by the GNU tool "bison" from the MOSEL-2 source file "parser.y".

The MOSEL-2 environment scans and parses the input file in one pass. This requires that each name, like a node name or a constant name, must have been defined before it can be used.

Invoking an Analysis Tool

Depending on the MOSEL-2 command line options, the MOSEL-2 model will be converted to the format of one of the supported tools: MOSES (in `create_moslang()`, file "moslang.c"), SPNP (in `create_cspl()`, file "cspl.c"), or TimeNET (in `create_timenet()`, file "timenet.c"). For each parameter combination – this is called *setting* in MOSEL-2 –, a separate model file will be created.

The analysis tool will be called (by one of the functions `run_moses()`, `run_spnp()`, or `run_timenet()` in file "result.c"), and the result file that has been created by the selected analysis tool will be parsed. The results are stored in an internal data structure (defined

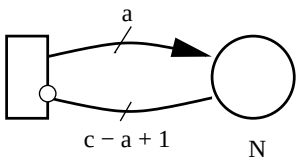
in "result.c"), printed to the result file (by `write_results()`), and the optional IGL file is created (by `write_igl_file()`).

Conversion to Petri Nets

A MOSEL-2 model is quite similar to a stochastic Petri net. This makes the conversion to a Petri net (which is needed by SPNP and TimeNET) rather easy, although some aspects of the MOSEL-2 language are a little bit harder to deal with, like "FROM *node*[*state*]" or "TO *node*[*state*]" rule parts.

Generally, nodes are converted to places, and rules are converted to transitions. IF conditions in rules are converted to guards. Note that TimeNET does not allow guards for timed transitions, so we must use a work-around (see below).

Since a node has a maximum capacity, we must take care of it in all transitions that change that node's state. For a "TO $N(a)$" rule part, we must place an inhibitor arc from n's place to the rule's transition which limits the number of tokens in that place (assuming that N has capacity c):

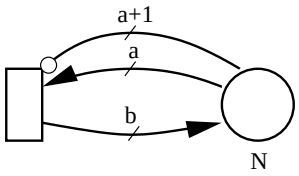


The inhibitor arc is not necessary if the MOSEL-2 node has no explicit capacity.

Setting a Node to a New State

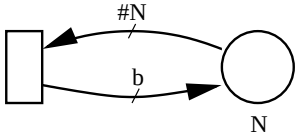
To translate a rule part of the form "TO $N[b]$", we have to distinguish two cases:

1. The same rule may contain a rule part "FROM $N[a]$". In this case, we know the previous state of the node, and we can convert both rules to the following subnet:

   The input arc of the transition empties the place N, while the output arc refills N. The inhibitor arc makes sure that the transition only fires if exactly a tokens are in N.

2. The same rule does not contain a rule part "FROM N...". In this case, we do not know the previous state of the node, so we must empty the corresponding place in the Petri net using an input arc with variable arity:

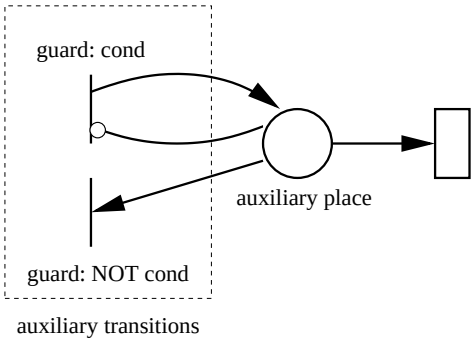
   The arity "#N" means that the input arcs takes as many tokens as are in place N.

Conversion to TimeNET

The file format of TimeNET has some restrictions that have to be dealt with by MOSEL-2. For example, the TimeNET interface language does not know functions, and timed transitions may not have guards. In the following sections, I will describe how those restrictions are circumvented.

Guards for Timed Transitions

In TimeNET, timed transitions must not have guards, although guards are allowed for immediate transitions. To translate IF rule parts in MOSEL-2 rules, we need a way to simulate such guards: We create an auxiliary place which, when non-empty, represents that the guard's condition is true; the place will be filled by an immediate transition that is enabled by the guard and inhibited by the auxiliary place. The place must be emptied immediately when the guard's condition is no longer true; this is achieved by a complementary transition that is enabled by the auxiliary place and the negated guard:



The auxiliary place and the auxiliary transitions for timed transitions are created in `print_transitions()` in file "timenet.c".

Expression Trees

MOSEL-2 has to transform and/or evaluate arithmetic-logic expressions in many places. Therefore, it uses a general internal format to store such expressions: An expression is stored as a ternary tree. Number literals, constants, nodes, and function calls are the leaves of such a tree. Operators like "`*`", "`/`", "`AND`" and "`NOT`" are represented by inner nodes. The tree is ternary since the operator "`IF`" needs three arguments, namely the condition, the expression that is used if the condition holds, and the expression that is used if the condition does not hold. All other operators are monary or binary. Expression trees are defined in the MOSEL-2 source in "expr.h" and "expr.c".

