Master Thesis

# Design and Implementation of a Tool for Modeling, Simulation and Verification of Component-based Embedded Systems

**by**

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LiTH-IDA-EX--04/114--SE

2004-12-17

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Examensarbete

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**av**

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**Abstract**

Nowadays, embedded systems are becoming more and more complex. For this reason, designers focus more and more to adopt component-based methods for their designs. Consequently, there is an increasing interest on modeling and verification issues of component-based embedded systems.

In this thesis, a tool, which integrates modeling, simulation and verification of component-based embedded systems, is designed and implemented. This tool uses the PRES+, Petri Net based Representation for Embedded Systems, to model component-based embedded systems. Both simulation and verification of systems are based on the PRES+ models.

This tool consists of three integrated sub-tools, each of them with a graphical interface, the PRES+ Modeling tool, the PRES+ Simulation tool and the PRES+ Verification tool. The PRES+ Modeling tool is a graphical editor, with which system designers can model component-based embedded systems easily. The PRES+ Simulation tool, which is used to validate systems, visualizes the execution of a model in an intuitive manner. The PRES+ Verification tool provides a convenient access to a model checker, in which models can be formally verified with respect to temporal logic formulas.

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Petri Net, IP, modeling, simulation, formal verification, model checking

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# Contents

# Chapter 1
# Introduction

This chapter introduces the motivation and objective of this thesis. Then the method used in the thesis will be described. Finally, a general view of the structure of this thesis will be presented.

## 1.1 Motivation

Embedded systems are currently used in the most diverse contexts from automobiles and aeronautics to home appliances, medical equipment, multimedia, and communication devices. With the increment of consumers' requirements, the embedded systems themselves are becoming more and more complex. This problem can be solved in design by reusing existing component. Furthermore, it is of great importance that these systems are correct. For these reasons, it is necessary to focus on both how to model component-based embedded systems and how to verify the correctness of them.

PRES+ [4], an extended timed Petri net model, has previously been proposed to represent component-based embedded systems. The PRES+ model is simple, intuitive, and can be easily handled by the designer [1].

A tool which integrates modeling, simulation and verification of PRES+ models is therefore desired.

## 1.2 Objective

The objective of this thesis is to design and implement a design tool which has the functions for modeling, simulating and verifying PRES+ models representing component-based systems. And corresponding to each function, a set of graphical user interfaces (GUIs) is required.

## 1.3 Method

The work behind the human computer interface, started out with a study of Petri nets in general [8][9][10], PRES+ [1][3], and the tool Uppaal [7], which is a similar tool for Timed Automata (TA) [6]. After that user and usability requirements were defined. The user tasks and objects were then modeled according to the requirements. Finally the GUI was prototyped and implemented.

In order to implement the functions, a study of certain background material, such as the Petri Net Class Library [5], was under taken. After this study, data structures and control flows were identified. In the end, the developed and implemented functions were integrated with the GUIs.

## 1.4 Acknowledgements

I especially thank Daniel Karlsson for his great help and patient guidance and Petru Eles for setting up this master project. I would also like to thank everyone who has supported me during my work on this master thesis, and all members of ESLAB for creating a friendly working atmosphere.

## 1.5 Structure of the paper

The thesis is structured as follows:

- Chapter 1 gives a general overview of this thesis, the motivation, the objective and the method.
- Chapter 2 gives some preliminary knowledge on major issues of this thesis.
- Chapter 3 lists the detailed requirements of this thesis.
- Chapter 4 presents the related works of this thesis.
- Chapter 5 detailed presents the design of each part of this thesis.
- Chapter 6 briefly introduces how to use the tool
- Chapter 7 summarizes this thesis, and gives the possible future works

# Chapter 2.

# Background

In this chapter the necessary theoretical background is presented. First, a brief introduction of Petri Nets is given, and then a formal definition of PRES+ is presented. The procedure used for verifying PRES+ relies on the existing tool UPPAAL. For this reason, PRES+ must be translated into the input language of UPPAAL, namely Timed Automata. So, timed automata is represented at the end of this chapter.

## 2.1 Petri Net

Petri Nets (PNs) were first developed by Carl Adam Petri in his PhD thesis in 1962. With subsequent developments generalizing the Petri Net, and allowing a wider variety of applications, the Petri Net is now a commonly used tool.

### 2.1.1 Description

Petri Nets are a modeling tool designed to capture information about the structure and dynamics of the modeled system. As a graphical and mathematical modeling tool [9], Petri nets are used to model procedures, organizations and devices where regulated flows, in particular information flows, play a role [8]. As a graphical tool, Petri nets can be used as a visual-communication aid similar to flow charts, block diagrams, and networks. As a mathematical tool, it is possible to set up state equations, algebraic equations, and other mathematical models governing the behavior of systems.

