GreatSPN

User's Manual

(version 2.0.2)

Performance Evaluation group

Dipartimento di Informatica
Università di Torino (Italy)

Contents

Chapter 1

Informal introduction to the formalisms

This chapter contains a brief history of *GreatSPN* and recalls part of the background material necessary to use the package. The Petri net formalism and some stochastic extensions are briefly described in the following sections. The descriptions are very concise and the reader may find major details about these formalisms in the book [4].

1.1 History of GreatSPN

The first impulse to the development of the *GreatSPN* package stemmed from the research pursued by the Torino group on generalized stochastic Petri nets (GSPN). GSPNs were initially developed as a tool for the specification and performance evaluation of computer architectures at the Dipartimento di Elettronica of the Politecnico di Torino and at the Dipartimento di Informatica of the Università di Torino [3], in the frame of the Progetto Finalizzato Informatica of the Italian Consiglio Nazionale delle Ricerche, MUMICRO project. The development of GSPNs was stimulated by the results on SPNs described in the Ph.D. thesis of M. K. Molloy [31]. In GSPNs a new class of transitions (called *immediate*) that fire in zero time with priority over timed transitions was introduced. A solution algorithm that exploits the reduction of the size of the Reachability Set (RS) due to the presence of immediate transitions was first described in [3].

Several computer programs were developed as part of PhD thesis to implement the steady-state numerical solution of GSPN models, eventually leading to the first documented software package for their analysis. This package allowed one to experiment with the new modeling tool and gain insight into the memory and CPU time requirements of the solution algorithms as functions of the size of GSPN models. The weak points of this package were poor portability and flexibility of the programs, and the lack of a graphical interface, which is the most natural type of support for the definition of GSPN models. Subsequent efforts were devoted to designing a package with the following characteristics: (1) user friendliness – in particular the availability of a graphical interface for model definition was considered a must to satisfy this requirement –, (2) portability, (3) modularity and easy upgradability, and (4) efficiency of the analysis modules.

The first step in this direction was the implementation of the software tool described in [10]. A decomposition was pursued both of the software tool and of the analysis steps. Several intermediate results were identified and stored in the form of separate files. Several independent programs cooperate to the production of final result files by taking as input intermediate result files produced by running other modules of the tool. Thanks to this modular software architecture [14], the tool was easily upgraded and adapted to different uses as soon as new theoretical results provided new analysis algorithms. From the functional point of view, earlier versions of *GreatSPN* included a graphical interface (based on the SunView package and on the PixRect utilities for basic graphics), all the algorithms for the generation and steady-state or transient solution of the "underlying Markov chain" of a GSPN, and a new algorithm for the analysis of a class of models containing a mix of exponentially distributed and deterministic timed transitions (DSPN) [5]. A Monte Carlo simulation program with confidence interval estimation was also introduced for two main reasons: (1) to provide a tool for performance evaluation in the general case of Timed Transitions Petri Nets (TTPN) that are not analytically solvable and (2) to provide a tool for the validation of models when numerical solutions cannot be implemented due to the size of the Reachability Graph (RG), which is equal to the number of states of the underlying Markov chain[1].

GreatSPN started to become an interesting and useful support tool for performance modeling, and many research and education institutions asked for permission to have it, so that the Dipartimento di Informatica of the Università di Torino began its free distribution. Using the package on increasingly larger and more complex models, we soon realised the need for some model validation and "debugging" tool. From this need, the Torino group started to look more carefully at the traditional techniques and algorithms used in the classical Petri net theory for the study of qualitative structural and behavioral properties. Major improvements in the validation capabilities of the package were achieved with the implementation of algorithms for the computation of Place- and Transition-invariants, that allowed an easy check of structurally necessary or sufficient conditions for boundedness and ergodicity before the exhaustive enumeration of the state space. More specific and powerful structural analysis techniques were also proposed for the qualitative validation of GSPNs [15] and included in *GreatSPN*. A major check-point was undertaken with the release 1.3 [11], which included all the structural analysis techniques for the validation of the underlying Petri net structure of a GSPN model. Major improvements in the validation capabilities of the package were achieved with the implementation of algorithms for the computation of Place- and Transition- invariants, and of the specific structural analysis techniques for the qualitative validation of GSPNs proposed in [15].

At this point the weakest part of the package was the simulation feature, which used a very straightforward (and inefficient) Monte Carlo non event-driven technique for the generation of the sample paths. The same structural properties computed for the model validation were then reconsidered from a different perspective: they were used for the optimization of the data structures of the analysis and simulation programs [13]. This idea led to a completely new set of solution and simulation programs, and eventually to the implementation of the interactive simulation facilities [7] of *GreatSPN* 1.4.

[1] In any case simulation usually requires costly and long computations.

One of the drawbacks of versions 1.3 and 1.4 was that they comprised both modules written in Pascal and modules written in C. In version *GreatSPN* 1.5 all the Pascal modules were rewritten in C in order to increase portability. Moreover, new algorithms and techniques were implemented for the efficient and direct construction of the Tangible Reachability Graph (TRG) [18, 8], further reducing the space and time requirements of this phase with respect to the technique proposed in [13]. In this version the possibility of general marking dependence for transition rates has been restricted: immediate transition weights are now constants, while in the case of timed transition the preferred way of expressing marking dependency is through the degree of enabling; general marking dependency for timed transitions is still possible, but its implementation is less efficient than that of enabling dependence. In version 1.6, the graphical interface was rewritten based on XView, a public domain toolkit (included in the MIT distribution tape of X11R5). The basic structure and features of the graphical interface of *GreatSPN* 1.3 were retained. Minor changes were introduced in order to present the control items in a more rational way. Some features have been added in a straightforward way in order to allow the visualization of the new structural, behavioral, and performance results obtained by the new analysis modules.

GreatSPN 1.7 represents a new major check-point for the package. New algorithms have been added for the fast computation of performance bounds based on linear programming techniques [16], working at a purely structural level. The computed bounds depend only on the average firing delay of the transitions while they do not depend on the p.d.f. of such delays. Algorithms have also been added for the analysis of high-level Petri net models providing the user with the possibility of designing models of complex systems in a more compact way. The chosen high-level formalism is Stochastic Well-Formed nets (SWNs), for which efficient algorithms have been defined, that automatically generate a compact RG (called Symbolic RG) exploiting the model symmetries [19, 23, 21]. The major objective of *GreatSPN* 1.7 was thus a consolidation of the package to allow an easier distribution, as well as a broader application scope, with more emphasis on the validation and the simulation of models and on the derivation of fast performance bounds.

Research is still going on, and will eventually produce new implementations to be introduced in *GreatSPN* on hierarchical modeling [17] and on the exploitation of parallel processing techniques for the efficient analysis of large models [22, 24]. Concerning the graphical interface, porting under OSF/Motif is being considered.

1.2 Petri Nets

Introduced for the first time in the sixties [34], Petri nets (PN) are a graphical and mathematical modeling tool for describing concurrent systems. A PN is a 5-tuple (P,T,I,O,H), where P is the set of places, T is the set of transitions, and I, O, H, are functions that defines weighted input, output and inhibitor arcs between places and transitions. PNs incorporate a notion of (distributed) state which is denoted by a function $M : P \rightarrow \mathbb{N}$, called *marking*.

A PN *system* is given by a *PN* structure plus an *initial marking* and it is defined as a 6-tuple (P,T,I,O,H,M_0)

where M_0 represents the initial distribution of tokens in the places of the net.

PN have an associated graphical representation, where places are circles, transitions are bars, input and output functions are weighted arrows, and inhibitor function are circle headed arrows. The marking is represented by inscribing place p with $M(p)$ tokens, represented as black dots.

Transitions describe events that may modify the system state and the *firing rule* defines the dynamic behaviour of PN models. For example, in the net below, transition t is *enabled* if $M(p_1) \geq n$, $M(p_2) \geq m$, *and* $M(p_3) < h$. Once enabled, transition t can fire consuming n tokens from place p_1, m from p_2 and depositing u tokens into p_4 and v into p_5.

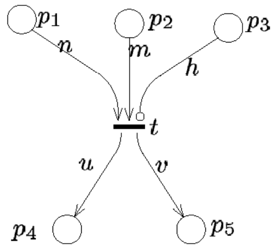


Figure 1.1: Example of enabling and firing.

An important consideration is that the enabling and firing rules for a generic transition t are “local”: indeed, only local information (i.e. input, inhibitor and output places) need to be considered to establish whether t can fire and to compute the change of marking. This justifies the assertion that the PN marking is intrinsically distributed.

A marking M' is said to be *immediately reachable* from M if M' can be obtained by firing a transition enabled in M. The set of transitions enabled in the marking M is denoted with $E(M)$ and the firing of a transition t is denoted with $M[\, t \,\rangle M'$.

Two transitions are said to be in *conflict* if they share input places and the firing of one transition disables the other by removing the token in the common input places.

Starting from the initial marking M_0 it is possible to compute the set of all the reachable markings, the so called *Reachability Set* (RS) of the model. The RS does not contain information about the transition sequences fired to reach each marking. This information is captured by the *Reachability Graph* (RG) whose nodes are labelled with the reachable markings and whose arcs are labelled with the transitions that the system has to fire to move from state to state.

PN models can be used for the (qualitative) analysis of *logical* properties of systems. Classical analysis techniques are structural (graph-based) analysis and reachability analysis which investigate, for example, the boundedness of the model or the presence of deadlocks.

1.3 Stochastic Petri Nets

Classical PN models include no notion of time and for this reason they have been traditionally used for the qualitative analysis of *logical* properties of systems. Several authors have proposed augmented PN models which include temporal specifications, so that a quantitative performance analysis of systems is possible. The introduction of temporal specifications in a PN has been done mostly by associating a delay with transitions. Stochastic Petri Nets (SPN) [30] are PN in which transition firing delays are exponentially distributed random variables: each transition t_i is associated with a random firing delay whose probability density function is a negative exponential with rate λ_i. Syntactically this extension amounts to adding a function $W : T \rightarrow \mathbb{R}^+$ such that the delay associated to a transition t is a random variable, distributed as a negative exponential, of rate $W(t)$. Thus a SPN system is defined as a 7-tuple (P,T,I,O,H,W,M_0) where P,T,I,O,H,M_0 are defined as in PNs and W specifies the rates to be associated with transitions.

The semantics of SPNs is described by a *race model*. When a marking simultaneously enables several (conflicting and/or concurrent) transitions, all activities associated with these transitions are assumed to execute in parallel, so that the next marking change is due to the transition whose firing delay in the present marking is minimum, i.e., to the transition that wins the race. The firing of the winning transition implies that the activity associated with it in the model is completed. The behaviour of the losing transitions can be specified in different ways. Indeed, it is possible for these transitions to either remember the time during which they have already been enabled (and thus worked), or not. However, the use of exponential distributions for the definition of temporal specifications makes unnecessary the distinction between the distribution of the delay itself, and the distribution of the remaining delay after a change of state, thus avoiding the need for the specification of the behaviour of the transitions that do not fire in a given marking.

When the set of enabled transitions $E(M)$ contains more than one element, the probability that transition t_i is the one that actually fires can be obtained from the temporal specifications as

$$P\{t_i|M\} = \frac{W(t_i)}{\sum\limits_{t_j \in E(M)} W(t_j)} = \frac{\lambda_i}{\sum\limits_{t_j \in E(M)} \lambda_j}$$

The definitions of the RS and the RG are still valid for SPNs but in this case the arcs of the RG are labelled with transition names and transition rates.

Molloy [31] showed that, due to the memoryless property of the exponential distribution of firing delays, SPN are isomorphic to continuous-time Markov chains (CTMC) in which

1. the states of the CTMC are in one-to-one correspondence with the SPN markings ($M_i \leftrightarrow i$);

2. the transition rate from state i (corresponding to marking M_i) to state j (M_j) of the CTMC is equal to the sum of the rates of the transitions that connect the corresponding markings in the RG of the net.

The translation of a SPN model into a CTMC is thus conceptually very simple. The RS of the SPN is generated, and the firing rates of enabled transitions are used to construct the state transition rate matrix **Q** of the CTMC.

If the CTMC is ergodic, it is possible to compute the steady state probability distribution of the markings solving the matrix equation

$$\pi\mathbf{Q} = 0$$

with the additional constraint

$$\sum_i \pi_i = 1$$

where π is the vector of the steady state probabilities. From the steady state distribution it is possible to obtain quantitative estimates of the behaviour of the SPN.

Difficulties may arise due to the computational complexity of the algorithm for this solution, when the number of reachable markings grows. This is the main problem associated with the utilisation of SPN which are otherwise very easy to employ, even for inexperienced users.

1.4 Generalized Stochastic Petri Nets

Sometimes it is not desirable to associate a random time with each transition of a model, since one would rather associate times only with the events that are believed to have the largest impact on system performance. For instance, the time required to test the condition to enter in a *while* loop can be considered negligible with respect to the time required to execute the *body* of the loop.

SPN models in which logical actions are represented by transitions whose firings take no time are known by the name of *generalized* SPN (GSPN) [3, 15]. Transitions that fire in zero time are called *immediate* (represented as black bars) to be distinguished from the transitions whose associated delays are exponentially distributed, which are called *timed* (represented as rectangular boxes).

Immediate transitions fire with priority over timed transitions and it is assumed that different priority levels can be defined over immediate transitions. Priorities equal to zero are associated with timed transitions, priorities equal or greater than one are associated with immediate transitions. Syntactically, this extension amounts to adding a priority function $\pi : T \rightarrow \mathbb{N}$ which assigns a natural number to each transition. A GSPN system is defined as a 8-tuple (P,T,I,O,H,W,π,M_0).

In GSPN the delay associated with a timed transition t is a random variable, distributed as a negative exponential, of rate $W(t)$. In the case of an immediate transition t instead, the value $W(t)$ specifies a weight.

When two or more timed transitions t_i are in conflict, the selection of the one that fires first is done according to the race policy. When two or more immediate transitions t_i are in conflict the selection of the one that fires first is done using the weights $W(t_i)$, normalised in such a way as to obtain a discrete probability distribution function.

Due to the presence of immediate transitions, the RS of a GSPN model contains two different types of markings that are classified as *tangible* and *vanishing*. A tangible marking is a state in which no immediate transitions are enabled and therefore the system spends some time in that state, while a vanishing marking is a state in which at least an immediate transition is enabled and therefore the time spent in a vanishing marking is equal to zero.

The execution of a GSPN model is not identical to a sample function of a Markov process, due to the existence of multiple discontinuities at the time instants corresponding to the entrance into vanishing markings. It is however possible to remove these markings from the analysis, since they do not contribute to the measurable behaviour of the model. The performance of a GSPN model can thus be analyzed by examining its evolution through the set of tangible markings only. It has been shown [3, 15] that there is a correspondence between GSPN models and CTMCs. Performance indices such as, for example, transition throughputs and the mean number of tokens in a place, can be associated with a GSPN model. They are computed starting from either the transient or the steady state probabilities of the associated CTMC.

Another extension that has been introduced by some authors is the possibility of defining marking dependent rates: the rate of the transition is therefore a function of the state of the system. If the dependence is only from the input and output place of the transition we still preserve the inherent distribution of the state proper of Petri nets, if we allow instead any type of dependence, then the locality of the firing of transition can be completely destroyed.

1.4.1 A GSPN example

To give an idea of the GSPN formalism we briefly describe an example that will be also used in Section 1.5.1 to describe the coloured formalism of Stochastic Well Formed nets. All the details about the construction and the analysis of GSPN models will be discussed in the next chapters.

The example, taken from the telecommunication area, is a multiple server cyclic polling system [6] comprising a set of waiting lines in which customers that arrive from the external world queue up waiting for service. A set of servers cyclically visit the queues providing service to the waiting customers. Upon service completion a customer departs from the system and the server proceeds to the next queue.

The net in Figure 1.2(a) shows the GSPN model of a generic queue i: place $p_a^{(i)}$ represents the number of free positions in the queue, whose maximum capacity is equal to K as specified by its initial marking. Timed transition $T_a^{(i)}$ models the customer arrival process; customers waiting for a server are queued in place $p_q^{(i)}$. Immediate transition $t_s^{(i)}$ models the start of a service and it can fire only when a customer is waiting in place $p_q^{(i)}$ and no other customers are currently served, i.e. when place $p_s^{(i)}$, (representing customers being served) is empty. Finally the firing of timed transition $T_s^{(i)}$ represents the service completion.

The GSPN model of the servers behaviour when polling queue i, is depicted in Figure 1.2(b): a token in place $p_p^{(i)}$ represents the presence of a server at queue i. The two immediate transitions $t_s^{(i)}$ and $t_w^{(i)}$ have priority 2 and 1 respectively. Transition $t_s^{(i)}$ should fire if a waiting customer is found in queue i so that service can be provided. If no customers are waiting, the server bypasses the queue (firing of transitions $t_w^{(i)}$) and walks towards

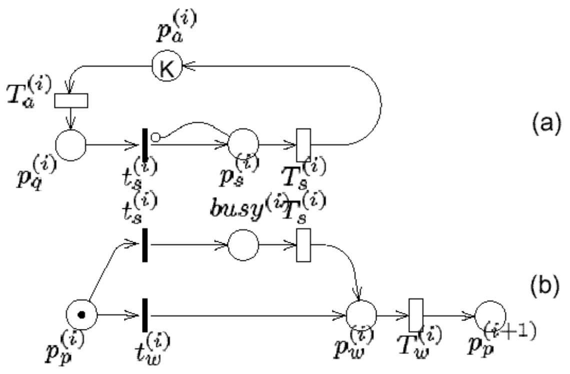


Figure 1.2: GSPN representations of a queue and a server.

the next queue (firing of timed transition $T_w^{(i)}$). The reason for assigning a higher priority to transition $t_s^{(i)}$ is to force the fact that a server can bypass a queue only if there is no possibility for it to provide service. Place $busy^{(i)}$ represents the condition *"server busy serving a customer at queue i"* and transition $T_s^{(i)}$ represents the corresponding ongoing service. Notice that both models in Figure 1.2 include immediate transition $t_s^{(i)}$ and timed transition $T_s^{(i)}$; the transitions with common names represent the same events in the two submodels.

The GSPN model of a polling system with four queues can be obtained by composition of four copies the submodel $\mathcal{N}_q^{(i)}$ representing the i^{th} queue and four copies of the submodel $\mathcal{N}_s^{(i)}$ representing the behaviour of a

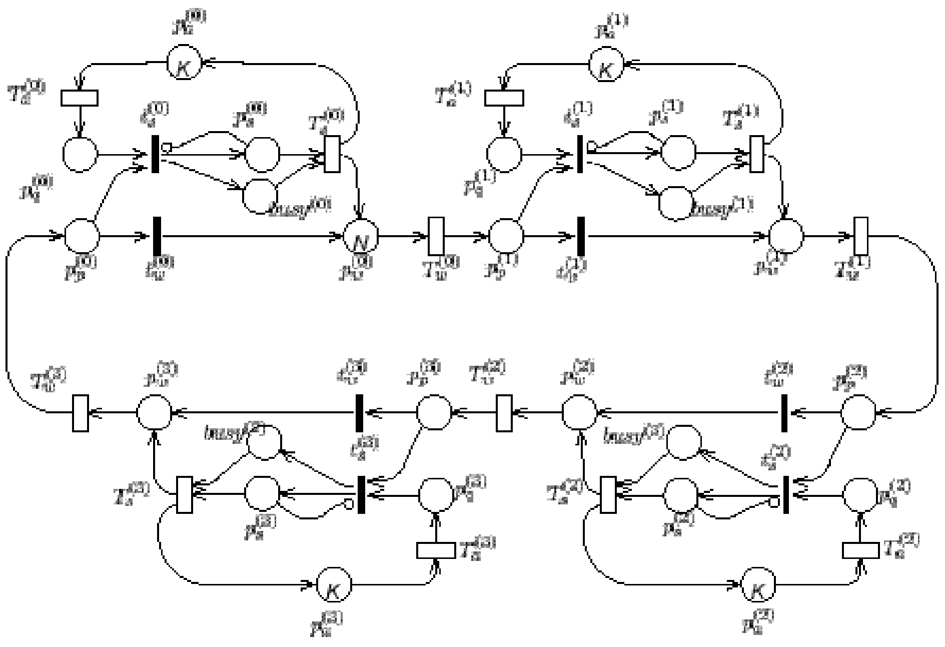


Figure 1.3: GSPN representation of a cyclic polling system.

server at queue i $(i = 0,1,2,3)$. Submodel $\mathcal{N}_q^{(i)}$ can be composed with submodel $\mathcal{N}_s^{(i)}$ by merging the transitions with same label (that is, immediate transition $t_s^{(i)}$ and timed transition $T_s^{(i)}$). On the other hand, the ring topology is obtained by superposition of places with the same name belonging to submodels[2] $\mathcal{N}_s^{(i)}$ and $\mathcal{N}_s^{(i+1)}$. The resulting model is depicted in Figure 1.3. The number of servers is parametric and it is modelled by assigning N tokens to place $p_w^{(0)}$ in the initial marking. Also the queues capacity K is parametric and is specified by the initial markings of places $p_a^{(i)}$ $(i = 0,1,2,3)$.

1.5 Stochastic Well Formed Nets

Stochastic Well Formed Nets (SWN) [21] are a coloured extension of SPNs that allows one to build a more compact and parametric representation of a symmetric system by *folding* similar subnets. In this way it is possible to represent very concisely systems that would have required a huge uncoloured net. When similar subnets are folded, some additional annotation is needed to distinguish tokens that end up being in the same folded place. These annotations constitute the *colour structure* of the net.

Tokens are no longer indistinguishable: each token can be regarded as an instance of a data structure whose meaning depends on the place to which the token belongs. The place *colour domain* (denoted $C(p)$) is defined as the Cartesian product of *basic colour classes*, possibly with repetitions of the same basic colour class. Each basic colour class is a finite set of basic objects and it is usually defined by enumeration of its elements (e.g. $C = \{c_1, c_2, \dots c_n\}$). Colour classes may be *ordered* and may be partitioned into disjoint subsets called *static subclasses*.

Transitions' colour domains (denoted $C(t)$) are defined analogously to places' colour domains. Transitions can be seen as procedures with formal parameters, the parameters being determined by the corresponding domain.

The enabling check of a transition and the state change caused by its firing depend on the *arc functions* that label the arcs connecting the transition to input, inhibitor and output places.

Arc functions are formal sums of tuples structured according to the corresponding place colour domain. If the place colour domain is the Cartesian product of k basic colour classes, then the corresponding arc function is a weighted sum of k-tuples. The j^{th} element in each k-tuple is a weighted sum of three basic functions, the *identity* function (denoted by a variable), the *successor* function ("!"), and the *synchronisation* function ("S").

The weights of the sum may be numbers or *predicates*. Predicates are logical expressions used to test either equality of pairs of basic objects, selected by some identity/successor function, or to check the membership of a selected basic object in a given static subclass.

A major interest of SWNs is that they provide a modeling framework in which the intrinsic symmetries are automatically detected and used naturally as a way for reducing the size of the underlying state space. The reduction is obtained thanks to the original concept of *symbolic marking*. Informally a symbolic marking corresponds

[2] The increment $i+1$ is modulo 4.

to an equivalence class representing a set of ordinary markings characterised by a common future behaviour. These ordinary markings in fact enable the same transitions whose firings lead to new ordinary states which are still equivalent, i.e. belong to the same symbolic marking. Symbolic markings are obtained by disregarding the identities of the objects within the places of the net and considering only their number. Colour classes are partitioned into *dynamic subclasses* and the only relevant information is the cardinality of these subclasses (i.e. the number of objects they contain). This shows how many elements in the net have the same behaviour at the same time.

This type of partitioning varies from one marking to another, hence it must not be confused with the static subclass partitioning which is part of the colour class definition.

With the introduction of dynamic subclasses places no longer contain coloured tokens but symbolic tokens whose components are expressed in terms of dynamic subclasses. All the ordinary markings which can be obtained by assigning identities to the objects of the dynamic subclasses belong to the same symbolic marking.

A *symbolic enabling rule* and a *symbolic firing rule*, which operate directly on the symbolic marking representation, and an efficient algorithm for the generation of an aggregated state space called *symbolic reachability graph* (SRG) have been defined [21] and implemented [**?**]. The SRG describes the evolution of a SWN model through a set of macro-states, the symbolic markings, that represent sets of more detailed states which are equivalent.

Several properties valid for the SRG have been introduced. For example, the equivalence between the SRG and the RG from the point of view of the reachability of the markings ensures that no information is lost by analysing the SRG instead of the RG. Formulae have been defined to compute both the number of ordinary markings belonging to the same equivalence class and the number of ordinary firings represented by each symbolic firing.

The SRG corresponds to a lumped version of the complete RG and this aggregation is reflected also at the level of the underlying Markov process. In [20] it has been proved that the SRG is isomorphic to an aggregated Markov process that can be used to compute the same performance estimates that can be computed from the general technique based on the RG, but with a lower computational cost.

1.5.1 A SWN example

Figure 1.4 shows the SWN model of the polling system example that has been obtained by folding all the replicas of the submodels $\mathcal{N}_q^{(i)}$ and $\mathcal{N}_s^{(i)}$ forming the GSPN model in Figure 1.3, into a single net structure.

The tokens carry information to distinguish the customers associated with different queues. We thus need one colour class defined as $Q = \{q_1, q_2, \ldots, q_M\}$ that represents the M queues.

In the polling system the ring connection induces a circular order relation among queues, characterised by the "next queue" relation. Q is thus defined to be an *ordered* colour class with the possibility of applying the successor function to any of its element (i.e., $!q_i = q_{(i+1) mod M}$).

The initial marking of place p_a is $K \cdot \langle S \rangle$ where K represents the maximum capacity of each queue and $\langle S \rangle$ is a special symbol denoting *all* the coloured tokens belonging to the place colour domain, i.e. $K \cdot \langle S \rangle = K \cdot \langle q_1 \rangle + \ldots + K \cdot \langle q_M \rangle$; the initial marking of place p_w represents the initial position of the N servers and it is equal to $N \cdot \langle q_1 \rangle$ as we are assuming that all servers are initially polling the first queue of the ring.

The identity function $\langle x \rangle$ labelling the arcs binds any element $q_j \in Q$ to the variable x. For example, transition T_a has a parameter x of type Q and a *coloured transition instance* is obtained assigning actual basic objects to this parameter. The coloured transition instance of T_a that assigns q_2 to parameter x is enabled in the initial marking. Its firing removes the coloured token $\langle q_2 \rangle$ from place p_a and adds it in place p_q thus modeling an arrival to the second queue. This is due to the fact that the same variable x labels both the input and output arcs of T_a, actually denoting the same coloured token. When one of the N servers polls the second queue (i.e., when place p_p contains the coloured token $\langle q_2 \rangle$) the service can be provided and the immediate coloured transition instance of t_s binding the parameter x to q_2 can fire.

The inhibitor arc connecting t_s and p_s prevents the enabling of transition t_s for any coloured token $\langle q_j \rangle$ present in place p_s. A server that polls a queue in which another server is working will bypass that queue (i.e., transition t_w will fire) because in the modeled system only one customer can be served in each queue. A server moving to the next queue is modeled by means of the combined presence of the identity function $\langle x \rangle$ and successor function $\langle !x \rangle$ labelling the input and the output arcs of transition T_w.

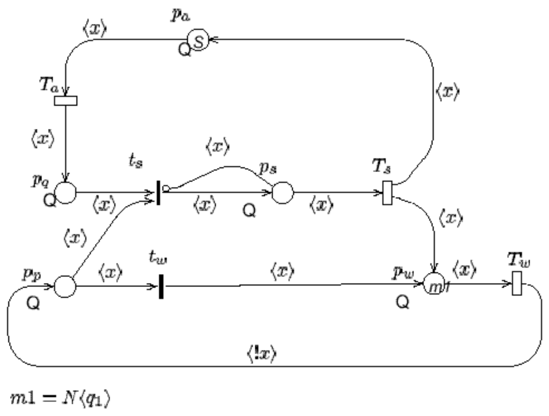


Figure 1.4: SWN representation of the cyclic polling system.

The SWN model in Figure 1.4 is parametric in the queue capacities (K), in the number of servers (N) and also in the number of queues in the system ($|Q|$). An important feature of this coloured model is that the service policy may be easily modified; for example it is possible to model a random service policy instead of the cyclic one, by simply replacing the successor function labelling the output arc of transition T_w with an identity function $\langle y \rangle$ plus the predicate $[x \neq y]$ to model the movement of a server to a different queue. Observe that such a variation in the GSPN model would require much more complex structure manipulation.

Chapter 2

Getting started

After *GreatSPN2.0.2* has been installed and the user environment has been set up according to the directions given in the Appendix C, the user can start the package and build and analyze his/her models. The aim of this chapter is to quickly introduce the user to (modeling) using *GreatSPN2.0.2* . By following this tutorial, the user will be able to construct a Petri Net model and to analyze it by means of the *GreatSPN2.0.2* graphical interface. The reader interested in a more in-depth presentation of the various *GreatSPN2.0.2* features may refer to Chapter 3. Throughout this chapter we shall use as an example the model of the well-known multiple-reader-single-writer problem in the access of a shared data base.

2.1 The Readers–Writers GSPN model

Let us consider a set of "processes" concurrently accessing a shared data base. When a process issues an access request, it declares whether a read or a write operation is required. Read operations may proceed concurrently with each other, while write operations require an exclusive access in order to maintain the consistency of the data base. A GSPN model of this system is depicted in Figure 2.1. A token in place *think* represents a process performing some local activity. After a random amount of time, a data base access request is issued (timed transition *arrival* fires). The type of request (read or write) is randomly chosen with equal probability (immediate transitions *isread* and *iswrite* have the same weight). If the operation is a read, then the access is granted if no other process is performing a write operation on the data base (place *nowrite* is marked), otherwise the process waits in place *Rqueue* until the access can be performed safely. The beginning of a read operation is represented by the firing of transition *StartR*, that has two effects. First, place *nowrite* is marked, meaning that other readers can access the data base. Second, place *reading* is marked, forbidding therefore the access to any writer process (there is an inhibitor arc from place *reading* to transition *StartW*). After the firing of the timed transition *EndR*, the status of the process is reset to "thinking".

Conversely, if the requested operation is a write, the process waits (in place *Wqueue*) until access can be granted, i.e. when no other process is performing a write access (place *nowrite* is marked) and no other process

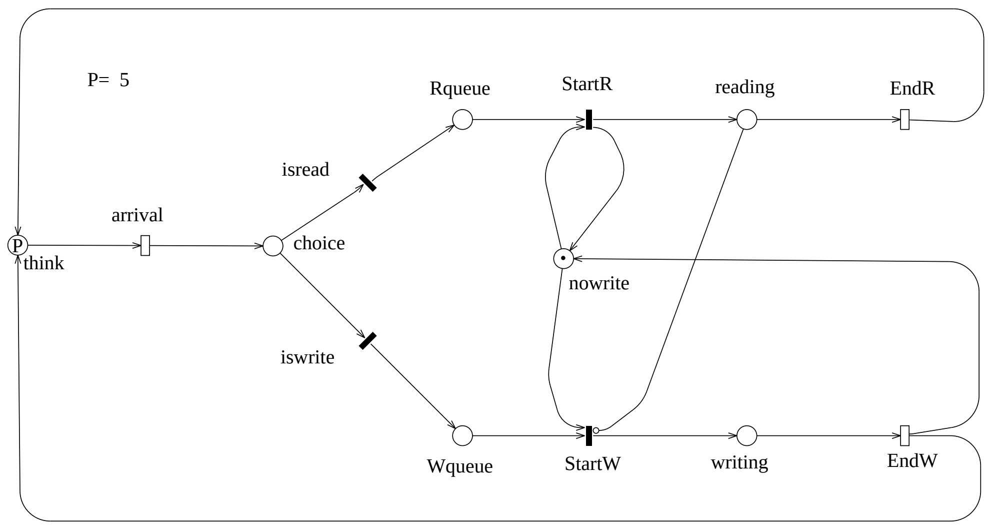


Figure 2.1: The Readers–Writers GSPN model

is performing a read access (place *reading* is empty). At the completion of the write operation, modeled by the firing of transition *EndW*, the absence of write access is signaled to other processes by marking place *nowrite*, and the status of the process is reset to "thinking".

2.2 Starting GreatSPN

GreatSPN2.0.2 is started by typing `greatspn` on the command line and pressing `<Return>`. After a few seconds the Control Panel, depicted in Fig. 2.2, pops up and the user can start a work session.
WARNING! When *GreatSPN2.0.2* GUI is launched for the first time a window is displayed before the Control Panel pops-up in which it is asked to the user to fill in the corresponding areas if he/she desires to change the default setting for some environment variables (see chapt. 3 for a more detailed description of this window). The user has to press the "OK" button to confirm either the modification made in the window areas or the default settings: the information contained in this window are saved into the `$HOME/.greatspn` file.

To create a new model, the user has just to start creating places and transitions (as discussed in Section 2.3), while if the user desires to modify an already created model, he/she can retrieve it by using the **File** menu.

2.3 Creating the Readers–Writers model

To create (or to modify) a model, the user selects the *action* to be performed and the *object type* (e.g. places, immediate transitions, place markings, etc.) on which the action will be applied. The general principle of

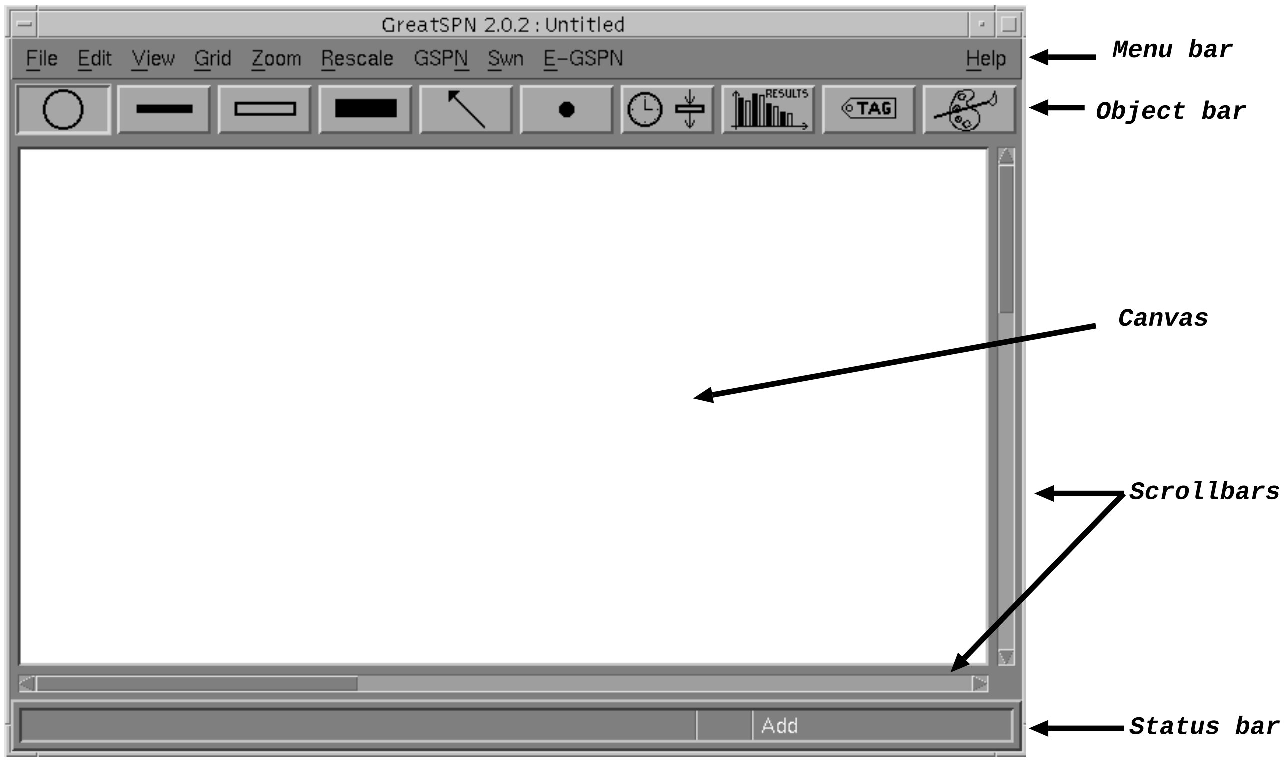

GreatSPN 2.0.2 : Untitled
File Edit View Grid Zoom Rescale GSPN Swn E-GSPN Help
RESULTS
TAG
Add
Menu bar
Object bar
Canvas
Scrollbars
Status bar

Figure 2.2: The *GreatSPN2.0.2* Control Panel

behavior of the *GreatSPN2.0.2* graphical interface is that the action selected by the user from the **Action** menu (shown in Fig. 2.3) becomes the default action until a new one is chosen, and such action affects only objects of the type currently selected. The current action is displayed in the *status bar* on the right. The **Action** pop-up menu is activated by pressing the right mouse button on any position of the *GreatSPN2.0.2* working area. To select an action, the user has to click with the left mouse button over the desired pull-down option[1]. An object type is selected by moving the mouse cursor on one of the icons of the *objects bar* (see Figure 2.2) and by clicking over it with the left mouse button. The object currently selected remains highlighted until another object type is chosen. The *mouse help* window, activated by selecting **Help**→*Mouse Help*, displays the action associated with each mouse button. Let us start the creation of the Readers–Writers GSPN model by creating the set of places first. To create places, we set the type of object to "place" by selecting the *place* icon in the *object bar* (indicated by a circle), and after this operation the shape of the mouse cursor is changed into a circle. After the selection of the **Action**→*Add* option, we can move the mouse cursor within the working area and start laying down the places of the net by clicking the left mouse button in the proper position, in order to obtain the screen image shown in Figure 2.4. The *GreatSPN2.0.2* graphical interface displays only a window on the real working area, that can be

[1] In the rest of this manual we shall use the notation **Menu Item**→*Option* to denote an option in a specific menu item of the *menu bar*. For example, **Action**→*Create* denotes the *Create* option of the **Action** menu.

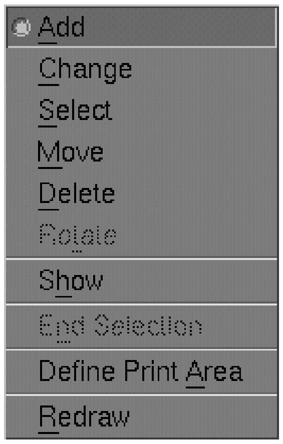


Figure 2.3: The *GreatSPN2.0.2* action menu

scrolled in all the directions by using the *scrollbars* placed on the right and bottom sides of the Control Panel.