Expansion of Functions

Functions (i.e. FUNCs and CONDs) are an important part of the MOSEL-2 language, which make the description of non-trivial models easier. Unfortunately, they have no counterpart in the TimeNET description language. The solution is to expand a function call in the expression where it is used. This is known as *inline expansion* in compiler technology. Explicit formal

arguments in the function definition have to replaced by their corresponding actual arguments in the function call.

For example, look at the following extract of a MOSEL-2 model:

```
FUNC min(a,b) := IF a <= b THEN a ELSE b;
...
FROM N1, N2 TO N3 RATE mue * min (N1, N2);
```

In the last line, the call of the function "`min`" would be inline-expanded, resulting in the following line:

```
FROM N1, N2 TO N3 RATE mue * (IF N1 <= N2 THEN N1 ELSE N2);
```

Of course, the MOSEL-2 environment will not generate such code, but the equivalent code in TimeNET format. Inline expansion is implemented in `expr_replace_names()` in file "expr.c".

Normalisation of a State Expression

Both MOSEL-2 and TimeNET have conditional operators. They are written as "IF *cond* : *expr* ELSE *expr*" in TimeNET and "IF *cond* THEN *expr* ELSE *expr*" in MOSEL-2. TimeNET only allows an IF expression in the *top level* of an expression, i.e., an IF expression may not be an operand of an arithmetic or logic operator. Therefore we must *normalize* the expression, i.e., move any conditional operators to the top level, before we can use it in TimeNET. We normalize an expression in two steps: First, we move all conditional operators from subexpressions to the top level. Then we remove conditional expressions in conditions of the top-level expression.

Conditional Operators in Subexpressions

Suppose we have an expression *expr* of the following form (where $m \geq 0$):

IF $cond_1$ THEN $expr_1$
ELIF $cond_2$ THEN $expr_2$
...
ELIF $cond_m$ THEN $expr_m$
ELSE $expr_{m+1}$

where $expr_i$ contains an inner conditional operator *inner* that looks like (where $n > 0$):

IF $cond'_1$ THEN $expr'_1$ ELIF ... ELIF $cond'_n$ THEN $expr'_n$ ELSE $expr'_{n+1}$

Then we will replace *expr* by the following expression:

IF $cond_1$ THEN $expr_1$
ELIF $cond_2$ THEN $expr_2$
...
ELIF ($cond_i$ AND $cond'_1$) THEN $expr_{i,1}$
...
ELIF ($cond_i$ AND $cond'_n$) THEN $expr_{i,n}$

ELIF $cond_i$ THEN $expr_{i,n+1}$
...
ELIF $cond_m$ THEN $expr_m$
ELSE $expr_{m+1}$

where $expr_{i,j}$ is equal to $expr_i$ after replacing *inner* by $expr'_j$ (for $j = 0, \ldots, n+1$).

This replacement rule must be applied repeatedly until all inner conditional expressions in subexpressions have been removed.

Conditional Operators in Subconditions

Suppose we have an expression *expr* of the following form (where $m \geq 0$):

IF $cond_1$ THEN $expr_1$
ELIF $cond_2$ THEN $expr_2$
...
ELIF $cond_m$ THEN $expr_m$
ELSE $expr_{m+1}$

where $cond_i$ contains an inner conditional operator. Then we will remove that conditional operator in $cond_i$ as described in the next section.

This replacement rule again has to be repeated until all inner conditional expressions in subconditions have been removed.

Normalization of a Condition

In MOSEL-2, conditions are used in IF rule parts, and in PROB expressions. In TimeNET, an IF rule part gets translated into a guard, and a PROB expression gets translated into a P{*cond*} expression, which yields the probability of *cond*. Both must not contain conditional operators, so we must *normalize* the condition, i.e., remove the conditional operators.

Assume *cond* is a condition that contains a comparison *comparison* of the form "$expr_1$ *comp-oper* $expr_2$", where $expr_1$ or $expr_2$, or both, contain a conditional expression and *comp-oper* is a comparison operator (<, =, ...). For simplicity, let's assume that $expr_2$ contains a conditional expression.

First, we have to normalize $expr_2$, as described above, so it will look like (where $n > 0$):

IF $cond'_1$ THEN $expr'_1$ ELIF ... ELIF $cond'_n$ THEN $expr'_n$ ELSE $expr'_{n+1}$

Then we will replace *comparison* by:

($cond'_1$ AND ($expr_1$ *comparison* $expr'_1$))
OR ((NOT $cond'_1$) AND $cond'_2$ AND ($expr_1$ *comparison* $expr'_2$))
...
OR ((NOT $cond'_1$) AND ... AND (NOT $cond'_n$) AND ($expr_1$ *comparison* $expr'_{n+1}$))

The NOT conditions can be factorized out, so the whole expression may be a little bit shorter.

This replacement rule must be applied until all conditional expressions have been removed.