As a special type of graph, a PN is a bipartite directed graph, and consists of two types of nodes. One is called ***place***, and usually denoted by a circle or an ellipse (Figure 2.1-a); the other type is called ***transition***, and is usually denoted by a bar, a square, or a rectangle (Figure 2.1-b). The edges of a PN are called ***arcs*** and are always directed (Figure 2.1-c). As a special property of a bipartite graph, an edge can connect only nodes that belong to different types. Therefore, an arc can be from a place to a transition, called ***Input arc*** (Figure 2.1-d), or from a transition to a place, called ***Output arc*** (Figure 2.1-e). In addition to the two types of nodes - places and transitions - and the arcs, a fourth object is introduced in order to describe the dynamics of a Petri Net. This object is the ***token*** (Figure 2.1-f), denoted by a solid dot, residing inside the circles representing the places. In classical PNs, however, the tokens do not represent specific information and are not distinguishable. They are only used to mark the PN’s state, called ***marking.*** A marking, denoted by M, is a map for recording the number of tokens in each place of the PN at a certain time. Each PN has an ***initial marking,*** denoted $M_0$.

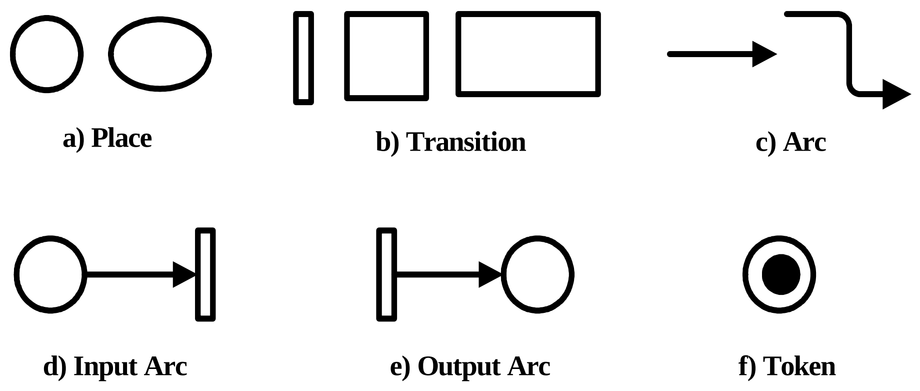


**Figure 2.1 Components of a PN**

## 2.1.2 Mathematical Definition

Formally, a classical PN is a five-tuple N = $(P, T, I, O, M_0)$ where
$P = \{p_1, p_2, \ldots p_m\}$ is a finite non-empty set of *places*;
$T = \{t_1, t_2, \ldots t_n\}$ is a finite non-empty set of *transitions*;

$I \subseteq P \times T$ is a finite non-empty set of *input arcs,* which define the flow relation between places and transitions;

$O \subseteq T \times P$ is a finite non-empty set of *output arcs,* which define the flow relation between transitions and places;
$M_0$ is the *initial marking* of the net. A *marking* $M: P \rightarrow \{0, 1\}$ is a function that denotes the absence or presence of tokens in the places of the net. $M(p) = 1$ whenever the place $p$ is marked (contains tokens), otherwise $m(p) = 0$.

## 2.1.3 Dynamic Behaviour

The execution of a PN depends on the marking of the net. The marking records the numbers of tokens in each place of the PN at a certain time. When there are enough tokens available in the input places of a transition, that is all the preconditions for the activity are fulfilled, we say the transition is enabled and can be fired. When the transition fires, it removes tokens from its input places and adds one token in each of its output places, resulting in another marking. For Example, in Figure 2.2, there is a token in place $p_0$, thus transition $t_0$ can be fired since there are enough tokens in its input places. After $t_0$ has fired, the PN reaches a new marking, shown in Figure 2.3 a). In this new marking, transition $t_1$ is enabled, which when fired leads to the marking in Figure 2.3 b), Figure 2.3 c).