To create the transitions we proceed as for places, that is by first choosing one of the three transition icons available, i.e. deterministic (represented by a thick black box), exponential (represented by a white box), and immediate (represented by a thin black box), and then by creating them. Note that we don't need to select the **Action**→*Add* action again, since we didn't change the selection done when places were created. The screen situation after the addition of transitions looks like Figure 2.5. Note that we have created transitions having

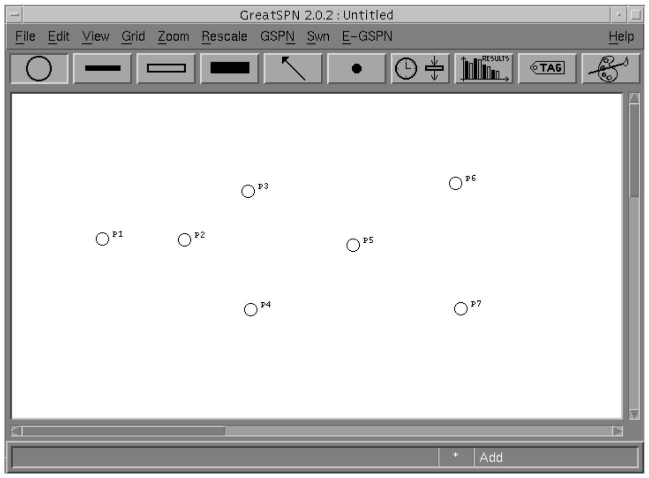

GreatSPN 2.0.2 : Untitled
File Edit View Grid Zoom Rescale GSPN Swn E-GSPN Help
RESULTS
TAG
P1
P2
P3
P4
P5
P6
P7
Add

Figure 2.4: Place layout of the Readers–Writers model of Fig. 2.1

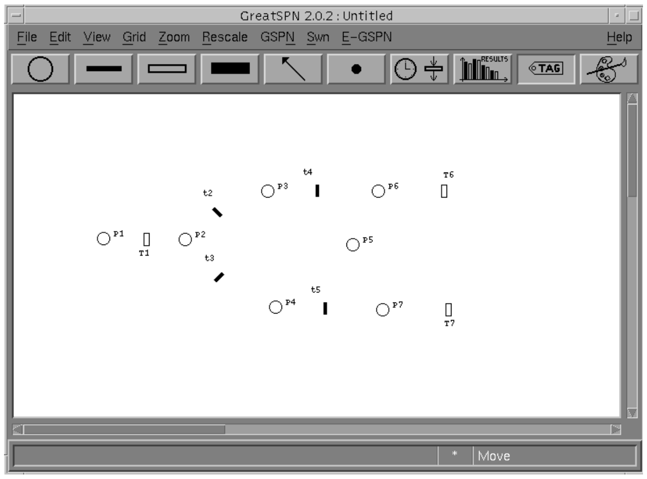

GreatSPN 2.0.2 : Untitled
File Edit View Grid Zoom Rescale GSPN Swn E-GSPN Help
RESULTS
TAG
P1
T1
P2
t2
t3
P3
t4
P4
t5
P5
P6
T6
P7
T7
Move

Figure 2.5: Place and transition layout of the Readers–Writers model

different orientations. To change the orientation of a transition, we can use the middle mouse button (each time this button is clicked, the transition rotates of 45 degrees clockwise) before clicking the left button to actually create the transition itself.

After a place or a transition has been placed on the working area, it can be moved by selecting the **Action**→*Move* option. An object can be dragged on the *canvas* by clicking on it with the left mouse button, by moving the cursor on its new position and by clicking the left button again.

The editor assigns default names ("tags") to places (*Px*) and transitions (*Tx* for timed and *tx* for immediate) where *x* is an integer representing the objects creation order. Such tags are displayed if the **View**→*Tag* option has been selected. Tags overlapping other objects of the net can be moved around in the same way as places or transitions, that is by selecting the **Action**→*Move* option after clicking on the *tag* icon, and by clicking on the place or transition to which the tag is associated.

Now that we have created the nodes of our Petri net, we are ready to connect them with arcs. This can be accomplished by choosing the *arc* icon in the *object bar* (indicated by an upward arrow). Again, if we didn't redefine the default action, we don't need to re-select the **Action**→*Add* option. To create an input arc from place *P1* to transition *T1* (see Figure 2.6), we have to click the leftmost button of the mouse twice: first over place *P1*, and then over transition *T1*. The output arc connecting transition *T1* to place *P2* can be created by clicking the left mouse button first over *T1*, and then over *P2*. The inhibitor arc connecting place *P6* to transition *t5* is created

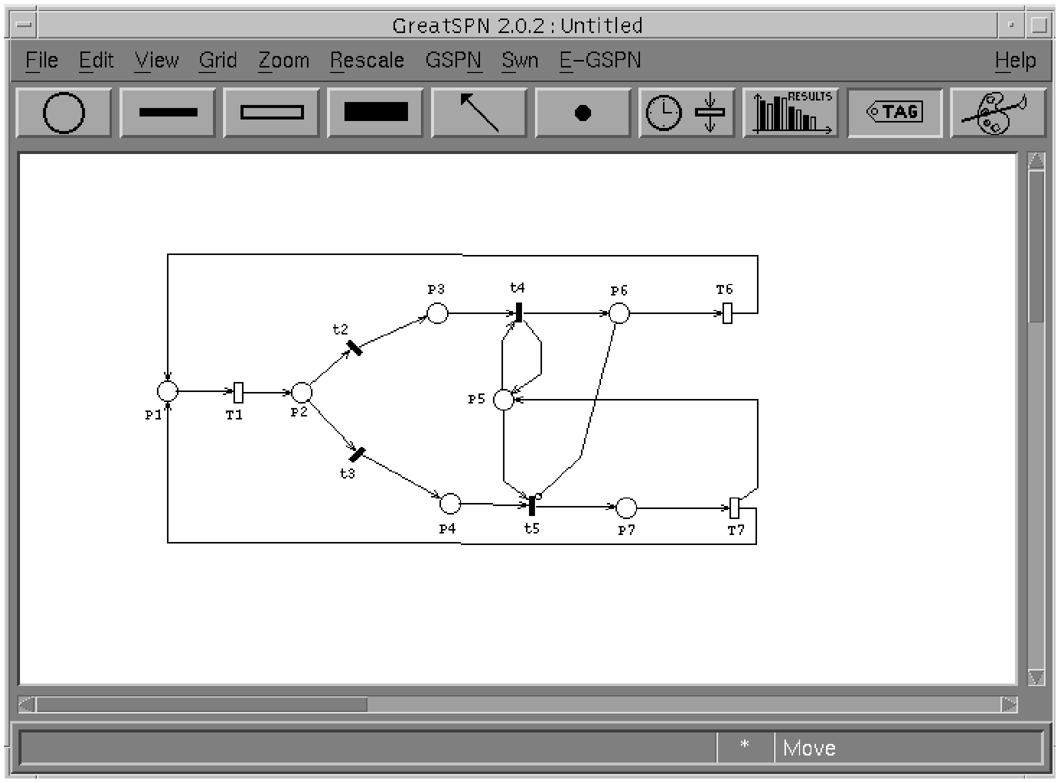
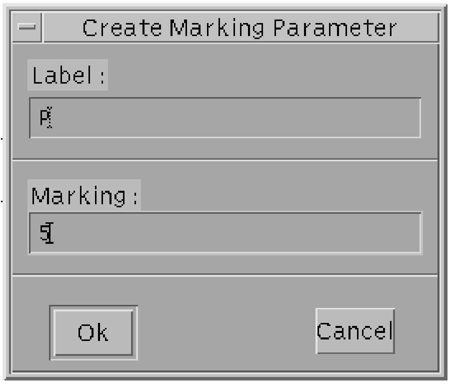


Figure 2.6: Creating arcs

by first clicking over *P6* with the *middle* mouse button, and then over *t5* with the left button. In the case of the output arc connecting transition *T7* to place *P1*, for aesthetical reasons we want to put two intermediate points between the place and the transition, rather then connecting them with a straight line. Intermediate points are added by just clicking the left mouse button over the desired position, provided that it is not too close to a node of the net.

In Petri nets it is forbidden to draw arcs connecting either places to places or transitions to transitions. *Great-SPN2.0.2* enforces this rule by forbidding the creation of such arcs. Note that once one has started the drawing of an arc, there is no way to interrupt the action, so if we realize that we started to draw an arc that we shouldn't, the only way to get out is to complete the arc and to delete it afterwards. To delete an arc (or, more generally, an instance of the currently–selected object), we have to click over the object we want to delete after the selection of the **Action**→*Delete* option.

Now the topology of the network is complete, and we may proceed defining the initial marking. Place marking can defined either directly, by associating an integer number of tokens with the place, or by means of a rate parameter which has been previously defined. In either case, the association of an initial marking with a place is performed by clicking with the left mouse button over the place we want to consider after the **Action**→*Change* option and the *place* icon have been selected. To create a *marking parameter* the user has to click over the *token* icon (graphically represented as a black dot) and to select the **Action**→*Add* option. After that, the user has to move the cursor in an empty *canvas* region and click the left mouse button. A dialog box (see Fig. 2.7 will pop-up, and will ask us to enter the name of a marking parameter (in our case the name is ”P”) and the corresponding numerical value (a positive integer).


Create Marking Parameter

Label :

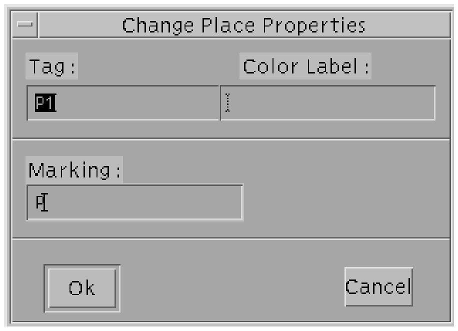
P

Marking :

5

Figure 2.7: Dialog box for the creation of marking parameters

After clicking on the button “Ok” of the above dialog box, the definition of the marking parameter (“P=5”) will appear on the chosen *canvas* position. Starting from this moment, the name “P” can be used as initial marking specification for any place in the net. In our example, two places hold a non-null initial marking, and we can define that by clicking the left mouse button on each of them. The *Change Place Properties* window (see Fig.2.8) will pop up, so that the place marking can be changed by specifing the initial value in the “Marking:” area.


Change Place Properties

Tag : P1

Color Label :

Marking : 1

Figure 2.8: Dialog box for changing place properties.

Alternatively, the same action can be performed by selecting the *token* icon. The initial marking of a place can be specified either as a nonnegative integer value or by using the name of an already-defined marking parameter.

As the network specification is complete, we may display a “nicer” version with rounded arcs by selecting the **View**→*Spline* option. This produces a net looking like the one depicted in Fig. 2.9.

So far we have retained the default names given by the editor at the moment of the object creation. Although this is useful to speed up the editing procedure, it may yield to a poor model readability, that can be improved by giving meaningful names to places and transitions. Tags can be modified by selecting the “tag” object, by choosing the **Action**→*Change* option and by pointing and clicking the left mouse button on the corresponding place or transition. A dialog box will pop up and will ask the user to specify the new object tag.

2.4 Saving and printing the model

After the model definition has been completed, we can save its description and/or print it using several different formats, by means of the **File** menu. A model is saved by selecting the **File**→*Save* option. If the model had been previously saved, this operation will cause the old description to be overwritten. If one wants to keep the old description, he/she can use the **File**→*Save As* option of the above menu to specify a new name for the net. The net description files are saved in the user directory defined by setting the environment variable GSPN_NET_DIRECTORY (as specified in the $HOME/.greatspn file of the user: see the Appendix C for details). *GreatSPN2.0.2* provides the possibility of specify comments, which are saved with the net description and which can be subsequently re-edited. To add a comment, simply select **File**→*Comment* option, and use the *Edit Net Comment* dialog box which pops-up. To create printouts of a model, or Encapsulated PostScript (EPS) files suitable for inclusion in LaTeXdocuments, we have to select the **File**→*Print* option. This option affects only that portion of the model that is included in the currently-defined *print area*, that is displayed as surrounded by a dotted line if the **View**→*Print Area* option is selected (see Fig. 2.9). To define the print area, we have to:

1. select the **Action**→*Define Print Area* option (the cursor shape will be changed into a cross);

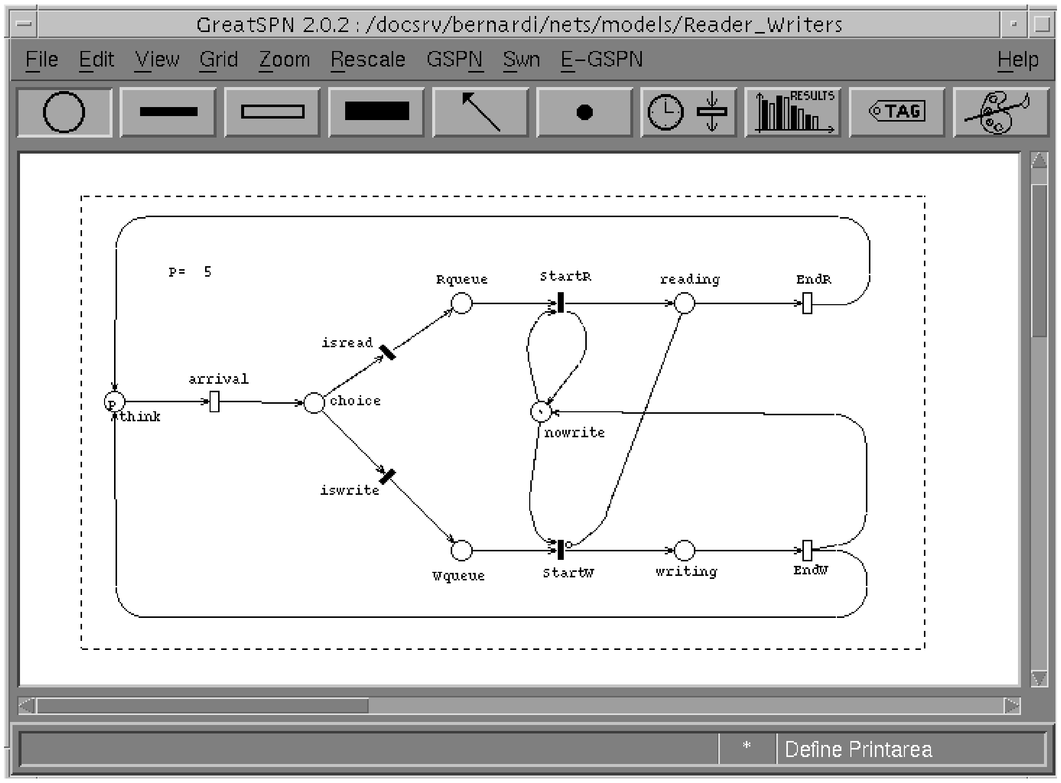


Figure 2.9: Print area used for the Readers-Writers model

2. click with the left mouse button over the *canvas* point corresponding to the upper-left corner of the print area;

3. move the mouse cursor on the lower-right corner of the desired print area and click either the left or the middle mouse button.

After the above operations have been completed, the **File**→*Print* command must be selected to cause the *Print* dialog box (shown in Fig. 2.10) to pop up. In the window contained in the leftmost part of the *Print* dialog box, *GreatSPN2.0.2* shows an overview of the entire working area (remember that only a window on a portion of the working area is shown in the Control Panel). The print area is surrounded by a thin black frame, that can be adjusted (allowing the redefinition of the print area) by positioning the mouse cursor over the lower-right corner (indicated by a small black square) and dragging it by clicking with the left mouse button *without releasing* the mouse button.

The six icons displayed just below the above window allow us to set:

- the format of the output , that can be chosen between raw PostScript (by clicking on the *PS* icon) and Encapsulated PostScript (by clicking on the *TeX* icon);

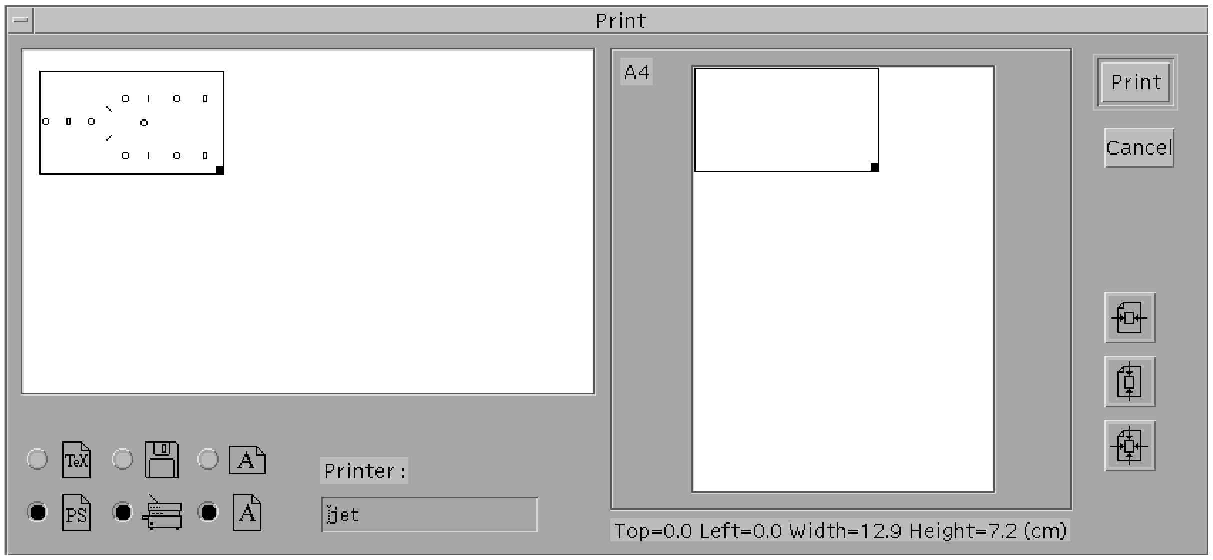


Figure 2.10: *GreatSPN2.0.2 Print* dialog box

- the destination of the output, that can be either a file (*Diskette* icon) or a PostScript printer (*Printer* icon): if the EPS format is chosen then only a printout on a file is allowed;
- the orientation of the output, that can be either portrait or landscape (the two *A* icons).

The right part of the *Print* dialog box contains a window that shows the page layout (an a A4 size sheet is assumed). The placement of the print area over the sheet can be changed either by dragging the thin black rectangle or by clicking over one of the three icons placed at the right of the window (that allow centering the picture on either dimension). Finally, the printout with the desired options is performed by clicking with the left mouse button on the "Print" button. If we decided to save the printout on a file, *GreatSPN2.0.2* will ask the user (by means of a suitable dialog box) to enter a file name that will be placed either in the default PostScript (PS) or Encapsulated Postscript (EPS) directory. The default PS and EPS directories can be set by means of the environment variables GSPN_PS_DIRECTORY and GSPN_EPS_DIRECTORY in the *$HOME/.greatspn* file (see Appendix C).

2.5 Analysis of the Readers-Writers model

Once we have defined both the net structure and the initial marking of the Readers–Writers model we can have a first understanding of its dynamic behavior by playing the "token game". *GreatSPN2.0.2* provides the user of an interactive token game that can be started by selecting the **GSPN**→*Simulation...* option. The *Simulation* window pops up and all the transitions of the model that are enabled in the initial marking become blinking (see Fig. 2.11). To simulate a possible behavior of the modeled system we have simply to click with the leftmost button of the mouse over the enabled (i.e. blinking) transition we want it to fire. In our running example, only transition *arrival* is enabled in the initial marking; by clicking on it, the firing action is executed, i.e. a token is removed from the input place *think* and a token is added to the output place *choice*. The new reached marking enables the two immediate transitions *isread*, *iswrite*: we can choose to fire one of them and to simulate the corresponding firing action (and so on). By default the "Untimed" and the "Forward" options of the *Simulation* window are set to play the forward token game: it is possible to play the backward token game by setting the "Backward" option in the *Simulation* dialog box.

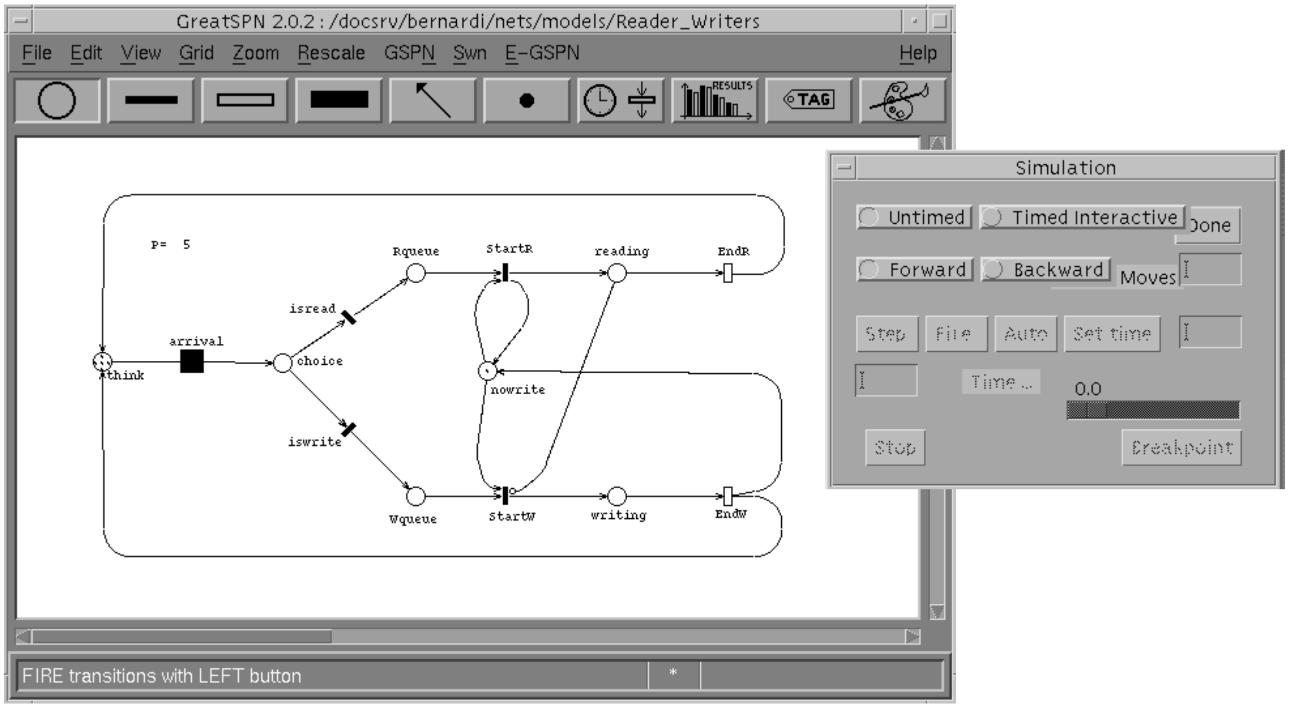


Figure 2.11: Token game of the Readers–Writers model.

GreatSPN2.0.2 provides the user with a set of structural analysis algorithms that can be used to validate the models. The user can access the above algorithms by selecting the **GSPN**→*Struct* option.[2] For example, the computation of minimal-support, canonical Place Invariants (by means of a modified Martinez–Silva algorithm [29]) can be accomplished by means of the option **GSPN**→*Struct*→*P invariants*. *GreatSPN2.0.2* will visualize the *Console* window (shown in Fig. 2.12), allowing one to start the P–invariant computation by clicking with the left mouse button over the "Start" button. At the end of the above computation, the *Console* window will contain the results, as displayed in Fig. 2.13.

After a GSPN model has been constructed and validated, it can be analyzed by means of the different perfor-

[2] **WARNING!** Before launching a *GreatSPN2.0.2* solver be sure that the hostname set in the "Hostname:" left area of the **File**→*Options* window is the name of the machine on which the Control Panel has been started.

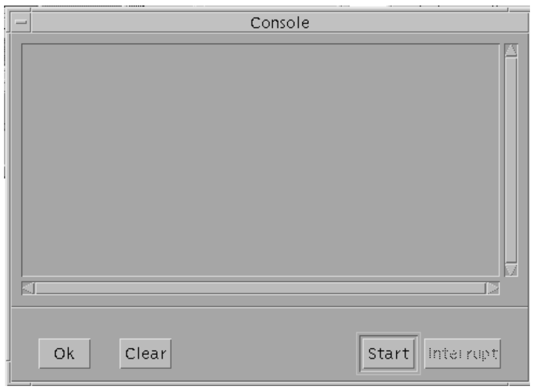
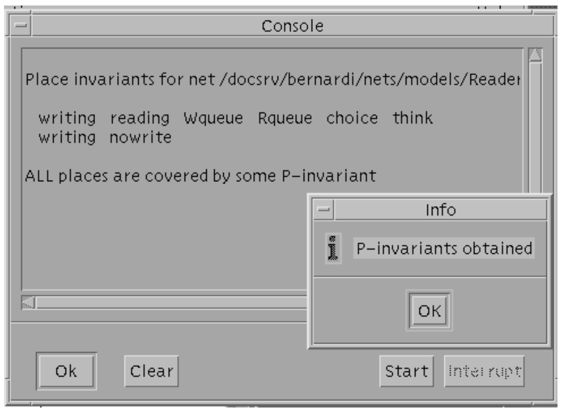


Figure 2.12: *GreatSPN2.0.2* Console

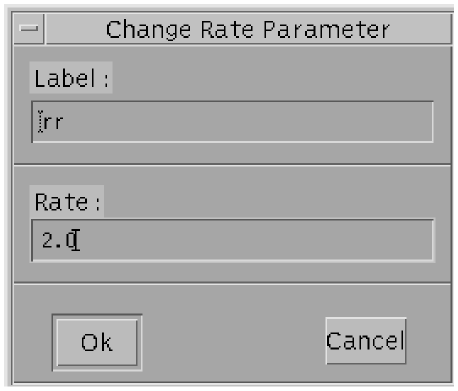


```
Place invariants for net /docsrv/bernardi/nets/models/Reader

  writing  reading  Wqueue  Rqueue  choice  think
  writing  nowrite

ALL places are covered by some P-invariant
```

P-invariants obtained

Figure 2.13: Results of P–invariant computation for the Readers–Writers model

mance evaluation techniques provided by *GreatSPN2.0.2* . Before starting the performance analysis of a given GSPN model, its performance–related parameters must be defined. The default rates associated with transitions can be displayed on the screen by selecting the **View**→*Rate* option. Rates overlapping some other object of the net can be moved around in the same way as tags, by selecting the **Action**→*Move* action after the icon corresponding to rates (indicated by a clock close to a timed transition) has been selected. Transition rates may be defined as positive real numbers, name of rate parameters, or marking–dependent expressions, governed by a context–free grammar (described in Appendix A). In this example we will only use rate parameter specifications, that are created much in the same way as marking parameter, by choosing the **Action**→*Add* action together with the *rate* icon. A dialog box (see Fig. 2.14) will pop up, allowing us to specify the name and the definition of rate parameters. We will define three rate parameters for transition rates: *arr = 1.0*, *rr = 2.0*, and *wr = 0.5*; and two rate parameters for choice probabilities between conflicting immediate transitions: *isr = 0.8*, and *isw = 0.2*. After their definition, the above parameters can be used to specify the transition rates (weights) by choosing

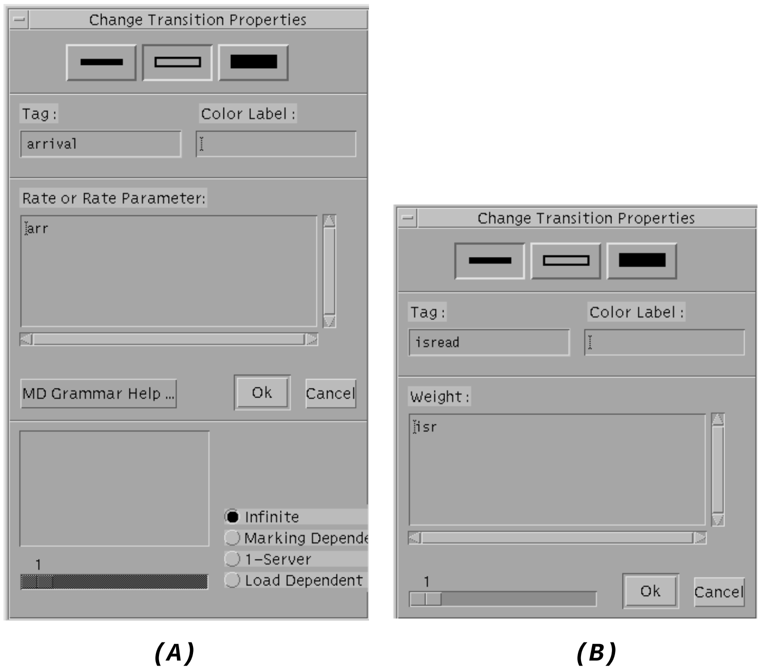


Label: rr

Rate: 2.0

Figure 2.14: Dialog box for the creation of rate parameters

the **Action**→*Change* action with the exponential (immediate) transition type selected, by clicking with the left mouse button over the appropriate transitions and by filling the *Rate or Rate Parameter* (*Weight*) field of the corresponding *Change Transition Properties* window (see Fig.2.15).



Change Transition Properties

Tag : arrival

Color Label :

Rate or Rate Parameter: arr

1

[✓ Infinite] Marking Depende 1–Server Load Dependent

Change Transition Properties

Tag : isread

Color Label :

Weight : isr

1

Figure 2.15: Windows for defining/changing properties of timed (A) and immediate (B) transitions.

The same window, depicted in Fig.2.15(A), allows the specification of the enabling dependence. The default enabling dependence for timed transition is of the “infinite server” type, but it can be changed by choosing the appropriate option (*Infinite, Marking Dependent, 1-Server*, and *Load Dependent*). In our example, only the *arrival* and the *endR* transitions are of the “infinite server” type, so the enabling dependence of all the other ones must be changed to *1-Server*. To change the priorities of immediate transitions, use the scrollbar on the bottom-left of the *Change Transition Properties* window (Fig.2.15(B)) of the corresponding transitions to increase/decrease their priorities.

With the specification of transition rates and probabilities as shown in Fig. 2.16, we have completed the specification of the behavior of the model. *GreatSPN2.0.2* provides three different performance analysis methods, namely computation of bounds for the throughput of transitions, Markovian solution and simulation. In this chapter we present an example of the Markovian solution of the Readers–Writers GSPN model, while the other techniques will be covered in Chapter 4. The Steady–State solution of the Embedded Markov Chain corresponding to the GSPN model of the Readers–Writers system of Fig. 2.16 is obtained by selecting the **GSPN**→*Solve*→*GSPN Solution*→*Steady State* option. The *Console* window will pop-up again, and after we click with the left button on the “Start” button, *GreatSPN2.0.2* will start the analysis phase. At the end of the analysis, *GreatSPN2.0.2*

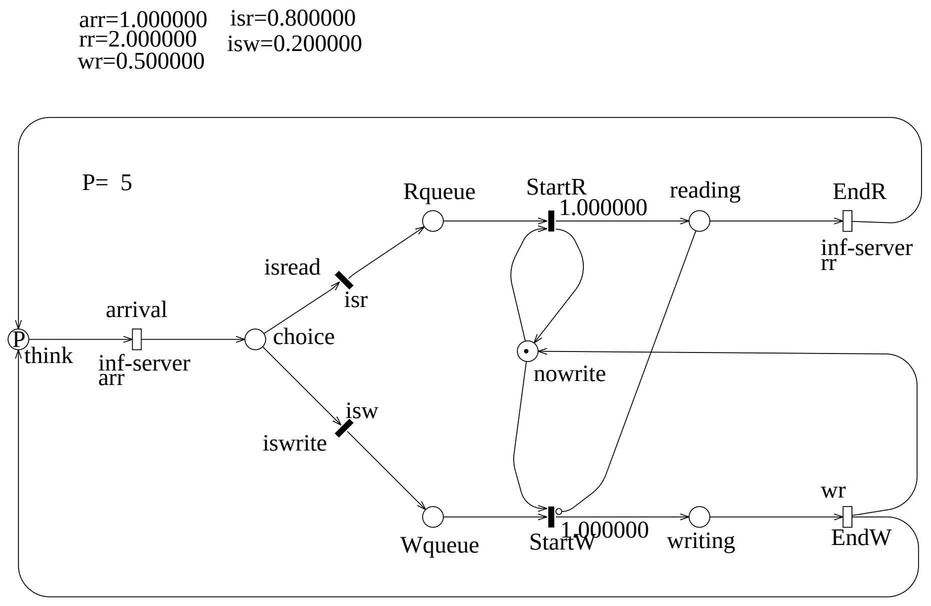


Figure 2.16: The Readers–Writers model with transition rate/probability specification

will show on the screen the values of the throughput of the various timed and immediate transitions, as well as the values of the defined performance indices (see Figure 2.17). We can visualize the distributions of token into places by selecting the **Action**→*Show* action together with the *result* icon, and by clicking on the place of interest. In Fig. 2.18 it is shown the token distribution for place *Wqueue*.

2.6 Colored version of the Readers-Writers model

Let us suppose that the processes which are concurrently accessing to the shared data base have different behaviors; in particular, a group of them access to the data base only to perform a write operation, while another group can issue either a writing or a reading request. In this section we describe how to obtain the colored *GreatSPN2.0.2* version of readers-writers model (see Fig.2.19) that captures the different behavior of the two kinds of processes. Starting from the previous non-colored model of the readers-writers system we first need to define the basic color classes representing the two kinds of processes. To create (or to modify) a basic color class definition simply click with the left mouse button on the *color* icon (indicated by a palette and a paintbrush) of the *object bar* and pop-up the **Action** menu, using the right mouse button, in order to select the “Add” option as the current action. After these operations, choose a place in the *canvas* to locate the definition of the class and click with the left mouse button: the *Create Color Definition* window pops-up (see Fig.2.20). The top left area named as “Label:” has to be filled with the name of the color class. The “Colorset” toggle, by default, is already switched on (a black dot is displayed in the circle near the toggle), indicating that the current definition is a definition of a

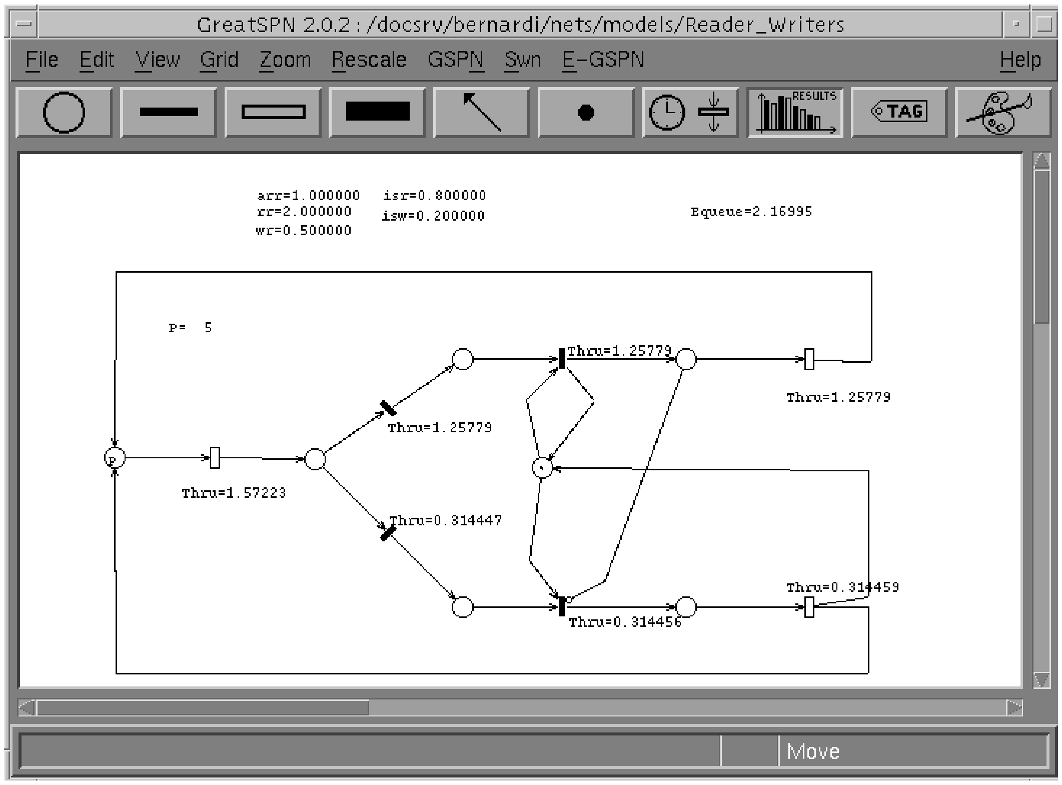


Figure 2.17: *GreatSPN2.0.2 canvas* after the Readers–Writers GSPN model has been solved

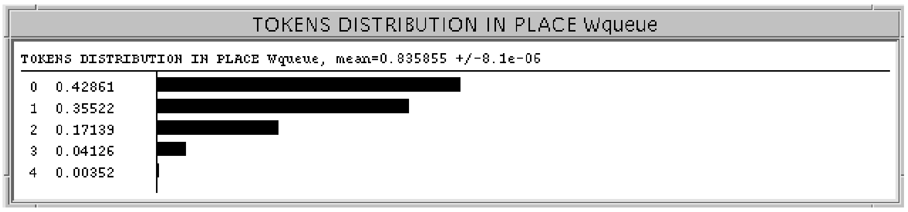

```
TOKENS DISTRIBUTION IN PLACE Wqueue

TOKENS DISTRIBUTION IN PLACE Wqueue, mean=0.835855 +/-8.1e-06
 0  0.42861
 1  0.35522
 2  0.17139
 3  0.04126
 4  0.00352
```

Figure 2.18: Token distribution in place *Wqueue*

basic color class. In the “Definition:” area, the definition of the basic color class is written using the SWN syntax (see Appendix A): in the example the class *P* is the unordered union of two static subclasses *P1* and *P2*. These two colored subclasses have to be defined as well, following the same procedure described above for the color class definition, i.e., by recalling and filling the areas of the *Create Color Definition* window for each of them (see Fig.2.21). In our example, we have used two different alternatives of the SWN syntax to express the subsets of colors *P1* and *P2*: the color subclass *P1* is defined as the set of two elements *p1, p2* while the color subclass *P2* is a set of three elements *c1, c2, c3*. Once the basic color classes has been defined, we proceed as follows:

- add color domains to places that may contain colored tokens. To modify place attributes, click on the *place* icon and select from the **Action** menu the *Change* option; place color domain *P* has to be written on the

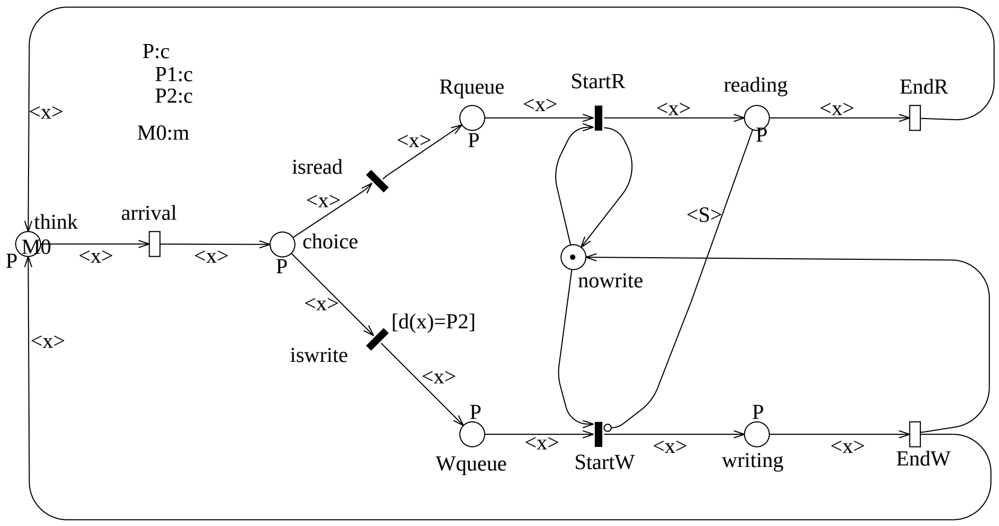
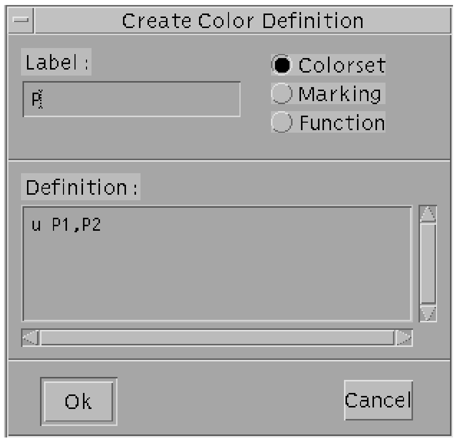


Figure 2.19: SWN model of the Readers-Writers system.