Conversion of a MEAN Expression

A MEAN(*expr*) expression in MOSEL-2 will be translated to "E{*expr*}" in TimeNET which yields the expectation of *expr*, but TimeNET does not allow IF expressions in *expr*. Instead, it offers an expression type "E{*expr* IF *cond*}" which computes the expected value of *expr*, which is set to zero where *cond* does not hold. If we have an expression that contains IF expressions, we must convert it to a sum of such conditional expectations, as follows:

First, normalize the expression, so it will look like

IF $cond_1$ THEN $expr_1$,
ELIF $cond_2$ THEN $expr_1$,
...
ELIF $cond_n$ THEN $expr_n$,
ELSE $expr_{n+1}$

where no $expr_i$ and no $cond_i$, for any i, contains any IF expression.

Then create the following TimeNET expression:

$$
\begin{aligned}
&\mathrm{E}\{expr_1 \text{ IF } cond_1\} \\
+\ &\mathrm{E}\{expr_2 \text{ IF NOT } (cond_1) \text{ AND } cond_2\} \\
&\ldots \\
+\ &\mathrm{E}\{expr_n \text{ IF NOT } (cond_1 \text{ OR } \ldots \text{ OR } cond_{n-1}) \text{ AND } cond_n\} \\
+\ &\mathrm{E}\{expr_{n+1} \text{ IF NOT } (cond_1 \text{ OR } \ldots \text{ OR } cond_n)\}
\end{aligned}
$$

Simplification of Expressions

Inline expansion and normalisation of expressions may create very large expressions. Therefore, MOSEL-2 tries to simplify each expression before writing it to the TimeNET file. The simplifications are quite simplistic:

- *Constant folding* replaces a constant subexpression by its value.
- We exploit arithmetic and logic identities like $1 \cdot x = x$, $0 \cdot x = 0$, $1/(1/x) = x$.

These simplifications are implemented in `simplify_expr()` in file "expr.c".

Chapter 8

Categorization of MOSEL-2 and Comparison

In this chapter, I will categorize the MOSEL-2 language in terms of specification languages and software ergonomy. Additionally, I will compare MOSEL-2 to some existing textual languages for stochastic modelling.

MOSEL-2 as a Specification Language

Jane Hillston and Marina Ribaudo [HR] state three features that may be present or absent in performance modelling paradigms. These are *compositionality*, *abstraction*, and *formality*.

Compositionality is the ability to build larger structures from smaller ones. This is inherently supported by stochastic process algebras. MOSEL-2 supports compositionality for result measures; the defining expression of a result measure may contain other result measures. A MOSEL-2 model itself is just a set of nodes and rules which may not subdivided into smaller parts by any language means, so it is not compositional. Since complex systems are often inherently composed of smaller parts, it would be helpful for clarity and adaptability if this could be reflected in the MOSEL-2 model.

A modelling language is *abstract* if complex models can be built from detailed components but disregarding internal behaviour when it is appropriate to do so [HR, page 237]. Programming languages, for clarification, may use the concepts of functions and modules as devices for abstraction. In MOSEL-2, abstraction is supported for result measures, since they may contain functions. On the level of the MOSEL-2 network, no abstraction facilities are provided, but they would be desirable.

A modelling language is *formal* if its syntax and its semantics are defined exclusively by formal means. To define the syntax of a textual specification language, some sort of context-free grammar formalism is usually used, like EBNF (see Chapter 2). Since it can only define the context-free aspects of the syntax, additional rules must be given for its context-sensitive aspects, like the consistent use of identifiers. This is normally done in informal English. The language definition of MOSEL-2 uses this approach. The situation is similar for the semantics of MOSEL-2: We show in Section 2.3 how a MOSEL-2 model can be mapped onto an underlying stochastic process, which gives a mathematical notation of its behaviour. Thus we have a formal semantic model for MOSEL-2. The translation process is explained in natural language, by mapping each constituent of a MOSEL-2 description to this model. Therefore, the language definition is much more readable than it would be if it

were defined in purely formal terms, and it can be understood without the knowledge of a semantic specification language.

According to [Wing], a (formal) specification language provides a notation, a semantic domain (formalized as a set of semantic objects), and a precise rule defining which objects satisfy each specification. The semantic domain can differ largely between specification languages. For example, programming languages are "used to specify functions from input to output, computations, predicate transformers, relations, and machine instructions" [Wing]. Stochastic modelling languages are usually used to specify stochastic processes, or similar constructs from the theory of probabilities. These processes are the semantic domain of stochastic modelling languages, but the purpose of a stochastic modelling language is to gain result measures by analysis or simulation from the specification; therefore tool support is needed. The specification must be *complete*, i.e., no non-determinisms, like unspecified firing distributions, may be left. Usually such underspecifications are eliminated by assumptions that stem from intuition or empirical evidence. The requirement of completeness distinguishes stochastic modelling languages from specification languages which are used in the software development process.

MOSEL-2 and Petri Nets

Stochastic Petri nets make a large field in the area of stochastic modelling, at least in academics. Analysis and simulation techniques for GSPNs are well-investigated, and evaluation methods for non-Markovian Petri Nets are also known. MOSEL-2 is strongly connected to Petri Nets, since two of its evaluation tools (TimeNET and SPNP) are Petri net analysators. Most Petri net tools offer a graphical user interface (GUI) for the construction of Petri nets. These interfaces are intuitive and instructive, since the overall structure of a net can be understood "at a glance". Furthermore, many Petri net GUIs offer a *token game*: They let the user play with the net by triggering enabled transitions and thus changing the marking. Using the token game, the user can check the model for correctness and consistency. MOSEL-2 does not have such capabilities, since its input is purely textual.