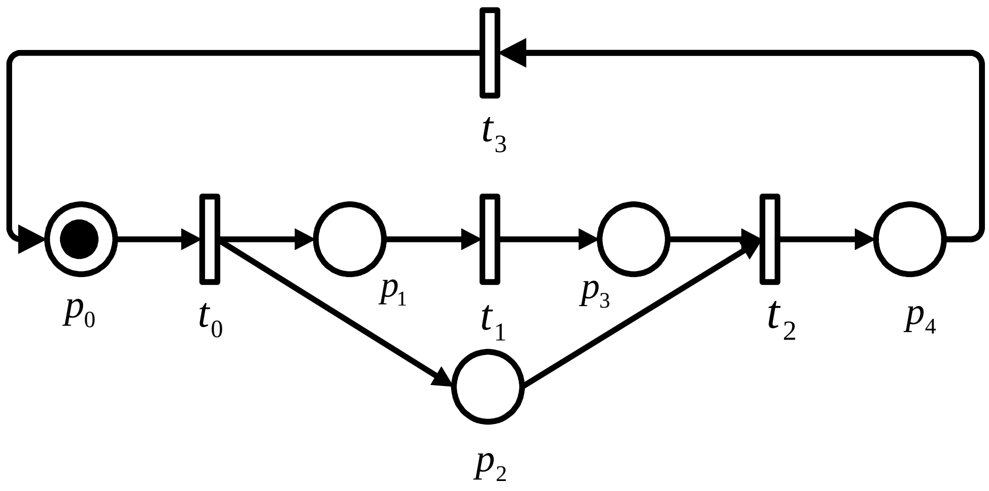
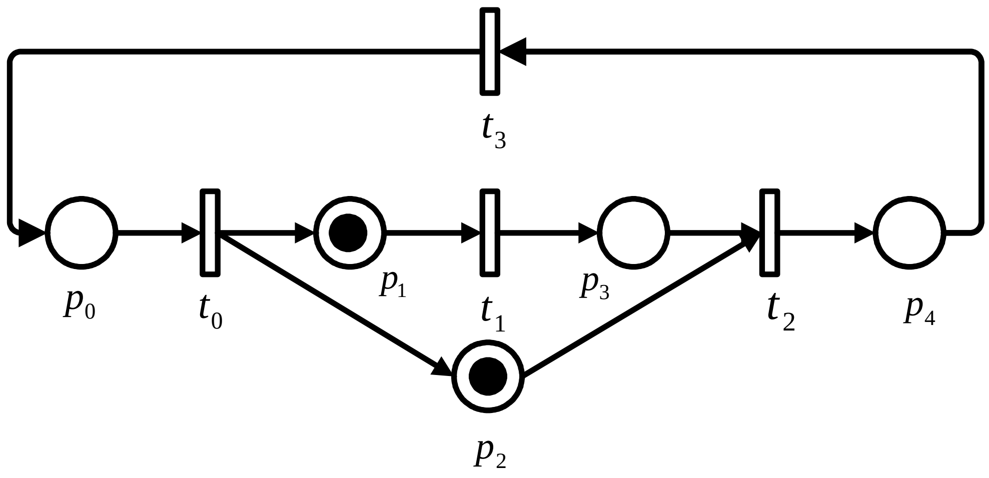
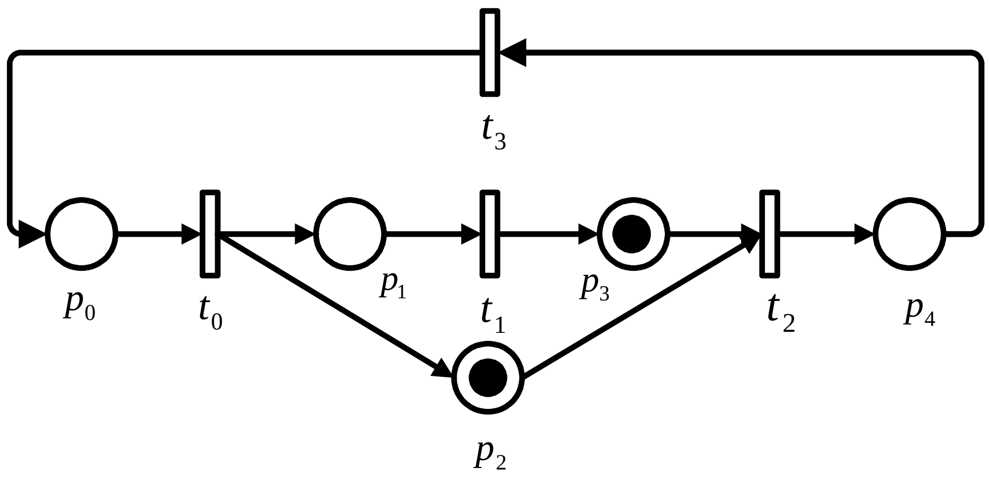


**Figure 2.2 A simple PN**



**a)**



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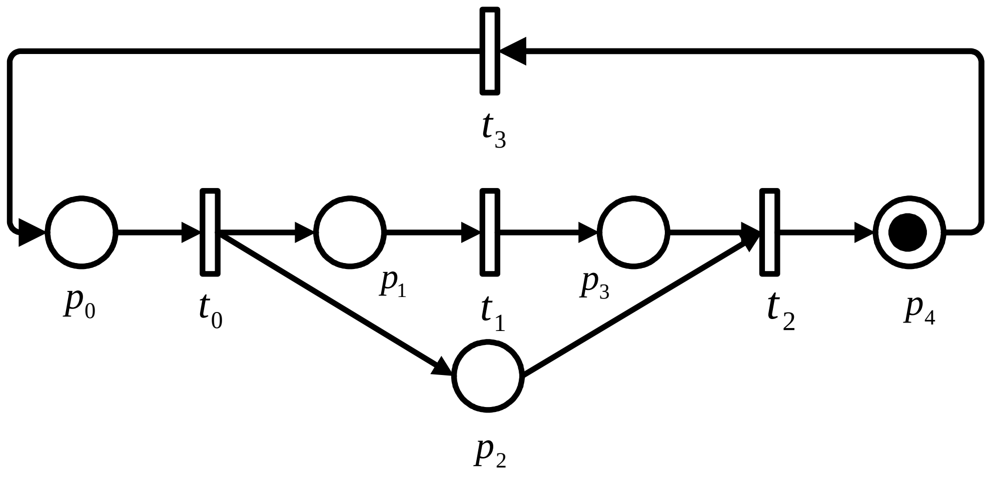