Label: P

[✓ Colorset] Marking Function

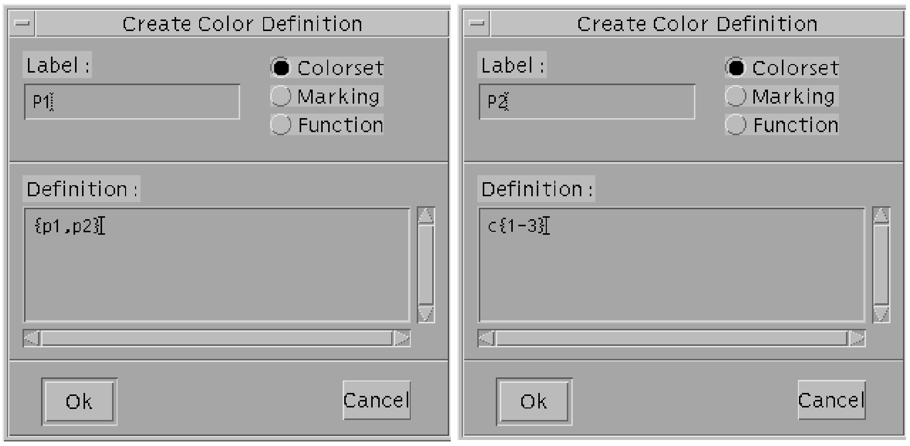
Definition:

```
u P1,P2
```

Figure 2.20: Create Color Definition window.

"Color label:" area of the *Change Place Properties* window (see Fig.2.8). In the model of Fig.2.19, all the places have color domains, except for place *nowrite*;

- add color attributes to the corresponding input/output arcs. To modify arc attributes, press the *arc* icon (we don't need to select again the **Action**→*Change* option since it is the current action), and click on the interested arc with the left mouse button; the *Change Arc Properties* window of Fig.2.22 pops-up. Press the "Color" toggle to set the right area into "Color" mode and then add in the area the color function according to the SWN syntax. In the model of Fig.2.19, all the arcs are characterized by the identity function $\langle x \rangle$, except for the input/output arcs of the non colored place and for the inhibitor arc connecting place *reading*


Create Color Definition

Label : P1

[✓ Colorset] Marking Function

Definition : {p1,p2}

Ok Cancel

Create Color Definition

Label : P2

[✓ Colorset] Marking Function

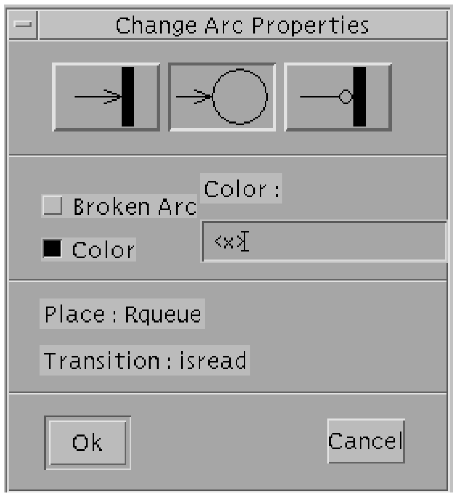
Definition : c{1-3}

Ok Cancel

Figure 2.21: Definition of static subclasses.

to the transition *StartW* that is labeled with the *whole place color domain* function $\langle S \rangle$;

- add a guard to the transition *iswrite*. A way to model the constraint that only the processes belonging to the static subclass *P2* are allowed to issue a writing request to the data base is to add a guard to the transition *iswrite*. To modify transition attributes, press one of the *transition* icons and select the interested transition: one of the *Change Transition Properties* windows of Fig.2.15 pops-up, depending on the type of transition, allowing to fill in the "Color Label:" area the guard according to the SWN syntax. In the model of Fig.2.19, transition *iswrite* can fire only when its input place contains a colored token $\langle x \rangle$ belonging to the static subclass *P2*.


Change Arc Properties

Broken Arc [✓ Color]

Color : <x>

Place : Rqueue

Transition : isread

Ok Cancel

Figure 2.22: Change Arc Properties window.

Finally, we define the colored marking parameter *M0* of the SWN model of Fig.2.19 by pressing the *color* icon of the *object bar* and by selecting the **Action**→*Add* option. The *Change Color Definition* window pops up again by clicking with the left mouse button on a location in the *canvas*. To define a colored marking parameter switch on the “Marking” toggle and then fill in the “Label:” and the “Definition:” areas with the name of the parameter (*M0*) and its definition ($\langle S\ P1\rangle + \langle S\ P2\rangle$) respectively. The initial marking of the SWN model of Fig.2.19, is then set by adding to the “Marking:” area of the *Change Place Properties* window related to the place *think* the colored marking parameter *M0*.

2.7 Analysis of the SWN Readers-Writers model

Concerning the analysis of SWN models, *GreatSPN2.0.2* supports the reachability graph generation (both ordinary and symbolic) with the corresponding Markovian solution, both in steady state and transient, and the simulation: in this section we will describe how to obtain the symbolic reachability graph (SRG) of the Readers-Writers model of Fig.2.19 and its corresponding Markovian solution, for a depth description of the different analysis techniques see Chapt.4.

Once the SWN model has been saved, we can compute the symbolic reachability graph by choosing from the **Swn**→*Symbolic* sub-menu the *Compute RG* option. In case last modifications of the current loaded model have not been saved before launching a *GreatSPN2.0.2* solver a warning window will pop-up asking to the user for saving or aborting the request. The request of computing the symbolic reachability graph of the SWN model will cause the *Console* window of Fig.2.12 to pop-up; it is then possible to obtain a verbose description of the symbolic reachability graph by setting on the “Verbose Show” toggle of the *SWN Symbolic RG Options* window (see Fig.2.23) which appears after the “Start” button of the *Console* window has been pressed.

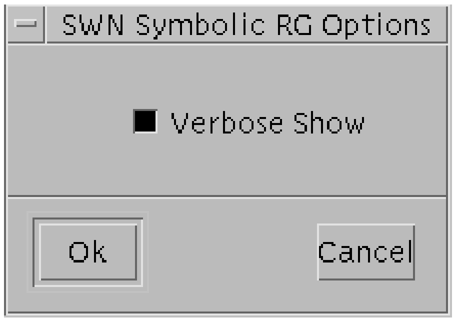


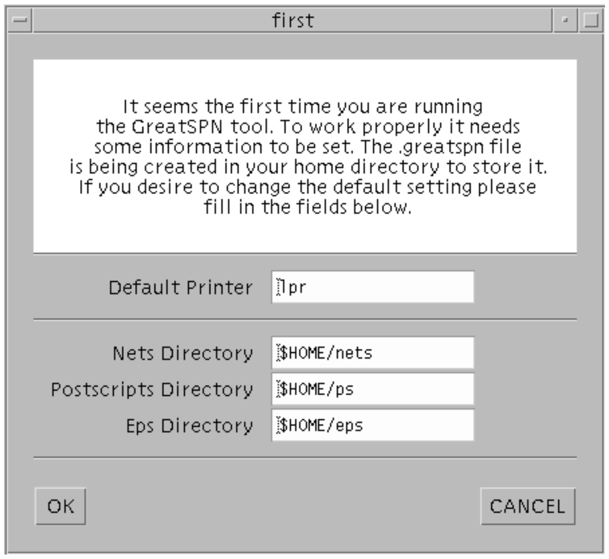
Figure 2.23: SWN Symbolic RG Options window.

Finally, choose “OK” button of the *SWN Symbolic RG Options* window to launch the *GreatSPN2.0.2* solver. The execution is displayed on the *Console* window and the results are visualized in the *GreatSPN2.0.2* canvas: the SWN model of Fig.2.19 is characterized by 45 Tangible Symbolic Markings (which correpond to 209 Tangible Ordinary markings) and no deadlocks are found. Results are saved in different files: the symbolic reachability graph is saved in file `netname.srgP5`, transition throughputs and performance indices defined by the user are contained instead in `netname.sta` file.

Chapter 3

GUI in depth

This chapter is a reference guide containing a detailed description of the various options provided by the Control Panel (CP). The CP is a unified graphical interface used for model specification and analysis. It is based on the X-windows systems and exploits the Motif libraries. The CP provides a graphical editor for Petri Net models (both colored and uncolored), as well as a set of pull-down menus providing access to the solver modules of the package.



It seems the first time you are running
the GreatSPN tool. To work properly it needs
some information to be set. The .greatspn file
is being created in your home directory to store it.
If you desire to change the default setting please
fill in the fields below.

Default Printer: lpr

Nets Directory: $HOME/nets
Postscripts Directory: $HOME/ps
Eps Directory: $HOME/eps

Figure 3.1: The initial window that appears when the tool is invoked for the first time after the installation.

Starting *GreatSPN2.0.2* After the *GreatSPN2.0.2* package has been installed correctly (see Appendix C), to invoke the CP, type `greatspn` followed by a carriage return. When *GreatSPN2.0.2* GUI is launched for the first time after the installation a previous window (Fig.3.1) pops-up in which it is asked to the user either to confirm or to change the default settings of the following *GreatSPN2.0.2* environment variables:

- GSPN_DEFAULT_PRINTER, containing the name of the default printer;
- GSPN_NET_DIRECTORY, containing the path directory of the net description files;
- GSPN_PS_DIRECTORY, containing the path directory of the printout of the nets in raw PostScript format;
- GSPN_EPS_DIRECTORY, containing the path directory of the printout of the nets in EncapsulatedPostcript format.

If the "OK" button is chosen then the settings are saved into the `$HOME/.greatspn` file and the CP window (Fig.3.2) appears on the user's terminal.

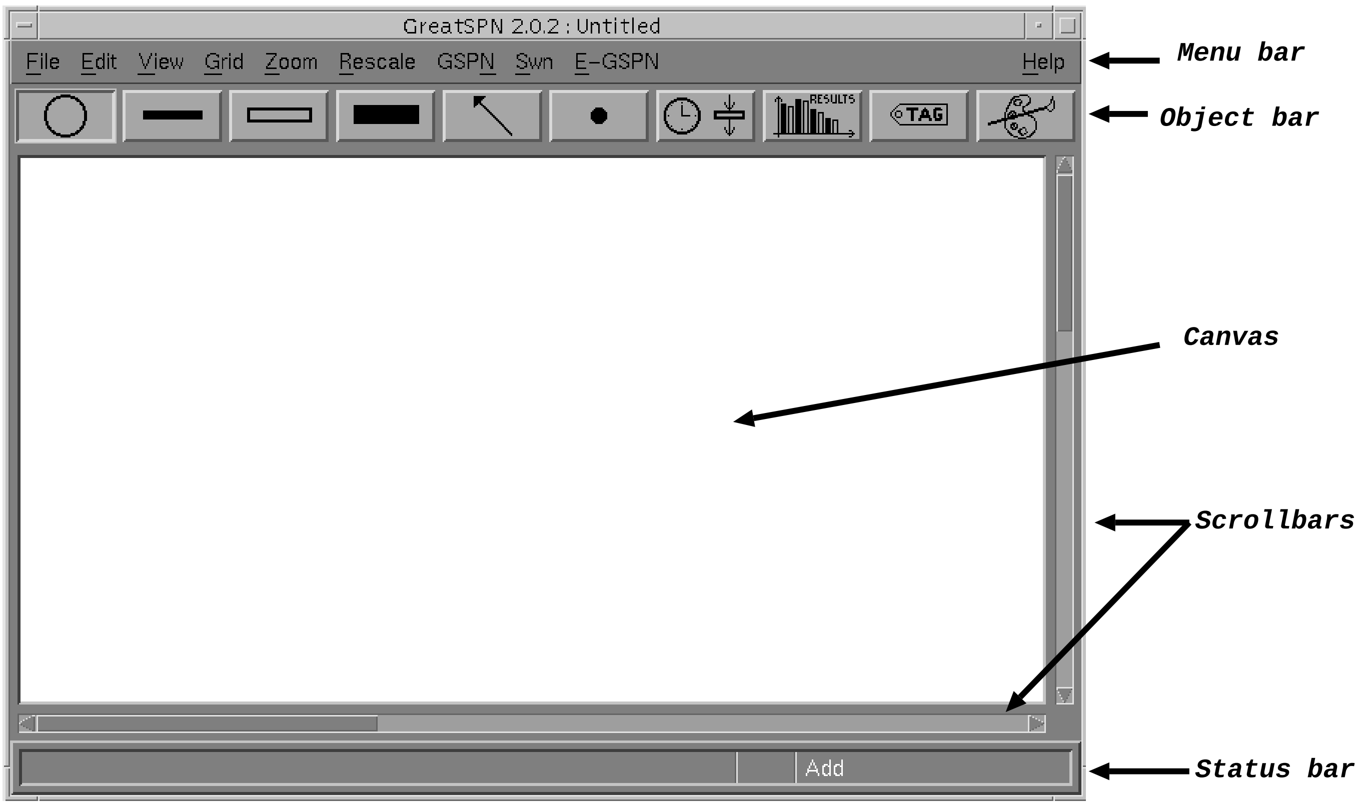

GreatSPN 2.0.2 : Untitled
File Edit View Grid Zoom Rescale GSPN Swn E-GSPN Help
RESULTS
TAG
Add
Menu bar
Object bar
Canvas
Scrollbars
Status bar

Figure 3.2: The *GreatSPN2.0.2* Control Panel

Control Panel Description As seen from Fig.3.2, the top portion of the window contains 10 menu items, each of them has a pull-down menu that provides several options. The menu items and their options allow to specify and solve the current loaded Petri net model. The *object bar* is just below the *menu bar* and it contains 10 icons which allow to perform operations, such as add/delete/change etc., on a specific object of the model. Petri net models are displayed in the *canvas*. The CP window shows only a part of the whole *canvas* and *scrollbars*, located on the right and on the bottom of the CP, allow to show different parts of it. Finally, on the bottom part of the CP there is the *status bar*, in which appropriate status messages and/or error messages are displayed.

3.1 The Menu Bar

To access the menus, position the cursor (which appears as an arrow) on the desired menu item. Press the left mouse button and hold it down (which highlights the particular option chosen) to walk through the menu options. Click (i.e., release the left mouse button) on a particular option to select it.

In the following we list and describe the possible options offered by each menu item. The notation **Menu Item**→*Option* is used to denote an option within a specific menu item.

3.1.1 File Menu

The File menu contains the following options:

File→*New* to edit a new model. The previous loaded one is discarded: if its last modifications performed have not been saved, *GreatSPN2.0.2* prompts the user with a message asking if a save action is desired before editing a new model.

File→*Open* to load a previously-saved model. A window pops up (Fig.3.3) allowing to navigate within directories selected by the filter and to choose the model to be loaded. By default, the filter is set on the user directory defined by the environment variable GSPN_NET_DIRECTORY.

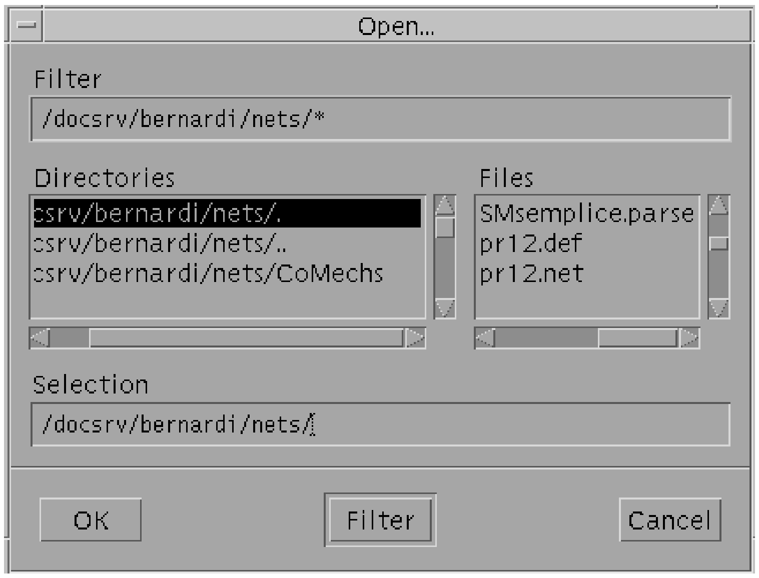
File→*Merge* to merge a Petri Net model previously defined to the current loaded model. This option is not available in the current version of *GreatSPN*. Merging of two *GreatSPN2.0.2* models can be performed using the **Composition** module, described in detail in chapt.5.

File→*Save* to save the current model using the corresponding name. If the model is new, *GreatSPN2.0.2* will ask the user to provide a name.

File→*Save As...* either to save the current model with a name, if the model is new, or to save it under a different name (i.e., to make a copy of it).

File→*Remove Results* to remove all the result files created during the analysis of the current loaded model.

File→*Remove All* to remove all the files related to the current loaded model, included the net definition files.



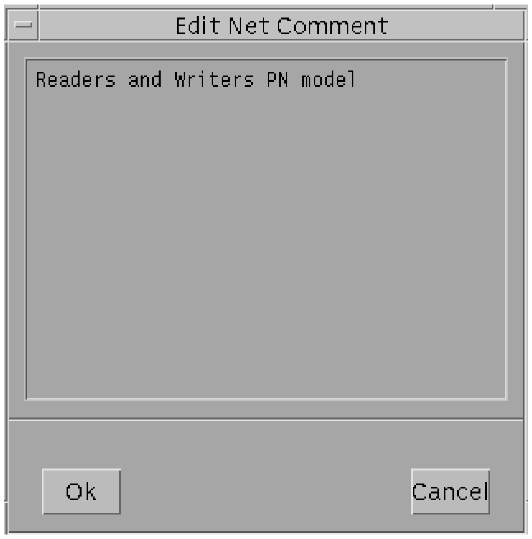
/docsrv/bernardi/nets/*

csrv/bernardi/nets/.
csrv/bernardi/nets/..
csrv/bernardi/nets/CoMechs

SMsemplice.parse
pr12.def
pr12.net

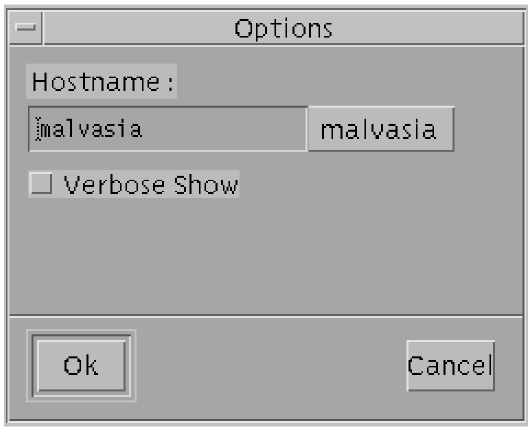
/docsrv/bernardi/nets/

Figure 3.3: *GreatSPN2.0.2 Open* dialog box.



Readers and Writers PN model

Figure 3.4: Comment editor display



malvasia

Figure 3.5: Options display

File→*Comment...* to specify a comment which is saved as part of the net description. The window of Fig. 3.4 pops up, allowing to edit the comment. To save the edited comment click with the left mouse button on the "OK" button. To abort the action, click on the "Cancel" button.

File→*Options...* to specify the machine on which the solution programs will be executed. The *Option* window of Fig. 3.5 pops up; the "Hostname:" right button is labeled with the name of the machine on which *GreatSPN2.0.2* has been started, while in the "Hostname:" left box appears the name of the machine on which

GreatSPN2.0.2 has been launched the last time.

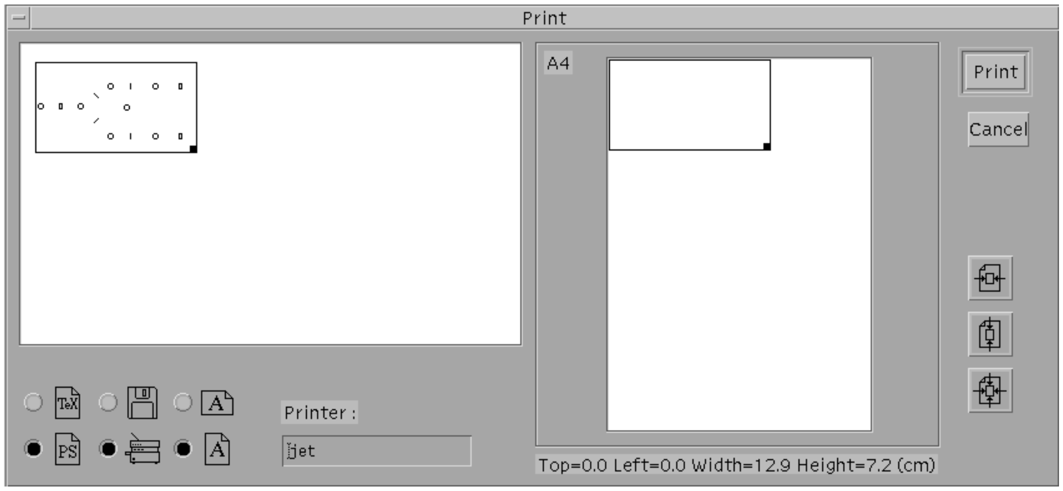
WARNING! The “Hostname” left box has to be updated with the name of the machine on which *GreatSPN2.0.2* has been launched in order to ensure that *GreatSPN2.0.2* solvers work properly: therefore simply press on the “Hostname:” button, then the name written on the button will be automatically copied into the “Hostname:” left box.

The “Verbose Show” option allows the user to require a verbose output during the execution of the analysis programs.

File→*Print...* to print the current loaded model. This option affects only that portion of the current loaded model that is included in the currently-defined print area, that is displayed as surrounded by a dotted line if the **View**→*Print Area* option is selected. To define the print area, we have to:

1. activate the *Action* menu (Fig.3.7) by pressing the right mouse button on any position of the *canvas* and select the **Action**→*Define Print Area* option (the cursor shape will be changed into a cross);
2. click with the left mouse button over the *canvas* point corresponding to the upper-left corner of the print area;
3. move the mouse cursor on the lower-right corner of the desired print area and click either the left or the middle mouse button.

The **File**→*Print...* option causes the *Print* dialog box (shown in Fig. 3.6) to pop up. In the window contained in



Top=0.0 Left=0.0 Width=12.9 Height=7.2 (cm)

Figure 3.6: *GreatSPN2.0.2 Print* dialog box

the leftmost part of the *Print* dialog box, *GreatSPN2.0.2* shows an overview of the entire working area (remember that only a window on a portion of the working area is shown in the CP). The print area is surrounded by a thin black frame, that can be adjusted (allowing the redefinition of the print area) by positioning the mouse cursor over the lower-right corner (indicated by a small black square) and dragging it by clicking with the left mouse button without releasing the mouse button. The six icons displayed just below the above window allow us to set:

- the format of the output, that can be chosen between raw PostScript (by clicking on the "PS" icon) and Encapsulated PostScript (by clicking on the "TeX" icon);
- the destination of the output, that can be either a file ("Diskette" icon) or a PostScript printer ("Printer" icon): if the EPS format is chosen then only a printout on a file is allowed;
- the orientation of the output, that can be either portrait or landscape (the two "A" icons).

The right part of the *Print* dialog box contains a window that shows the page layout (an A4 size sheet is assumed). The placement of the print area over the sheet can be changed either by dragging the thin black rectangle or by clicking over one of the three icons placed at the right of the window (that allow centering the picture on either dimension). Finally, the printout with the desired options is performed by clicking with the left mouse button on the "Print" button. If we decided to save the printout on a file, *GreatSPN2.0.2* will ask the user (by means of a suitable dialog box) to enter a file name that will be placed either in the default PostScript (PS) or Encapsulated Postscript (EPS) directory. The default PS and EPS directories are the ones specified by the environment variables GSPN_PS_DIRECTORY and GSPN_EPS_DIRECTORY, respectively, which are located in the *$HOME/.greatspn* file.

File→*Exit* to terminate *GreatSPN2.0.2* session. If the current loaded model has not been saved since its last modification, *GreatSPN2.0.2* will prompt a message asking the user if he/she wishes to save it.

3.1.2 Edit Menu

The Edit menu allows to graphically edit portions of the model; some of the options of the Edit menu are available only if a portion of the model has been selected. The model portion affected by the Edit options can be selected in the following way. First, activate the **Action** menu (Fig.3.7) and choose the **Action**→*Select* option. Then, position the mouse pointer on the upper left corner of the desired area, click and hold down the middle mouse button, move the mouse pointer on the lower right corner of the above area, and then release it by clicking with the left mouse button. The Edit menu contains the following options:

Edit→*Undo* to undo the effects of the last modification performed on the layout of the model. This option is not available when the *Select* action is active.

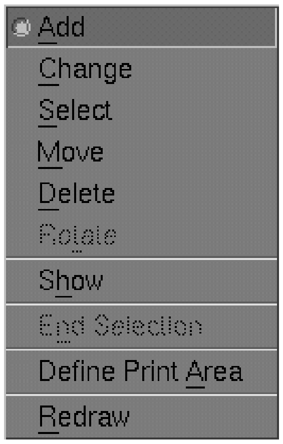


Figure 3.7: **Action** menu options.

Edit→*Add* to make a copy of the objects, i.e., places, transitions and subnets, located in the selected area. The copied objects can be dragged around following the movements of the mouse cursor and eventually placed on the desired location by clicking the left mouse button. Arcs connecting the selected object are also copied and the added places/transitions are renamed. Same operation can be performed by activating the *Add* option of the **Action** menu. To terminate the *Add* option, set the *End Selection* option selected either from the Edit menu or from the **Action** menu.

Edit→*Delete* to delete all the items placed on the selected area.

Edit→*End Selection* to disactivate the selected area.

Edit→*Move* to move on the *canvas* the objects contained in the selected area. The starting and terminating nodes of arcs are not changed.

Edit→*Modify* to modify the layout of currently-selected area. Allowed transformations are:

- clockwise rotation of a multiple of 45 degrees;
- flip X-axis: change the sign of the x coordinates of the selected objects obtaining a vertical mirror transformation;
- flip Y-axis: change the sign of the y coordinates of the selected objects obtaining a horizontal mirror transformation;

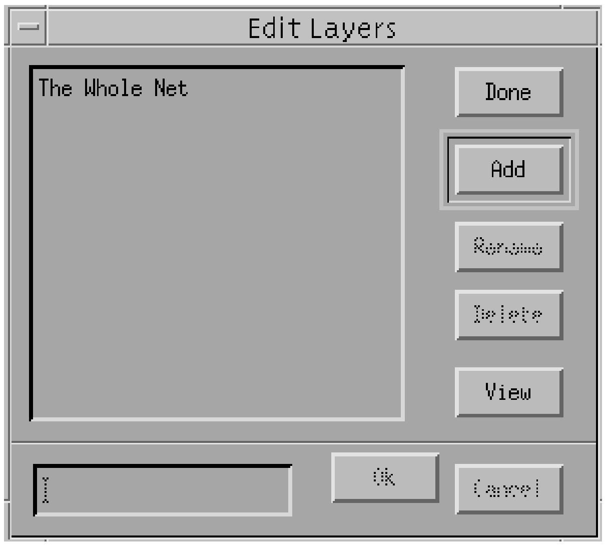


Figure 3.8: Edit layer window.

- mirror: the vertical and the horizontal lines crossing at the current mouse position in the *canvas* represent traces of two mirrors with respect to which an image copy of the selected subnet may be created by clicking the left (or middle) mouse button.

Edit→*Layers...* to edit the layers of the current loaded net. Layers can be set visible or not, independently of each other. This *GreatSPN2.0.2* feature can be effectively exploited to develop "dense" nets with numerous crossing arcs, as in the case of places representing global states of a system that must be tested by many logically distinct subnets. When this option is selected the *Edit Layers* window of Fig.3.8 pops-up, allowing to create, destroy, rename and set visible or not layers of the net. When a *GreatSPN2.0.2* model is created "The Whole Net" layer, representing the whole model, is automatically generated and, by default, is set visible.

In order to describe how to generate layers of a current loaded model, let us consider the example of a fault-tolerant multiprocessor system in which processors may access a common memory through a bus. The basic fault-free behavior has been modeled by the net shown in Fig.3.9. Place *running* contains tokens representing processors running on their own private memory. Transition *memreq* models the time necessary for a processor to issue a shared memory access request. Immediate transition *startacc* represents the start of a shared memory access using the bus. Timed transition *access* models the time needed to complete a shared memory access and to release the bus. The net of Fig.3.9 is our starting point in the construction of a more complex model including not only the normal system operation, but also the activities related to fault detection and recovery. This initial net can be thought of as the first layer of the more complex model. Our first modeling step will be the definition of two layers, which will be called *run* and *repair*, representing the normal operation of the system and the activities related to reconfigurations and repairs of faulty processors, respectively. After loading our initial net description,

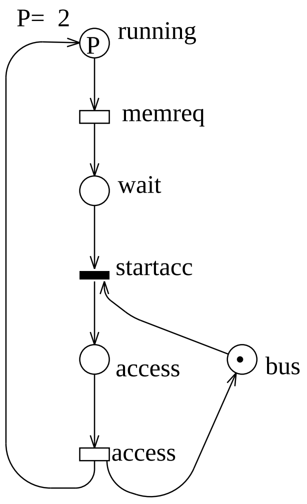


Figure 3.9: Fault-free multiprocessor system model.

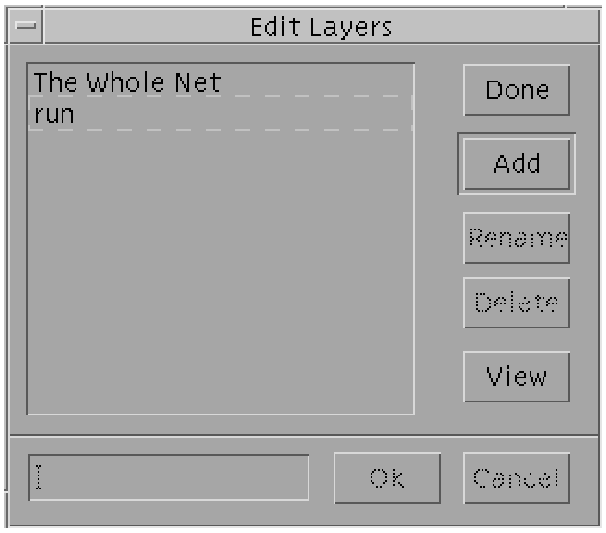


Figure 3.10: Edit layer window after the newly added layer.

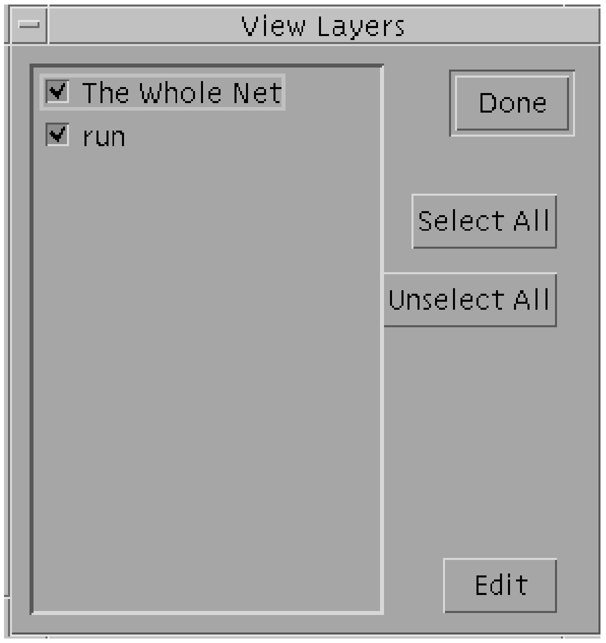


Figure 3.11: View layer window.

the first operation is to open the *Edit Layers* window, by selecting the **Edit**→*Layers...* option, that appears as the one of Fig.3.8 since no layers have already been added. Click on the "Add" button to activate the box located at the left bottom of the window and write in that box the name of the new layer (*run*) to be created. Click on the "OK" button to confirm the previous operation: the new layer *run* has been added to the list of the current layers of the net, shown on the main box of the window (see Fig.3.10). When we click the "View" button the *View Layer* window pops-up, see Fig.3.11: this window allows to set a layer visible (with the associated box checked) or not (with the associated box empty) by simply clicking on the corresponding box. In order to notify the editor that the objects already defined in the net must belong to the *run* layer, we have to perform the following operations:

- select the objects: 1) set **Action**→*Select* option from the **Action** menu (Fig.3.7) 2) click with the middle mouse button over the *canvas* point corresponding to the upper-left corner of the select area 3) move the mouse cursor on the lower-right corner of the desired select area and 4) click either the left or the middle mouse button;
- switch off the “The Whole Net” layer in the *View Layers* window (Fig.3.11);
- choose the **Action**→*Add* option from the **Action** menu (Fig.3.7).

In this way the content of the selected subnet is added to the *run* layer. Now we may proceed to the definition of a new layer; click on the “Add” button of the *Edit Layer* window and define the new layer *repair*. Note that after this action, the newly added layer as well the “The Whole Net” layer are both switched on in the *View layer* window, while the other layers (in the current example, the layer *run*) are all switched off. In this situation, any object created is automatically added both to the net description and to the *repair* layer. We can then start to add objects in the usual way, until the net depicted in Fig.3.12 is obtained. The subnet corresponding to this new *repair*

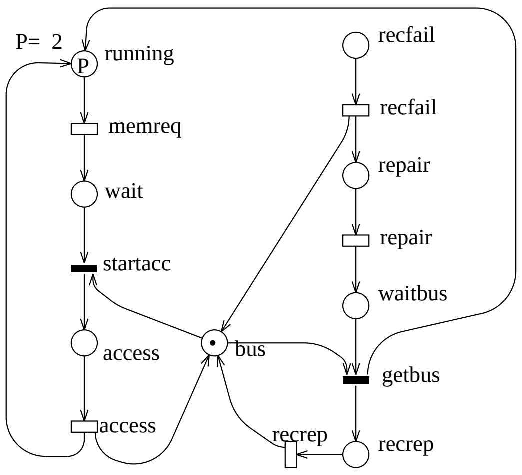


Figure 3.12: The first two layers of the fault-tolerant system example.

layer has its particular meaning: transition *recfail* represents the reconfiguration of the system needed after the detection of a processor failure. Place *repair* models the faulty processor held off-line. Transition *repair* models the time needed to repair or substitute the faulty processor. Transition *recrep* represents the reconfiguration needed after the repair or substitution of the faulty processor in order to put it on-line again.

Note that places *running* and *bus* should belong to both *repair* and *run* layers. We can include them in the new layer *repair* by selecting them, switching off the "The Whole Net" layer, and by choosing the **Action**→*Add* option from the **Action** menu. Unfortunately, as shown in Fig.3.13, this operation has included into *repair* layer not only the two places, but also the two arcs connected to them. These arcs can be removed from the layer by:

- choosing the **Action**→*Delete* option from the **Action** menu (Fig.3.7),
- activating the *arc* icon from the *object bar*,
- picking the arcs in excess with the left button of the mouse.

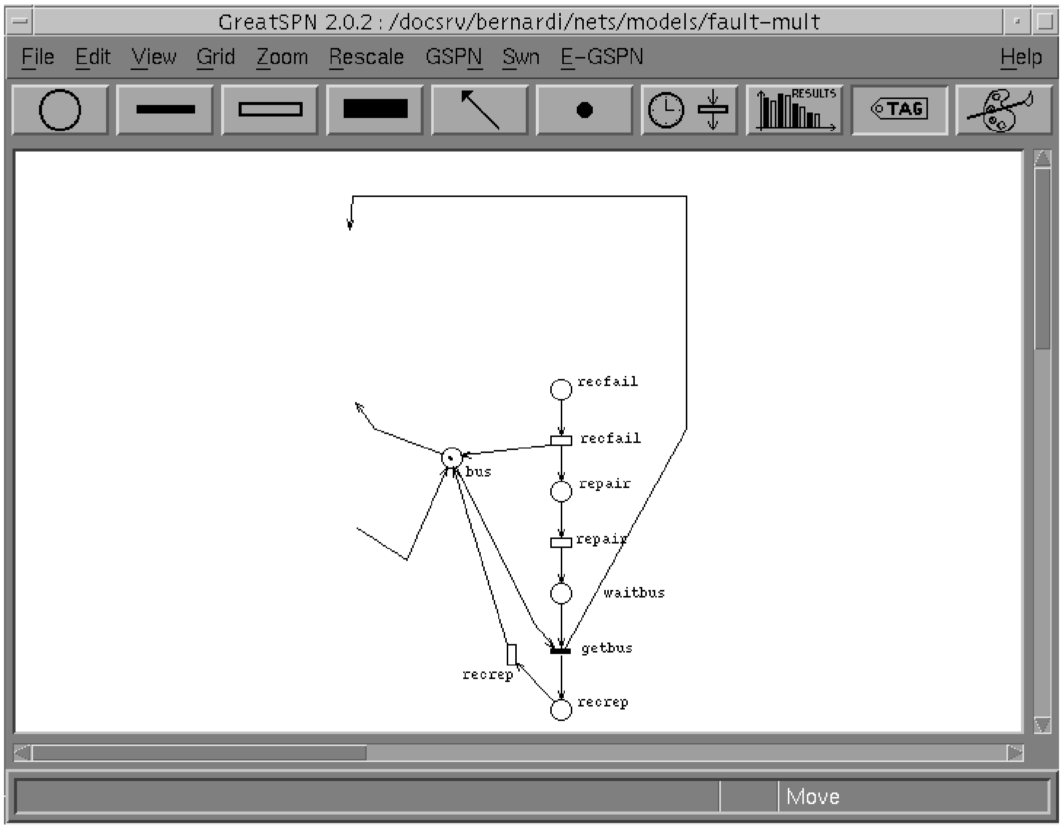

GreatSPN 2.0.2 : /docsrv/bernardi/nets/models/fault-mult
File Edit View Grid Zoom Rescale GSPN Swn E-GSPN Help
RESULTS
TAG
recfail
recfail
bus
repair
repair
waitbus
getbus
recrep
recrep
Move

Figure 3.13: Inclusion of places 'running' and 'bus' into 'repair' layer.