Using a GUI, larger Petri nets are harder to construct and to maintain, since their graphical representation usually does not fit on the screen anymore. Therefore, most Petri net GUIs allow the working area to be scrolled, but since only a part of the current model is shown at any time, the display is still confusing. Some Petri nets (for example HCPNs in TimeNET) may be hierarchically decomposed, which helps alleviate this problem. For larger Petri nets, an optimal, or at least non-confusing, placement of places, transitions and especially arcs is hard to find. Automatical tool support for the placement is lacking in all GUIs that I know of.

MOSEL-2 is better suited for the construction and maintenance of larger models than monolithic graphical Petri nets, as has been proven by the porting of an IEEE 801.11 WLAN model [HG], which was initially written in the hierarchical compositional textual-graphical Petri net language SPNL [German2] and consists of about 100 places and 150 transitions. The loop construct of MOSEL-2 was a great help to model replicated subsystems, although a MOSEL-2 language construct for the composition of submodels (as in SPNL) would be desirable. Comments may be inserted anywhere in a MOSEL-2 file and have proven to be very useful for the documentation and structuring of larger descriptions. The fixed order of the MOSEL-2 section – constants, nodes, functions, and rules – is not so well-suited for the description of large models: nodes and functions are defined apart from the rules that use them. A division of a MOSEL-2 file into only two sections, namely model description

and result measures, seems to be more desirable. Modifications of the WLAN model are rather easy; for example, we had to simulate a discrete uniform firing distribution, which is supported by SPNL, but not by the TimeNET simulation tool used by MOSEL-2. That modification was quickly accomplished without any problems.

MOSEL-2 and CSPL

When MOSEL-2 uses the SPNP tool for analysis, the model description is converted into the CSPL format (**C**-based **SP**N **L**anguage). But CSPL descriptions can also be written directly by the user, as demonstrated by numerous examples in the SPNP Manual [SPNP]. Figure 8.2 shows an example from page 86 of that manual (the analysis options are omitted here). The Petri net is graphically shown in Figure 8.1. Figure 8.3 shows an equivalent MOSEL-2 description.

In CSPL, the Petri net structure is built up in function `net()` by calling functions that generate nodes, transitions, and arcs, respectively. Marking-dependent reward functions are defined as ordinary C functions. Result measures are evaluated in the function `ac_final()`.

MOSEL-2 descriptions are usually more readable and much shorter than equivalent CSPL descriptions, as demonstrated in the presented example. In MOSEL-2, reward functions that are used as arguments for marking-dependent weights or result measures need not be defined explicitly; instead, expressions can be included in the rule definition or result definition, respectively. The same holds for guards. On the other hand, CSPL offers the full power of the C programming language, since it is embedded into C as a function library. Furthermore, transitions have names in CSPL, so their firing rate can be used as a result measure, while MOSEL-2 rules are anonymous. This is the reason why the firing rates in the present example must be computed from the utilization of the input places.

MOSEL-2 and SHARPE

SHARPE (**S**ymbolic **H**ierarchical **A**utomated **R**eliability amd **P**erformance **E**valuator) [STP] is a modelling environment that supports a variety of model types, like fault trees, task graphs, Markov chains and GSPNs, and offers alternative analysis algorithms for them, from which the user can choose. As an example, the GSPN in Figure 8.4 has been modelled in SHARPE, as shown in Figure 8.5. The same model can be modelled in MOSEL, as shown in Figure 8.6.

The GSPN description in Figure 8.5 is subdivided into six sections, each of which is terminated by an "`end`" [STP]:

1. the places together with their initial numbers of tokens;
2. the timed transition names, types and rates;
3. the immediate transition names and weights;
4. input arcs and multiplicities;
5. output arcs and multiplicities;
6. inhibitor arcs and multiplicities.