**c)**

**Figure 2.3 Example of the dynamic behaviour of a PN**

## 2.2 PRES+

PRES+ (Petri net based Representation for Embedded Systems) [3] is a computational model based on Petri nets that allows to capture important features of embedded systems. Since PRES+ is a Petri Net based model, it not only inherits the characteristics of Petri Nets, but also on top of this, it adds some special features. For example, PRES+ overcomes the lack of expressiveness of classical Petri nets where tokens are considered as "black dots". In PRES+ tokens hold information that makes it possible to obtain more succinct representations suitable for practical applications, and when transitions are fired, the information will be transferred. Moreover, PRES+ can capture timing aspects by associating lower and upper limits to the duration of activities related to transitions and keeping time information in token stamps. Thus the PRES+ is more suitable to represent the real-time embedded system than classical Petri nets.

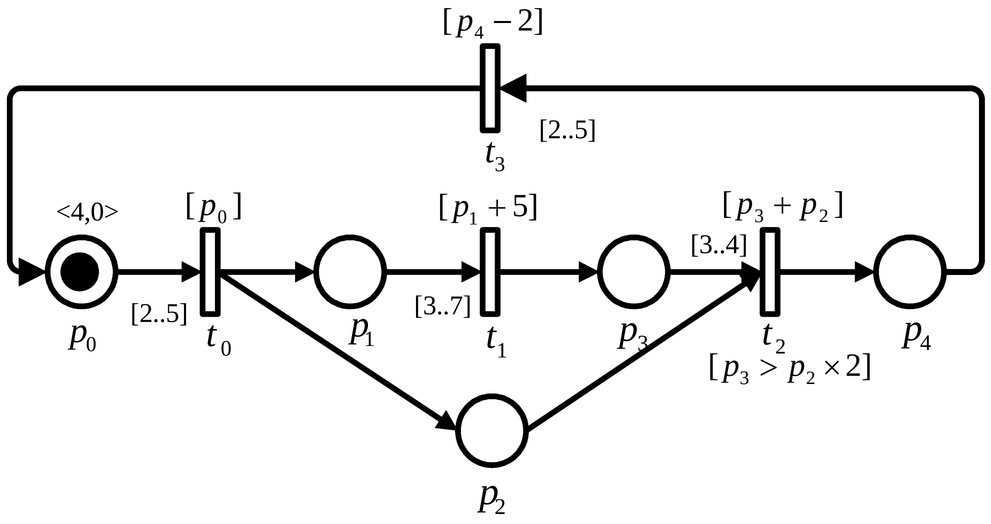


**Figure 2.4 A simple PRES+ model**

### 2.2.1 Description

Figure 2.4 presents a simple PRES+ model in Figure 2.4, according to which we describe the characteristics of PRES+ as follows.

- In this PRES+, P={$p_0$, $p_1$, $p_2$, $p_3$, $p_4$} and T={$t_0$, $t_1$, $t_2$, $t_3$}.

- As introduced before, tokens carry information. So in PRES+, a token is a pair *k*=<*v*, *r*> where *v* is the token value, and this value may be any type. *r* is the token time, a non-negative real number representing the time stamp of the token. In Figure 2.4, the token in place $p_0$ is *k*=<4, 0>, where the token value is 4, an integer, and time stamp is 0.

.