Similarly, we should define two more layers as depicted in Fig.3.14, representing the failure detection and the priority given to recovery procedures over normal operation, respectively.

Fig.3.15 shows the appearance of the complete net with all the layers switched on. Compare the level of readability of this last figure, with that of the sequence of the four layers shown separately. Note also that the last two layers are not easily recognized as 'proper' subnets, and would not be easily managed by tools based on hierarchical decomposition concepts.

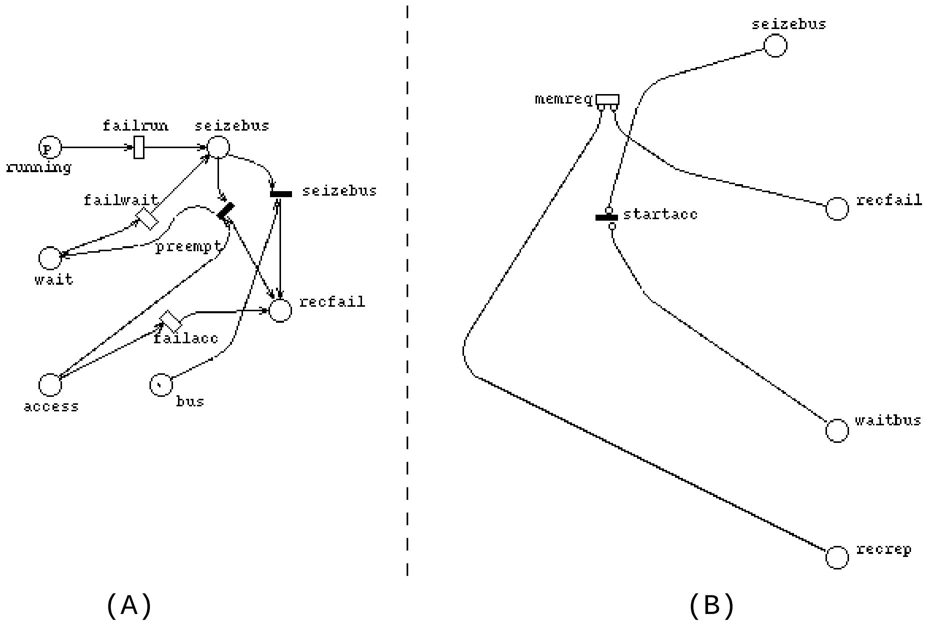


Figure 3.14: The ‘fail’ (A) and the ‘priority’ (B) layers.

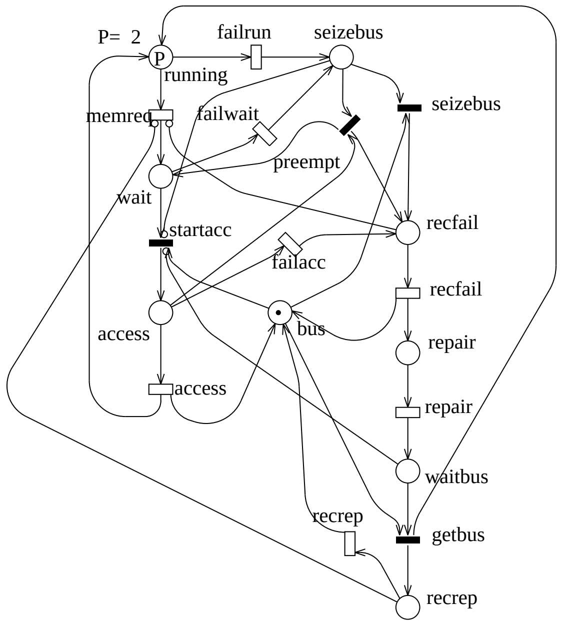


Figure 3.15: The complete net with all the layers switched on.

In fact, different layers can be associated with different hierarchical views of the system, but in general the use of layers is not limited to hierarchy; they can be used to partition a complex ‘flat’ model just in ‘slices’ among which no hierarchy is defined, as in our example.

3.1.3 View Menu

This menu allows to set several options concerning the graphical display of the current loaded Petri net model. Options remain set until they are deactivated. The View menu contains the following options:

View→*Spline* to display arcs with splines. Splines are slower to draw, but often result in nets easier to understand.

View→*Tag* to show/hide the names of the net objects.

View→*Rate* to show/hide the transition rates.

View→*Overview* to show/hide net overview.

View→*Find...* this option is not available in the current version of the package.

View→*Print Area* to show/hide the print area. When the **View**→*Print Area* option is set the current print area is surrounded by a thin broken frame. To change print area definition, choose the **Action**→*Define Print Area* from the **Action** menu (Fig.3.7), the cursor shape will be changed into a cross; click with the left mouse button over the *canvas* point corresponding to the upper-left corner of the desired print area; move the mouse cursor on the lower-right corner of the desired print area and click either the left or the middle mouse button.

View→*Layers...* to pop-up the *View Layer* dialog box (Fig.3.11): the layers of the loaded net are listed in the left box; each layer can be set visible (the associated check-box checked) or not visible (the associated check-box empty) by clicking on its corresponding check-box. To close the *View Layer* dialog box click on the “Done” button; to set visible all the defined layers click on the “Select All” button; to set not visible all the defined layers click on the “Unselect All” button. The “Edit” button located on the bottom-right of the dialog box allows to pop-up the *Edit Layer* window (see Fig.3.8).

3.1.4 Grid Menu

The Grid menu allows to set grid in the *canvas* in order to simplify a regular layout of the net. The size of the gap between points in the grid ranges from one pixel to 50 pixels (the default gap size is one pixel which mean the “None” option is set). When a grid is set, objects are added and moved in the nearest point of the grid with respect to the mouse cursor position.

3.1.5 Zoom Menu

The Zoom menu allows to show the objects of the current loaded net at five different ”zoom” levels, by selecting the proper zooming factor (*1, 3/2, 2, 1/2, 3/4*). “Zoom” operation causes the resizing of all the objects contained in the *canvas* during a *GreatSPN2.0.2* session, however it doesn’t affect the actual dimension of the objects of the net. The default zoom factor of the editor is 1.

3.1.6 Rescale Menu

Net coordinates of the current net can be rescaled by selecting the Rescale menu which contains sixteen different rescale factors ranging from *0.5* to *2*. Choosing one of the rescaling factors, the coordinates of all the objects contained in the *canvas* are multiplied by that coefficient.

WARNING! Rescaling is completely different from zooming the net: “zoom” operation affects only the editor view of the net while “rescale” operation affects the actual coordinates of the objects of the net.

The following three subsections give a short explanation of the **GSPN** of the **SWN** and of the **E-GSPN** menus respectively; a depth description of the *GreatSPN2.0.2* solvers is given in Chapt. 4.

The choice of launching either a structural (**GSPN**→*Struct* submenu) or a numerical analyzer (**GSPN**→*Solve* submenu) for GSPN models, as well as the choice of carrying out either a numerical analysis or a simulation run on a SWN model (**SWN** menu) - or on a E-GSPN model (**E-GSPN** menu) - causes the *Console* window of Fig.3.16 to pop-up: to launch the corresponding execution module press the “Start” button. When a solution module is launched, then the “Interrupt” button becomes active: press it to interrupt the execution of the current solution module.

WARNING! In some cases, the “Interrupt” action actually does not kill the launched process but only some sub-processes originated by the former: then it is better to check from a terminal if the process is still alive or not.

When the “Clear” button is pressed then a previous computed solution is removed. Finally the “OK” button allows to close the *Console* window.

3.1.7 GSPN Menu

The GSPN menu contains the options that allows to launch *GreatSPN2.0.2* solvers for GSPN models.

GSPN→*Struct* to compute the structural properties of the current loaded GSPN model. It pops-up a sub-menu which contains in turns the following options:

- **P-invariants**: to compute the minimal-support non-negative place invariants;

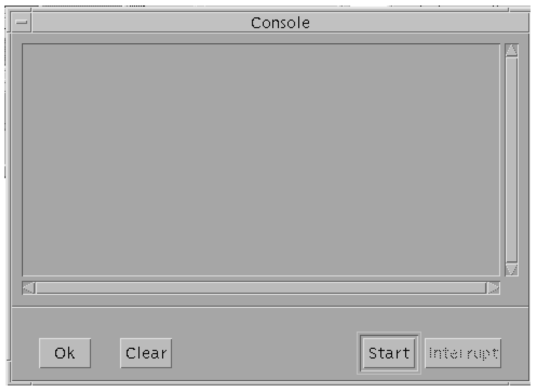


Figure 3.16: *GreatSPN2.0.2* Console

- **T-invariants**: to compute the minimal support transition invariants;
- **Minimal deadlocks**: to compute the minimal deadlocks, i.e., the sets of places that once emptied cannot be marked anymore;
- **Minimal traps**: to compute the minimal traps, i.e., the sets of places that once marked cannot loose tokens anymore;
- **ECS Confusion ME SC CC**: to compute the ECS, Extended Conflict Sets of immediate transitions, Confusion between transitions (non free-choice conflicts), ME, structural and marking Mutual Exclusion between transitions, SC, Structural Conflicts between non-mutually exclusive transitions, and CC, structural Causal Connection between transitions.
- **Structural boundedness**: to verify the structural boundedness and, in case of unbounded nets, to compute the transition sequences that can arbitrarily increase the marking of some place.

The computation of the above structural properties requires that the net description is saved on a file.

GSPN→*Solve* to carry out analysis of the current loaded GSPN model, in particular:

- **Compute TRG**: to generate the Tangible Reachability Graph;
- **Compute EMC**: to compute the Embedded Markov Chain, that is the CTMC associated to the TRG;
- **GSPN solution**: to compute the CTMC solution, i.e., the probability distribution of the number of tokens in each place and the performance results. GSPN solution can be obtained both in *steady* state and in *transient* state.

In case of transient solution request, when the “Start” button of the *Console* window (Fig.3.16) is pressed, the *Input* window of Fig.3.17 appears. The value (positive real) of the time instant at which the transient solution will be computed has to be inserted in the corresponding box *transient time* .....

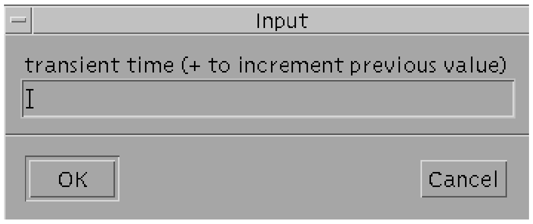


Figure 3.17: *GreatSPN2.0.2* Input window

GSPN→*Simulation...* to play the interactive token-game and to launch the interactive simulation. When this option is chosen the *Simulation* window pops-up (Fig.3.18) and all the transitions of the current loaded model that are enabled in the initial marking become blinking.

Token game. To simulate a possible behavior of the current loaded GSPN model simply click with the leftmost button of the mouse over the enabled (i.e. blinking) transition you want to fire it. By default the “Untimed” and the “Forward” options of the *Simulation* window are set to play the forward token game: it is possible to play the backward token game by setting the “Untimed” and “Backward” options in the *Simulation* dialog box.

“Moves” area allows to set the slowness of the token flow from the input places of the firing transition to its output places: higher is the value filled in this area slower is the token flow.

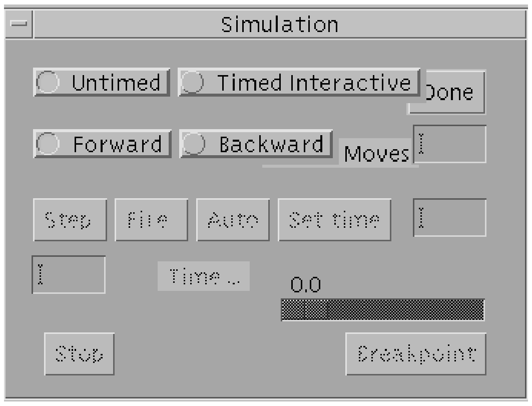


Figure 3.18: *GreatSPN2.0.2* Simulation window

Simulation. To activate the interactive simulation of the current loaded GSPN model set the “Timed Interactive” option: when this option is set, then the “Step”, “Fire”, “Auto”, “Set time”, “Stop” and “Breakpoint” buttons become available. To simulate the behavior step-by-step press the “Step” button: the area located below this button allows to set the number of automatic firings, e.g., if you fill in the value 2, then two successive firings are displayed. Press the “Auto” button to start the simulation run: the firing sequences are displayed in the canvas automatically until an interruption command is given by the user. To interrupt the execution press the “Stop” button, the transition throughputs computed up to the interruption (transient results) are visualized in the canvas and they are saved in the `netname.sta` file. To restart the simulation from the interrupted point press the “Auto” button again. To terminate the simulation execution press the “Stop” button first, and then the “Done” button.

WARNING! The interactive simulation does not work properly on some GSPN models: to use simulation techniques on a GSPN model in order to obtain performance results is better to use the simulation solvers available from the **E-GSPN** menu.

3.1.8 SWN Menu

The SWN menu contains the following options:

SWN→*Symbolic* to compute solution of SWN models. In particular:

- **Simulation**: to launch the simulation for colored models using an abstract representation of markings, i.e., symbolic markings;
- **Compute RG**: to compute the Symbolic Reachability Graph of the model and to obtain performance indices in steady state;
- **Transient**: to compute the Symbolic Reachability Graph of the model and to obtain performance indices in transient state.

SWN→*Ordinary*

- **Simulation**: to launch the simulator for colored models using ordinary markings;
- **Compute RG**: to compute the Reachability Graph of the model and to obtain performance indices in steady state;
- **Transient**: to compute the Reachability Graph of the model and to obtain performance indices in transient state.

SWN Reachability Graph computation The launch of a Reachability Graph solver - either symbolic or ordinary - is carried out by pressing the “Start” button of the *Console* window (Fig. 3.16) and it causes a *RG Options* window (see Fig. 3.19) to appear. It is possible to obtain a verbose description of the symbolic (or ordinary) reachability graph by setting on the “Verbose Show” toggle of this window an by choosing the “OK” button. The execution is displayed on the *Console* window and the results are visualized in the *GreatSPN2.0.2* canvas.

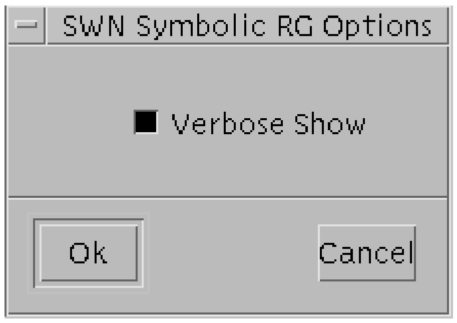


Figure 3.19: SWN Reachability Graph Options window.

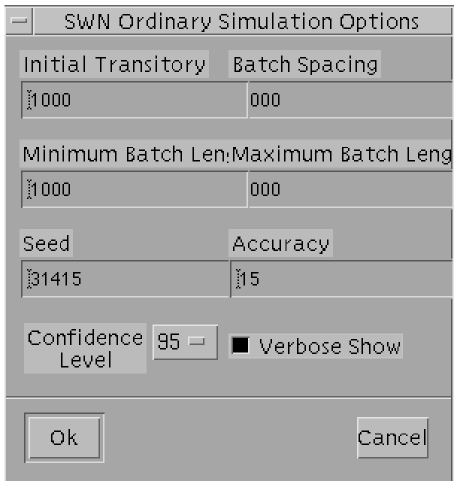
SWN simulation The launch of a SWN simulation - either symbolic or ordinary - is carried out by pressing the "Start" button of the *Console* window (Fig. 3.16) and it causes a *Simulation Options* window (see Fig. 3.19) to appear. Through this window, the user can modify the default values of the simulation parameters, in particular:

- "Initial Transitory": the length of initial transitory period that has not to be taken into account for the computation of the performance measures;
- "Batch Spacing": the length of evolution phase between batches that has to be discarted;
- "Minimum Batch Length": the dimension of the minimum batch;
- "Maximum Batch Length": the dimension of the maximum batch;
- "Seed": the seed of the random number generator;
- "Accuracy": the precision of the approximation in the parameters estimation;
- "Confidence Level": the confidence level in the parameters estimation.

All these parameters, except for the confidence level, can be modified by typing directly in the corresponding area of the *Simulation Options* window. The "Confidence Level" can be changed instead by choosing the desired value from the pull-down menu that pops up when the corresponding toggle is clicked. To obtain a verbose description of the simulation results set the "Verbose Show" toggle of this window.

Click on the "OK" button to confirm the settings: the simulation execution is displayed on the *Console* window and the results are visualized in the *GreatSPN2.0.2* canvas.

SWN transient The launch of a SWN transient solver - either symbolic or ordinary - is carried out by pressing the "Start" button of the *Console* window (Fig. 3.16) and it causes the *Input* window of Fig. 3.17) to appear. As is the case of GSPN transient solutions, the *transient time...* area of this window has to be filled in with the value (positive real) of the time instant at which the SWN transient solution will be computed.


SWN Ordinary Simulation Options

Initial Transitory: 1000
Batch Spacing: 000
Minimum Batch Len: 1000
Maximum Batch Leng: 000
Seed: 31415
Accuracy: 15
Confidence Level: 95
■ Verbose Show

Figure 3.20: SWN Simulation Options window.

3.1.9 E-GSPN Menu

The E-GSPN menu concerns the Extended-GSPN models, that is GSPN models in which firing times of timed transitions can have more general distributions than the negative exponential. The **E-GSPN** menu contains the following options:

E-GSPN→*Simulation* to launch the simulation;

E-GSPN→*Compute RG* to compute the Reachability Graph of the model and to obtain the performance indices in steady state;

E-GSPN→*Transient* to compute the Reachability Graph of the model and to obtain performance indices in transient state.

All the solvers launched from the **E-GSPN** menu come from the same source files used for producing the SWN solvers and they have the same functionalities of the latters.

WARNING! Note that the solvers lauched from the **E-GSPN** menu work also if the file *netname.dis*, used for the general temporal specifications of the timed transitions, has not been created (or it is not located in the same directory where the net definition files of the current model are saved).

3.1.10 Help Menu

The Help menu, located on the right of the *menu bar*, contains the following options:

Help→*Mouse Help* to display information about the use of the mouse buttons; the *Mouse Help* window pos-up (Fig.3.21) describing the current functions of the mouse buttons. To remove the *Mouse Help* window, deactivate the **Help**→*MouseHelp* option.

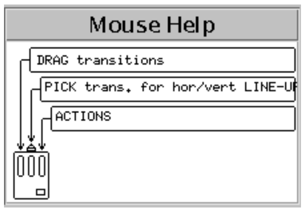


Figure 3.21: Mouse help window.

Help→*About* when this option is chosen a window displaying the current release of *GreaSPN* pops-up: to remove the window, click on the “OK” button.

3.2 The Object bar

The *object bar*, located just below the *menu bar* on the *GreatSPN2.0.2* Control Panel (see Fig. 3.2), contains 10 icons which allow to perform operations - add/delete/change... - on a specific object of the PN model. To execute an operation on a specific object:

- activate the **Action** menu (see Fig. 3.7) by pressing the right mouse button on any position in the *canvas*;
- click with the left mouse button over the desired action: the selected action is displayed on the *status bar* of the CP and it becomes the default action until a new one is chosen;
- select the object type by clicking on the corresponding icon button of the *object bar*: the default action will affect only the objects of the type currently selected.

Depending on the type of action activated and of the type of selected object, different windows will pop-up; in the following, going from the left to the right, each icon of the *object bar* is described, together with the possible actions that can be carried out on the corresponding object type.

3.2.1 Places

It is the first icon of the *object bar* and it is depicted as a circle.

Add: *add a new place* operation causes the shape of the mouse cursor to change into a circle: to locate the new place in the *canvas*, move the mouse cursor and click the left mouse button in the desired position.

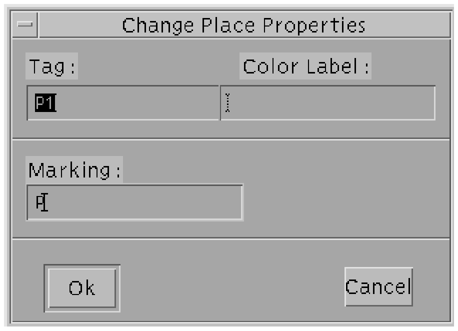


Figure 3.22: Dialog box for changing place properties.

Change: *change place properties* operation causes the dialog box of Fig. 3.22 to pop-up.

This dialog box is characterized by the “Tag:” area, that contains the name of the place, the “Color Label:” area, that contains the color domain definition in case of colored places (SWN models) and the “Marking:” area, that contains either a non negative number or a marking parameter which indicates the initial marking of the place. To change one of the above mentioned place properties (either place name or color domain or initial marking), click with the left (middle) mouse button over the corresponding area of the *Change Place Properties* dialog box in order to activate it and write the proper definition.

Renaming of places via GUI is subject to the constraint that places of a model must to have distincts tags (i.e., names); the attempt of renaming a place with an existing tag (i.e., with a string corresponding to the name of another place of the current model) provokes an error message window to pop-up. This constraint has been introduced to avoid problems in the computation of performance results, in particular performance indices that are functions of the places with the same name. However, if the modeler wants to define places with the same tag, then he/she has to modify directly the net definition file of the model.

WARNING! The assignment of an undefined initial marking parameter to a place provokes an error message window to pop-up. This type of control is not carried out for the color domain definition: be careful then to assign a correct color domain to a place, i.e., both by following the SWN grammar (see Table A.1 of Appendix A) and by defining basic color classes before.

Select: *select a place* operation allows to select a specific place of the current loaded model by clicking over the place with the left mouse button; this action causes a broken rectangle to surround the place. Selection operation is normally used along with other operations, e.g., with the *Add* action to make a copy of the place together with its input and output sets. To reset the *Select* operation, choose in the **Action** menu the *End Selection* option (the broken rectangle that surrounds the selected area, in this case a place, will disappear).

Move: *move a place* operation causes the shape of the mouse cursor to change into a cross; to move a place simply click with the left mouse button over the place to be moved, move the mouse cursor to choose the desired location in the *canvas* to put the place and click again to fix the place in the desired location.

Delete: *delete a place* operation allows to delete a place present in the *canvas*; to delete an existing place click over the place to be removed with the left mouse button.

Show: *show a place* operation allows to visualize place properties; to choose the property of a place to be displayed click with the right mouse button over the place to pop-up the *Place Property* menu and then click with the left mouse button over the corresponding option to set the desired property. The *Place Property* menu contains the following options:

P-invariants To display P-invariants the place belongs to: all the places belonging to the same P-invariant start blinking and a *Show* menu pops-up in which the algebraic expression of the current P-invariant is visualized (this expression is also visualized on the *status bar*).

Minimal deadlocks To display minimal deadlocks the place belongs to: all the places belonging to the same minimal deadlock start blinking and a *Show* menu pops-up in which the algebraic expression of the current minimal deadlock is visualized (this expression is also visualized on the *status bar*).

Minimal traps to display minimal traps the place belongs to: all the places belonging to the same minimal trap start blinking and a *Show* menu pops-up in which the algebraic expression of the current minimal trap is visualized (this expression is also visualized on the *status bar*).

WARNING! To visualize the above properties, i.e., P-invariants, minimal deadlocks and minimal traps it is necessary to launch the corresponding structural solvers before, by choosing the related options on the **GSPN**→*Struct* submenu, otherwise a window will pop-up displaying a warning message of type: *Sorry, no up-to-date place invariants (or deadlocks or traps) available*.

Implicit places To display pairs of implicit places : the couple of implicit places start blinking and a *Show* menu pops-up in which the implication is visualized (it is also visualized on the *status bar*).

Absolute Marking Bounds To display the structural bounds on the number of tokens in a place. To compute the upper bound click with the left mouse button over the place, while to compute the lower bound click with the left-right (or middle) mouse buttons; bounds are visualized both on the *Show* window which pops-up and on the *status bar*. In case of unboundedness, a message will be displayed.

Average Marking Bounds To display the bounds for the steady state mean of a place. Bounds are obtained from the net structure, the initial marking and the transition rates by solving a linear programming problem. To compute the upper bound click with the left mouse button over the place, while to compute the lower bound click with the left-right (or middle) mouse buttons; bounds are visualized both on the *Show* window which pops-up and on the *status bar*. In case of unboundedness, a message will be displayed.

WARNING! Absolute and average marking bounds can be computed only if the `lp_solve` package[28], used for solving linear programming problems, has been installed and the *GreatSPN2.0.2* environment variable GSPN2LPSOLVE has been set with the path-name of the executable.

End Show To reset the *Show* option.

3.2.2 Transitions

There are three icons corresponding to a transition object: the *IMM* icon, depicted as a thin black bar, the *EXP* icon, depicted as a thick white bar, and the *DET* icon, depicted as a thick black bar. These icons correspond, respectively, to an immediate transition object, an exponentially distributed timed transition object and a deterministic distributed timed transition object.

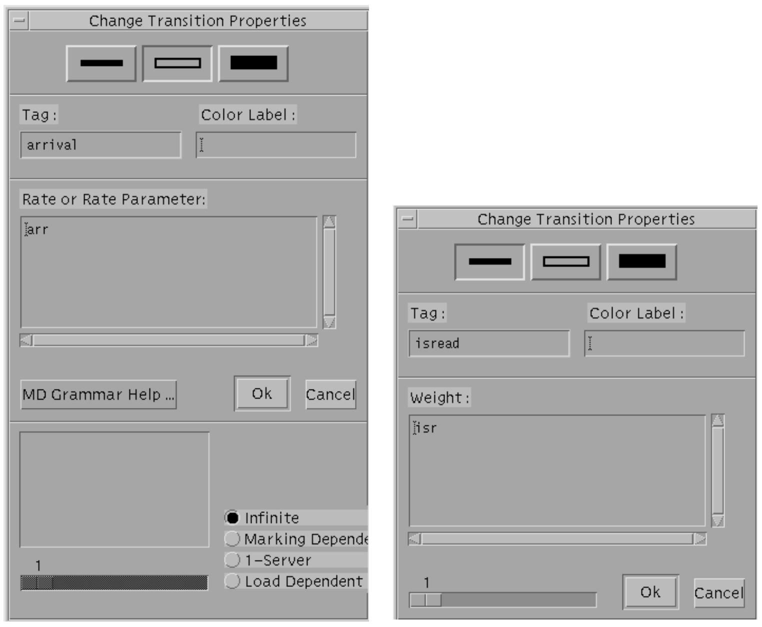
Add: *add a transition* operation causes the shape of the mouse cursor to change into the corresponding transition icon - *IMM*, *EXP* or *DET* - depending on the type of transition selected. To locate the new transition in the *canvas*, move the mouse cursor and click the left mouse button in the desired position.

Change: *change a transition properties* operation causes a dialog box to pop-up.

Timed transitions.

The dialog box in this case is the one of Fig. 3.23(A) in which the *EXP* icon, located on the top of the window, is pressed. In case *DET* icon is pressed, i.e., it is the *Change Transition Properties* for a deterministic transition, the bottom part of the dialog box, which concerns the type of server semantics to be set, is not present. The common areas of the dialog box for exponentially distributed transitions and for deterministic distributed transitions are the followings:

- "Tag:" it contains the name of the transition. By default, names of timed transitions are of type `T#`, where `#` is a number given in progressive order with respect to the transition creation.
- "Color Label:" it contains the guard definition of the transition (SWN models). No syntactical control is carried out for the guard of its definition.
- "Rate or Rate Parameter:" for exponentially distributed transitions, it contains either the value of the rate or the name of a rate parameter. In the latter case the rate parameter has to be previously



Tag: arrival
Color Label:
Rate or Rate Parameter: arr
[✓ Infinite] Marking Depende 1−Server Load Dependent
1

Tag: isread
Color Label:
Weight: isr
1

(A) **(B)**

Figure 3.23: Windows for defining/changing properties of timed (A) and immediate (B) transitions.

defined, otherwise an error message will be displayed. For deterministic distributed transitions, values assigned in this area are considered as delays. By default, the rate (delay) value assigned is 1.0.

WARNING! In case of timed transition, a zero value as transition rate is accepted even though this assignment will cause a segmentation fault when launching the solutions. Transition rates assigned from GUI, are stored in the net definition file with at most six decimal digits, i.e., if you assign a value lower than $10E-6$ to a transition rate then the value will be truncated at the 6^{th} decimal digit in the `.net` file.

To change one of the above mentioned transition properties (either transition name or guard or rate), click with the left (middle) mouse button over the corresponding area of the *Change Transition Properties* dialog box in order to activate it and write the proper definition.

For exponentially distributed transitions, *GreatSPN2.0.2* allows the user to define different server semantics. Let $\mu(M)$ be the marking dependent parameter of the negative exponential distribution $F(x,M) = Pr\{X \leq x\} = 1 - e^{-\mu(M)x}$ associated to a timed transition t, and let $ED(t,M)$ be the enabling degree of t in marking M, then depending on the semantics adopted for the timed transition, a different marking dependent firing rate $\mu(M)$ is assigned.

Infinite Every enabling set of tokens is processed as soon as it forms in the input places of the transition. Its corresponding firing delay is generated at this time, and the timers associated with all these enabling sets run down to zero concurrently. Multiple enabling sets of tokens are thus processed in parallel.

The firing rate of t is given by the function $\mu(M) = ED(t,M)\mu$, where μ is the value set in the "Rate or Rate Parameter:" area of the *Change Transition Properties* window. This semantics is the default option, i.e., the "Infinite" toggle of the *Change Transition Properties* dialog box is switched on.

Marking Dependent Firing rate of t is function of the marking of a subset of places of the net; this subset of places is not necessary equal to the set of input and inhibitor places of the transition. To choose this option, click with the left (left-right) mouse button over the "Marking Dependent" toggle to switch it on and to define the function $\mu(M)$ in the "Marking Dependent Definition" area, follow the syntax given in Table A.3 of Appendix A. It is possible to display the grammar on line by clicking over the "MD Grammar Help ..." button.

K-Server In case of single server semantics, i.e., $K = 1$, random firing delay is set when the transition becomes first enabled, new delays are generated upon transition firing if the transition is still enabled in the new marking. This means that enabling sets of tokens are processed serially and that the temporal specification associated with the transition is independent of the enabling degree, i.e., the firing rate of transition t is given by the (constant) function $\mu(M) = \mu$, where μ is the value set in the "Rate or Rate Parameter:" area of the *Change Transition Properties* window. In case of multiple server semantics, i.e., $K \in \{2,...,127\}$, enabling sets of tokens are processed as soon as they form in the input places of the transition up to the maximum degree of parallelism K. For larger values of the enabling degree, the timers associated with new enabling sets of tokens are set only when the number of concurrently running timers decreases below the value K. The firing rate of transition t is given by the function $\mu(M) = min(ED(t,M),K)\mu$. To choose this option, click with the left (left-right) mouse button over the "1-Server" toggle to switch it on: the scrollbar located at the bottom left of the dialog box becomes active. In case of K-Servers semantics, with $K > 1$ move the scrollbar by keeping the mouse button pressed to fix the desired value for K. The "1-Server" toggle will be changed into "K-Server" toggle automatically when the mouse button will be released.

Load Dependent Firing rate of t is a function, given in tabular form, of its enabling degree $\mu(M) = f(ED(t,M))$. This semantics is a particular case of marking dependent semantics in which the firing rate of t when $ED(t,M) = K$ corresponds to the the throughput of a short-circuited queueing network in which exactly K jobs are circulating in it (i.e., t represents the load-dependent equivalent server).

To choose the load dependent server semantics switch on the "Load Dependent" toggle to activate the scrollbar, then move the scrollbar by keeping the mouse button pressed to fix the desired value *MAX* (it corresponds to the maximum population of the short-circuited queueing network). When the mouse button is released, *MAX* lines are added in the area located above the scrollbar and they appear as follows:

```
Rate --> 1.000000
```

```
2 --> 1.000000
3 --> 1.000000
...
MAX --> 1.000000
```

Each line is of type `# --> ratevalue`, apart from the first one in which the string `Rate` replaces the number `1`, where `ratevalue` corresponds to the value assigned to the firing rate when the enabling degree of the transition is equal to `#`. By default, all the `ratevalue` are equal to 1.000000. To change one of the `ratevalue`, click with the left mouse button over the corresponding line: automatically, the `ratevalue` appears on the "Rate or Rate Parameter (Weight)" area. Type the desired value and then press `<Return>` command: the new value for the `ratevalue` will be set and the corresponding line in the area above the scrollbar will be updated.

Immediate transitions.

The dialog box in this case is the one of Fig. 3.23(B) in which the *IMM* icon, located on the top of the window, is pressed. It is characterized by the following areas:

- "Tag:" it contains the name of the transition. By default, names of immediate transitions are of type `t#`, where `#` is a number given in progressive order with respect to the transition creation.
- "Color Label:" it contains the guard definition of the transition (SWN models). No syntactical control is carried out for the guard at the moment of its definition.
- "Weight:" it contains the weight of the transition. By default the weight value assigned is 1.0. Admissible values are non-negative real numbers, in case of conflict among different immediate transitions a normalization of the weight is performed when the solution are launched.

To change one of the above mentioned transition properties (either transition name or guard or weight), click with the left (middle) mouse button over the corresponding area of the *Change Transition Properties* dialog box in order to activate it and write the proper definition.

Finally, on the bottom-left part of the *Change Transition Properties* dialog box, there is a scrollbar that allows to assign a priority level to the transition. By default, the priority level is one; the admissible priority levels range from 1 to 126. To change the priority level of the current immediate transition, simply click with the mouse button over the scrollbar and move it by keeping the mouse button pressed until you find the desired value.

WARNING! Renaming of transitions via GUI is subject to the constraint that transitions of a model must to have distincts tags (i.e., names); the attempt of renaming a transition with an existing tag (i.e., with a string corresponding to the name of another transition of the same type) provokes an error message window to pop-up. This constraint has been introduced to avoid problems in the computation of performance results, in particular performance indices that are functions of the transitions with the same name. However, if the modeler wants to define transitions with the same tag, then he/she has to modify directly the net definition file of the model.

Select: *select a transition* operation allows to select a specific transition of the current loaded model by clicking over the transition with the left mouse button; this action causes a broken rectangle to surround the transition. Selection operation is normally used along with other operations, e.g., with the *Add* action to make a copy of the transition together with its input and output sets. To reset the *Select* operation, choose in the **Action** menu the *End Selection* option (the broken rectangle that surrounds the selected area, in this case a transition, will disappear).

Move: *move a transition* operation causes the shape of the mouse cursor to change into a cross; to move a transition simply click with the left mouse button over the transition to be moved, move the mouse cursor to choose the desired location in the *canvas* to put the transition and click again to fix the transition in the desired location.

Delete: *delete a transition* operation allows to delete a transition present in the *canvas*; to delete an existing transition click over the transition to be removed with the left mouse button.

Rotate: *rotate a transition* operation causes the shape of the mouse cursor to change into a transition icon (either *IMM* or *EXP* or *DET* icon depending on which transition icon is set on the *object bar*); to rotate a transition click over the transition with the left mouse button: each “click” of the mouse button will rotate the transition clockwise of a multiple of 45 degrees.

Show: *show a transition* operation allows to visualize transition properties; to choose the property of a transition to be displayed click with the right mouse button over the transition to pop-up the *Transition Property* menu and then click with the left mouse button over the corresponding option to set the desired property. The *Transition Property* menu contains the following options:

T-invariants To display T-invariants the transition belongs to: all the transitions belonging to the same T-invariant start blinking and a *Show* menu pops-up in which the algebraic expression of the current T-invariant is visualized (this expression is also visualized on the *status bar*).

ECS To display the Extended Conflict Sets (ECS) of the set of immediate transitions: all the immediate transitions belonging to the same ECS start blinking and a *Show* menu pops-up in which the algebraic expression of the current ECS is visualized (this expression is also visualized on the *status bar*).

WARNING! Since the ECSs are computed only on the subset of immediate transitions, then to visualize them it is necessary that the *IMM* icon of the *object bar* is set. Otherwise, if another transition icon (either *EXP* of *DET*) is set, the *show ECS* operation causes a warning message to pop-up (i.e., *"Sorry, NO Ext.Conflict Sets is computed for timed transitions"*) although the request has been carried out by clicking on a specific immediate transition.

ME To display the pairs of transitions that are structurally mutually exclusive.

SC To display the pair of transitions that are in structural conflict relation.

CC To display the pair of transitions that are in causal connection relation.

Unbounded Sequences To display the firing sequences of transition that add tokens to an unbounded place. Click over the unbounded place, the place and the unbounded firing sequence start blinking alternately and the algebraic expression of the firing sequence is displayed in the *Show* window that pops-up; to visualize all the unbounded firing sequences, click repeatedly over the same unbounded place, each click of the mouse allows, in turn, to show a unbounded firing sequence.

WARNING! To visualize the above properties, i.e., T-invariants, ECS, ME, SC, CC, and Unbounded Sequences it is necessary to launch the corresponding structural solvers before, by choosing the related options on the **GSPN**→*Struct* submenu, otherwise a window will pop-up displaying a warning message of type: *"Sorry, no up-to-date transition invariants (or conflict sets or ...) available"*.

Actual liveness Bounds To display the actual liveness bounds of a transition.

LP liveness Bounds To display the liveness bounds of a transition.

LP throughput Bounds To display the bounds for the steady state throughput of a transition. Bounds are obtained from the net structure, the initial marking and the transition rates by solving a linear programming problem. To compute the upper bound click with the left mouse button over the transition, while to compute the lower bound click with the left-right (or middle) mouse buttons; bounds are visualized both on the *Show* window which pops-up and on the *status bar*. In case of unboundedness, a message will be displayed.

End Show To reset the *Show* option.

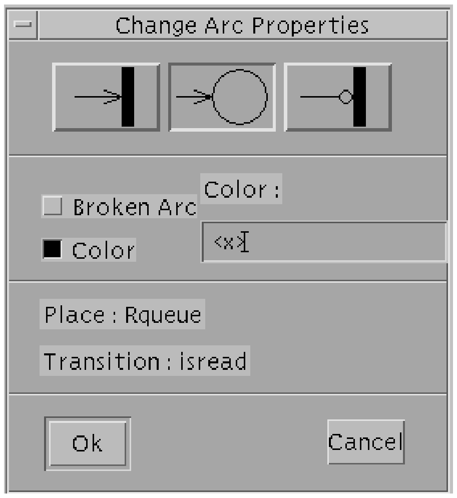
3.2.3 Arcs

It is the fifth icon of the *object bar* and it is depicted as an arrow.

Add: *add an arc* operation causes the shape of the mouse cursor to change into an arrow: to connect a place (transition) to a transition (place) click with the left mouse button over the place (transition) first, and then click over the transition (place) with the left mouse button. To add an inhibitor arc click with the middle mouse button over the inhibitor place (inhibited transition) first and them click over the inhibited transition (inhibitor place) with the left mouse button.

WARNING! Since, by definition of PNs, it is not possible to have an arc connecting two objects of the same type, *GreatSPN2.0.2* does not allow to connect either two transitions or two places with an arc. In case, you have clicked on the first object and then you realize that this was not you intended to do, it is better to continue and to terminate the *add arc* operation and then to delete the just added wrong arc than to suspend the operation by activating another action since a suspended arc provokes a segmentation fault.