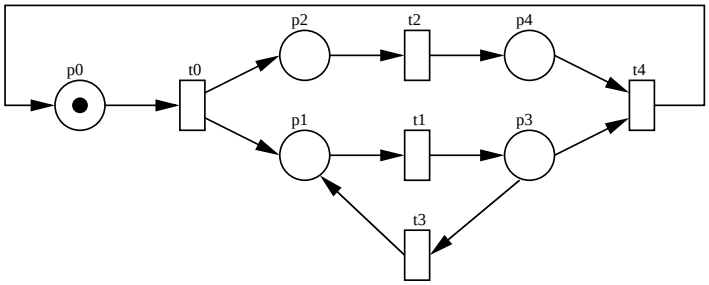


Figure 8.1: "Molloy's example", taken from [SPNP], page 86.

```
#include "user.h"

void options() {
  (options are omitted here)
}

void net() {

  place("p0");
  init("p0",1);
  place("p1");
  place("p2");
  place("p3");
  place("p4");

  rateval("t0",1.0);
  rateval("t1",3.0);
  rateval("t2",7.0);
  rateval("t3",9.0);
  rateval("t4",5.0);

  iarc("t0","p0");  oarc("t0","p1");  oarc("t0","p2");
  iarc("t1","p1");  oarc("t1","p3");
  iarc("t2","p2");  oarc("t2","p4");
  iarc("t3","p3");  oarc("t3","p1");
  iarc("t4","p3");  iarc("t4","p4");  oarc("t4","p0");
}

int assert() {
  if (mark("p3") > 5)
    return(RES_ERROR);
  else
    return(RES_NOERR);
}
```

```
void ac_init() {
  fprintf(stderr,"\nExample from Molloy's Thesis\n\n");
  pr_net_info(); /* information on the net structure */
}

void ac_reach() {
  fprintf(stderr,"\nThe RG has been generated\n\n");
  pr_rg_info(); /* information on the reachability graph */
}

/* general marking dependent reward functions */
double  ef0() { return((double)mark("p0")); }
double  ef1() { return((double)mark("p1")); }
double  ef2() { return(rate("t2")); }
double  ef3() { return(rate("t3")); }
double  eff() { return(rate("t1") * 1.8 + (double)mark("p3") * 0.7); }

void ac_final() {

  solve(INFINITY);

  pr_mc_info(); /* information about the Markov chain */
  pr_expected("mark(p0) ",ef0);
  pr_expected("mark(p1) ",ef1);
  pr_expected("mark(t2) ",ef2);
  pr_expected("mark(t3) ",ef3);
  pr_expected("rate(t1) * 1.8 + mark(p3) * 0.7",eff);
  pr_std_average(); /* default measures */
}
```

Figure 8.2: SPNP description of Molloy's example, taken from [SPNP], page 87.

```
NODE p0 := 1;
@<1..4>{ NODE p#; }

FROM p0     TO p1, p2 RATE 1.0;
FROM p1     TO p3     RATE 3.0;
FROM p2     TO p4     RATE 7.0;
FROM p3     TO p1     RATE 9.0;
FROM p3, p4 TO p0     RATE 5.0;

ASSERT p3 <= 5;

PRINT expected_p0 := MEAN(p0);
PRINT expected_p1 := MEAN(p1);
PRINT expected_t2 := UTIL(p2) * 7.0;
PRINT expected_t3 := UTIL(p3) * 9.0;
PRINT expected_result := UTIL(p1) * 3.0 * 1.8 + MEAN(p3) * 0.7;
```

Figure 8.3: MOSEL-2 description of Molloy's example.

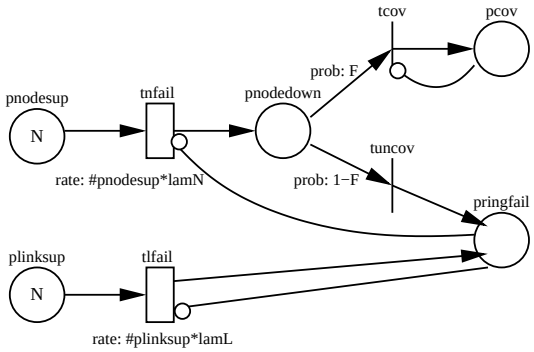


Figure 8.4: GSPN model of ring network, taken from [STP], page 199.

```
bind lamL 0.000001
bind lamN 0.000001

gspn ringrelg(N,F)
* places
pnodesup N
pnodedown 0
plinksup N
pringfail 0
pcov 0
end
* timed trans
tnfail dep pnodesup lamN
tlfail dep plinksup lamL
end
* immed trans
tcov ind 1-F
tuncov ind F
end
* input arcs
pnodesup tnfail 1
plinksup tlfail 1
pnodedown tcov 1
pnodedown tuncov 1
end
* output arcs
tnfail pnodedown 1
tlfail pringfail 1
tcov pcov 1
tuncov pringfail 1
end
* inhib arcs
pringfail tnfail 1
pringfail tlfail 1
pcov tcov N-1
end

cdf(ringrelg;16,.2)
end
```

Figure 8.5: SHARPE description for ring network, taken from [STP], page 200.

```
CONST lamL := 1E-6;
CONST lamN := 1E-6;
CONST N := 16;
CONST F := 0.2;
NODE pnodesup := N;
NODE plinksup := N;
NODE pringfail[1];
NODE pcov[1];
NODE pnodedown[1];
IF pringfail = 0 FROM pnodesup TO pnodedown RATE pnodesup * lamN;
                 FROM plinksup TO pringfail RATE plinksup * lamL;
FROM pnodedown { TO pringfail WEIGHT F;
                 TO tcov      WEIGHT 1-F; }
PRINT mttf := TIME TO pringfail > 0;
```

Figure 8.6: MOSEL-2 description for ring network.

Comments start with an asterisk at the beginning of a line. Guards are not available in SHARPE Petri nets. SHARPE model descriptions are quite dense, since they use a minimum amount of "syntactic sugar". For example, you must know the order of the sections to tell apart the input arcs, the output arcs and the inhibitor arcs. The present example contains a comment at the beginning of each section that indicates its function, but these comments are not checked by the SHARPE environment. Therefore the lack of "syntactic sugar" decreases the descriptions' readability, at least for people that are not accustomed to the SHARPE language. The strict order of the sections prohibits to put all arcs in a subpart that belongs to a specific transition; this prevents the user from structuring the description after the structure of the modelled system.