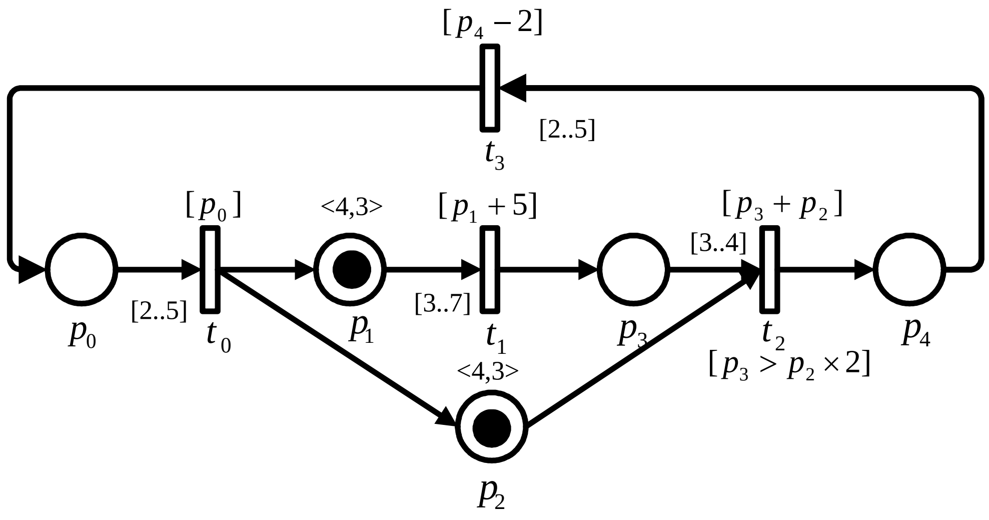
- In Figure 2.4, this PRES+ is in the initial marking $M_0$, which indicates place $p_0$ contains a token initially.

- Every transition $t \in T$ has an associated function and a condition guard. In addition, timing aspects are captured by the fact that there exists a time delay interval in each transition.
  - The function *f* associated to *t* has as input arguments the values of the tokens which are in the input places of the transition *t*, and the output of *f* is found in the values of the tokens that will be in the output places of *t*. Transition functions are very important when describing the behavior of the system to be modeled. They allow systems to be modeled at different levels of granularity with transitions representing simple arithmetic operations or complex algorithms. For example, in Figure 2.4, transition $t_1$ has the function $f=p_1+5$, where $p_1$ means the value of the token that will appear in place $p_1$, and after $t_1$ fired, the value of the token in place $p_3$ will be the value of the token in place $p_1$ plus five.
  - The guard *G* of a transition *t* is an important factor to determine if *t* can be enabled. In Figure 2.4, transition $t_2$ has a guard *G*=TRUE if $p_3>(p_2\times 2)$ is correct, where $p_3$ and $p_2$ are the values of the tokens in place $p_3$ and place $p_2$ respectively, or *G*=FALSE otherwise. And for other transitions in Figure 2.4, their guards are always TRUE.
  - The time constraints of a transition *t* consist of two transition delays, the *minimum transition delay* $d^-$ and the *maximum transition delay* $d^+$. The non-negative real numbers $d^-$ and $d^+$ ($d^- \leq d^+$) represent the lower and upper bounds for the execution time (delay) of the function associated to the transition. But sometimes some transitions have no upper bounds, then we denote $d^+=\infty$ or $d^+=inf$, which means that the transition may not fire. In figure 2.4, the time constrains of transition $t_0$ is *[2..5]*, where $d^-=2$ and $d^+=5$. The delays give the limits in time for firing a transition since it becomes enabled, and the actual

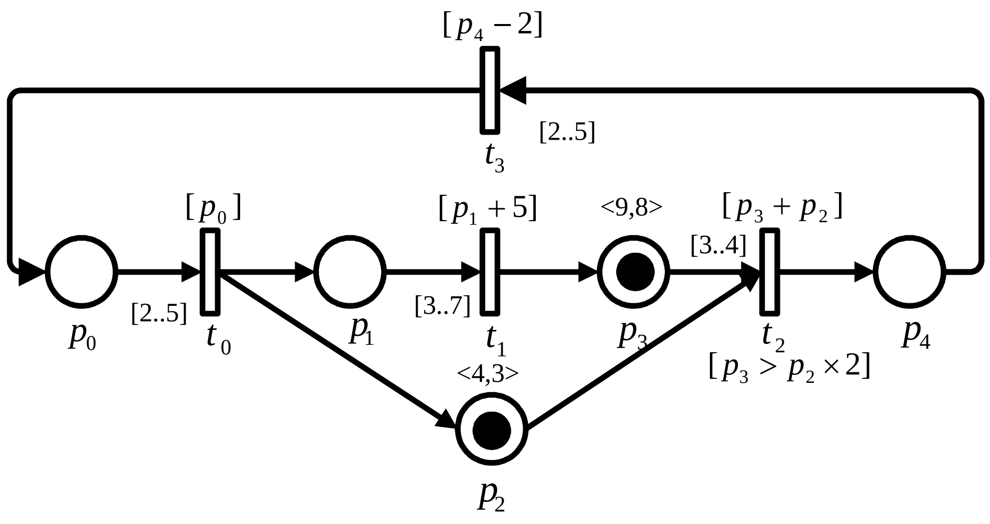
execution time will be add to the time stamps of the tokens in the output places of the transition.