Change: *change an arc* operation causes the dialog box of Fig.3.24 to pop-up. The upper part of the dialog


Change Arc Properties

☐ Broken Arc

■ Color

Color :

<x>

Place : Rqueue

Transition : isread

Figure 3.24: Change Arc Properties window.

box contains three icons. Always, only one of them is active and it indicates the current type of arc; in particular, going from the left to the right, the first icon represents an input arc, the second represents an output arc and the third one represents an inhibitor arc with respect to the transition. The tags of the place and of the transition connected with the arc are displayed in the bottom part of the dialog box. For example, the dialog box of Fig. 3.24 displays the properties of the output arc which connects transition *isread* to the place *Rqueue*. Below the three icons, there are two toggles: the “Broken Arc” toggle and the “Color” toggle.

- “Broken Arc”: when it is not set, i.e., the corresponding rectangle is white, then the arc is fully displayed in the *canvas*; when it is set, i.e., the corresponding rectangle is black, then the arc is partially displayed in the *canvas*, this means that only the ending parts of the broken line representing the arc are displayed.

  WARNING! To draw a broken arc it is necessary to break the line representing the arc with at least two intermediate points first, then to set the “Broken Arc” toggle.

- “Color”: it is related with the area located on the right of the toggle. When it is not set, i.e., the corresponding rectangle is white, then the “Multiplicity” area contains the multiplicity value associated to the arc. When it is set (in case of SWN models), i.e., the corresponding rectangle is black, then the “Color:” area contains the arc function associated to the arc. Arc function definitions are given in the SWN definition grammar of Table A.1 of Appendix A.

By default, the two toggles described above are not set and the arc multiplicity is equal to one.

Move: *move an arc* operation allows to draw the arc as a broken line by adding some intermediate points. To add an intermediate point just click with the left mouse button over the arc and move the mouse cursor in the *canvas* to choose the point as intermediate one, then fix the point by clicking again with the left mouse button. To change the source (destination) of an arc, click with the middle mouse button over the source (destination) object and then click with the left mouse button over the new source (destination) object.

Delete: *delete an arc* operation allows to delete an arc present in the *canvas*; to delete an existing arc click over the arc to be removed with the left mouse button.

3.2.4 Marking parameters

It is the sixth icon of the *object bar* and it is depicted as a token.

Add: *add a marking parameter* operation is used to create a new marking parameter that will be used as initial marking of the GSPN system when solutions are launched. When this action is active, the shape of the mouse cursor is an arrow, click on a free location of the *canvas* to fix the position of the marking parameter that is going to be defined: this action causes the dialog box of Fig. 3.25 to pop-up.

The dialog box is characterized by two areas: the “Label:” area, that has to be filled with the name of the marking parameter, and the “Marking:” area, that has to be filled with a non negative integer. To fill in the areas of the *Create Marking Parameter* dialog box click over the corresponding areas to activate them and then type the related name or value. Finally, either click over the “OK” button to confirm the settings or click over the “Cancel” button to do not confirm.

The attempt to insert a negative value in the “Marking:” area causes a warning message to be displayed. The name of the marking parameter has to be unique in the current loaded model.

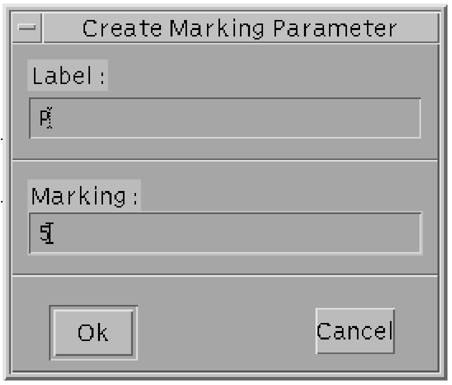


Figure 3.25: Create Marking Parameter dialog box.

Change: *change a marking parameter* allows to change specification of an existing marking parameter. To change the specifications of an existing marking parameter click over the marking parameter located somewhere in the *canvas*: this action causes a dialog box similar to the one of Fig. 3.25 to pop-up[1].

To change the values in the areas of the *Change Marking Parameter* dialog box click over the corresponding areas to activate them and then overwrite the old values with the new ones. Finally, either click over the "OK" button to confirm the changes or click over the "Cancel" button to keep the old settings.

Select: *select a marking parameter* operation allows to select a specific marking parameter of the current loaded model by clicking over the marking parameter with the left mouse button; this action causes a broken rectangle to replace the marking parameter. Selection operation is normally used along with other operations, e.g., with the *Move* action to move the marking parameter in a different location of the *canvas*. To reset the *Select* operation, choose in the **Action** menu the *End Selection* option (the broken rectangle that replaces the selected marking parameter, will disappear).

Move: *move a marking parameter* operation causes the shape of the mouse cursor to change into an arrow; to move a marking parameter simply click with the left mouse button over the marking parameter to be moved, move the mouse cursor to choose the desired location in the *canvas* to put the marking parameter and click again to fix the marking parameter in the desired location.

Delete: *delete a marking parameter* operation allows to delete a marking parameter present in the *canvas*; to delete an existing marking parameter click over the marking parameter to be removed with the left mouse button.

[1]Actually, the dialog box differs only for the title that in case of change action is *Change Marking Parameter*.

3.2.5 Rate parameters

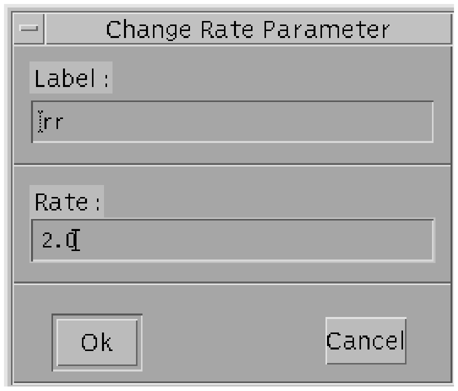
It is the seventh icon of the *object bar* and it is depicted with a clock and a transition.

Add: *add a rate parameter* operation is used to create a new rate parameter that will be used in the temporal specifications of one or more timed transitions of the GSPN system. When this action is active, the shape of the mouse cursor is an arrow, click on a free location of the *canvas* to fix the position of the rate parameter that is going to be defined: this action causes a dialog box similar to the one of of Fig. 3.26 to pop-up[2].

The dialog box is characterized by two areas: the "Label:" area, that has to be filled with the name of the rate parameter, and the "Rate:" area, that has to be filled with a non negative integer. To fill in the areas of the *Create Rate Parameter* dialog box click over the corresponding areas to activate them and then type the related name or value. Finally, either click over the "OK" button to confirm the settings or click over the "Cancel" button to do not confirm.

The attempt to insert a negative value in the "Rate:" area causes a warning message to be displayed. The name of the rate parameter has to be unique in the current loaded model.

Change: *change a rate parameter* allows to change specification of an existing rate parameter. To change the specifications of an existing rate parameter click over the rate parameter located somewhere in the *canvas*: this action causes the dialog box of Fig. 3.26 to pop-up.



Label: rr

Rate: 2.0

Figure 3.26: Change Rate Parameter dialog box.

To change the values in the areas of the *Change Rate Parameter* dialog box click over the corresponding areas to activate them and then overwrite the old values with the new ones. Finally, either click over the "OK" button to confirm the changes or click over the "Cancel" button to keep the old settings.

Select: *select a rate parameter* operation allows to select a specific rate parameter of the current loaded model by clicking over the rate parameter with the left mouse button; this action causes a broken rectangle to

[2]Actually, the dialog box differs only for the title that in case of create action is *Create Rate Parameter*.

replace the rate parameter. Selection operation is normally used along with other operations, e.g., with the *Move* action to move the rate parameter in a different location of the *canvas*. To reset the *Select* operation, choose in the **Action** menu the *End Selection* option (the broken rectangle that replaces the selected rate parameter, will disappear).

Move: *move a rate parameter* operation causes the shape of the mouse cursor to change into an arrow; to move a rate parameter simply click with the left mouse button over the rate parameter to be moved, move the mouse cursor to choose the desired location in the *canvas* to put the rate parameter and click again to fix the rate parameter in the desired location.

Delete: *delete a rate parameter* operation allows to delete a rate parameter present in the *canvas*; to delete an existing rate parameter click over the rate parameter to be removed with the left mouse button.

Show: *show rate parameters* operation allows to visualize the rates/rate parameters associated to the timed transitions as well as the weight associated to the immediate transitions of the current loaded model; this action causes the **View**→*Rate* option to be switched on.

End Show: To reset the *Show* option.

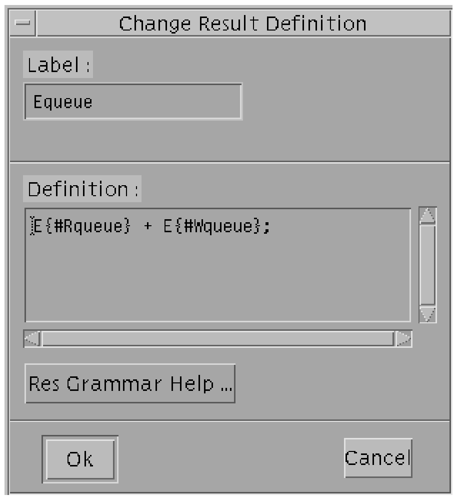
3.2.6 Result definitions

It is the eighth icon of the *object bar* and it is depicted with a bar diagram.

Add: *add a result* operation is used to create a user-defined performance result by following the grammar syntax of Tab. A.3. When this action is active, the shape of the mouse cursor is an arrow, click on a free location of the *canvas* to fix the position of the performance result name that is going to be defined: this action causes a dialog box similar to the one of Fig. 3.27 to pop-up. The dialog box is characterized by two areas: the "Label:" area that has to be filled with the name of the performance result, e.g., in Fig. 3.27 the name `Equeue` has been assigned; and the "Definition:" area that has to be filled with the definition of the performance result, e.g., in Fig. 3.27, the performance result has been defined as the sum of the steady state number of tokens in place `Rqueue` and of the steady state number of tokens in place `Wqueue`. It is possible to display the grammar on line by clicking over the "Res Grammar Help..." button.

WARNING! In case of steady state solutions, both the capital and the small letters `E,e` (`P,p`) can be used to define the mean (the probability). In case of transient solutions, instead, the small letter has to be used.

Change: *change a result* operation allows to change specifications of an existing user-defined performance result. To change a previous definition of a given performance result, click over its name located somewhere in the *canvas*: this action causes the dialog-box of Fig. 3.27 to pop-up. To change the values in the areas of



```
E{#Rqueue} + E{#Wqueue};
```

Figure 3.27: Change Result Definition dialog box.

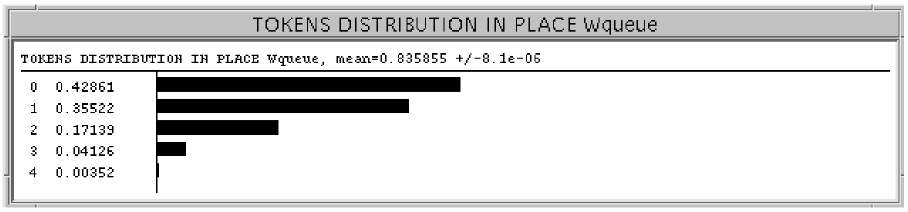
the *Change Result Definition* dialog box click over the corresponding areas to activate them and then over-write the old values with the new ones. Finally, either click over the "OK" button to confirm the changes or click over the "Cancel" button to keep the old settings.

Select: *select a result* operation allows to select a specific user-defined performance result of the current loaded model by clicking over the performance result name with the left mouse button; this action causes a broken rectangle to superpose the performance result name. Selection operation is normally used along with other operations, e.g., with the *Move* action to move the performance result name in a different location of the *canvas*. To reset the *Select* operation, choose in the **Action** menu the *End Selection* option (the broken rectangle that superposes the selected performance result name, will disappear).

Move: *move a result* operation causes the shape of the mouse cursor to change into an arrow; to move a performance result simply click with the left mouse button over the performance result to be moved, move the mouse cursor to choose the desired location in the *canvas* to put the performance result and click again to fix it in the desired location.

Delete: *delete a result* operation allows to delete a performance result present in the *canvas*; to delete an existing performance result click over the performance result to be removed with the left mouse button.

Show: *show result* operation allows either to visualize the definition of the performance result or, in case of GSPN models, to display the token distribution in places. In the first case, just click with the left mouse button over the interested performance result name: a *Show* window will pop-up displaying the current definition of the result. In the second case, instead, click with the left mouse button over the interested place: a window similar to the one of Fig. 3.28 will pop-up displaying the token distribution of the place, either steady state or transient depending on which solver has been launched last. To quit a *Token distribution* window, click with the left mouse button over it.



```
TOKENS DISTRIBUTION IN PLACE Wqueue, mean=0.835855 +/-8.1e-06
 0  0.42861
 1  0.35522
 2  0.17139
 3  0.04126
 4  0.00352
```

Figure 3.28: Token distribution dialog box

3.2.7 Changing place/transition tags

It is the ninth icon of the *object bar* and it is depicted as a label.

Change: *change tag* operation allows to change the label of an object (i.e., place, transition, marking parameter,...) of the current loaded model. To change the label of a given object click over it with the left mouse button: the corresponding *Change ...* window will pop-up.

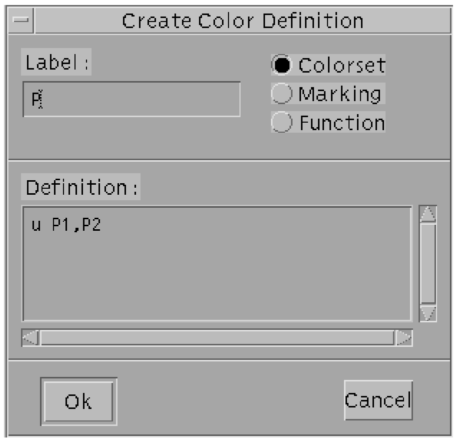
Move: *move tag* operation allows to move the label of a transition (place): to move the label of a given transition (place) click with the left mouse button over the label, move the mouse cursor to choose the desired location in the *canvas* to put it and click again to fix the label in the desired location.

3.2.8 Colour definition

It is the tenth icon of the *object bar* and it is depicted with a palette and a paintbrush.

Add: *create a color definition* operation allows to define basic color classes, static subclasses, initial colored markings (ordinary and symbolic) and colored functions (i.e., guards and color domain). When this action is active, the shape of the mouse cursor is an arrow, click on a free location of the *canvas* to fix the position of the colored object that is going to be defined: this action causes the *Create Color Definition* dialog to pop-up (see Fig. 3.29). The dialog box is characterized by the following areas: the "Label:" area that has to be filled with the name of the colored object, e.g., in Fig.3.29 the name `P` has been assigned to a colored class; and the "Definition:" area that has to be filled with the definition of the colored object, e.g., in Fig. 3.29, the colored class has been defined as the unordered union of two static subsclasses named as `P1` and `P2` (see the SWN grammar of Table A.1). The type of the colored object is indicated by switching on one of the three toggles that are located on the top-right part of the dialog box:

- "Colorset": to define either a colored class or a colored static subclass;



Label: P

Definition:

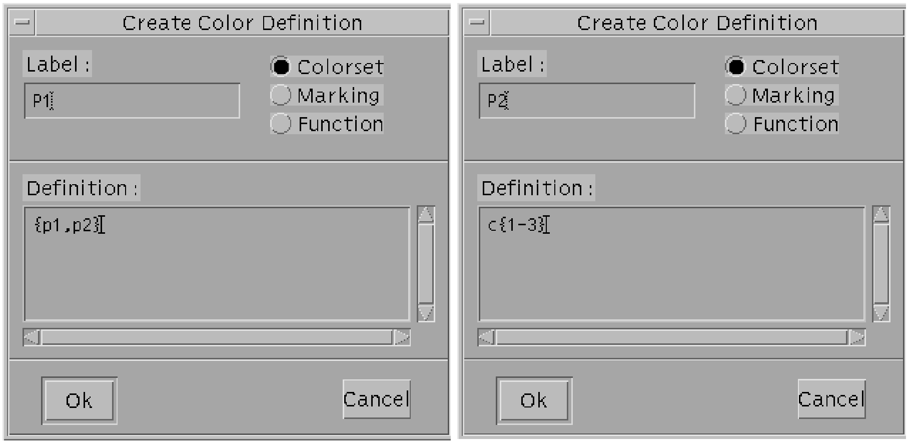
```
u P1,P2
```

Figure 3.29: Create Color Definition window.

- "Marking": to define an initial colored marking, either ordinary or symbolic;
- "Function": to define a guard or a color domain.

To switch on a toggle, click over the empty circle located near the name of the toggle with the left mouse button.

Examples of static subclass definition In Fig. 3.30 examples of static subclass definition is given: in both the *Create Color Definition* dialog boxes, the toggle "Colorset" is switched on; the name of the subclasses `P1` and `P2`, respectively, are filled in the corresponding "Label" areas. Static subclass `P1` is defined as the set containing two colors `p1` and `p2`. Static subclass `P2`, instead, is defined as a set of three colors `c1,c2` and `c3`. Both the definitions are correct in the *GreatSPN2.0.2* syntax.



Label: P1

Definition:

```
{p1,p2}
```

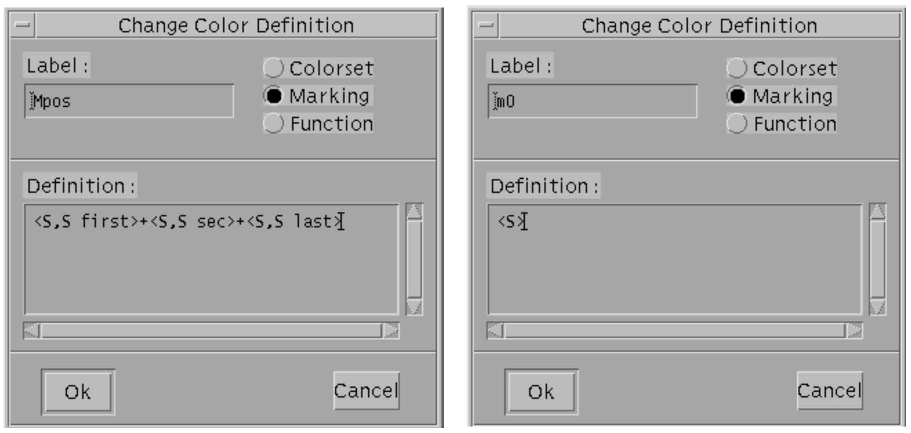
Label: P2

Definition:

```
c{1-3}
```

Figure 3.30: Definition of static subclasses.

Examples of initial marking definition In Fig.3.31 examples of initial ordinary (colored) marking definition is given:


Change Color Definition

Label : Mpos

Colorset [✓ Marking] Function

Definition : <S,S first>+<S,S sec>+<S,S last>

Change Color Definition

Label : m0

Colorset [✓ Marking] Function

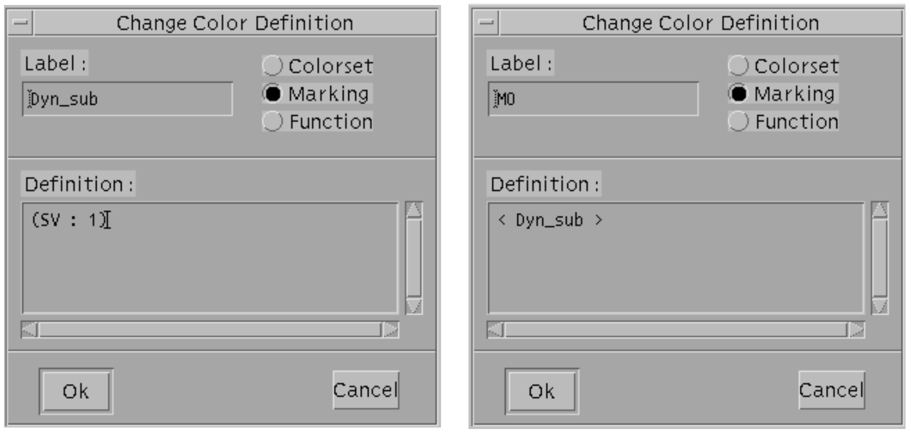
Definition : <S>

Figure 3.31: Definition of initial ordinary colored markings.

the toggle “Marking” is switched on; the name of the initial markings `Mpos` and `m0`, respectively, are filled in the corresponding “Label” areas. Initial marking `Mpos` has to be assigned to a place that has a color domain defined as the cartesian product of two colored classes say `X` and `Y` respectively. `Mpos` is the set containing all the combinations of pairs of colors in which the first element belongs to the class `X` (the first component of the place color domain) and the second element belongs to one of the static subclasses tt first, sec, last of the colored class `Y`. Initial marking `m0` has to be assigned to a place that has a color domain defined as a single colored class; it is the set of all the elements belonging to the place color domain.

In the SWN syntax `<S>` is the standard notation for the whole place color domain.

In Fig.3.32 an example of initial symbolic marking definition is given. Symbolic initial markings contain


Change Color Definition

Label : Dyn_sub

Colorset [✓ Marking] Function

Definition : (SV : 1)

Change Color Definition

Label : M0

Colorset [✓ Marking] Function

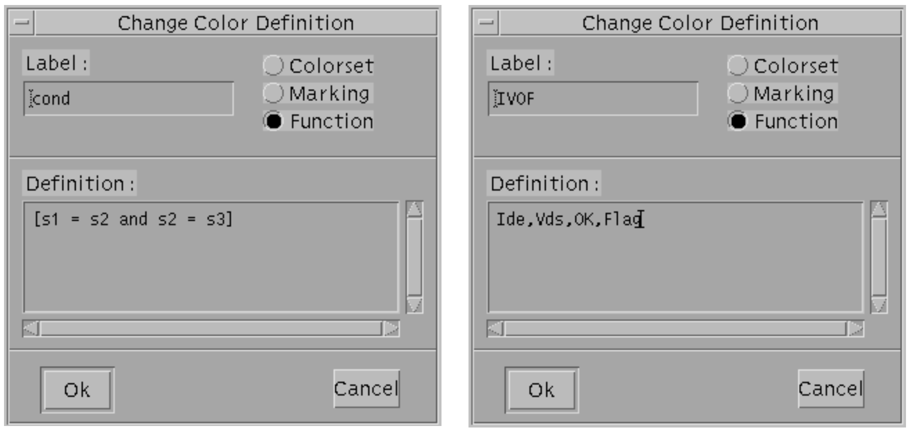
Definition : < Dyn_sub >

Figure 3.32: Definition of initial symbolic colored markings.

dynamic subclasses and they are used when it is necessary to initialize a place of the net with a fixed number of elements belonging to the place color domain independently from their identity. The left dialog box of Fig. 3.32 shows the definition of the dynamic subclass `Dyn_sub`: it is a colored object of type “Marking” defined as a set containing a single element drawn from the static subclass `SV`. The right dialog box of Fig. 3.32 shows the definition of the symbolic initial marking for a place whose color domain contains the static subclass `SV`: the initial marking is simply defined as the dynamic subclass `Dyn_sub`.

WARNING! SWN models in which symbolic initial marking are used can be analyzed only with symbolic solver.

Example of function definition In Fig.3.33 examples of colored function definition is given:



Label : cond
Colorset [✓ Function] Marking
Definition : [s1 = s2 and s2 = s3]

Label : IVOF
Colorset [✓ Function] Marking
Definition : Ide,Vds,OK,Flag

Figure 3.33: Definition of colored functions.

the toggle “Function” is switched on; the name of the functions `cond` and `IVOF`, respectively, are filled in the corresponding “Label” areas. Function `cond` is a macro defined as the guard `[s1 = s2 and s2 = s3]` that has to be assigned to a color label of a transition; function `IVOF`, instead, is a macro defined as the cartesian product of the following colored classes `Ide,Vds,OK` and `Flag` that has to be assigned to a place color domain.

Change: *change color* operation allows to modify the colored definitions and the color attribute of the objects (place/transition/arc). To change a previous specification of a given colored definition (or a colored attribute of an object), click over the colored definition name (the object) located somewhere in the *canvas*: this action causes the corresponding *Change* dialog-box to pop-up. For example, in case of modification of a colored definition, to change the values in the areas of the *Change Color Definition* dialog box click over the corresponding areas to activate them and then overwrite the old values with the new ones. Finally, either click over the “OK” button to confirm the changes or click over the “Cancel” button to keep the old settings.

Select: *select a color definition* operation allows to select a specific color definition of the current loaded model by clicking over the color definition name with the left mouse button; this action causes a broken rectangle to superpose the color definition name. Selection operation is normally used along with other operations, e.g., with the *Move* action to move the color definition name in a different location of the *canvas*. To reset the *Select* operation, choose in the **Action** menu the *End Selection* option (the broken rectangle that superposes the selected color definition name, will disappear).

Move: *move a color* operation causes the shape of the mouse cursor to change into an arrow; to move a either a color definition or a color label (place color domain, guard, arc expression) simply click with the left mouse button over the colored item to be moved, move the mouse cursor to choose the desired location in the *canvas* to put it and click again to fix it in the desired location.

Delete: *delete a color* operation allows to delete a color definition present in the *canvas*; to delete an existing color definition click over the color definition result to be removed with the left mouse button.

Show: *show a color definition* operation allows to visualize the definition of the colored item.

Chapter 4

Solvers

GreatSPN2.0.2 is composed of many separate programs that cooperate in the costruction and analysis of PN models by sharing files. Using network file system capabilities, different analysis modules can be run on different machines in a distributed computing environment.

All solution modules use special storage techniques to save memory both for intermediate result files and for program data structures. The more restrictive constraints are on the Reachability Graph construction phases; the current practical limit depends on the specific model, but indicatively ranges from few hundred thousands up to few millions markings on Pentium III PCs with 256 MB of memory. The current modular structure of *GreatSPN2.0.2* is shown in Figure 4.1, in which rectangles represent program modules while ovals represent both the intermediate and the result files generated by the modules. In this chapter we will describe the *GreatSPN2.0.2* modules and result files related to the analysis of a GSPN/SWN model, while the compositionality aspect and the links to other tools will be dealt in chapters 5 and 6 respectively.

Elimination of result files The elimination of all the files resulting from the solvers execution can be performed either through the GUI (see **File**→*Remove Results* option in Chapt. 3) or by typing the following command:

`> RMNET [-n]` *netdirectory/netname*

where *netdirectory* is the directory in which the GSPN model has been saved and *netname* is the name of the net (without extensions). If the `-n` option is used then also the net definition files are removed.

4.1 Structural analyzers

The structural analysis portion of the *GreatSPN2.0.2* package implements most of the classical structural analysis techniques for the analysis of Place/Transition nets, plus the ad-hoc techniques proposed by our group for the detection of conflicts, mutual exclusion and confusion in the framework of nets with priorities and inhibitor arcs. All the modules that support the structural analysis of a GSPN model read the net description files (see

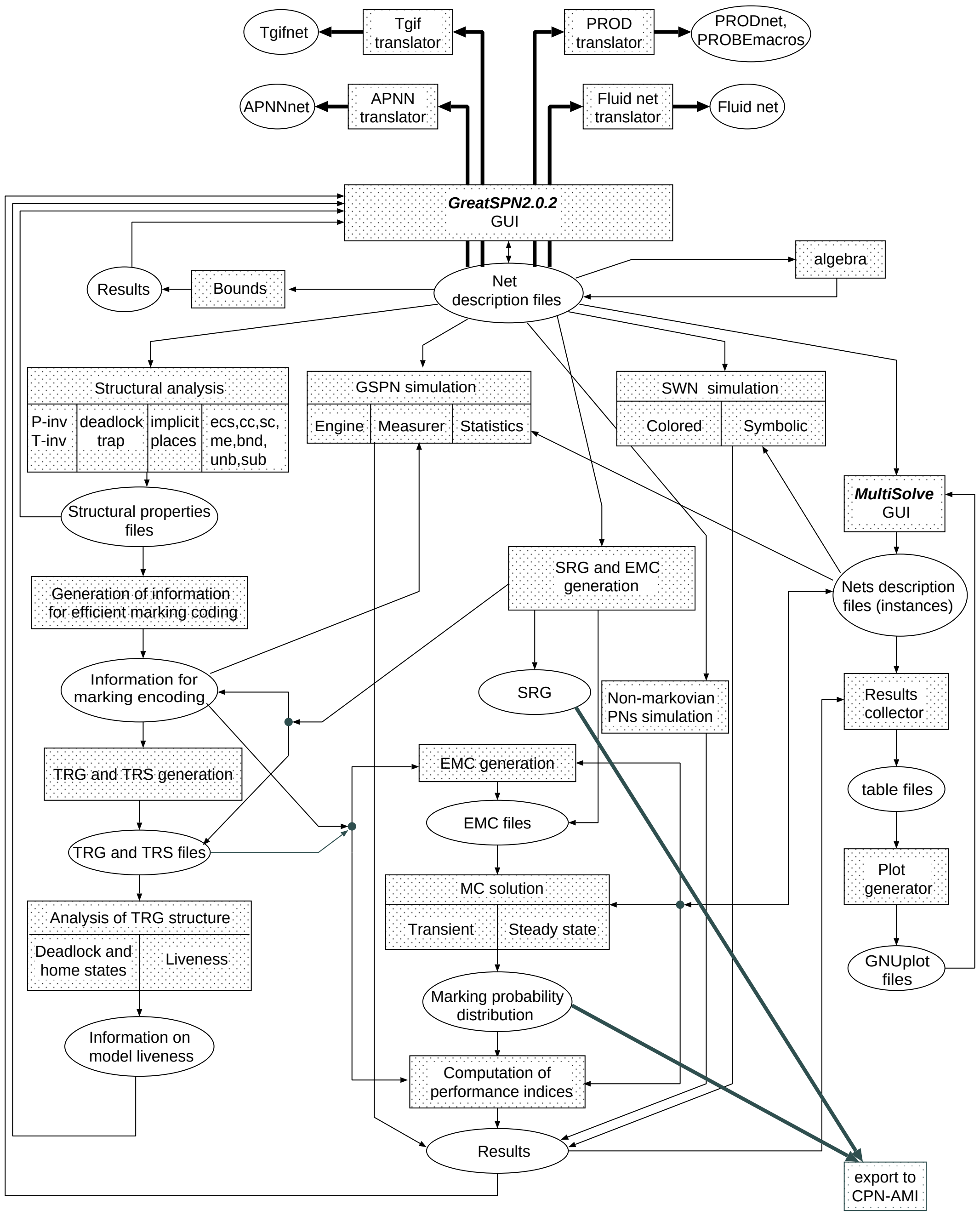


Figure 4.1: Graphical representation of the modular structure of *GreatSPN2.0.2* .

the appendix A for their format definition) and produce one or more intermediate result files in ASCII form. A complete list is given in table 4.1. They are all independent of each other apart from `struct.c` which depends on the result file produced by module `pinvar.c` (since the mutual exclusion property is computed based on the knowledge of the elementary P-invariant as well as the net structure). Result files contain sequences of either sets or bags of transitions and/or places, according to the following descriptions.

extension	format	description
.bnd	N pairs	upper and lower bound for tokens in places
.cc	T pairs	causal connection
.ecs	T sets	ECS and confusion structures
.impl	P bags	implicant places for implicit place
.mdead	P sets	minimal deadlocks
.me	T pairs	mutual exclusion
.mtrap	P sets	minimal traps
.pin	P bags	place invariants
.sc	T pairs	structural conflict
.sub	T sets	immediate subnet partition
.tin	T bags	transition invariants
.unb	T bags	structurally unbounded places and transition sequences

Table 4.1: List of structural result files.

4.1.1 Invariants

4.1.1.1 Modules

`pinvar.c`,`tinvar.c`: compute minimal-support, canonical Place and Transition invariants, respectively, with a modified Martinez-Silva algorithm [29]. P(T)-invariants modules can be launched either through the *GreatSPN2.0.2* GUI (see Chapt.3) or from a terminal. In the latter case the following commands have to be used:

> `pinv` *netdirectory/netname* for P-invariant computation and

> `tinv` *netdirectory/netname* for T-invariant computation,

where *netname* is the name of the *GreatSPN2.0.2* net and *netdirectory* is the directory containing *netname*. The commands compute and display the P(T)-invariant of the model.

4.1.1.2 Result files structure

`.pin` file: contains a list of Bags of places to be interpreted as the P-invariants computed on the net description contained in the corresponding `.net` file.
First line: integer containing the total number of bags in the file.
Subsequent lines (one per P-invariant): integer containing the number of non-null entries of the bag, followed on the same line by one pair of integers per non-null entry: the first integer of the pair represents the multiplicity; the second integer of the pair represent the ordinal number of the place (position of the place in the list of places as contained in the `.net` file).
Last Line: always 0 as a first integer of the line (a null Bag).

`.tin` file: contains a list of Bags of transitions to be interpreted as the T-invariants computed on the net description contained in the corresponding `.net` file.
First line: integer containing the total number of bags in the file.
Subsequent lines (one per T-invariant): integer containing the number of non-null entries of the bag, followed on the same line by one pair of integers per non-null entry: the first integer of the pair represents the multiplicity; the second integer of the pair represent the ordinal number of the transition (position of the transition in the list of transitions as contained in the `.net` file).
Last line: always 0 as a first integer of the line (a null Bag).

4.1.2 Minimal deadlocks and traps

4.1.2.1 Module

`deadlock.c`: compute minimal Deadlocks or Traps with a modified Alaiwan-Toudic algorithm [1]. Minimal deadlocks and traps computation and visualization can be obtained either by choosing the corresponding options in the **Net**→*Struct* menu of the *GreatSPN2.0.2* GUI (see Chapt.3) or by launching the following commands from a terminal:

> `deadl` *netdirectory/netname* for minimal deadlocks computation and

> `traps` *netdirectory/netname* for traps computation,

where *netname* is the name of the *GreatSPN2.0.2* net and *netdirectory* is the directory containing *netname*.

4.1.2.2 Result files structure

`.mdead` file: contains a list of Sets of places to be interpreted as the minimal deadlocks computed on the net description contained in the corresponding `.net` file.
First line: integer containing the total number of sets in the file.

Subsequent lines (one per minimal deadlock): integer containing the number of non-null entries of the set, followed on the same line by one integer per non-null entry representing the ordinal number of the place (position of the place in the list of places as contained in the `.net` file).
Last line: always 0 as a first integer of the line (a null Set).

`.mtrap` file: contains a list of Sets of places to be interpreted as the minimal traps computed on the net description contained in the corresponding `.net` file.
First line: integer containing the total number of sets in the file.
Subsequent lines (one per minimal trap): integer containing the number of non-null entries of the set, followed on the same line by one integer per non-null entry representing the ordinal number of the place (position of the place in the list of places as contained in the `.net` file).
Last line: always 0 as a first integer of the line (a null Set).

4.1.3 Implicit places

4.1.3.1 Module

`implp.c`: verifies structurally implicit places with Silva's algorithm [35]. Implicit place verification can be checked either through the *GreatSPN2.0.2* GUI (see Chapt.3) or by launching the following command from a terminal:

> `implp` *netdirectory/netname placenumber*

where *netname* is the name of the *GreatSPN2.0.2* net, *netdirectory* is the directory containing *netname* and *placenumber* is the number of the place of the net to be tested as appears in the net definition file *netname.net*.

4.1.3.2 Result file structure

`.impl` file: contains a list of bags of places containing the implicant places of a given places tested for the property of being implicit. The place is not implicit if no bag of implicant places is found.
First line: an integer containing the number of bags of implicant places, listed in the following of the file, one bag per line.
Each implicant places line: first integer containing the number $N \geq 2$ of non-null entries of the bag, followed on the same line by one pair of integers per non-null entry: the first integer of the pair represents the multiplicity; the second integer of the pair represent the ordinal number of the place. The last entry of the bag represents the implicit place itself.
Last line: always 0 as a first integer of the line (a null Bag).

4.1.4 ECS-Confusion-ME-SC-CC

4.1.4.1 Module

`struct.c` computes structural token bounds for places and structural conflict, mutual exclusion, causal connection, extended conflict sets, structural confusion, and subnets of independent higher priority transitions, for priority nets with inhibitor arcs, as described in [12, 33, 2].

4.1.4.2 Result files structure

`.cc` file: contains a description of the causal connection relations (*CC*) holding for each transition. One line is listed per transition, the ***i***-th line referring to the ***i***-th transition (transition in position *i* in the list of transition as contained in the `.net` file).
Each line: contains the set of transition in *CC* relation with the current one. The first integer tell the number of non-null entries of the set; then one integer follows per non-null element, with the ordinal number of the transition.

`.ecs` file: contains both a description of the Extended Conflict Sets of immediate transitions (*ECSs*), and the possible confusion relations. These two results are stored as two subsequent lists, each one terminated by a `0` character on a separate line.
One line per *ECS*: an integer representing the number of transitions in the current *ECS*, followed on the same line by one integer per non-null item of the set representing the ordinal number of an immediate transition (i.e. the position of the immediate transition in the list of transitions as contained in the `.net` file).
Last line of the *ECS* list: One integer value = 0 used as a list terminator.
One line per confusion relation: a first integer representing the ordinal number of the confused *ECS*, i.e. the position of the *ECS* description line in the above list; a second integer containing the number $N \geq 3$ of transitions in confusion relation; two integers containing the ordinal numbers of two transitions of the current *ECS* that are in confusion relation with each other; a possible list of integers (as many as $N-3$) representing the ordinal number of the transition originating the confusion.
Last line of the confusion list: one integer value = 0 used as a list terminator.

`.me` file: contains a description of the mutual exclusion relations (*ME*) holding between transition pairs. One line is listed per transition pair in *ME* relation.
Each line: contains two integers with the ordinal numbers of the transitions in *ME* relation (i.e. their position in the list of transitions as contained in the `.net` file).
Last line: one integer value = 0 used as a list terminator.

`.sc` file: contains a description of the structural conflict relations *SC* holding for each transition. One line is listed per transition, the *i*-th line referring to the *i*-th transition (transition in position *i* in the list of transitions as contained in the `.net` file).
Each line: contains the set of transition in *SC* relation with the current one. The first integer tell the number of non-null entries of the set; then one integer follows per non-null element, with the ordinal number of the transition.

`.sub` file: contains the partition of the net in subnets of independent immediate transitions.
First line: an integer containing the number $N \geq 1$ of subnets in which the net is partitioned. The first subnet contains all timed transitions, while the following ones contain independent sets of immediate transitions.
After the first line the file is organized in two subsequent lists of subnet description lines. The first list contains two consecutive lines per subnet. The second list contains one line per subnet.
Each of the following $n = 1, \ldots, N$ pairs of consecutive lines: First line of the pair: set of places of the *n*-th, stored as a first integer with the number of non-null entries of the set, followed by one integer number per entry containing the ordinal number of the place.
Second line of the pair: set of transitions of the *n*-th subnet, stored as a first integer with the number of non-null entries of the set, followed by one integer number per entry containing the ordinal number of the transition.
Each of the following $2N + n$ lines $(n = 1, \ldots, N)$ set of input/inhibition places of the *n*-th subnet, stored as a first integer with the number of non-null entries of the set , followed by one integer number per entry containing the ordinal number of the place.