In the MOSEL-2 language, the FROM and TO parts of a rule (which correspond to a transition's input and output arcs) are part of the rule definition. This is usually more readable. But MOSEL-2 does not allow to mix nodes and rules that belong to the same subsystem, either. This would be a desirable change in the MOSEL-2 language.

MOSEL-2 and Stochastic Process Algebras

The basic modelling primitives of MOSEL-2 and Stochastic Process Algebra (SPA) languages, like PEPA [HR] or TIPP [GHR], are quite different. SPAs are composed of actions that may synchronise by sharing the same name. The state space of a process algebra is not given explicitly, but it is derived as part of the analysis. In MOSEL-2, the nodes that determine the model's state are explicitly specified, and their values are explicitly changed by the rules. MOSEL-2 rules are anonymous, so they cannot be composed into more complex rules (apart from the fact that a rule may have subrules). In SPAs, the computation of throughput of activities is straightforward, which does not hold for MOSEL-2. On the other hand, a MOSEL-2 model may contain elaborated state-based reward measures, which are difficult or even impossible to define for an SPA model. As experience has shown, both formalisms are suitable to write concise model descriptions.

Chapter 9

Conclusion

In this chapter, I will summarize the what has been done in the present thesis. I will also suggest possible further extensions to the MOSEL-2 language that would increase its expressive power or its suitability to write concise, readable descriptions of complex models.

What has been achieved?

The topic of the present thesis was to integrate the Petri Net analysis tool TimeNET into the model analysis environment MOSEL. The original version of MOSEL, as described in [BBH], is very much orientated towards the abilities of CSPL, the model description language of SPNP. Therefore MOSEL, like CSPL, allows the user to write functions in the C programming language, and to use variables. These elements of the language MOSEL are very helpful when modelling complex systems. TimeNET's model description language, "`.TN`", unfortunately does not support these language elements, which hinders the translation of a MOSEL model to the `.TN` format, or even makes it impossible.

Therefore I have revised the MOSEL language, calling the revised version "MOSEL-2". It offers, among other features, FUNCs and CONDs as a replacement for MOSEL's, which are fitted to the needs of MOSEL-2 models. MOSEL's variables have been replaced by constants, whose values can be arbitrary arithmetic expressions, unlike in MOSEL, wich only allows literal numbers. Also, MOSEL-2 allows additional stochastic distribution types that can be used for the rules' firing delays, like deterministic distributions or uniform distributions. A result measure in a MOSEL-2 model can be defined as the expectation value of any state-dependent expression, or as the probability of any state-dependent condition. Finally, result measures themselves can be used as operands in other arithmetic expressions.

On this occasion, I also changed some hard-to-understand constructs in MOSEL to more pleasant forms, like the result measures for probabilities. Some features have been generalised, like MOSEL's shortcuts (loops) and macros, which have been replaced by the new loop construct. Other features that have practically never been used have been eliminated, like nested nodes, and some features have been changed to a more regular form, like the varieties of reward measures in MOSEL.

In the original language definition of MOSEL, only the syntax has been defined formally. The semantics of a MOSEL model was defined partly by informal text, partly by examples, and partly by showing the generated CSPL code of a certain MOSEL construct. —- In order to have an exact definition of the meaning of a MOSEL-2 model, I have formally defined the semantics of MOSEL-2. To that aim, I have subdivided the language definition in two parts:

(1) Core MOSEL-2, which offers the full expressive power of MOSEL-2 using a minimum number of language features, and (2) Full MOSEL-2, which extends Core MOSEL-2 by additional language features that make modelling in MOSEL-2 more convenient and clearer but do not increase its expressive power.

The semantics of Core MOSEL-2 is defined by a giving a method that maps a Core MOSEL-2 description onto a stochastic chain in three steps:

1. A description is mapped from the Core MOSEL-2 format onto the so-called *Explicit State Model* (ESM). The ESM is very similar to the MOSEL-2 model, but it is more regular and uses mathematical notation.

2. The ESM is mapped onto a continuous-time Markov process, whose states correspond to the states of the ESM, but which additionally contain a supplementary variable for each rule which specifies the remaining time until the rule will be executed. By adding these supplementary variables, the process is always Markovian, even when the corresponding ESM contains rules with non-Markovian distributions.

3. The Markov process is mapped onto a stochastic chain with finite state space by dropping the supplementary variables.

Finally, formal definitions show how the MOSEL-2 result measures can be derived from that Markov process.

The semantics of the additional language features of Full MOSEL-2 is defined by giving equivalent Core MOSEL-2 constructs for them.

The MOSEL language revision and the integration of the TimeNET support required substantial changes in the MOSEL environment. In retrospect, a total rewrite of the MOSEL environment would have required less effort.