### 2.2.2 Dynamic Behaviour

Like the dynamic behaviour feature of Petri Nets, in PRES+ model, when a transition is enabled, it can be fired. A transition *t* is said to be enabled if all of its input places are marked, and its guard is satisfied. Figure 2.5 illustrates the dynamic behaviour of the PRES+ given in Figure 2.4. In its initial marking, transition $t_0$ can be fired, and we assume the actual execution time of $t_0$ is 3 time units, between the lower bound 2 and upper bound 5. Then the situation in Figure 2.5 a) is reached. Now transition $t_1$ is enabled, and can be fired between 3 and 7. If $t_1$ fires after 5 time units, we obtain the situation in Figure 2.5 b). In Figure 2.5 b), there is a token in place $p_3$ with value 9, and a token in place $p_2$ with value 4. Since 9 is bigger than double of 4, the guard *G* of transition $t_2$ is satisfied and $t_2$ can be fired. Assuming after 3 $t_2$ is fired, then the tokens in places $p_2$ and $p_3$ are removed, and a new token with value 9+4=13 and time stamp *max*(3,8)+3=11 will put in place $p_4$, as can be seen in Figure 2.5 c). Transition $t_3$ is enabled next. A token will appear again in place $p_0$ after firing $t_3$ at 5 time units in Figure 2.5 d).



**a )**



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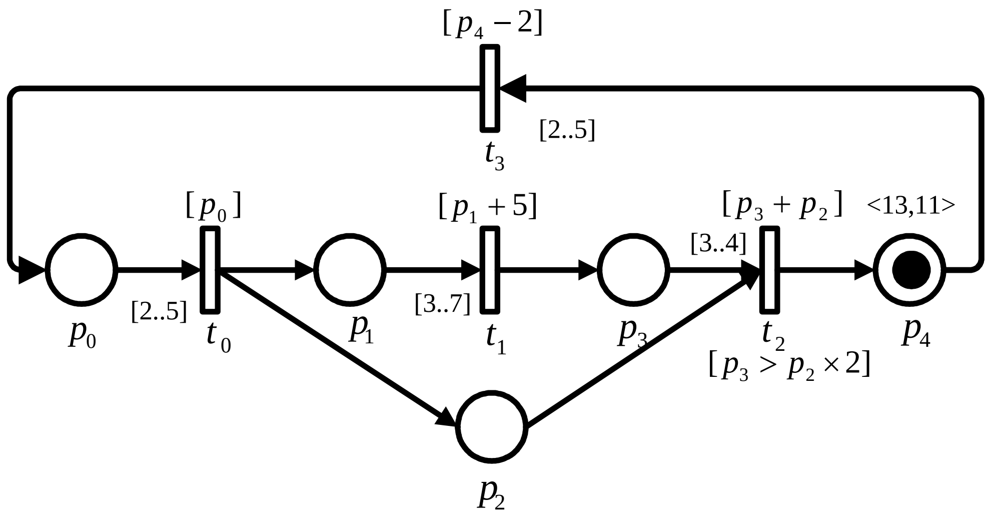
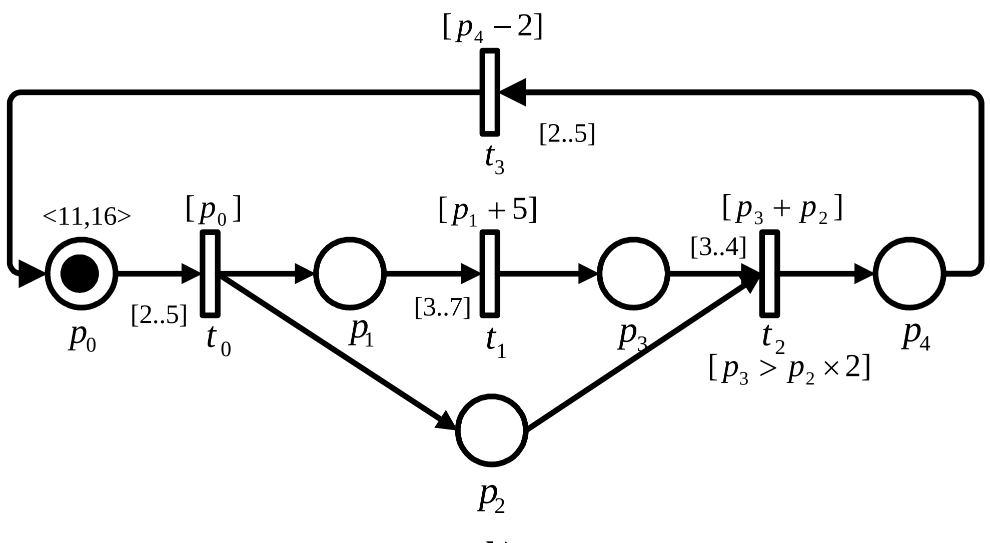


**c )**



**d )**

**Figure 2.5 Example of the dynamic behaviour of a PRES+**

### 2.2.3 Forced Safe PRES+

The bound of a PN is the maximum number of tokens that can reside in a place in any reachable marking. A PN is said to be *safe* if the bound is 1. In this work, we would like to enforce safeness in order to facilitate translation into Timed Automata. For this reason, the concept in Forced Safe PNs (FSPNs) is introduced in [1]. In FSPNs, the enabling rule is changed so that, in addition to the original rules, all output places (except those which are also input places) must be empty. FSPN can be translated into standard PN in the following way.