4.1.5 Structural boundedness

4.1.5.1 Module

`unbound.c`: verifies the structural unboundedness and associated unbounded transition sequences with a modified version of Molloy's method [32];

4.1.5.2 Result files structure

`.bnd` file: contains a description of the upper and lower bounds on the number of tokens in each place of the net. One line is listed per place, the *i*-th line referring to the *i*-th (place in position *i* in the list of places as contained in the `.net` file).
Each line: contains a pair of integers. The first integer tells the lower bound for the number of tokens in the corresponding current place. The second integer tells the upper bound for the number of tokens in the corresponding current place.

`.unb` file: contains a list of sets of unbounded places together with the transitions bags that, if fireable as transition sequences, make them unbounded. One line is used to store one set of unbounde places and their corresponding transition bag. The list is terminated by a line containing only the integer value 0.
Each line: first integer containing the number of non-null entries of the set of unbounded places, followed on the same line by one integer per non-null entry representing the ordinal number of the place (position of the place in the list of places as contained in the `.net` file). Always on the same line, one integer follows containing the number of non-null entry: the first integer of the pair represents the multiplicity; the second integer of the pair represent the ordinal number of the transition.
Last line: always 0 as a first integer of the line (a null Set).

4.2 Performance bounds solver

GreatSPN2.0.2 package includes modules for the computation of the performance structural bounds of both places and transitions of the net. Bounds are obtained from the net structure, the initial marking and the transition rates by solving a linear programming problem (LPP) presented in[16].

4.2.1 Modules

`disab_lp.c`: 1) decomposes the marking vector in disabling components for each immediate transition with more than one input/inhibition arcs; 2) produces the reachability constraints; 3) produces the throughput flow balance constraints for every place; 4) detects the vanishing places; 5) produces the Extended Free Choice throughput constraints; 6) produces the inequalities for Persistent or Age Memory or Preselection Timed Transitions. Structural conflicts of immediate transitions are optimized.

WARNING! The case of conflict with race policy and with enabling memory policy for timed transitions is not properly handled. The net description is assumed not to contain such cases.

`flow_lp.c`: produces equations of type: $\forall p \in P : \; \sum_{t \in {}^\bullet p} x_t W(t,p) \geq \sum_{t \in p^\bullet} x_t W(p,t)$, i.e., the throughput flow balance constraints for all places.
`mark_lp.c`: produces equations of type $M = M_0 + C\sigma$, i.e., the reachability constraints, for a predefined list of marking vectors.

4.2.2 Result file structure

The performance bound modules produce the list of result files given in Table 4.2 in ASCII format.
WARNING! In order to obtain correct results, to compute performance bounds of a transition, launch the performance bound solver on a place first.

extension	format	description
.lp_disab	ascii	list of all the constraints of the LPP
.lp_in	ascii	place/transition name whose bounds are computed and list of all the constraints of the LPP
.lp_mark	ascii	linear programming equations
.lp_out	ascii	solution of the LPP

Table 4.2: List of performance bounds result files.

4.3 Analytic solvers

Analytic solvers produce the list of intermediate and result files given in Table4.3. Sets are described in ASCII files as lists of either place or transition ordinal numbers[1]. Bags are described in ASCII files as lists of pairs of natural numbers representing the multiplicity and the ordinal number of either places or transitions.

Unsigned compacts in the range $[0, 2^{22} - 1]$ are stored in non-ASCII files using a compact coding in one, two, or three bytes [2]

WARNING!

1. The maximum capacity of each place is $MAX = 255$ even though this constraint is not signalled when an analytic module is launched from the GUI.
2. If the net is characterized by an initial dead marking, the launch of an analytic solver provokes a segmentation fault.
3. Reachability graph generator does not produce the RG in case of nets with all immediate transitions.

4.3.1 GSPN solvers

4.3.1.1 Reachability Graph generator

Modules `grg.c`, `grg_prep.c`, `grg_stndrd.c` perform the Reachability Graph expansion of a GSPN model by reading the net description files. The algorithm begins by putting the initial marking into the Reachability Set, then all the enabled transitions in newly found markings are fired. Timed transition firing proceeds using a breadth-first policy, while immediate transition paths are followed depth-first until a tangible marking is reached.

[1]As ordinal number we mean the number of line in the net definition file that describes the place or the transition

[2]Numbers in the range $[0, 127]$ are encoded in a single byte, with the most significant bit set to 0; numbers in the range $[128, 2^{14} - 1]$ are encoded in two bytes, with the two most significant bits of the first byte set to 10; numbers in the range $[2^{14}, 2^{22} - 1]$ are encoded in three bytes, with the two most significant bits of the first byte set to 11. Since most of the information is recorded using small integers (falling in the range $[0, 127]$, this coding technique allows the use of only one byte for each piece of information most of the times.

extension	format	description
GSPN models		
.grg	ascii	data structure description for reachability graph
.aecs	T sets	actual conflicts sets found in the reachability graph
.rgr_aux	ascii	auxiliary information on reachability graph
.crgr	special code	coded tangible reachability graph
.ctrs	uns. bytes	coded tangible reachability set
.livlck	uns. comp.	terminal strongly connected components of the RG
.liveness	N lists	enabling and liveness bounds for transitions
.gmt	ascii	data structure description for EMC construction
.doubles	C doubles	floating point numbers contained in the EMC
.emc	special code	compact coded EMC state transition matrix
.epd and .mpd	C doubles	marking probability distribution vectors
.gst	ascii	data structure description for performance result computation
.tpd	C doubles	token probability distributions in places
.sta	ascii	output performance results

Table 4.3: List of analytical result files.

The ordering of the markings in the Reachability Set resulting from this firing policy is exploited by the following modules of the package to implement a very efficient reduction of vanishing markings in the case that no-zero time loop is present. In the program data structure, markings are lexicographically ordered by means of a balanced binary tree in order to improve the efficiency of the search procedures. GSPN Reachability Graph generator can be launched either through the *GreatSPN2.0.2* GUI (see Chapt.3) or by typing the following command from a terminal:

> `newRG` *netdirectory/netname*

where *netdirectory* is the directory in which the GSPN model has been saved and *netname* is the name of the net (without extensions).
Module `show_stndrd.c` displays the Tangible Reachability Graph (TRG) of a GSPN model without net-dependent files compilation. To display the TRG of a GSPN model already generated use the following command from a terminal:

> `showRG` *netdirectory/netname* `[opt]`

where *netdirectory* is the directory in which the GSPN model has been saved and *netname* is the name of the net (without extensions). Possible display options `[opt]` are:

-s to show the Tangible Reachability Set;

-t to show the Tangible Reachability Graph (default option);

-r to show the Reverse Tangible Reachability Graph.

4.3.1.2 TRG structure analyzer

Module `strong_con.c` computes the livelocks and the deadlock states of the TRG of a GSPN model.
Module `liveness.c` computes transition enabling and liveness bounds of a GSPN model: in particular, it takes the TRG and its associated livelock description as inputs and computes the actual bounds for infinite server timed transitions.

To launch the reachability graph generator and the structure analyzer of the created TRG of a GSPN model from a terminal, use the following command:

`> checkRG` *netdirectory/netname*

where *netdirectory* is the name of the directory in which the GSPN model has been saved and *netname* is the name of the net without extensions.

4.3.1.3 Markov Chain generator

Modules `gmt_prep.c, gmt_stndrd.c`: converts the Tangible Reachability Graph of a GSPN model into the corresponding Continuous Time Markov Chain (CTMC) without net-dependent files compilation. The module uses a depth-first algorithm to follow the immediate transition tangible to tangible paths and keep tracks of the resulting probabilities of already followed paths to achieve a higher computational efficiency. To launch the Reachability Graph generator and the CTMC generator from a terminal use the following command:

`newMT` *netdirectory/netname*

where *netdirectory* is the name of the directory in which the GSPN model has been saved and *netname* is the name of the net without extensions.
To display the infinitesimal generator matrix, type the following command:

`shownmtx` *netdirectory/netname*

where *netdirectory* is the name of the directory in which the GSPN model has been saved and *netname* is the name of the net without extensions.

4.3.1.4 Steady State solver

`ggsc.c`: computes the steady-state solution of the CTMC underlying a GSPN model. The solver has been implemented using standard sparse matrix computation algorithms, adapted to the solution of a set of linearly dependent equations augmented with the probability normalization condition. The Gauss elimination (actually a modified L-U direct decomposition) proceeds without pivoting to preserve the sparse band-diagonal structure of the matrix resulting from the breadth-first firing of the Reachability Graph. Indeed, row or column permutation would determine a large fill-in during the elimination phase, thus making impractical the analysis of large matrices. Despite this simplification the algorithm exhibits a very good numerical stability, due to the fact that the diagonal elements used as pivot, actually are (by definition) partial pivots, since they are made equal to the sum of all the other elements in the row as proved in[26]. Indeed it is possible to use this method even in case of "stiff" problems with matrix entries differing up to eight orders of magnitude on machines with 64 bit floating-point representation. The size of the matrix to be solved can range up to 1023×1023. In case of larger matrices it is necessary to resort the Gauss-Seidel iterative method. In the present implementation, sparse matrices of order up to 32000-64000 can be solved, but the convergence is badly affected by ill-conditioned or "stiff" problems. To launch the Steady State solver from a terminal use the following command:

`newSO` *netdirectory/netname*

where *netdirectory* is the name of the directory in which the GSPN model has been saved and *netname* is the name of the net without extensions.

To display the state probability vector, type the following command from a terminal:

`showprob` *netdirectory/netname*

where *netdirectory* is the name of the directory in which the GSPN model has been saved and *netname* is the name of the net without extensions.

4.3.1.5 Transient solver

`gtrc.c`: computes the transient solution of the CTMC underlying a GSPN model using a matrix exponentiation algorithm. The major problem in this case is a "good" choice of the time integration step: large integration steps, depending on the matrix eigenvalues, can result in large round-off errors and poor numerical stability; on the other hand, steps that are too small may involve unnecessary row by column matrix products. In our program an initial estimate of the optimal integration step is made according to the maximum transition rate found in the matrix; then the step is dynamically adjusted in order to keep it as large as possible, without incurring in too large round-off errors during vector addition.

4.3.2 SWN solvers

to be completed

4.4 Simulators

4.4.1 GSPN simulation

GSPN simulator uses a “Natural Regeneration” method mechanism[27] to provide point of estimates of the average number of tokens in each place together with their confidence intervals, as well as to collect the user defined statistical results. Machine-independent congruent pseudo-random sequence generators are used to implement stochastic transition timings. This program provides a bypass to other solution modules, and can be effectively exploited to obtain results in case of analytically untractable models. GSPN simulator can be launched through the *GreatSPN2.0.2* GUI (see Chapt.3).

4.4.1.1 Modules

`engine_control.c`: simulation control and communication module for the simulation engine.
`engine_event.c`: event-driven simulation kernel for simulation engine of *GreatSPN2.0.2* package. The program allows both normal (forward) and reversed (backward) simulation. Periodic checkpoints are stored on file in order to allow both extended backtracking and possibility of continuation and resume of previous runs.
`engine_pn.c`: PN routines for the simulation engine. No marking dependency is allowed for immediate transitions. This module is derived from “grg_stndrd.c ” and it uses similar data structures and the same type of optimization techniques.
`measure_checkpoint.c`: checkpoint routines for measurer module of *GreatSPN2.0.2* .
`measure_pn.c`: module for the definition of measurement of performance indices for GSPN simulation.

4.4.1.2 Result file structure

In this part the files resulting from the launch of a GSPN simulator are described.

extension	format	description
.etrace	ascii	
.mtrace	ascii	
.strace	ascii	
.tpd	C doubles	token probability distributions in places
.sta	ascii	output performance results

Table 4.4: List of GSPN simulation result files.

4.4.2 SWN simulation

4.4.2.1 Modules

SWN simulators can be launched either through the *GreatSPN2.0.2* GUI (see Chapt.3) or by typing the following commands from a terminal:

> `swn_ord_sim [opt]` *netdirectory/netname*

for ordinary simulation and

> `swn_sym_sim [opt]` *netdirectory/netname*

for symbolic simulation[], where *netdirectory* is the name of the directory in which the net definition files are located and *netname* is the name of the net model without extensions. `[opt]` represents the following list of options that allow to set the parameters for a simulation run:

`-f`	*first_tr_length*	to set the length of evolution phase between batchs that must be discarded;
`-t`	*tr_length*	to set the length of initialization phase;
`-m`	*min_btc*	to set the dimension of the minimum batch;
`-M`	*max_btc*	to set the dimension of maximum batch dimension;
`-a`	*approx*	to set the precision of the approximation in the parameters estimation;
`-c`	*conf_level*	to set the confidence level in the parameters estimation;
`-s`	*seed*	to set the seed for the random numbers generation;
`-o`	*start*	to set the starting time for debug output.

WARNING! The results computed from a simulation run are basically the mean number of token in places and throughputs of transitions and they are all independent from the color classes. Refined results - color class dependent - and, in general, user defined results can be obtained by using the extended SWN ordinary simulation (see Section 4.5).

4.4.2.2 Result file structure

In this part the files resulting from the launch of a SWN simulator are described.

extension	format	description
.simres$Cl_1n_1Cl_2n_2\ldots Cl_nn_n$	ascii	output performance results
.sta	ascii	output performance results

Table 4.5: List of SWN simulation result files.

4.5 Extended SWN features

Several extensions have been developed for the SWN analysis modules; in the following we will describe the most important new added features.

4.5.1 Transient analysis of SWN models

The SWN reachability analysis prototypes have been interfaced with the transient analysis software developed for the GSPN models (implementing a numerical approach based on a randomization technique).

4.5.2 Simulation of SWN models with GEN transitions

The simulation of SWN models with ordinary marking has been extended to include generally distributed firing time transitions (GEN transitions), diferent memory policies and several policies for the disabling and re-enabling of firing instances.

Temporal specifications of GEN transitions have to be defined in a file named as *netname.dis*, where *netname* is the name of the SWN model constructed with *GreatSPN2.0.2* , and located in the same directory of the net specification files. *netmame.dis* is an ASCII form file, in which each row represents the temporal specification of a GEN transition of the corresponding SWN model. Table 4.6 shows the line syntax, expressed in BNF format, to be used for the temporal specifications of GEN transitions. All the terminal keywords are represented as C-language strings within quotation marks except for the following terms: <*real_number* >, indicates a positive real number, and <*integer* >, indicates a non negative integer number. Notation *#(XX)*{...} denotes the repetition of the string in braces for a number of times derived by interpreting the string *XX* as a natural number.

4.5.2.1 Rescheduling/descheduling policies

Rescheduling and descheduling policies need to be defined in case of GEN transitions characterized by multiple/infinite server semantics. Rescheduling policy defines which transition instance of a multiple enabled GEN transition previously suspended has to be inserted again in the event list. Descheduling policy defines, instead, which transition instance of a multiple enabled GEN transition which decreases its enabling degree has to be removed from the event list. Possible choices are:

RANDOM : the transition instance is chosen randomly;

FIRST_DRAWN : the transition instance among those suspended/enabled that was first generated;

LAST_DRAWN : the transition instance among those suspended/enabled that was last generated;

FIRST_SCHED : in case of descheduling, the enabled transition instance with the least scheduling time. In case of rescheduling, the suspended transition instance with the least value of the timer;

<row >	::=	*<tr_name > <firing_pol > <reschedule_pol > <deschedule_pol > <distrib >*
<firing_pol >	::=	"AGE" | "ENABLING"
<reschedule_pol >	::=	*<pol >*
<deschedule_pol >	::=	*<pol >*
<pol >	::=	"RANDOM" | "FIRST_DRAWN" | "LAST_DRAWN" | "FIRST_SCHED" | "LAST_SCHED"
<distrib >	::=	"DET" | "ERL" *<n_stage >*| "IPO" *<n_stage >* #(*<n_stage >*) { *<rate >* } | "IPER" *<n_stage >* #(*<n_stage >*) { *<prob > <rate >* }| "UNIF" *<lower > <upper >* | "NORM" *<mean > <devstd >* | "BAR" *<n_unif >* #(*<n_unif >*) { *<lower > <upper > <prob >* }
<n_stage >	::=	*<integer >*
<n_unif >	::=	*<integer >*
<rate >	::=	*<real_number >*
<prob >	::=	*<real_number >*
<lower >	::=	*<real_number >*
<upper >	::=	*<real_number >*
<mean >	::=	*<real_number >*
<devstd >	::=	*<real_number >*

Table 4.6: BNF format of a line of the *.dis* file

LAST_SCHED : in case of descheduling, the enabled transition instance with the greatest scheduling time. In case of rescheduling, the suspended transition instance with the greatest value of the timer.

4.5.2.2 Firing time distributions of the GEN transitions

SWN simulator allows to specify for each GEN transition of the model one the following types of distributions:

DET Deterministic distribution $D[\tau]$: no further parameter needs to be specified. The delay value τ is read from the net definition file `.net` and it corresponds to the value associated either to the rate or to the rate parameter of the transition. Rate/rate parameter has to be defined during the model specification via the *GreatSPN2.0.2* GUI.

ERL Erlang distribution $Erl[k,\lambda]$: the number of stages k must be specified as parameter. The stage rate λ is read from the net definition file `.net` file and it corresponds to the value associated either to the rate or to the rate parameter of the transition.

IPO Ipo-exponential distribution $Ipo[k,\lambda_1,\ldots,\lambda_k]$: the number of stages k and the stage rates $\{\lambda_i\}_{i=1,\ldots,k}$ must be specified as parameters list.

IPER Hyper-exponential distribution $Hyp[k,(\alpha_1,\lambda_1),\ldots,(\alpha_k,\lambda_k)]$: the number of stages k and the pairs describing the probability and the rate of each stage $\{(\alpha_i,\lambda_i)\}_{i=1,\ldots,k}$, must be specified as parameters list.

UNIF Uniform distribution $U[l,u]$: the lower l and upper u bounds must be specified as parameters.

NORM Normal distribution $\mathcal{N}(\mu,\sigma)$: the mean value μ and the standard deviation σ must be specified as parameters.

BAR Composition of Uniform Distributions $\sum_{i=1}^{k} p_i U[l_i,u_i]$: the number of uniform distributions k and, for each uniform distribution U_i, the lower bound l_i, the upper bound u_i and the associated probability p_i must be specified as parameters list.

WARNING! When constructing the SWN model via GUI, all the GEN transitions have to be specified as they were negative exponential distributed, i.e. white-box transitions **also in case of deterministic transitions.**

How to launch the simulation Launch the SWN ordinary simulator (see command 4.4.2.1) from a terminal together with the desired simulation options. Assuming the executable module `swn_ord_sim` is located in the directory `./experiment`, then the SWN model has to be saved in the subdirectory `./experiment/nets`.

4.5.3 Refined perfomance results

The statistical analysis module of SWN ordinary simulation has been extended to estimate structured performance indexes. Besides the aggregated mean number of tokens and transition throughput, it is possible to estimate the mean number of tokens that satisfy criteria based on the place color domain as well as the estimation of transition throughput when the firing instances satisfy a given predicate.

4.5.3.1 Mean number of tokens in a place

GreatSPN2.0.2 allows to define the mean number of tokens in a place at the following levels of detail:

1. mean number of tokens with no color distinction (simple performance index);
2. mean number of tokens for each element of the static partition the place color domain is made of. It is a structured performance index consisting of n different values where n is the cardinality of the static partition of the place color domain (maximum refinement);
3. mean number of tokens that satisfy a given predicate on the place color domain (intermediate refinement).

Example 1 Let us assume that a place p has been characterized by the following place color domain:

$$\begin{array}{lcl} CD(p) & = & Cl1 \times Cl1 \times Cl2 \\ Cl1 & = & sub1cl1 \cup sub2cl1 \cup sub3cl1 \\ Cl2 & = & sub1cl2 \cup sub2cl2 \end{array}$$

Then a color consists of a triplet $\langle Cl1\_1, Cl1\_2, Cl2\_1 \rangle$ where $Cl1\_1 \in subicl1$, $Cl1\_2 \in subjcl1$, and $Cl2\_1 \in subkcl2$, for $i, j \in \{1,2,3\}, k \in \{1,2\}$.

1. Case of simple performance index. In *GreatSPN2.0.2* syntax has to be defined as:

   `E{ #p }`

   We obtain a unique performance result that represents the mean number of tokens in place p and it is computed considering tokens without identities.

2. Case of maximum refinement. In the *GreatSPN2.0.2* syntax has to be defined as:

   `E{#p(*)}`

   We get a result for each element of the static partition of the place color domain that represents the mean number of tokens whose colors belong to the element. In case of ex. 1, we obtain 18 results of type $p[subicl1, subjcl1, subkcl2] = m_{ijk}$, $i, j \in \{1,2,3\}, k \in \{1,2\}$, where m_{ijk} is the mean number of tokens whose colors belong to the element $\langle subicl1, subjcl1, subkclk \rangle$ of the static partition of the place color domain.

3. Case of intermediate refinement. Between the two previous level of details, there are different types of means number of tokens in place p that can be obtained; we have classified them with respect to their granularity in *projection, selection* and *general predicate* means.

   Projection. This type of results are obtained by performing a projection with respect to those component classes of the place color domain we are interested in. In ex.1, we can choose to project the color domain of place p with respect to the second and the third component classes, in *GreatSPN2.0.2* syntax:

   `E{#p(Cl1_2,Cl2)}`

   where `Cl1_2` indicates the second repetition of the colored class $Cl1$[3], obtaining for each subset $Cl1 \times subjcl1 \times subkcl2 \quad j \in \{1,2,3\}, k \in \{1,2\}$ of the static partition of the place color domain, the mean number of tokens mp_{jk}, whose colors belong to that subset. Geometrically, the color domain of place p can be represented by a parallelepiped: its projection with respect to the second and the third component classes results in the rectangle highlighted in Fig. 4.2 lying on the plane $Cl1\_2 \times Cl2$.

[3]The third component, since it is a unique repetition of the colored class $Cl2$, is referred by using the name of the class without specifying its repetition, i.e., `Cl2_1 = Cl2`.

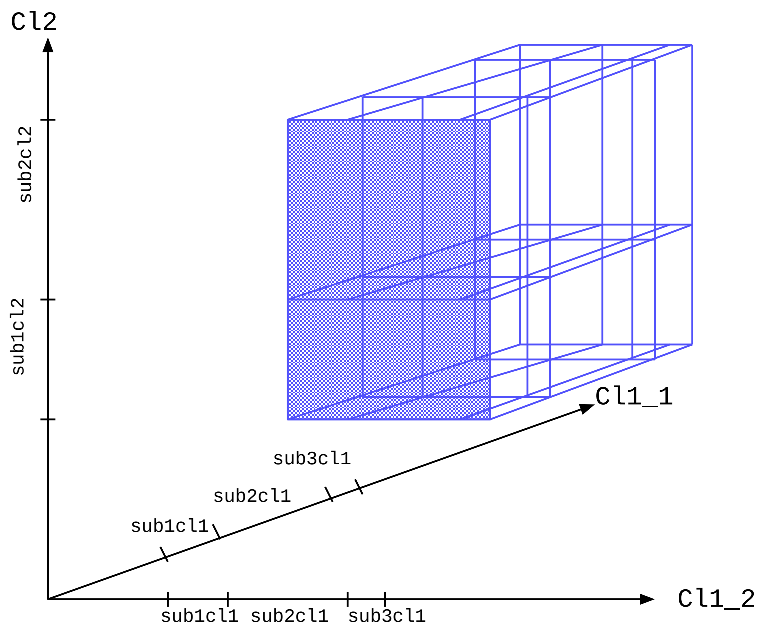


Figure 4.2: Projection of the color domain of place p.

The following relations hold among these means and the ones obtained in case of maximum refinement:

$$mp_{jk} = \sum_{i=1}^{3} m_{ijk}, \quad j \in \{1,2,3\}, k \in \{1,2\}.$$

Selection. This type of results are obtained by performing a selection among the set of means got from projection operation. The selection operation allows to extract the means number of tokens whose colors belong to a specific element of the static partition of the place color domain we are interested in. In ex.1, among the six means mp_{jk} we can choose to compute only the two means $mp_{2k}, k \in \{1,2\}$ by defining the following structured result:

```
E{#p(Cl1_2,Cl2) | SEL = [d(Cl1_2) = sub2cl1] }
```

WARNING! The selection operation can contain only predicates that specify the membership (or not membership) of a color belonging to the defined projection of the place color domain.

General predicate. This type of results are obtained by extracting specific elements of the place color domain when its component classes are made of subclasses containing more than one element. General predicates are applied after a projection operation and, in case, a selection operation have been performed. In ex.1, the structured result:

```
E{#p(Cl1_2,Cl2) |
SEL = [d(Cl1_2) = sub2cl1)], COND = [d(Cl1_1) <> sub1cl1 and Cl1_1 <> Cl1_2] }
```

consists of two means and it is obtained by giving two constraints over the elements of the place color domain: 1) the first component of a color do not have to belong to the static subclass $sub1cl1$ of the color class $Cl1$; 2) the firsts two components of a color have to be different as well in case they belong to the same static subclass. For example, let us assume that the static subclasses are defined as the following sets of elements:

$$\begin{aligned} sub1cl1 &= \{a\} \\ sub2cl1 &= \{b,c\} \\ sub3cl3 &= \{d\} \\ sub1cl2 &= \{e,f\} \\ sub1cl2 &= \{g,h,l\} \end{aligned}$$

and, in a given reachable marking of the net, the place p contains tokens with the following colors:

$$\langle c,d,e\rangle,\ \langle a,b,e\rangle,\ \langle b,b,h\rangle,\ \langle d,b,e\rangle,\ \langle c,b,g\rangle$$

Then, in the computation of the two means, tokens in place p characterized by one of the first three colors will not be considered (color $\langle c,d,e\rangle$ is eliminated by the *selection* predicate, color $\langle a,b,e\rangle$ is eliminated by the first part of the COND predicate, while color $\langle b,b,h\rangle$ is eliminated by the second part of the COND predicate). Instead, tokens characterized by one of the last two colors will contribute to the computation of the two means mp_{21}, mp_{22}.

4.5.3.2 Transition throughput

Similarly to the mean number of tokens in a place, in case of transition throughput as well, *GreatSPN2.0.2* allows to define results at the following levels of details:

1. transition throughput with no color distinction of the firing instances (simple performance index);
2. transition throughput for each element of the static partition of transition color domain is made of. It is a structured performance index consisting of n different values where n is the cardinality of the static partition of the transition color domain (maximum refinement);
3. transition throughput for those colored instances that satisfy a given predicate on the transition color domain (intermediate refinement).

The only difference with respect to the mean number of tokens in a place is the notation: for the computation of transition throughputs we can use directly the variables appearing on the input/output arcs of the transition instead of using the notation `ClassName_i` to indicate the $i^(th)$ component, belonging to the class *ClassName*, of a variable.

Example 2 Let us have a transition T, depicted in Fig. 4.3, with two input places and an output place. All the arcs are characterized by the identity function: the variables of the two input arcs are equal to $\langle x\rangle$ and $\langle y\rangle$,

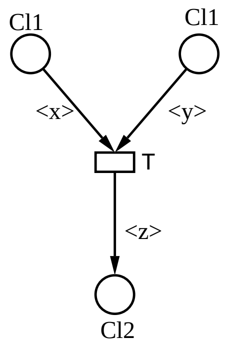


Figure 4.3: Domain of transition T.

respectively, and the variable of the output arc is equal to $\langle z \rangle$. Input places have color domains equal to $Cl1$ and the output place has color domain equal to $Cl2$, where $Cl1, Cl2$ are defined in ex.1, then the transition color domain is defined as $Cl1 \times Cl1 \times Cl2$.

1. Case of simple performance index. In *GreatSPN2.0.2* syntax has to be defined as:

   `X{ #T }`

   We obtain a unique performance result that represents the mean throughput of transition T and it is computed considering firing instances without identities.

2. Case of maximum refinement. In the *GreatSPN2.0.2* syntax has to be defined as:

   `X{#T(*)}`

   We get a result for each element of the static partition of the transition color domain that represents the mean throughputs of the firing instances whose colors belong to the element. In case of ex. 2, we obtain 18 results of type $T[subicl1, subjcl1, subkcl2] = X_{ijk}$, $i, j \in \{1,2,3\}, k \in \{1,2\}$, where X_{ijk} is the mean throughput of the firing instances whose colors belong to the element $\langle subicl1, subjcl1, subkclk \rangle$ of the static partition of the transition color domain.

3. Case of intermediate refinement. Between the two previous level of details, there are different types of (mean) throughputs of transition T that can be obtained; as is the case of the mean number of tokens in a place, we have classified the results with respect to their granularity in *projection, selection* and *general predicate* mean throughputs.

   Projection. This type of results are obtained by performing a projection with respect to those component classes of the transition color domain we are interested in. In ex.2, we can choose to project the color domain of transition T with respect to the second and the third component classes, in *GreatSPN2.0.2* syntax:

   `E{#T(y,z)}`

where `y` is the variable belonging to the second repetition of the colored class $Cl1$ and `z` is the variable belonging to the colored class $Cl2$, obtaining for each subset $Cl1 \times subjcl1 \times subkcl2 \quad j \in \{1,2,3\}, k \in \{1,2\}$ of the static partition of the transition color domain, the mean throughputs Xp_{jk} of the firing instances whose colors belong to that subset. The following relations hold among these mean throughputs and the ones obtained in case of maximum refinement:

$$Xp_{jk} = \sum_{i=1}^{3} X_{ijk}, \quad j \in \{1,2,3\}, k \in \{1,2\}.$$

Selection. This type of results are obtained by performing a selection among the set of means got from projection operation. The selection operation allows to extract the mean throughputs of firing instances whose colors belong to a specific element of the static partition of the transition color domain we are interested in. In ex.2, among the six means Xp_{jk} we can choose to compute only the two means $Xp_{2k}, k \in \{1,2\}$ by defining the following structured result:

```
E{#T(y,z) | SEL = [d(y) = sub2cl1] }
```

General predicate. This type of results are obtained by extracting specific elements of the transition color domain when its component classes are made of subclasses containing more than one element. General predicates are applied after a projection operation and, in case, a selection operation have been performed. In ex.2, the structured result:

```
E{#T(y,z) |
SEL = [d(y) = sub2cl1)], COND = [d(x) <> sub1cl1 and x <> y] }
```

consists of two mean throughputs and it is obtained by giving two constraints over the elements of the transition color domain: 1) the first component of a color do not have to belong to the static subclass $sub1cl1$ of the color class $Cl1$; 2) the firsts two components of a color have to be different as well in case they belong to the same static subclass.

4.5.3.3 Probability

In *GreatSPN2.0.2* it is also possible to specify as performance result to compute the probability that a certain logic condition be satisfied. Logic conditions are expressed in terms of place markings and, as in cases of mean computations, they may be either color-independent or color-dependent: in the last case structured probability results will be obtained. In *GreatSPN2.0.2* syntax to compute a probability result the keyword `P` is used instead of the keyword `E` (see the SWN extended grammar of Appendix A).

<*row* >	::=	<*user_index* > | <*tr_name* > | <*place_name* >
<*user_index* >	::=	<*index_name* > “NOPRIORITY” | <*index_name* > “ACC” <*approx_val* >
<*tr_name* >	::=	<*string* >
<*place_name* >	::=	<*string* >
<*index_name* >	::=	<*string* >
<*approx_val* >	::=	<*real_number* >

Table 4.7: BNF format of a row of the .*stat* file

4.5.4 The result .stat file

The .*stat* file contains, for each row, these kinds of information:

- a place (transition) name, in this case during a simulation run of a SWN model the mean number of tokens (transition throughput) will be computed without taking into account the colors (simple performance indices).
- a user-defined performance index name along with one of the following keywords: 1) “NOPRIORITY”, in this case the index will not considered in the test of convergence during a simulation run; 2) “ACC”, in this case the default value assigned to the approximation parameter of the simulator is replaced for this index by the value that follows the keyword.

The row syntax of the .*stat* file, expressed in BNF format, is shown in Table 4.7. All the terminal keywords are represented as C-language strings within quotation marks except for the following terms: <*real_number* >, indicates a positive real number, and <*string* >, indicates any non-empty character string not containing blank characters.

WARNING! If the .*stat* file does not exist, then all the performance indices (both the user-defined and the default ones) are computed. Viceversa, if the .*stat* file exists, the default indices (not colored mean number of tokens in places and not colored transition throughputs) are computed only if a row with the corresponding object name (place/transition) appears. Instead, the user-defined performance indices, if they are not specified in a different manner in the .*stat* file, they are always computed (i.e., they have priority).

4.5.5 Number of batches in a simulation run

The option `-e` has been added to the SWN simulator option-list, it allows to set the maximum number of batches during a simulation run.

4.5.6 Inclusion of “reset” transitions

The SWN model specification has been enriched by using a special transition, named *reset transition*, with the following semantics: when a reset transition is enabled its firing brings the model back to the initial marking. A further generalization (not yet implemented) is the possibility of specifying any marking to be reached through the firing of a reset transition; this extension has been introduced to ease the modeling task in several application field (e.g., in system availability analysis).

4.6 Multiple experiments

MultiSolve is a simple graphical interface to the solution algorithms of *GreatSPN2.0.2* . It allows to perform multiple experiments with different parameters and to create figures depicting the results of the experiments.

SW Requirements In order to run correctly, MultiSolve requires the following software to be installed:

- *Java* (version 1.2.2 or higher);
- *GreatSPN2.0.2* package;
- *Gnuplot* (version 3.7 or higher). To download it visit[25]).

Starting MultiSolve To invoke MultiSolve simply type `multisolve` followed by a carriage return. This causes a window as shown in Fig.4.4 to appear on the user’s terminal.

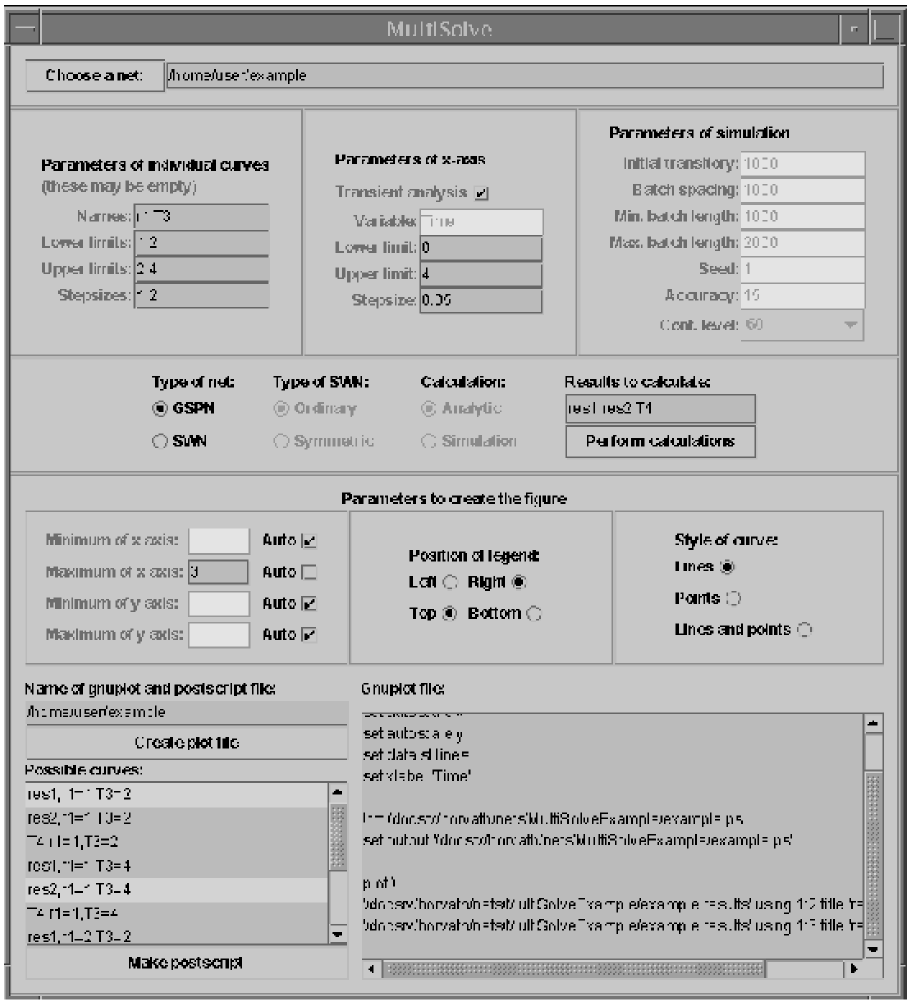
How to launch a set of experiments We describe how to use MultiSolve by means of an example. Let us suppose we have constructed the simple net depicted in Fig. 4.5 by using *GreatSPN2.0.2* package.

The net is characterized by the rate parameter $r1$ which has been assigned to transitions $T1$ and $T3$ and by the two measures $res1 = p\{\#P1 = 1\}$; and $res2 = p\{\#P3 = 1\}$;.

The first step is to load the net to work with on MultiSolve. This can be done either by clicking on the button labeled as **Choose a net** placed in the upper left corner of the window, or by typing directly the name of the net without extension into the uppermost text field.

The second step is to define the parameters that are used in the experiments. Since MultiSolve is designed for creating figures containing multiple curves that reflect measures, we have to define

1. the parameters of the individual curves,
2. the parameter that corresponds to the x-axis of the figure,
3. the measures that corresponds to the y-axis of the figure.



Choose a net: /home/user/example

Parameters of individual curves (these may be empty)
Names: r1 T3
Lower limits: 1 2
Upper limits: 2 4
Stepsizes: 1 2

Parameters of x-axis
Transient analysis [✓]
Variable: Time
Lower limit: 0
Upper limit: 4
Stepsize: 0.05

Parameters of simulation
Initial transitory: 1000
Batch spacing: 1000
Min. batch length: 1000
Max. batch length: 2000
Seed: 1
Accuracy: 15
Conf. level: 60

Type of net: [✓ GSPN] SWN
Type of SWN: [✓ Ordinary] Symmetric
Calculation: [✓ Analytic] Simulation
Results to calculate: res1 res2 T1

Parameters to create the figure
Minimum of x axis: Auto [✓]
Maximum of x axis: 3 Auto [ ]
Minimum of y axis: Auto [✓]
Maximum of y axis: Auto [✓]

Position of legend:
Left [✓ Right]
[✓ Top] Bottom

Style of curve:
[✓ Lines]
Points
Lines and points

Name of gnuplot and postscript file: /home/user/example

Possible curves:
res1, r1=1 T3=2
res2, r1=1 T3=2
T4 r1=1,T3=2
res1, r1=1 T3=4
res2, r1=1 T3=4
T4 r1=1,T3=4
res1, r1=2 T3=2

Gnuplot file:

```
set autoscale y
set data style lines
set xlabel 'Time'

!rm /docs/horvath/nets/MultiSolveExample/example.ps
set output '/docs/horvath/nets/MultiSolveExample/example.ps'

plot \
'/docs/horvath/nets/MultiSolveExample/example.results' using 1:2 title 're
'/docs/horvath/nets/MultiSolveExample/example.results' using 1:3 title 're
```

Figure 4.4: MultiSolve

The parameters of the individual curves are defined in the left upper panel of the window. A list of names of parameters may be given in the text-field labeled **Names**. The entries of the list are separated by spaces. Each entry may be the name of a transition, a rate parameter, or a marking parameter. In the other three text-fields of the panel the user defines the set of values the parameters take. These three text-fields contain lists with as many entries as many parameters were chosen. In the case of the example given in Fig.4.4 the rate parameter $r1$ takes the values 1 and 2, while the rate of transition $T3$ takes the values 2 and 4. The experiments will be carried out considering all the 4 different combinations. The text-fields of this panel may remain empty.