The MOSEL-2 environment has been tested by translating about twenty smaller and larger MOSEL descriptions to MOSEL-2, partly by the me and partly by Jörg Barner, my advisor. They were analysed using the tools SPNP and TimeNET, and the results have been compared. SPNP proved to be generally more stable than TimeNET, concerning program failures as well as accuracy of the results. This might be partly caused by the more complex algorithms needed to solve eDSPNs, which are a generalization of GSPNs (the Petri net class that can be solved by SPNP). We have also encountered models that were solved more accurately by TimeNET than by SPNP.

By the integration of TimeNET, MOSEL-2 can now analyse (and simulate) models that include deterministic and (discrete) uniform firing distributions. This facilitaties the analysis of more realistic models, for example in the area of network communication.

But, of course, MOSEL-2 inherits all the weaknesses of the analysis tools it uses. Non-exponential, non-immediate firing distributions are costly to deal with in analysis. Therefore, non-trivial models that use such distributions usually require much analysis time and lots of memory.

The present thesis contains a practical introduction into modelling with MOSEL-2, which primarily addresses users without former knowledge in the description of formal models. As a real-world example, a MOSEL-2 model for the power consumption of a hard disk is given. For people which are already accustomed to modelling with MOSEL, the differences between MOSEL and MOSEL-2 are detailed in an own chapter, and for many of the obsolete MOSEL language features, equivalent MOSEL-2 constructs are suggested.

Possible Future Work

Due to lack of time, I have only implemented the most important firing distributions that are handled by TimeNET (immediate, exponential, deterministic, uniform and discrete uniform). General expolynomial distributions (including Dirac impulses) have been left out from MOSEL-2. Since expolynomial distributions can represent, or at least approximate, a number of distributions that are of practical significance, it seems desirable to implement expolynomial distributions in MOSEL-2. Expolynomial distributions are difficult to deal with since their overall probabilities must not necessarily be 1. Therefore it would also be helpful if MOSEL-2 could "normalize" expolynomial distributions, so that they yield an overall probability of 1.

Bigger models of, say, more than 100 lines, may often be decomposed into functional parts: certain constants, nodes, functions and rules taken together may form a functional part of the model which is only loosely coupled to the remaining parts. It is desirable, then, to group those definitions together in a own subsection of the MOSEL-2 description. The fixed order of the sections in a MOSEL-2 description does not allow this, since all constant definitions must precede all node definitions, etc. Therefore, it would be desirable to relax the order of the definitions, allowing to intermix the definitions of constants, nodes, functions, and rules. Results and pictures should perhaps remain in a section of its own, since they make up the evaluation part, in contrast to the modelling part, which consists of nodes and rules.

Two of the tools that are supported by MOSEL-2, namely SPNP and TimeNET, support Fluid Stochastic Petri Nets (FSPNs), which have been sketched in the TimeNET description in Chapter 1. The MOSEL-2 language could be extended to support FSPNs.

A current research topic is the modularisation of complex stochastic models, as already stated in Chapter 1, since it helps the modeller to keep the overall view, and since decomposition can sometimes be exploited by analysis tools, resulting in faster and more memory-efficient analysis. Therefore, the revision and extension of the MOSEL-2 language to implement some mechanism of modularization is a worthwile goal.

Appendix A

Syntax Summary

Here are all context-free syntax rules of the MOSEL-2 language in EBNF notation. They are extracted from Section 2.1 and Section 2.2, and ordered alphabetically. Definitions of lexical items are marked by an asterisk ("*"). The start symbol is *mosel-file*.

actual-args ::= "(" *state-expr* {"," *state-expr*} ")" .

and-condition ::= *not-condition* {"AND" *not-condition*} .

arity ::= *int-expr* | *node* .

assertion ::= "ASSERT" *condition* ";" .

atom ::= "(" *expr* ")"
| *number* | *constant* | *result* | *node* | *enum* | *formal-arg*
| ("SIN" | "SQRT" | "FLOOR") "(" *expr* ")"
| *function* [*actual-args*]
| ["AVG"] "PROB" "(" *condition* ")"
| ["AVG"] "UTIL" "(" node ")"
| ["CUM" | "AVG"] "MEAN" "(" *state-expr* ")" .

*comment** ::= "//" *line*
| "/*" *text* "*/" .

compare-oper ::= "=" | "/=" | "<=" | ">=" | "<" | ">" .

cond-def ::= "COND" *named-cond* [*formal-args*] ":=" *condition* ";" .

condition ::= *and-condition* {"OR" *and-condition*} .

constant ::= *identifier* .

const-def ::= "CONST" *constant* ":=" *const-expr* ";"
| "PARAMETER" *constant* ":=" *range* {"," *range*} ";"
| "ENUM" *enum* ":=" "{" *constant* {"," *constant*} "}" ";" .

const-expr ::= *expr* .

curve ::= (*result* | *duration*) [*string*] .

*digit** ::= "0" | ... | "9" .