Parameters of the x-axis are defined in the middle upper panel. In case of transient analysis one has to define the lower and the upper limit of the transient time, and the step-size that will be used to step ahead in time. If steady-state analysis is performed the variable that corresponds to the x-axis has to be given as well. As before, this variable may be the name of a transition, a rate parameter, or a marking parameter.

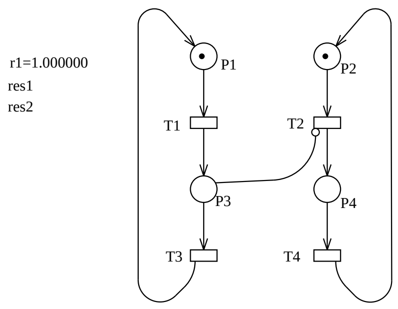


Figure 4.5: A simple example

The measures that will be computed have to be given in the text-field called **Results to calculate**. This text-field contains a list separated by spaces in which an entry is either a measure already defined in the net or the name of a transition. If the name of a transition is given then the throughput of the transition is computed. In case of our example the two measures and a transition name compose the set of results to calculate.

Having defined the parameters of the figure, we have to choose the type of analysis to perform. One has define the type of net to work with. A net may be a GSPN or a SWN, a SWN may be ordinary or symmetric. In case of steady-state analysis the user may choose between exact (analytic) or simulative solution. The above choices can be made by selecting appropriately among the options represented by the check-buttons named **Type of net, Type of SWN** and **Calculation**. In case of simulation the parameters of the simulation can be modified in the right upper panel of the window.

The calculations are performed by clicking on the button named **Perform calculations**. The results of the

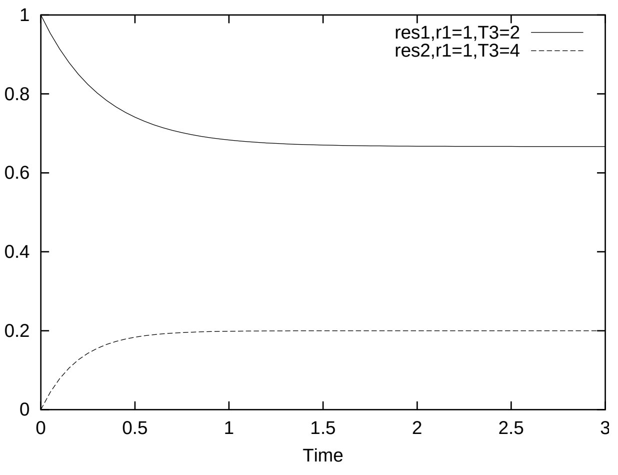


Figure 4.6: Example I

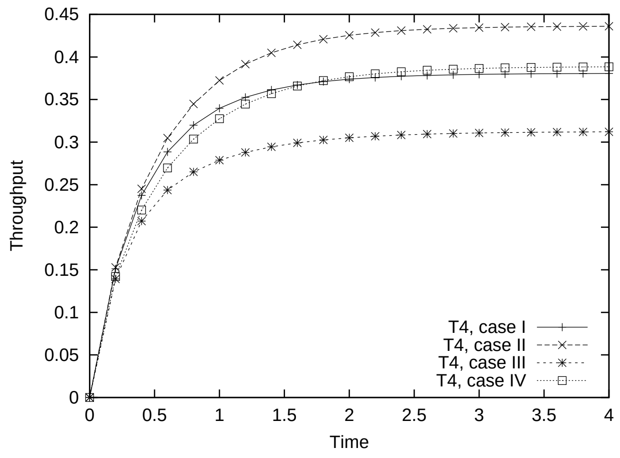


Figure 4.7: Example II

calculations are saved in a file in table format. The name of the file is composed by the name of the net and the extension `results`. The first column of the file contains the values along the x-axis. The other columns corresponds to a measure with a combination of parameters. In the case of the example in Fig.4.4, the file contains 13 columns: the first describes the transient time, while the other 12 correspond to the 4×3 parameter-measure combinations. For example, the second column of the file gives the value of the measure $res1$ for different values of transient time in case of $r1 = 1, T3 = 1$. The first line of the file gives the description of each column.

Having performed the calculations it is possible to create figures. Parameters of the figure are set on the three panels under the title **Parameters to create...**. One can set the minimum and maximum values along the axises (or let gnuplot to determine it automatically), define the position of the legend and the style of the curve. The set of possible curves are listed in the bottom left side of the window. By clicking on the entries of the list the user chooses which curves will be part of the figure (multiple selection is possible by holding down `CTRL` or `SHIFT`). By clicking on the button **Create plot file** a file is created with gnuplot commands; the file is loaded into the text-area **Gnuplot file**. The user may modify the gnuplot commands (to learn more about `Gnuplot` see manual at [25]) and then by clicking **Make postscript** the commands in the text-area are executed.

Fig.4.6 was created by the settings shown in Figure 4.4 not modifying the text-area. The maximum of the x-axis is set to 3, the position of the legend is top right, the curves are plotted by lines. Another example is given in Fig.4.7. In this case the throughput of transition $T4$ is depicted. The position of the legend is changed, the style of the curve is "lines and points". The titles of the curves are changed by modifying the gnuplot commands. Moreover, a title is given to the y-axis by the command `set ylabel 'Throughput'`.

Example of steady state analysis is shown in Fig.4.8. The steady-state value of the throughput of transition $T4$ is depicted as a function of the rate of transition $T3$ for 4 different values of the parameter $r1$. The four text-fields describing the x-axis are set to `T3, 0.2, 6, 0.6` from top to bottom. Grid is added to the figure by adding the command `set grid` to the gnuplot text-area.

WARNING! It is important to note that MultiSolve does not perform exhaustive check of the parameters provided by the user. The parameters are checked only in a syntactic manner. Hence, in order to control if the desired experiments are possible on the chosen net, it is always suggested to perform some computations using *GreatSPN2.0.2* itself before using MultiSolve.

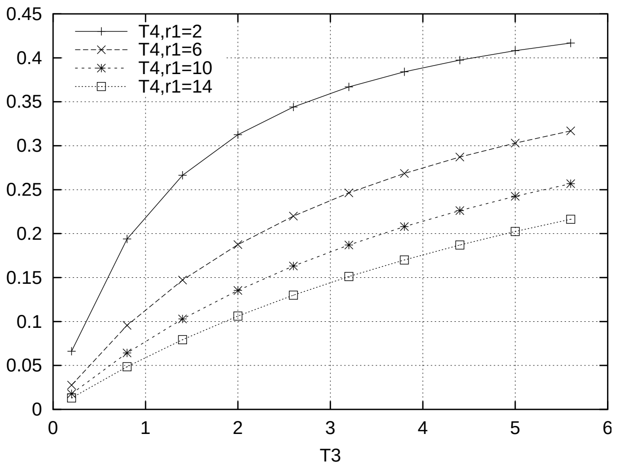


Figure 4.8: Example III

Chapter 5

Compositionality in GreatSPN

The composition of two labelled GSPNs/SWNs is performed by means of the superposition of either (1) transitions or (2) places of matching labels or by applying both kinds of superposition simultaneously.

Both the nets involved in the operation may have non-injective labelling, i.e. the same label may appear connected to two or more transitions or places.

Constraints

1. Only one of the two nets may be multilabelled, i.e. one net (from now on we assume that the 1st operand) may contain places, transitions with multiple labels. This constraint is motivated by the fact that having two multilabelled operands the definition of the operators is a non-trivial task.

2. Concerning SWN models, the colour domains of those places which are to be superposed have to be identical.

In the next section, we give an informal description of composition of two labelled SWNs implemented in the *GreatSPN2.0.2* package, similar considerations can be done for labelled GSPNs.

5.1 Composition of two labelled SWNs

In the following, instead of giving a rigorous definition, the functioning of the operators will be described. First, we concentrate on the case in which only transitions are superposed.

Let's us consider the labelled SWN $\mathcal{N} = \langle P, T, \mathbf{Pre}, \mathbf{Post}, \mathbf{Inh}, \mathbf{pri}, \mathcal{C}, cd, \mathbf{w}, \lambda \rangle$ obtained by the composition of $\mathcal{N}_1$ and $\mathcal{N}_2$ in which:

- the set of places in the resulting net is simply the union of the sets of places, i.e. $P = P_1 \bigcup P_2$ (renaming of place names may be necessary in order to avoid matching names). The colour domain function cd gives $cd_1(\mathsf{p})$ if $\mathsf{p} \in P_1$, $cd_2(\mathsf{p})$ otherwise.

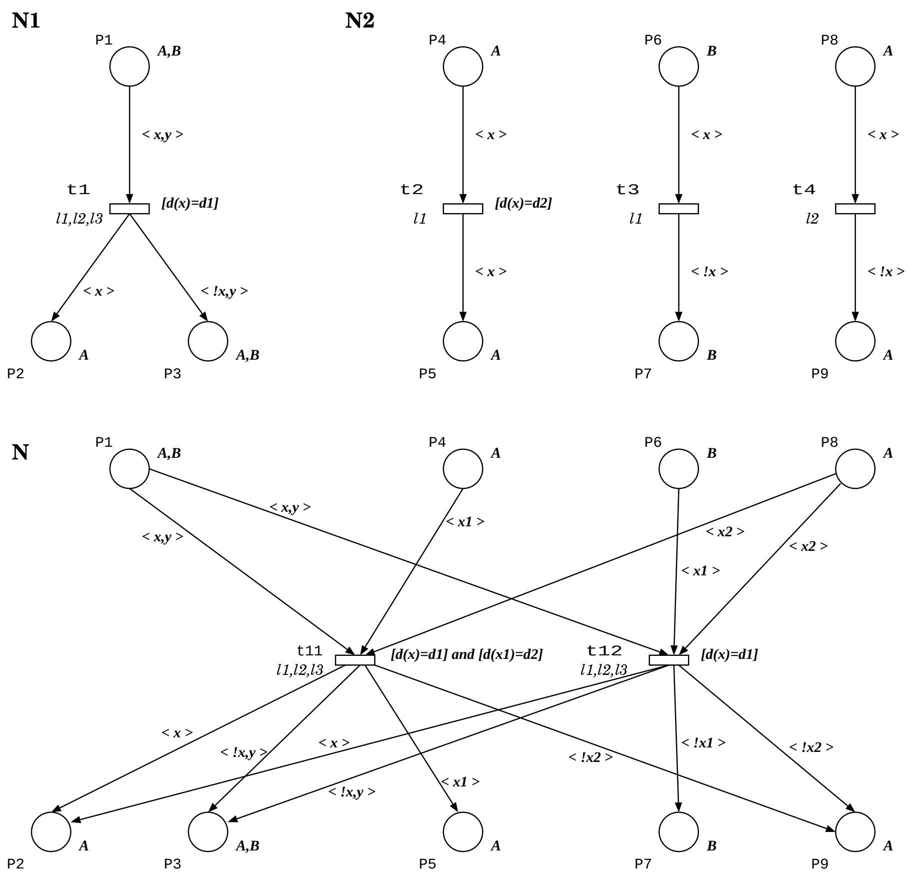


Figure 5.1: A multilabelled, non-injective example

- The unlabelled transitions are considered non-observable with respect to the composition, and those whose labels do not appear in the other operand, are not involved in superposition. These transitions are simply copied into T (as for places, renaming may be necessary). To show how the operation proceeds to superpose transitions let us assume that $\mathcal{N}_1$ is multilabelled, while $\mathcal{N}_2$ is not, and the labelling is non-injective. Let $T_2(l)$ denote the set of transitions $\mathtt{t}'$ of T_2 with $l \in \lambda(\mathtt{t}')$, where $\lambda(\mathtt{t})$ gives the set of labels of $\mathtt{t}$. In $\mathcal{N}$ there will be a replica of $\mathtt{t} \in T_1$ for each element in $\bigotimes_{l \in \lambda(\mathtt{t}), T_2(l) \neq \emptyset} T_2(l)$, where $\bigotimes$ is the cartesian product. An example is shown in Fig. 5.1, for transition t1: $\lambda(\mathtt{t1}) = \{l1, l2, l3\}$ and the above defined cartesian product has the elements $\{\mathtt{t2}, \mathtt{t4}\}$ and $\{\mathtt{t3}, \mathtt{t4}\}$. In the composed net t11 (t12) is obtained by superposing t1,t2 and t4 (t1,t3 and t4).

  If two arcs connected to different transitions that are involved in the same superposition have identical variable names in their arc expression, then these variables are renamed in the arc expression of all the arcs connected to one of the two transitions. If these variables appear in the guard of the transition whose arcs' expressions are changed, the renaming is performed in the guard as well. As an example, in Fig. 5.1, during the superposition of t1, t2 and t4 the variable x of the arcs and guard function connected to t2 is renamed to $x1$. (As it will be mentioned in Section 5.2 the implemented version of the algorithm allows the user to override the above described renaming rule to "unify" values of the nets.) When two superposed transitions have both a guard function these guard functions are joined with logical *and* relation.

- The matrices **Pre**, **Post**, **Inh** describing the arc structure of $\mathcal{N}$ are built in the following way: the arcs of $\mathcal{N}_1$ and $\mathcal{N}_2$ connected to transitions that are not involved in superposition are simply copied into $\mathcal{N}$. An arc connected to a transition involved in superpositions will have as many instances as the times the transition is superposed. In our example the arc P1-t1 has two instances in the composed net: P1-t11 and P1-t12.

- The priority function **pri** gives the same value as before for the transitions that are not involved in superposition. A transition resulting from superposition inherits the priority value from the involved transition of $\mathcal{N}_1$. The labelling functions λ and **w** are handled similarly to the priority one. We assume that there are not marking dependent rates and weights, and we basically leave the user the task of redefining **pri** and **w** for the final net[1].

- The set of basic colour classes $\mathcal{C}$ and their definitions are assumed to be common for $\mathcal{N}_1$ and $\mathcal{N}_2$.

The operation to superpose places is the direct counterpart of the operation described above. However to superpose places is less complicated as it does not require renaming of arc or guard expressions and we are assuming that places to be superposed have the same colour domain.

The simultaneous application of superposing places and transitions has two features that were not shown in the above description. First, having an arc whose place (transition) is involved in n_p (n_t) superpositions, there will be $n_p \cdot n_t$ instances of the arc in the composed net connecting all the instances of its place with all the instances of its transition. Second, having two arcs whose places and transitions are superposed, the arc expressions of these two arcs are added. An example for the latter is shown in Fig. 5.2 where the arc expressions of the arcs P1 – t1 and P3 – t2 are summed.

5.2 The algebra package

The *GreatSPN2.0.2* package **algebra** consists of the **Composition** and the **Remove** modules; in the following we will give a description of the usage of both of them.

5.2.1 Composition module

The **Composition** module allows to perform the composition of two GSPNs/SWNs by using and producing GreatSPN format. The modeler may build the component nets using the graphical interface of *GreatSPN2.0.2* .

[1] To find a more sophisticated and compositional way to handle **pri** and **w** is an open question, attempts to address this problem may be found in the literature.

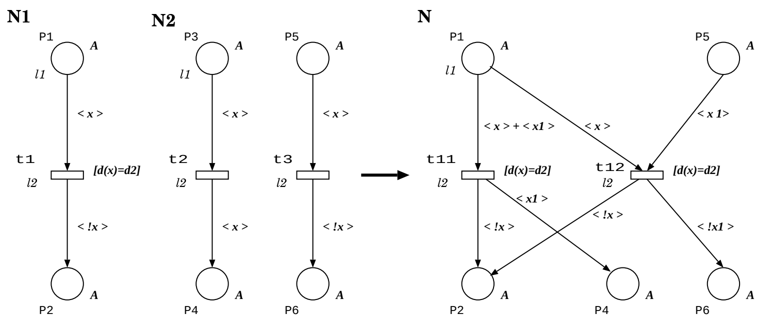


Figure 5.2: Superposition of places and transitions

Labels are encoded in the name of the transitions and places, so both transition and place names have the structure tag|label1|label2..., where tag is the name of the transition or place followed by its labels separated by bars.

The user may define the set of labels to be used for subnets composition. This feature may be useful when composition involves more than two nets and hence is performed in several steps: in this case the modeler can select which labels are to be considered at each stage of the composition.

The **Composition** module creates a graphical representation of the composed net in which the "shape" of the original components is maintained: in case of transitions (or places) with multiple instances in the resulting net, the additional instances are placed around the position of the originating place/transition, moreover the arcs that connect places and transitions belonging to different subnets are drawn as "broken arcs" in the resulting net, to improve its readability. The user has some options to control the layout of the final net by indicating the placement of each component.

A small example for the output of the tool is given in Fig. 5.3[2]: the example demonstrates another feature of the tool: if a variable name starts with the character #, it is not renamed during the superposition. This allows the modeler to use the same variables in different components, so as to "unify" values.

The **Composition** module is launched from the prompt of a console window by typing the command *algebra* followed by a list of input parameters. When it is launched without parameters the complete synopsis is diplayed:

```
Usage:
 algebra [switches] net1 net2 operator restfile resultname [placement shiftx shifty]


Switches: -no_ba: no broken arcs will be used between subnets
          -rs number: result will be rescaled by number
Operators: 't': Superposition Over Transitions
           'p': Superposition Over Places
```

[2]Note that *GreatSPN2.0.2* does not draw arc expressions on broken arcs, so those in the figure are written "by hand".

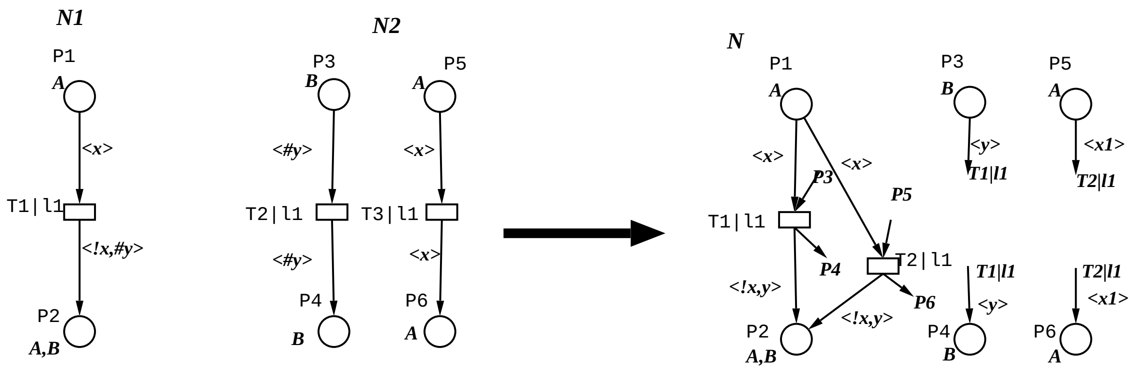


Figure 5.3: Superposition using SWN

```
           'b': Superposition Over Places & Transitions
restfile: contains the labels to be used for synchronization
placement: 1 ---> net1 net2
           2 ---> net1
                  net2
           3 ---> net2 is shifted by (shiftx,shifty)
```

The two operands `net1` and `net2` are the *GreatSPN2.0.2* names (without extensions) of the two nets that have to be composed[3], the resulting composed GSPN/SWN is saved in `resultname`. The first operand `net1` may be multilabelled. The operator is defined by `operator` and may be `t` to superpose transitions, `p` to superpose places or `b` to superpose both places and transitions. The set of labels over which the superposition will be performed may be restricted to a given subset of labels, these subsets are listed in the file `restfile`, this file has the following format:

```
transition={tl1|tl2}
place={pl1|pl2|pl3}
```

The labels that are not given in this file are not considered during the operation. If the file does not exist all labels are considered. The last three arguments may be used to define the placement of the components: if the parameter `placement` is 1 (2) the two nets are placed next to each other horizontally (vertically), if it is 3 the second net is shifted by (`shiftx,shifty`) with respect to the first net. Further options that can be set launching the command:

- `-no_ba` to visualize all the arcs in the composed net; by default, the arcs connecting objects belonging to different components are not entirely displayed, i.e., they are broken;

[3]If the nets to be composed are saved in a directory different from the current one, the complete path is required

- `-rs number` to rescale the composed net by a factor given by `number`.

Merging of two models **Composition** module can be use also to merge two no-labelled *GreatSPN2.0.2* models. Let us assume `model1` and `model2` be the names of two models, then the command:

```
algebra model1 model2 t nolabel model1_2 [placement shiftx shifty]
```

where the file `nolabel` contains the following line:

```
transition={}
```

merges the two models saving the result in file names as `model1_2`.

5.2.2 Remove module

Together with the **Composition** module, the package **algebra** includes also the **Remove** module that has been implemented to eliminate labels and the character `#` from the nets. Typing the command *remove* without parameters the following output is displayed:

```
Usage:
 remove net1 net2 function [labelfile]

net1: Net to work on
net2: Resulting Net
Functions: 'l': Remove labels
           '#': Remove '#'-s
           'b': Do both
labelfile: contains the labels to be removed
           (if not given all labels are removed)
```

`net1` is the name (without extensions) of the input net while `net2` is the name of the output one. As function `l`, `#` or `b` may be given to eliminate labels, the characters `#` or both, respectively. The set of labels to be deleted may be a subset of the set of all the labels, and these subsets may be defined the same way as described for `restfile` in case of the *algebra* command.

Chapter 6

Export to other tools

6.1 Model checking: PROD translator

The PROD translator module is an interface to the PROD tool[36], it translates a GSPN/SWN model defined in *GreatSPN2.0.2* format into the corresponding model described in PROD format. The PROD translator also produces a file containing a list of useful macros to be used during model-checking performed by means of queries during a **probe** session.

6.1.1 Installation

Source files are all stored into the tar-zipped file `PRODtranslDDMMYY.tar.gz`, where DDMMYY is a date (DD=day,MM=month,YY=year). To install the PROD translator the C compilator **gcc**, the lexical and syntactic analyzers **lex** and **yacc** are required. The installation procedure consists in the execution of the following commands:

```
gunzip PRODtransl.tar.gz
tar xvf PRODtransl.tar
cd PRODtransl
install-transl
```

As result of such execution a directory `PRODtransl` is created. This directory contains the following subdirectories:

- `SOURCE`: contains the source files of the translator;
- `DOCS`: contains the documentation related to the translator;
- `bin`: contains the executable files `prod-translator` and `ExploreRG`.

`prod-translator` is the module that allows to translate a GSPN/SWN model defined in *GreatSPN2.0.2* format to the corresponding PROD model; while `ExploreRG` is a script file that contains the sequence of commands the user have to execute to perfom pre-processing of the translated net, to generate its reachability graph (RG), to compute the strongly connected components of RG, to launch the interactive program **probe** and, finally, to remove all the files created during the RG generation once the analysis of the model has been finished and the **probe** session has been closed.

6.1.2 Use of the PROD translator

Once the installation procedure has been performed it is possible to translate a *GreatSPN2.0.2* model through the command:

`prod-translator` *netname*

where *netname* is the name of a GSPN/SWN model created with *GreatSPN2.0.2* without extensions[1]. The translation procedure produces the following output files:

- *netname_prod.net*: that contains the PROD net description;
- *netname_prod.macro*: that contains a list of macros to be used during the model checking performed through the interactive program `probe`;
- *netname_prod_funz.c*, *netname_prod_funz.h*: these files are generated only in case of SWN models and contain information related to the coloured definitions of the net. In case of translation of a SWN model the subdirectory *netname_prod.src* has to be created - if not already existent - where these files have to be move to.

Alternatively, if the user wants to give a different name from the one assigned by default to the translated net, the following command has to be used:

`prod-translator` *netname myprodnet*

where *netname* is the name of the *GreatSPN2.0.2* model to be translated and *myprodnet* is the desired name for the translated PROD model. So the following files will be generated:

myprodnet.net – myprodnet.macro – myprodnet_funz.c – myprodnet_funz.h

6.1.2.1 Nets with inhibitor arcs

Since the PROD tool doesn't allow to define inhibitor arcs, additional information are required to the user if the *GreatSPN2.0.2* model contains inhibitor arcs in order to carry out a properly translation of such arcs into test arcs

[1]The *GreatSPN2.0.2* net definition files *netname.def* and *netname.net* have to be stored both in the same directory

on the complementary places. During the translation of a GSPN model with inhibitor arcs, if the file *netname.bnd* does not exist in the current directory, the user has to give the upper bound, i.e. maximum capacity, of each place having an outgoing inhibitor arc. For example, if the place $p1$ of a GSPN model has an outgoing inhibitor arc, then there will be following request:

```
   Please, introduce bound for place < p1 >:  5
```
[2]

If the bound of a place is unknown, we suggest to set the value 255 that is the maximum bound allowed for a place in a *GreatSPN2.0.2* model. In case of a SWN model, then the user has to provide:

- the initial marking of the complementary place of an inhibitor place, and
- the function to be assigned to the test arc that connects the complementary place to the inhibited transition;

both of these information have to be given using the *GreatSPN2.0.2* syntax. Let us consider the net of Fig.6.1:

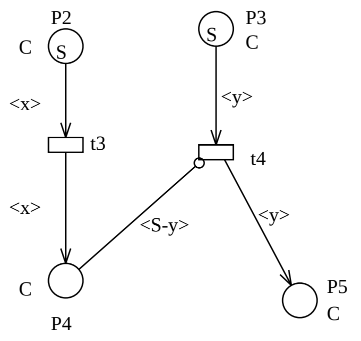


Figure 6.1: SWN net with an inhibitor arc

during the translation execution, the following requests will be displayed:

```
   Please, introduce initial marking for the dual place of p4
domain of place p4:  C
M0(p4) = 0
Use 'e' for empty initial marking :  <S>
   Please, introduce arc_function for inhibitor_arc <S-y>
between place p4 and transition t4
function for input/output arc:  <S-y>
```

It is possible to define an empty initial marking using the *GreatSPN2.0.2* expression `0<S>` or simply the `e`

[2]From here until the end of this chapter the underlined character represents the input given by the user.

letter. If we add an arc from $t4$ to $p4$ with arc function $< x >$ in the net of Fig.6.1 and the guard $[x <> y]$ to the transition $t4$, then the following requests will be displayed:

```
   Please, introduce arc_function for inhibitor_arc <S-y>
between place p4 and transition t4
(there is also an output arc from t4 to p4 with function <x>)
function for input arc:  <S-y>
function for output arc:  <S-y-x>
```

6.1.2.2 SWN nets with symbolic markings

When a SWN net contains a symbolic marking, then only one of the possible assignments is considered in the translation into the corresponding PROD net. Hence, the reachability graph of the PROD net will be reduced with respect to the one obtained from the *GreatSPN2.0.2* model. For example, let's consider the following *GreatSPN2.0.2* symbolic marking:

$$\text{M2} : < M1 >, \ \text{M1} : (\text{C:2}), \quad \text{C} : \text{u C1}, \quad \text{C1} = \text{a1,a2,a3}$$

it corresponds to the following different PROD ordinary markings:

$$< .a1..a2. >, \ < .a2..a3. >, \ < .a1. > + < .a3. >$$

So if only one of the above assignments is considered then the reachability graph of the PROD net is 1/3 of the one obtained for the *GreatSPN2.0.2* one.

6.1.2.3 The script ExploreRG

Once the *GreatSPN2.0.2* net has been translated into the PROD net it is then possible to perform model-checking using the PROD tool. To investigate the reachability graph (RG) of the PROD net *netname_prod* the following command have to be executed:

```
prod netname_prod.init
netname_prod
strong netname_prod
probe -l netname_prod.macro netname_prod
```

that perform the corresponding actions:

preprocessing of *netname_prod*
RG generation of *netname_prod*
computation of the strongly connected components of the RG of *netname_prod*
activation of the analyzer of the RG of *nomerete_prod*

After the last command has been launched, the interactive RG analyzer `probe` is running (it is in prompt state `0#`); it is then possible to submit queries to investigate the RG of the net. Besides the basic queries of the PROD syntax, the user can exploit the predefined macros contained in the file *netname_prod.macro* that can be displayed from the `probe` prompt with the command `defs`.
Alternatively to the command

```
probe -l netname_prod.macro netname_prod
```

the commands `probe netname_prod` and `load netname_prod.macro` have to be launched.
The command `quit` causes the termination of the `probe` session and hence the ending of the RG inspection. Afterwards, we suggest to execute the command:

```
prod netname_prod.clean
```

that removes all the files produced during the RG generation. The sequence of commands listed at the beginning of this paragraph included this last command is summarized in the script file `ExploreRG` that defines a macro command to be used as follows:

```
ExploreRG netname_prod
```

this command generates the RG of the PROD net defined in `netname_prod`, allows to inspect the RG through queries, included the ones predefined in the file `netname_prod.macro` and finally, removes all the files created during the RG generation.

6.1.2.4 The pre-defined macros

All the predefined macros generated by the PROD translator are stored in the file `netname_prod.macro`: they can be used during the inspection of the RG of the net *netname_prod* through the interactive analyzer `probe`. Besides the macro definitions, the definitions of the marking parameters and of the coloured tokens of the net are also listed. Some macros takes account of the characteristics of the translated net, others are independent of the structure of the net. Moreover, some macros are simply *alias* of some `probe` commands such as:

```
#define qv query verbose
#define qn query node
#define qmn query mute node
#define qvn query verbose node
```

Let us consider a net with the following subsets of transitions:

- `T1`, `T2`, `T3` timed transitions (exponential);
- `t4`, `t6` timed transitions (deterministic);
- `t5`, `t7` immediate transitions with priority `G1`;
- `t8`, `t9` immediate transitions with priority `G2`;

a first group of macros consists of a list of definitions of the above subsets of transitions:

`#define TEMP_CLASS (\`	exponential timed
`T1(1) || T2(1) || T3(1))`	transitions subset
`#define DET_CLASS (\`	deterministic timed
`t4(1) || t6(1))`	transitions subset
`#define G1_CLASS (\`	immediate transitions with
`t5(1) || t7(1))`	priority G1 subset
`#define G2_CLASS (\`	immediate transitions with
`t8(1) || t9(1))`	priority G2 subset
`#define IMM_CLASS (\`	immediate transitions
`G1_CLASS || G2_CLASS)`	subset

The second group of macros consists of a set of queries to be used as a command from the `probe` prompt, the `probe`'s answer will be of type:

```
8 PATH
built set %12
```

that means that either 8 paths or 8 markings, satisfy the submitted query and the result of the query is saved into a set denoted as `%12`.

During the queries it is possible to "jump" from a node of the RG to another through the command `goto n` where n is the number that identifies a node of the RG.

In the following the second group of macros is listed:

1. `TangMark`
   detects the set of tangible markings of the net, deadlock markings are not included;

2. `VanMark`
   detects the set of vanishing markings of the net;

3. `M0pathTO(markSet)`
   detects and displays the set of paths P such that $P = \bigcup_{i=1}^{n} P_i$ where P_i is the shortest path from M_0 to M_i, $M_i \in$ markSet and markSet=$\{M_1, .., M_n\}$;

4. `PathTO(markSet)`
   detects and displays the set of paths P such that $P = \bigcup_{i=1}^{n} P_i$ where P_i is the shortest path from the current marking to M_i, $M_i \in$ markSet and markSet=$\{M_1,..,M_n\}$;

5. `Deadlock`
   detects the set of deadlock markings;

6. `M0pathTOdeadlock`
   detects and displays the set of the shortest paths from M_0 to each deadlock marking;

7. `PathTOdeadlock`
   detects and displays the set of the shortest paths from the current marking to each deadlock marking;

8. `Livelock`
   displays all the livelocks of the net;

9. `M0pathTOlivelock(livelockSet)`
   detects and displays the set of the shortest paths from M_0 to each marking belonging to the livelock `livelockSet`, where `livelockSet` is a set of the form `%%n` where n is its identifier number[3];

10. `PathTOlivelock(livelockSet)`
    detects and displays the set of the shortest paths from the current marking to each of the markings belonging to `livelockSet`, such set have to be of the form `%%n` where n is its identifier number;

11. `AllMarkEnabOnly(lastset,transSet)`
    detects and displays the set of markings in which only transitions belonging to the set `transSet` are enabled;

12. `ExistPathM1toM2(lastset,mark1,mark2)`
    detects and displays the shortest path from marking `mark1` to the marking `mark2`, if no path is found between the two markings the answer to this query is `0 PATH`;

13. `AllPathM1toM2(lastset,mark1,mark2)`
    detects and displays all the paths, without loops, from `mark1` to `mark2`, if no path is found between the two markings the answer to this query is `0 PATH`;

14. `MarkingSetEnab(trans)`
    detects and displays the set of markings that enable transition
    t trans;

[3]In `probe` the strongly connected components of RG, hence the livelocks, are denoted as %%n.

15. `TransEnab(mark)`
    detects and displays the set of transitions enabled in marking `mark`;

16. `Successor(mark, trans)`
    detects and displays the marking M_1 reached from marking `mark` after the firing of `trans`, i.e.:

17. `Enable(mark,trans)`
    verifies if the marking `mark` enables the transition `trans`;

18. `Mark(node)`
    displays the marking identified by the number `node`;

19. `MarkSetEnabOR(setT1,setT2)`
    detects and displays the following set of markings:

    $$markSet = \{M_i| \ \ M_i[t_v \vee M_i[t_w \text{ where } t_v \in \texttt{setT1} \wedge t_w \in \texttt{setT2}\}$$

    i.e the set of markings that enable at least either a transition of the set `setT1` or a transition of the set `setT2`;

20. `MarkSetEnabAND(lastset,setT1,setT2)`
    detects and displays the following set of markings:

    $$markSet = \{M_i| \ \ M_i[t_v \wedge M_i[t_w \text{ where } t_v \in \texttt{setT1} \wedge t_w \in \texttt{setT2}\}$$

    i.s. the set of markings that enable at least a transition of the set `setT1` and at least a transition of the set `setT2`;

21. `MarkBelongSet(lastset,mark,markSet)`
    verifies if the marking `mark` belongs to the set of markings `markSet`;

22. `LogicCond(formula)`
    detects and displays the set of markings that satisfy condition expressed by `formula`.

We emphasize the form of the parameters appeared in some macros of the previous list and not explicitly described:

- `lastset` has to be the number of the last set computed by `probe`, usually the one obtained as a result from the last submitted query;

- `transSet` is a set of transitions, it has to be expressed with the same syntax used for the definition of the sets `TEMP_CLASS` and `IMM_CLASS`, that is:

Transname1(1) || Transname2(1) || ....

- `mark` is a marking that corresponds to a node of RG, it has to be expressed as `n`, that is the number that identifies the node of RG, for example:

  ```
  TransEnab(5)
  ```

  where `5` represents a marking of RG.

- `markSet` is a set of markings and it has to be expressed as `%n` where n is the number that identifies the set containing the considered markings; it can be either a basic set defined by `probe` or a set obtained as a result of a query[4], for example:

  ```
  MarkBelongIns(4,10,%2)
  ```

  where `4` is the last set created by `probe`, `10` represents a marking and `%2` is a set of markings.

- `formula` is a formula that can be expressed using the PROD grammar[5]:

formula	::=	**(**formula**)** | **not** formula | formula **and** formula |
		formula **or** formula | expr
expr	::=	simple_expr | mark **==** mark | mark **!=** mark |
		mark >= mark | mark <= mark | mark < mark |
		mark > mark | op1 expr | expr op2 expr
simple_expr	::=	**card(** mark **)** | **(** expr **)** | digits
mark	::=	simple_mark | mark **+** mark | simple_expr simple_mark
simple_mark	::=	place_name | **empty** | < . rangelist . > |
		< .. > | **(** mark **)**

  Non terminal symbols *op1* and *op2* are respectively the unary and the binary operators used in the expressions of the C programming language. Let us consider some examples of formulae accepted by the PROD grammar:

`card(p1)>=card(p2)`	the total number of tokens in place `p1` is equal to the total number of tokens in place `p2`
`card(p1)==N`	the total number of tokens in place `p1` is equal to the value of the parameter `N`
`p1==p2`	the marking in place `p1` is equal to the marking in place `p2`[6].

[4]It is worth to notice that in general the sets generated by `probe` are sets of paths, the markings are considered as paths of zero length.

[5] The grammar described in the following is simplified, for a full description see the PROD reference manual[36]

`p1<N p2`	the marking in place `p1` is less than the marking in place `p2` multiplied by the value of the parameter `N`[7].

Let us see some example on the usage of the macro 22, that accept as a input parameter a formula:

`0#LogicCond( card(p1)==2 and p2==empty)`
detects the set of markings in which the place `p1` is marked with 2 tokens and the place `p2` is empty;

`0#LogicCond( p1==(<.a1,p1.>+<.a2,p2.>))`
detects the set of markings in which the marking of place `p1` is the one specified by the query. Symbols `a1`,`p1`,`a2`,`p2` are numeric constants that represent coloured tokens.

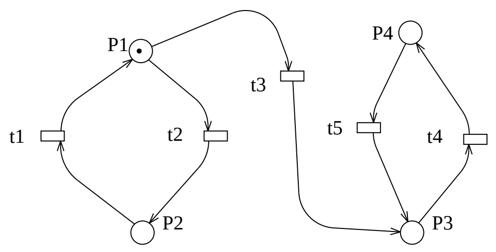


Figure 6.2: GSPN net with a livelock

Macros 9 and 10 do not guarantee that the paths found are the shortest paths that brings to a livelock, really it should be verified that every path does not contain more than one node belonging to the livelock.

Let us consider the net of Fig.6.2 the following queries can be submitted:

```
0#livelock
Component %%0
------------------------------------------------
   1,        3
%%0 has 2 nodes
------------------------------------------------
1 nontrivial terminal strongly connected components
------------------------------------------------
0#M0pathTOlivelock(%%0)
PATH
Node 0, belongs to strongly connected component %%1
  P1: <..>
```

[6]The number of occurrences of a single coloured token is compared in the two markings.

[7]The marking `Np2` is obtained from the marking of the place `p2` by multiplying the occurrences of each coloured token `N` times.

```
Arrow 0: transition t3, precedence class 0
Node 1, belongs to strongly connected component %%0
  P3: <..>
------------------------------------------------
PATH
Node 0, belongs to strongly connected component %%1
  P1: <..>
Arrow 0: transition t3, precedence class 0
Node 1, belongs to strongly connected component %%0
  P3: <..>
Arrow 0: transition t4, precedence class 0
Node 3, belongs to strongly connected component %%0
  P4: <..>
------------------------------------------------
2 paths
Built set %1
------------------------------------------------
```

Two paths have been detected, but only the first one is the shortest path that brings the net to the livelock. We can then select the shortest path by means of the query:

`ExistPathM1toM2(1` [8] `,0,1).`

6.2 Kronecker solutions: APNN translator

The **APNN** translator transforms the *GreatSPN2.0.2* net description files into a corresponding APNN notation: the *GreatSPN2.0.2* layers are interpreted as a partition of the net into subnets which synchronize over transitions (Superposed GSPNS), for a subsequent application of Kronecker based solution methods.