*digits** ::= *digit* {*digit*} .

duration ::= *identifier* .

enum ::= *identifier* .

expr ::= *simple-expr*
| "IF" *condition* "THEN" *simple-expr*
{"ELIF" *condition* "THEN" *simple-expr*}
"ELSE" *simple-expr* .

factor ::= *atom* {"^" *atom*} .

fixed-param ::= *pic-param* "=" *const-expr* .

formal-arg := *identifier* .

formal-args ::= "(" *formal-arg* {"," *formal-arg*} ")" .

from-or-to-part ::= *node* ["(" *arity* ")"]
| *node* "[" *int-expr* "]" .

func-def ::= "FUNC" *function* [*formal-args*] ":=" *state-expr* ";" .

function ::= *identifier* .

*identifier** ::= (*letter* | "_") {*letter* | *digit* | "_"} .

int-expr ::= *const-expr* .

*letter** ::= "A" | ... | "Z" | "a" | ... | "z" .

mosel-file ::= {*const-def*}
node-def {*node-def*}
{*func-def* | *cond-def*}
rule-def {*rule-def*}
{*result-def*}
{*picture-def*} .

named-cond ::= *identifier* .

node ::= *identifier* .

node-def ::= "NODE" *node* ["[" *int-expr* "]"] [":=" *int-expr*] ";" .

not-condition ::= ["NOT"] *simple-condition* .

*number** ::= *digits* ["." *digits*] [("e" | "E") ["+"| "-"] *digits*] .

p-expr ::= *expr* .

pic-element ::= "CURVE" *curve* {"," *curve*}
| "CURVE" ["AVG"] "DIST" *node* [*string*]
| "FIXED" *fixed-param* {"," *fixed-param*}
| "PARAMETER" *pic-param*
| "XLABEL" *string*
| "YLABEL" *string* .

pic-param ::= "TIME" | *parameter* .

picture ::= "PICTURE" [*string*] {*pic-element*} [";"] .

range ::= *const-expr*
| *const-expr* ".." *const-expr* ["STEP" *const-expr*] .

result ::= *identifier* .

result-def ::= ("PRINT" | "RESULT") *result* ":=" *p-expr* ";"
| "PRINT" ["AVG"] "DIST" *node* ";"
| "PRINT" *duration* ":=" "TIME" "TO" *condition* ";" .

results ::= [*time-def*] {*result-def*} .

rule-def ::= *rule-parts* “;”
| *rule-parts* “{” *rule-parts* “;” {*rule-parts* “;”} “}”
| *rule-parts* “THEN” “{” *rule-parts* “;” {*rule-parts* “;”} “}” .

rule-part ::= “AFTER” *const-expr*
| “AFTER” *const-expr* “..” *const-expr*
| “FROM” *from-or-to-part* {“,” *from-or-to-part*}
| “IF” *condition*
| “PRIO” *int-expr*
| “TO” *from-or-to-part* {“,” *from-or-to-part*}
| “WEIGHT” *state-expr*
| “RATE” *state-expr*
| “PRD” | “PRS” .

rule-parts ::= *rule-part* {*rule-part*} .

simple-condition ::= *state-expr compare-oper state-expr*
| “(” *condition* “)”
| *named-cond* [*actual-args*] .

simple-expr ::= *term* {(“+” | “-”) *term*} .

state-expr ::= *expr* .

*string** ::= “"” sequence of printable chars “"” .

term ::= *factor* {(“*” | “/”) *factor*} .

time-def ::= “TIME” *number* [“..” *number* “STEP” *number*] “;” .

Appendix B

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Appendix C

Glossary

Distribution: see *Node Distribution* or *Firing Distribution*.

Duration: A special result measure in MOSEL-2 that gives the expected time until a certain condition holds.

EBNF: **E**xtended **B**ackus **N**aur **F**orm. A formal device to define the syntax of a programming or specification language, whose expressivity is identical to Context Free Grammars.

eDSPN: An extension of GSPN, which additionally allows general firing distributions for transitions.

Firing Distribution: A probabilistic distribution of a rule's firing delay, started at the moment when the rule is being enabled. Examples: immediate, deterministic, exponential and uniform distribution.

GSPN: **G**eneralized **S**tochastic **P**etri **N**et. A stochastic timed Petri Net formalism with (1) timed transitions that fire with exponentially distributed probabilistic transition delays and (2) immediate transitions.

IGL: **I**ntermediate **G**raphics **L**anguage. The proprietary format of MOSEL and MOSEL-2 in which result graphs are stored. Also the name of the TCL/Tk program that displays and prints these graphs.

Node Distribution: A complex result measure that gives the probabilities for all possible values of a node.

PRD: **Pr**e-emptive **D**ifferent. A re-enabling policy for rules (in MOSEL-2) and transitions (in stochastic Petri Nets), stating that the remaining firing time is re-sampled when the rule/transition is re-enabled.

PRS: **P**re-emptive **Re**sume. A re-enabling policy for rules (in MOSEL-2) and transitions (in stochastic Petri Nets), stating that the remaining firing time at the time point when the rule/transition got disabled is used when the rule/transition is re-enabled.

Remaining Firing Time: The time span that has still to elapse until an enabled rule fires. In simulations, this time span is usually determined by a random generator with appropriate probabilistic distribution when the rule is being enabled.