6.3 Tgif translator

The **gspn2tgif** program translates a model defined in *GreatSPN2.0.2* format into a *Tgif* [9] .obj file: each net object is translated into a *Tgif* graphical object so that the graphical appearance of the converted GSPN/SWN model can then be modified using the *Tgif* GUI.

6.4 Fluid nets translator

The **net2fspn** translator provided with the *FSPNEdit* software package, transforms the **.net** files saved by *Great-SPN2.0.2* into the **.fspn** files required by the solution components of the FSPN analysis tool. User can then add

[8]This is the identifier number of the set obtained with the previous query.

fluid places and continuous arcs to the generated files and analyze them using the tools provided by the *FSPNEdit* package. In particular the generated FSPN may be solved either by simulation (using the software component **FSPNsim**) or by numerical analysis (using **FSPNsolve**).

6.5 Refinement of SWN performance indexes: PERFSWN

This text has been written by Serge Haddad, Patrice Moreaux, and M. Sene

PERFSWN is a set of tools providing an interactive framework to define, compute and present to the user steady state performance indices of SWN insofar as these indices relate only to static subclasses of the SWN. These tools complement *GreatSPN2.0.2* to exploit the SRG and the steady state probability vector of the SWN. In addition to *GreatSPN2.0.2* , PERFSWN leans on several Perl scripts that we have developed and on the interactive numerical environment Scilab (available at http://www-rocq.inria.fr/scilab).

The user environment is composed of several working sessions. A *GreatSPN2.0.2* session is dedicated to SWN definition and computation of performance indices available in the tool. A Scilab session supplements *GreatSPN2.0.2* to compute various performance indices and to provide graphical presentations of data (plots, graphs, etc). Beside these two sessions, the user can enter commands into a terminal session to run the interface software which extracts results and compute new ones from *GreatSPN2.0.2* results.

A typical sequence of operation in PERFSWN is the following. The user defines its SWN with the graphical interface of *GreatSPN2.0.2* . Next, he asks *GreatSPN2.0.2* for the computation of the Symbolic Reachability (SRG) with output into an ASCII file, alone, or together with the solution of the aggregated Markov chain of the SWN. Under the terminal session, the user can now process the Tangible Symbolic Reachability Set (TSRS) and obtain a Scilab script version of the solution vector $\widehat{\pi}$ for the TSRS. If no change is done to the structure of the SWN, the TSRS does not need to be reloaded when new stochastic parameters are given. Then he begins its Scilab session by loading the TSRS and $\widehat{\pi}$ (i.e. running our corresponding scripts). Consequently, the user works with data from the TSRS and the vector $\widehat{\pi}$ into the Scilab session. If needed, the user asks for specific symbolic firings in the terminal session. He can now compute the throughput of these transition firings into theScilab session by calling interactively functions of our libraries.

PERFSWN benefits from all features of Scilab for the definition of high level functions (for instance reward functions based on the static partitio ns of the symbolic markings), as well as for the management of the working session (save and restore of sessions, batch execution, etc.).

Computation of performance indices (in steady state) is based on the (colored) token distributions, the throughput of transitions and the response times of subnets. The general method to obtain a performance index (say a) is to define a reward function giving, for each tangible marking $\mathbf{m} \in TRS$, a reward value $r(\mathbf{m})$ contributing to a. Then we have $a = E(r) = \sum_{\mathbf{m} \in TRS} r(\mathbf{m})\pi(\mathbf{m})$. PERFSWN is able to compute these indices, provided that they relate to the number of tokens per static subclasses only. PERFSWN extracts the TSRS with the static partitions of all tangible symbolic markings (the canonical representations are discarded) into a Scilab session. Moreover, firings instances of a given transition are retrieved from the SRG based on a boolean expression we call a *bindings formula*. The syntax of bindings formulae is the classical combination of logic (or, and, not) with basic boolean expressions giving the static subclass of the instantiation of a variable of the transition.

PERFSWN provides two basic Scilab libraries for performance indices computation. `swn.sci` is dedicated to specific SWN functions (for instance, display symbolic markings, find markings with specific property, define and compute reward functions). In addition to performance computations, the user can in this way, examine several qualitative properties of the system. The second library, `perf.sci`, is a set of general purpose functions useful in the area of performance evaluation. It provides the user with mean reward computation from a user defined reward function (for instance over symbolic markings), distribution computation, like tokens distribution in one or several places, plot of cumulative distributions functions, etc. Obviously this library could be easily extended by any user.

Appendix A

Net description files

The *GreatSPN2.0.2* net description is stored in two ASCII files called `netname.net` and `netname.def` respectively.

The `.net` description file contains the description of the structure of a *GreatSPN2.0.2* model according to the following Backus-Naur Form (BNF) format. Capital keywords are non-terminals, while terminals are represented as C language strings. The following special terminals are used: `empty` indicates void fields; `string` indicates any non-empty character string not containing blank characters; `space` indicates any sequence of blank and tab characters; `natural` indicates a non-negative integer; `pint` indicates a positive integer; `preal` indicates a positive real; `coords` indicates a pair of non-negative real number representing object coordinates with a space between them. The notation `#(XX)...` denotes the repetition of the string in braces for a number of times derived by interpreting the string `XX` as a natural number. Moreover we used C-like notation `/* comments */` to comment some lines.

The `*.def` description file contains the description of additional information of a *GreatSPN2.0.2* model. In particular:

- definition of the coloured part (SWN models only) according to the SWN BNF grammar given in Table A.1;
- definition of rate parameters according to the Marking-Dependent Rate Definition BNF grammar given in Table A.2;
- definition of (no default) results, to be computed using either markovian or simulator solvers, according to the Result Definition BNF grammar given in Table A.3.

In addition to the special terminal keywords adopted previously, in the definition of the `*.net` file, we use also the following ones: special terminal keyword `<assign>` to indicate a marking dependent rate parameter definition; `<result>` to indicate a result definition; `<fun_def>` to indicate a coloured definition.

A.1 Format of the .net file

```
NETFILE  ::= COMMENT NOOBJS MARKS PLACES RATES GROUPS TRANS LAYERS
COMMENT  ::= "|0|\n" COMHEAD  "|\n"
COMHEAD  ::= empty "|\n" | "Comment on this GSPN:\n" { COMLINE "\n" }
COMLINE  ::= space | string | empty | COMLINE space | COMLINE string
NOOBJS   ::= "f" space NM  space NP space NR space NT space NG
            space "0" space NL space "\n"
NM       ::= natural   /* number of marking parameters */
NP       ::= natural   /* number of places */
NR       ::= natural   /* number of rate parameters */
NT       ::= natural   /* number of transitions */
NG       ::= natural   /* number of groups   */
NL       ::= natural   /* number of layers   */
MARKS    ::= #(NM) { NAME space MVAL space coords LEVELS "\n" }
NAME     ::= string
MVAL     ::= pint
LEVELS   ::= space "0" | space pint LEVELS
PLACES   ::= #(NP) {NAME space PMARK space coords space coords LEVELS COL "\n" }
PMARK    ::= natural | "-" MPINDX
MPINDX   ::= pint     /*  0  <  #(MPINDX)  <=  #(NM) in case of GSPN   */
COL      ::= empty | coords string
RATES    ::= #(NR){ NAME space RVAL space coords LEVELS "\n" }
RVAL     ::= preal
GROUPS   ::= #(NG){NAME space coords space PRI "\n" }
PRI      ::= pint    /* priority */
TRANS    ::= #(NT){NAME space TRATE space TSERV space TKND space TINP space
                   TROT space coords space coords space coords LEVELS COL "\n"
                   LDCOEFFS TIARCS TOUT TOARCS TINH THARCS }
TRATE    ::= preal | "-" RPINDX | MDRATE
RPINDX   ::= pint   /*   0 < #(RPINDX)  <= #(NR)  */
MDRATE   ::= "-510"   /*  A MD rate is defined in file .def  */
TSERV    ::= natural |  "-" LDPOP
LDPOP    ::= pint   /* max population of LD equivalent server */
TKND     ::= EXPT | DETT | IMMT
```

```
EXPT     ::= "0"
DETT     ::= "127"
IMMT     ::= pint  /* priority level group s.t.  0 < #(IMMT) < #(NG) */
TINP     ::= natural  /*  No. Input Arcs  */
TROT     ::= "0" | "1" | "2" | "3"  /*  rotation coefficient  */
LDCOEFFS ::= (#(LDPOP) - 1){ preal "\n" }
TIARCS   ::= #(TINP){ AMULT space APLACE space APOINTS LEVELS
                 COL "\n" APLIST }
AMULT    ::= pint   /* arc multiplicity  */
APLACE   ::= pint   /* place index s.t. 0 < #(APLACE) <= #(NP)  */
APOINTS  ::= natural   /* No. intermediate points  for broken arcs */
APLIST   ::= #(APOINTS){ coords "\n" }
TOUT     ::= natural "\n"   /*  No. Output Arcs  */
TOARCS   ::= #(TOUT){AMULT space APLACE space APOINTS LEVELS
                 COL "\n" APLIST }
TINH     ::= natural "\n" /*  No. Inhibitor Arcs  */
THARCS   ::= #(TINH){AMULT space APLACE space APOINTS LEVELS
                 COL "\n" APLIST }
LAYERS   ::= { NAME "\n" }   /* list of Layer names
                               one per layer used in objects  */
```

A.2 Format of the .def file

```
DEFMD    ::=     "|" TI "\n" RATE_DEF "\n"
TI       ::=     pint    /* transition relative position inside ".net" */
RATE_DEF ::=     <assign>
RESULT   ::=     RES RESULT  |  "|\n"
RES      ::=     "|" NAME space coords space ":" space RES_DEF "\n"
NAME     ::=     string
RES_DEF  ::=     <result>
COLOR    ::=     COL COLOR | empty
COL      ::=     "(" NAME space CT space coords space "(@" CT "\n"
                 <fun_def> "\n ))"
CT       ::=     "c"  |  "f"  |  "m"
```

A.3 Grammars

The SWN syntax (Table A.1), the marking-dependent rate definition grammar (Table A.2) and the performance result definition grammar (Table A.3) are given according to the following BNF format.

All the terminal keywords are represented as C-language strings in quotation marks except for the following terms: $<$*real_number* $>$ indicates a positive real number, $<$*integer* $>$ indicates a non negative integer number, $<$*string* $>$ indicates any non-empty character string not containing blank characters and $<$*empty* $>$ indicates void fields. Concerning the $<$*color_class_type* $>$ keyword it can assume either “o” or “u” values which stand for “ordered” and “unordered” respectively.

```
<fun_def >                             ::=  <color_class_description > |
                                            <static_subsclass_description > |
                                            <initial_marking_description > |
                                            <dynamic_subclass_description >
<color_class_description >             ::=  <color_class_type > <static_subclasses_list >
<static_subclasses_list >              ::=  <static_subclass_name > |
                                            <static_subclasses_list > “,” <static_subclass_name >
<color_class_type >                    ::=  “o” | “u”
<static_subclass_description >         ::=  <string > “{” <integer > – <integer > “}” |
                                            “{” <objects_list > “}”
<objects_list >                        ::=  <object_name > | <objects_list > “,” <object_name >
<place_color_domain_description >      ::=  <color_classes_list > | <empty >
<color_classes_list >                  ::=  <color_class_name > |
                                            <color_class_name > “,” <color_classes_list >
<arc_function_description >            ::=  <empty > | <coefficient > “ID” |
                                            <ordinary_function >
<ordinary_function >                   ::=  <coefficient >
                                            [ <predicate > ] “<” <function_list > “>” |
                                            <ordinary_function > <sum_op > <coefficient >
                                            [ <predicate > ] “<” <function_list > “>”
<function_list >                       ::=  <function_kernel > |
                                            <function_kernel > “,” <function_list >
<function_kernel >                     ::=  <term > | <function_kernel > <sum_op > <term >
<term >                                ::=  <synchronization_term > | <projection_term > |
                                            <successor_term > | <predecessor_term >
<synchronization_term >                ::=  <coefficient > “S” |
```

		<*coefficient* > “S” <*static_subclass_name* >
<*projection_term* >	::=	<*coefficient* > <*function_name* >
<*successor_term* >	::=	<*coefficient* > “!” <*function_name* >
<*predecessor_term* >	::=	<*coefficient* > “ˆ” <*function_name* >
<*initial_marking_description* >	::=	<*short_marking* > | <*ordinary_marking* >
<*short_marking* >	::=	<*coefficient* > “S”
<*ordinary_marking* >	::=	<*coefficient* > “<” <*marking_list* > “>” |
		<*ordinary_marking* > <*sum_op* >
		<*coefficient* > “<” <*marking_list* > “>”
<*marking_list* >	::=	<*marking_item* > | <*marking_list* > “,” <*marking_item* >
<*marking_item* >	::=	<*dynamic_subclass_name* > | “S” <*static_subclass_name* > |
		“S” | <*object_name* >
<*cardinality* >	::=	<*integer* > |
		“|” <*color_class_name* >“.”<*static_subclass_name* > “|” |
		“| <*color_class_name* > “|”
<*object_name* >	::=	<*string* >
<*dynamic_subclass_description* >	::=	“(” <*static_subclass_name* > “:” <*cardinality* > [“:” <*integer* >] “)”
<*predicate* >	::=	<*predicate* > “or” <*pterm* > | <*pterm* >
<*pterm* >	::=	<*pterm* > “and” <*pfatt* > | <*pfatt* >
<*pfatt* >	::=	“(” <*predicate* > “)” |
		“d” “(” <*string* > “)” <*eqop* > <*d_operand* >
		| <*string* > <*eqop* > <*str_operand* >
<*d_operand* >	::=	“d” “(” <*string* > “)” | <*static_subclass_name* >
<*str_operand* >	::=	<*string* > | “!” <*string* > | “ˆ” <*string* >
<*color_class_name* >	::=	<*string* >
<*function_name* >	::=	<*string* >
<*static_subclass_name* >	::=	<*string* >
<*dynamic_subclass_name* >	::=	<*string* >
<*coefficient* >	::=	<*integer* > |
		“|” <*color_class_name* >“.”<*static_subclass_name* > “|” |
		“|” <*color_class_name* > “|” | <*empty* >
<*sum_op* >	::=	“+” | “–”
<*eqop* >	::=	“=” | “<>”

Table A.1: SWN syntax for the *GreatSPN2.0.2* package.

<*assign* >	::=	{ “when” <*logic_cond* > “:” <*value* > “;”}
		“ever” <*value* > “;”
<*logic_cond*>	::=	<*compare* > | “ ˜ ” <*logic_cond* > | “(” <*logic_cond* > “)” |
		<*logic_cond* > “&” <*logic_cond* > | <*logic_cond* > “o” <*logic_cond* >
<*compare* >	::=	<*marking* > <*comp_oper* > <*integ_const* >
<*marking* >	::=	“#” <*place_name* >
<*place_name* >	::=	<*string* >
<*comp_oper* >	::=	“=” | “/=” | “>” | “<” | “>=” | “<=”
<*integ_const* >	::=	<*integer* > | <*mark_par* > | <*marking* >
<*mark_par* >	::=	<*string* >
<*value* >	::=	<*real_val* > | “(” <*value* > “)” | <*value* > <*arithm_op* > <*value* >
<*real_val* >	::=	<*real_number* > | <*marking* > | <*rate_par* >
<*rate_par* >	::=	<*string* >
<*arithm_op* >	::=	“+” | “–” | “*” | “/”

Table A.2: BNF of the marking-dependent rate definition grammar.

<*result* >	::=	<*sum* > “;”
<*sum* >	::=	<*item* > | <*item* > “+” <*sum* > | <*item* > “–” <*sum* >
<*item* >	::=	[<*real_val* >] “p{” <*logic_cond* > “}” | [<*real_val* >] “P{” <*logic_cond* > “}” |
		[<*real_val* >] “e{” <*marking* > “}” | [<*real_val* >] “E{” <*marking* > “}” |
		[<*real_val* >] “e{” <*marking* > “/” <*logic_cond* > “}” |
		[<*real_val* >] “E{” <*marking* > “/” <*logic_cond* > “}”
<*real_val* >	::=	<*real_number* > | <*rate_par* >
<*rate_par* >	::=	<*string* >
<*logic_cond* >	::=	<*compare* > | “ ˜ ” <*logic_cond* > | “(” <*logic_cond* > ”)” |
		<*logic_cond* > “&” <*logic_cond* > | <*logic_cond* > “o” <*logic_cond* >
<*compare* >	::=	<*marking* > <*comp_oper* > <*integ_const* >
<*marking* >	::=	“#” <*place_name* >
<*place_name* >	::=	<*string* >
<*comp_oper* >	::=	“=” | “/=” | “>” | “<” | “>=” | “<=”
<*integ_const* >	::=	<*integer* > | <*mark_par* > | <*marking* >
<*mark_par* >	::=	<*string* >

Table A.3: BNF of the performance result definition grammar.

A.4 Extended SWN grammar

The SWN grammar has been extended to allow the definition of the refined performance indices. In particular, the extended grammar allows to define four main categories of performance indices:

- linear combinations of mean number of token in places and probabilities;
- linear combinations of throughputs;
- average crossing times;
- multiple results.

Table A.4 formalizes the extension according to the following BNF format. All the terminal keywords are represented as C-language strings in quotation marks except for the following terms: <*real_number* > indicates a positive real number, <*integer* > indicates a non negative integer number, <*string* > indicates any non-empty character string not containing blank characters.

```
<result >          ::=   <sum > “;” | <sum_t > “;” |
                         <item_fam > “;” | <sum > “/” <sum_t > “;”
<sum >             ::=   <item > | <item > “+” <sum > | <item > “-” <sum >
<item >            ::=   [ <real_val > ] “P{” <logic_cond > “}” |
                         [ <real_val > ] “E{” <marking > “}” |
                         [ <real_val > ] “E{” <marking > “/” <logic_cond > “}”
<marking >         ::=   “#” <place_name > | “#” <place_name > “[” <pred > “]”
<sum_t >           ::=   <item_t > | <item_t > “+” <sum_t > | <item_t > “-” <sum_t >
<item_t >          ::=   [ <real_val > ] “X{” <marking_t > “}” |
                         [ <real_val > ] “X{” <marking_t > “/” <logic_cond > “}”
<marking_t >       ::=   “#” <transition_name > |
                         “#” <transition_name > “[” <pred > “]”
<item_fam >        ::=   [ <real_val > ] “E{” <marking_fam > “}” |
                         [ <real_val > ] “E{” <marking_fam > “/” <logic_cond > “}” |
                         [ <real_val > ] “X{” <marking_fam > “}” |
                         [ <real_val > ] “X{” <marking_fam > “/” <logic_cond > “}”
<marking_fam >     ::=   “#” <obj_name > “(*)” |
                         “#” <obj_name > “(*)| SEL=[” <pred > “]” |
                         “#” <obj_name > “(*)| SEL=[” <pred >“], COND=[” <pred > “]” |
                         “#” <obj_name > “(*)| COND=[” <pred >“]” |
```

		“#” <*obj_name* > “(”<*obj_list* >“)” |
		“#” <*obj_name* > “(”<*obj_list* >“)| SEL=[” <*pred* > “]” |
		“#” <*obj_name* > “(”<*obj_list* >“)| SEL=[” <*pred* > “], COND=[” <*pred* > “]” |
		“#” <*obj_name* > “(”<*obj_list* >“)| COND=[” <*pred* > “]”
<*place_name* >	::=	<*string* >
<*transition_name* >	::=	<*string* >
<*obj_list* >	::=	<*obj_name* > | <*obj_list* > “,” <*obj_name* >
<*obj_name* >	::=	<*string* >
<*real_val* >	::=	<*real_number* > | <*rate_par* >
<*rate_par* >	::=	<*string* >
<*logic_cond* >	::=	<*compare* > | “ ˜ ” <*logic_cond* > | “(” <*logic_cond* > “)” |
		<*logic_cond* > “and” <*logic_cond* > | <*logic_cond* > “or” <*logic_cond* >
<*compare* >	::=	<*marking* > <*comp_oper* > <*integ_const* > |
		<*multiset_def* > <*comp_oper* > <*multiset* >
<*comp_oper* >	::=	<*rel_op* > | “>” | “<” | “>=” | “<=”
<*integ_const* >	::=	<*integer* > | <*mark_par* > | <*marking* >
<*multiset* >	::=	<*multiset_const* > | <*multiset_def* >
<*multiset_def* >	::=	“#” <*place_name* > “(*)” | “#” <*place_name* > “(” <*class_list* > “)” |
		“#” <*place_name* > “(*)[” <*pred* > “]” |
		“#” <*place_name* > “(” <*class_list* > “)[” <*pred* >“]”
<*multiset_const* >	::=	“[” <*real_number* >“] <” <*obj_list* > “> |
		“[” <*real_number* > “]<” <*obj_list* > “> +” <*multiset_const* >
<*class_list* >	::=	<*class_name* > | <*class_list* > “,” <*class_name* >
<*class_name* >	::=	<*string* >
<*mark_par* >	::=	<*string* >
<*pred* >	::=	<*compare_p* > | “(” <*pred* > “)” | <*pred* > “and” <*pred* > | <*pred* > “or” <*pred* >
<*compare_p* >	::=	“d(” <*obj_name* > “)” <*rel_op* > <*subclass* >
<*rel_op* >	::=	“=” | “<>”
<*subclass* >	::=	<*string* >

Table A.4: SWN extended syntax for colored performance indices definition.

Appendix B

Known bugs and Warnings

A lot of bugs presented in the previous version of *GreatSPN2.0.2* have been discovered and eliminated. However some of "known" bugs still remain in the current version and a list of them follows, in the next section a summary of warnings is given.

1. Simulation of GSPN models: to terminate correctly the simulation without provoke an infinite loop when the "Timed interactive" option of the *Simulation* window is chosen together with the "Auto" mode it it is good choice to press the "Stop" button first and then to click on the "Done" button, instead of pressing directly the "Done" button.

2. Places with the same tag: it may occur that when places are copied by using the *Select* and *Add* options from the **Action** menu, the new added places are created with the same tags of the copied ones.

3. SWN syntax is not checked at editor level.

4. transitions rates of order of magnitude less than 10^{-6} are cut off (i.e. only the first six decimals are considered) when saved from GUI into the net definition file.

5. It may occur that when transitions with different priorities are renamed the priority groups are not updated once the net is saved or different priority groups are saved with the same name.

6. syntax error in the warning text appearing in the window that pops-up when the **File**→*RemoveResults* option is chosen.

7. The **View**→*Overview* does not work correctly.

8. The **File**→*Merge* option has not been implemented.

B.1 Warnings

1. Before launching a *GreatSPN2.0.2* solver be sure that the hostname set in the “Hostname:” left area of the **File**→*Options* window is the name of the machine on which the Control Panel has been started.

2. Rescaling is completely different from zooming the net: ”zoom” operation affects only the editor view of the net while ”rescale” operation affects the actual coordinates of the objects of the net.

3. The interactive simulation does not work properly on some GSPN models: to use simulation techniques on a GSPN model is better to transform it into an equivalent SWN model, i.e., with the same state space, and to launch the ordinary simulation available for SWN models.

4. Performance bound solver: the case of conflict with race policy and with enabling memory policy for timed transitions is not properly handled. The net description is assumed not to contain such cases.

5. Performance bound solver: to obtain correct results in case of computation of performance bounds for transition throughputs, launch the solver on a place first.

6. The maximum capacity of each place is $MAX = 255$ even though this constraint is not signalled when an analytic module is launched from the GUI.

7. If the net is characterized by an initial dead marking, the launch of an analytic solver provokes a segmentation fault.

8. Reachability graph generator does not produce the RG in case of nets with all immediate transitions.

9. SWN simulation: the results computed from a simulation run are basically the mean number of token in places and throughputs of transitions and they are all independent from the color classes. Refined results - color class dependent and, in general, user defined results - can be obtained by using the extended SWN simulation (see Section4.5).

10. SWN simulation in case of models with GEN transitions: when constructing the SWN model via GUI, all the GEN transitions have to be specified as they were negative exponential distributed, i.e. white-box transitions also in case of deterministic transitions.

11. Multiple experiments: MultiSolve does not perform exhaustive check of the parameters provided by the user. The parameters are checked only in a syntactic manner. Hence, in order to control if the desired experiments are possible on the chosen net, it is always suggested to perform some computations using *GreatSPN2.0.2* itself before using MultiSolve.

Appendix C

Installation

The *GreatSPN2.0.2* package has been successfully compiled on various Linux distribution (Mandrake, Slackware, Red Hat) coming with OpenMotif as well as SunOS5.x systems. In particular the following "combinations" of machines and environment are the one that have been tested at our site:

```
SunOS 4.1.3      SunOS 5.5,5.6,5.7,5.8 (SPARC)    SunOS 5.5.1,5.6 (INTEL)
gcc 2.5.8        gcc 2.7.2                        gcc 2.7.2
Motif 1.2        Motif 1.2                        Motif 1.2
X11R5            X11R5                            X11R5

Linux Redhat 4.1,Slackware,Mandrake,SuSE 7.1 (INTEL)
gcc
Motif 2.0
X11R6
```

You can try other combinations, but please remember that some features of *GreatSPN2.0.2* do make use of interprocess communication, so that recompilation for whatever Unix/Linux system may not work.

C.1 System requirements for compiling the tool

- the following utilities should be available at the command line prompt (modify the `PATH` environment variable if not):

  make GNU make, which is different from the classical `/bin/make` command;

  gcc GNU C-compiler;

  lex & yacc (or **flex & bison**) lexical analyser and parser generator;

sh standard shell and command interpreter;

rsh remote shell (in case the user wants to launch *GreatSPN2.0.2* solvers on remote machines): it must work without asking password, that is to say if M is a remote machine on which you have an account, the `rsh M` command should not ask for a password; if this is not the case, ask your system manager about, or you will get misterious error at run time, saying that you do not have privilige to execute solution programs;

- X11 and Motif runtime environments: in particular, *GreatSPN2.0.2* makes use of Motif libraries (*Mrm* and *Xm*), thus to compile the tool you need the *Xt* and *Motif* development environments being installed on your system;
- the user-interface-language (uil) compiler: it is used to define the widgets of the *GreatSPN2.0.2* GUI (comes with Motif distribution but often is not included in the default installation).

  WARNING! If the `which uil` command does not find it, ask your system manager to find it for you or to install it if it is not already there. If you are using the Lesstif clone of Motif be sure that it works.

C.2 Compiling and installing the tool

To compile and install the *GreatSPN2.0.2* package go through the following steps:

- get the zipped archive `greatspn-2.1-src.tar.gz`;
- create a new directory - the install directory - where you want to locate the tool, e.g., `/usr/local/GreatSPN/`;
- umcompress and extract the archive into the install directory by using the commands

  ```
  gunzip greatspn-2.0.2-src.tar.gz
  ```

  ```
  tar -xvf greatspn-2.0.2-src.tar /usr/local/GreatSPN/
  ```
- move to the subdirectory `SOURCE`, where the source code and the makefiles are placed:

  ```
  cd /usr/local/GreatSPN/SOURCES/
  ```
- Currently two makefiles are given, one for SunOS platforms and the other for Linux platforms; according to the system your machine is running, edit the appropriate makefile. Only the first lines of the makefile closed between the #-filled lines have to be changed: you will find some examples of common settings placed in the commented lines. Check your system and make the right modifications;
- return to the shell prompt and type the command:

  ```
  make -f Makefile.<platform> <target>
  ```

where `<platform>` is the name of the installation platform, i.e., SunOS5.x or Linux-OpenMotif, and `<target>` has to be replaced with the desired installation options. If you want to install the overall package omit `<target>`, otherwise type any combination of the options: `greatspn`, `algebra` and `multisolve`;

- if everything goes right you will find in the current directory two new subdirectories:

  `/usr/local/GreatSPN/bin` and `/usr/local/GreatSPN/<platform>`

  the former contains the executable (they are all shell-scripts) and the latter the binaries of the tool;

- to launch the *GreatSPN2.0.2* GUI type the command: `greatspn`. To launch the MultiSolve GUI type the command: `multisolve`, see sect. 4.6 (chapt.4) for information about how to use it. To launch the **algebra** composition module type the command: `algebra`, see chapt.5 for information about how to use it.

C.3 Setting the environment

To run *GreatSPN2.0.2* is necessary to set the *GreatSPN2.0.2* environment variables, in particular:

- the `/usr/local/GreatSPN/bin` directory has to be added to the user `path` environment variable;

- the user `LD_LIBRARY_PATH` environment variable has to be set appropriately before running *GreatSPN2.0.2* . This variable has to contain the paths to the Motif and X11 libraries and if it is not set at all, errors of the type *can't find xyz* appears, while when it is not set to the right path a segmentation fault error usually occurs. The path us dufferent under Solaris, SunOS and Linux; in our environment, the command to set the appropriate values are:

  - For SunOS4 (non Solaris):

    `setenv LD_LIBRARY_PATH "/usr/local/X11R5/lib:/usr/lib"`

  - For SunOS5 (Solaris):

    `setenv LD_LIBRARY_PATH "/usr/openwin/lib:/usr/lib"`

  - For Solaris on PC: `setenv LD_LIBRARY_PATH "/usr/dt/lib"`

  but they may be different on your system;

- the *GreatSPN2.0.2* environment variable `GSPN2LPSOLVE` has to be set equal to the pathname of the executable `lp_solve`, i.e., `GSPN2LPSOLVE = /usr/local/GreatSPN/bin/lp_solve`.

  WARNING! Currently, the *GreatSPN2.0.2* installation procedure does not include the installation of the **lp_solve** package: you have to install the package separately, see[28] to download it (version 3.2).

- the `MULTISOLVE_AWK` environment variable has to be set with the path of the **awk** utility, i.e.,

  `MULTISOLVE_AWK = /usr/xpg4/bin/awk`.

The following *GreatSPN2.0.2* environment variables:

- GSPN_DEFAULT_PRINTER, containing the name of the default printer;
- GSPN_NET_DIRECTORY, containing the path directory of the net description files;
- GSPN_PS_DIRECTORY, containing the path directory of the printout of the nets in raw PostScript format;
- GSPN_EPS_DIRECTORY, containing the path directory of the printout of the nets in EncapsulatedPostcript format;

are set at the moment the *GreatSPN2.0.2* GUI is launched for the first time: a window pops-up in which it is asked to the user to fill in the areas corresponding to the above environment variables if he/she want to change the default ones. Default options are:

```
GSPN_DEFAULT_PRINTER= "lpr"
GSPN_NET_DIRECTORY= "$HOME/nets"
GSPN_PS_DIRECTORY= "$HOME/ps"
GSPN_EPS_DIRECTORY= "$HOME/eps"
```

and they are saved in the `$HOME/.greatspn` file.

And finally.... We hope that you have been able to build and install *GreatSPN2.0.2* with litle cost in patience and time. If you can't make your way through it, you can contact us at the following e-mail address:

greatspn@di.unito.it

Moreover any comment and suggestion on the installation procedure will be highly appreciated.

Good luck,
the PE group of the University of Torino.

Bibliography

[1] J. R. Agre and S. K. Tripathi. Approximate solution to multichain queueing networks with state dependent service rates. *Performance Evaluation*, 5(1):45–55, February 1985.

[2] M. Ajmone Marsan, G. Balbo, G. Chiola, and G. Conte. Generalized stochastic Petri nets revisited: Random switches and priorities. In *Proc. Int. Workshop on Petri Nets and Performance Models*, pages 44–53, Madison, WI, USA, August 1987. IEEE-CS Press.

[3] M. Ajmone Marsan, G. Balbo, and G. Conte. A class of generalized stochastic Petri nets for the performance analysis of multiprocessor systems. *ACM Transactions on Computer Systems*, 2(1), May 1984.

[4] M. Ajmone Marsan, G. Balbo, G. Conte, S. Donatelli, and G. Franceschinis. *Modelling with Generalized Stochastic Petri Nets*. John Wiley, 1995.

[5] M. Ajmone Marsan and G. Chiola. On Petri nets with deterministic and exponentially distributed firing times. In *Proc. 7th European Workshop on Application and Theory of Petri Nets*, pages 151–165, Oxford, England, June 1986. reprinted in G. Rozenberg, ed., Advances on Petri Nets '87, LNCS 266, pp.132–145, Springer Verlag, 1987.

[6] M. Ajmone Marsan, S. Donatelli, and F. Neri. GSPN models of Markovian multiserver multiqueue systems. *Performance Evaluation*, 11(4):227–240, 1990.

[7] G. Balbo and G. Chiola. Stochastic Petri net simulation. In *Proc. 1989 Winter Simulation Conference*, Washington D.C., December 1989.

[8] G. Balbo, G. Chiola, G. Franceschinis, and G. Molinar Roet. On the efficient construction of the tangible reachability graph of generalized stochastic Petri nets. In *Proc. Int. Workshop on Petri Nets and Performance Models*, Madison, WI, USA, August 1987. IEEE-CS Press.

[9] W.C. Cheng. Tgif's Home Page. http://bourbon.cs.umd.edu:8001/tgif/.

[10] G. Chiola. A software package for the analysis of generalized stochastic Petri net models. In *Proc. Int. Workshop on Timed Petri Nets*, Torino, Italy, July 1985. IEEE-CS Press.

[11] G. Chiola. A graphical Petri net tool for performance analysis. In *Proc.* 3rd *Int. Workshop on Modeling Techniques and Performance Evaluation*, Paris, France, March 1987. AFCET.

[12] G. Chiola. Structural analysis for generalized stochastic Petri nets: Some results and prospects. In *Proc.* 8th *European Workshop on Application and Theory of Petri Nets*, pages 317–332, Zaragoza, Spain, June 1987.

[13] G. Chiola. Compiling techniques for the analysis of stochastic Petri nets. In R. Puigjaner and D. Potier, editors, *Proc.* 4th *Int. Conf. Modeling Techniques and Tools for Computer Performance Evaluation*, Palma de Mallorca, Spain, September 1988. Plenum Press, New York.

[14] G. Chiola. GreatSPN 1.5 software architecture. In *Proc.* 5th *Int. Conf. Modeling Techniques and Tools for Computer Performance Evaluation*, Torino, Italy, February 1991.

[15] G. Chiola, M. Ajmone Marsan, G. Balbo, and G. Conte. Generalized Stochastic Petri Nets: A Definition at the Net Level and its Implications. *IEEE Transactions on Software Engineering*, 19(2):89–107, February 1993.

[16] G. Chiola, J. Campos, J.M. Colom, M. Silva, and C. Anglano. Operational analysis of timed Petri nets and applications to the computation of performance bounds. In *Proc. 5th Intern. Workshop on Petri Nets and Performance Models*, pages 128–137, Toulouse, France, October 1993. IEEE-CS Society Press.

[17] G. Chiola and S. Donatelli. A framework for studying sets of related Petri net models. Technical Report 90/51, Université Paris 6, 4 Place Jussieu, 75252 Paris Cedex 05, France, July 1990. IBP Tech. Report.

[18] G. Chiola, S. Donatelli, and G. Franceschinis. GSPN versus SPN: what is the actual role of immediate transitions? In *Proc. 4th Intern. Workshop on Petri Nets and Performance Models*, pages 20–31, Melbourne, Australia, December 1991. IEEE-CS Press.

[19] G. Chiola, C. Dutheillet, G. Franceschinis, and S. Haddad. On well-formed coloured nets and their symbolic reachability graph. In *Proc.* 11th *International Conference on Application and Theory of Petri Nets*, Paris, France, June 1990. Reprinted in *High-Level Petri Nets. Theory and Application*, K. Jensen and G. Rozenberg (editors), Springer Verlag, 1991.

[20] G. Chiola, C. Dutheillet, G. Franceschinis, and S. Haddad. Stochastic well-formed coloured nets and multiprocessor modelling applications. In K. Jensen and G. Rozenberg, editors, *High-Level Petri Nets. Theory and Application*. Springer Verlag, 1991.

[21] G. Chiola, C. Dutheillet, G. Franceschinis, and S. Haddad. Stochastic well-formed coloured nets for symmetric modelling applications. *IEEE Transactions on Computers*, 42(11):1343–1360, November 1993.

[22] G. Chiola and A. Ferscha. Distributed simulation of Petri nets. *Parallel and Distributed Technology*, 1(3):33–50, August 1993.

[23] G. Chiola, R. Gaeta, and M. Ribaudo. Designing an efficient tool for Stochastic Well-Formed Coloured Petri Nets. In R. Pooley and J. Hillston, editors, *Proc.* 6th *Int. Conference on Modelling Techniques and Tools for Computer Performance Evaluation*, pages 391–395, Edinburg, UK, September 1992. Antony Rowe Ltd.

[24] S. Donatelli. Superposed generalized stochastic Petri nets: definition and efficient solution. In *Proc.* 15th *International Conference on Application and Theory of Petri Nets*, Zaragoza, Spain, June 1994.

[25] Gnuplot central. http://www.gnuplot.org.

[26] W.H. Harrod and R.J. Plemmons. Comparison of Some Direct Methods for Computing Stationary Distributions of Markov Chains. *SIAM Journal Sci. Stat. Comput.*, 5, June 1984.

[27] S.S. Lavenberg. Statistical Analysis of Simulation Outputs. Technical report, IBM Research Report, 1980. Yorktown Heights, NY.

[28] lp_solve: library for solving linear programming problems. http://www.cpan.org/modules/by-category/11_String_Lang_Text_Proc/Number/WIMV/.

[29] J. Martinez and M. Silva. A simple and fast algorithm to obtain all invariants of a generalized Petri net. In *Proc.* 2nd *European Workshop on Application and Theory of Petri Nets*, Bad Honnef, West Germany, September 1981. Springer Verlag.

[30] M. K. Molloy. Performance analysis using stochastic Petri nets. *IEEE Transaction on Computers*, 31(9):913–917, September 1982.

[31] M.K. Molloy. *On the Integration of Delay and Throughput Measures in Distributed Processing Models*. PhD thesis, UCLA, Los Angeles, CA, 1981. Ph.D. Thesis.

[32] M.K. Molloy. Fast bounds for stochastic Petri nets. In *Proc. Int. Workshop on Timed Petri Nets*, Torino, Italy, July 1985. IEEE-CS Press.

[33] M.K. Molloy. Balanced stochastic Petri nets. Technical report, Carnagie-Mellon University, Pittsburgh, PA, USA, November 1986. Dept. of Computer Science Report.

[34] C.A. Petri. Communication with automata. Technical Report RADC-TR-65-377, Rome Air Dev. Center, New York, NY, 1966. Tech. Rep. RADC-TR-65-377.

[35] M. Silva. *Las Redes de Petri en la Automatica y la Informatica*. Ed. AC, Madrid, Spain, 1985. in Spanish.

[36] K. Varpaaniemi, J. Halme, K. Hiekkanen, and T. Pyssysalo. PROD reference manual. Technical Report Series B, number 13, Helsinki University of Technology, August 1995. http://www.tcs.hut.fi/prod/.