If we assume the simple PRES+ model in Figure 2.4 is a forced safe PRES+ model, its equivalent standard PRES+ model is illustrated in Figure 2.6. In the equivalent standard PRES+ model, each place $p_i$ has a duplicated shadow place $ex\_p_i$, and if $p_i$ has an initial token, then $ex\_p_i$ has not and vice versa. In addition, for each input arc $<p_i, t_j>$, there has an output arc $<t_j, ex\_p_i>$ corresponded. And for each output arc $<t_i, p_j>$, there also has an input arc $<ex\_p_j, t_i>$.

It is necessary to note that in the rest of this thesis, all models are considered to be forced safe.

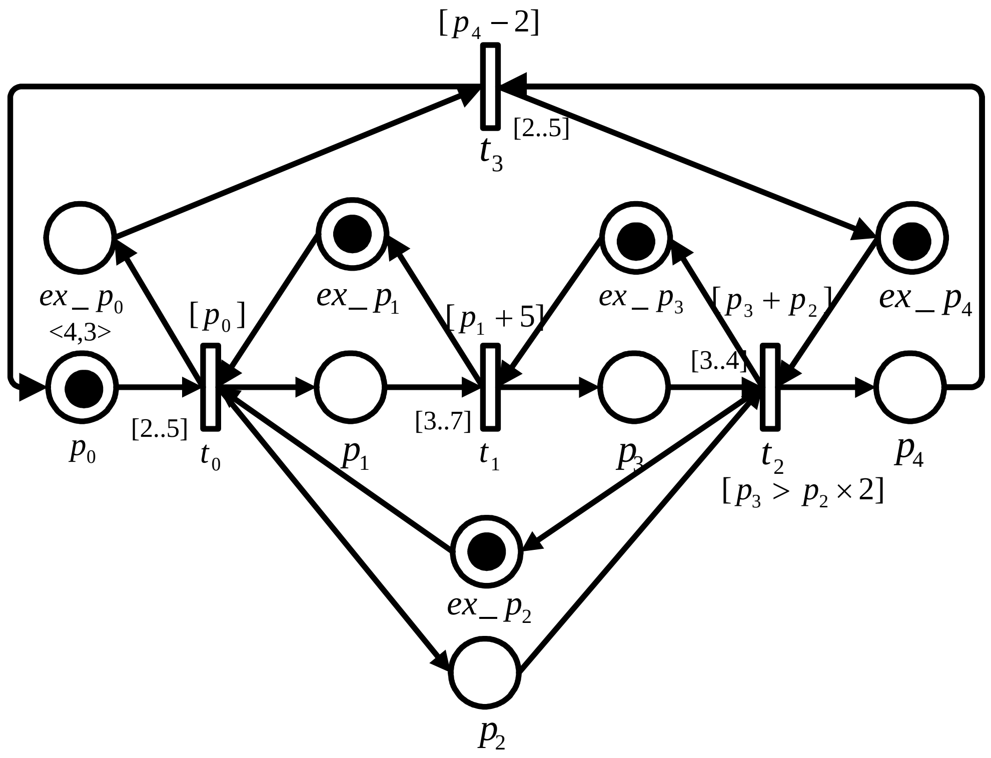


**Figure 2.6 An equivalent standard PRES+ model of the forced safe PRES+ model in Figure 2.4**

### 2.2.4 XML Format of PRES+

It is necessary to record the PRES+ model into a standard format. So that, on one hand, it will minimize the possibility of the translation-user to make mistakes when building net [5]; On the other hand, it is the base of some future applications, for example, PRES+ model information could be transfer among users in a uniform format. XML, since it is a common format of structured information and a format recommended by W3C, in this thesis, is selected to represent PRES+ model with the schema PresPlus [5]. As an example, the PRES+ model illustrated in Figure 2.4 can be represented as follow:

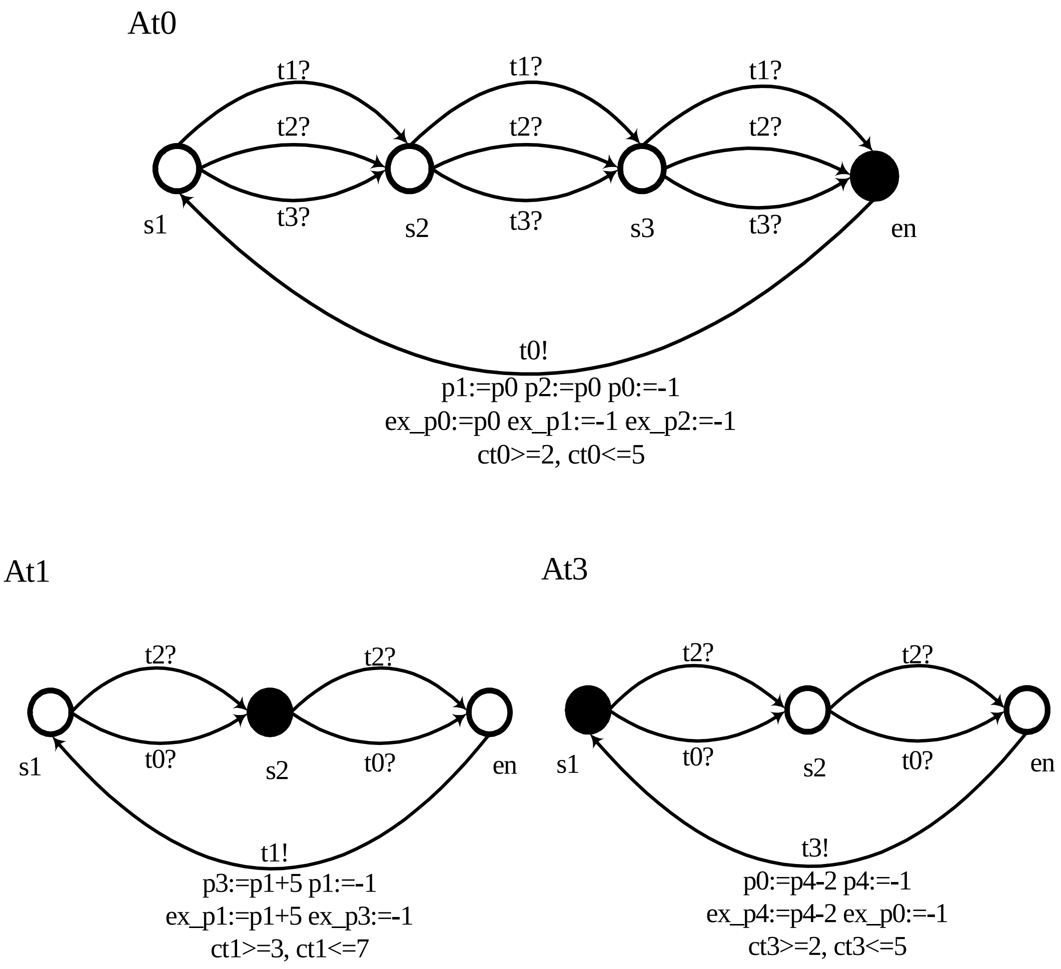
```
<?xml version="1.0" encoding="iso-8859-1"?>
<petriNet xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
          xsi:noNamespaceSchemaLocation='PresPlus.xsd'>
    <place id = "p0">
        <token time = "0" value = "4"/>
    </place>
    <place id = "p1"/>
    <place id = "p2"/>
    <place id = "p3"/>
    <place id = "p4"/>

    <transition id = "t0" assignment = "p0">
        <interval start = "2" stop = "5"/>
    </transition>
    <transition id = "t1" assignment = "p1+5">
        <interval start = "3" stop = "7"/>
    </transition>
    <transition id = "t2" assignment = "p2+p3" guard = "p3>p2*2">
        <interval start = "3" stop = "4"/>
    </transition>
    <transition id = "t3" assignment = "p4-2">
        <interval start = "2" stop = "5"/>
    </transition>

    <inputArc id = "i01" placeId = "p0" transitionId = "t0"/>
    <inputArc id = "i02" placeId = "p1" transitionId = "t1"/>
    <inputArc id = "i03" placeId = "p3" transitionId = "t2"/>
    <inputArc id = "i04" placeId = "p2" transitionId = "t2"/>
    <inputArc id = "i05" placeId = "p4" transitionId = "t3"/>

    <outputArc id = "o01" placeId = "p1" transitionId = "t0"/>
    <outputArc id = "o02" placeId = "p2" transitionId = "t0"/>
    <outputArc id = "o03" placeId = "p3" transitionId = "t1"/>
    <outputArc id = "o04" placeId = "p4" transitionId = "t2"/>
    <outputArc id = "o05" placeId = "p0" transitionId = "t3"/>

</petriNet>
```

## 2.3 Timed Automata

The *timed automaton model* is a labeled transition system model for components in real-time systems [6]. In this thesis, we use an extended Timed Automata model (TA) [4] for using existing model checking tool.

Before we perform the model checking, we need translate a PRES+ model into a TA model. The detailed translation procedure is represented in [5]. Following we give out the equivalent TA model of the PRES+ model given in Figure 2.4, and in Figure 2.7 the graph representation of the TA model is shown.

Note that the PRES+ model must be forced safe PRES+ model when translated into timed automata for guaranteeing the correctness of the translation result.



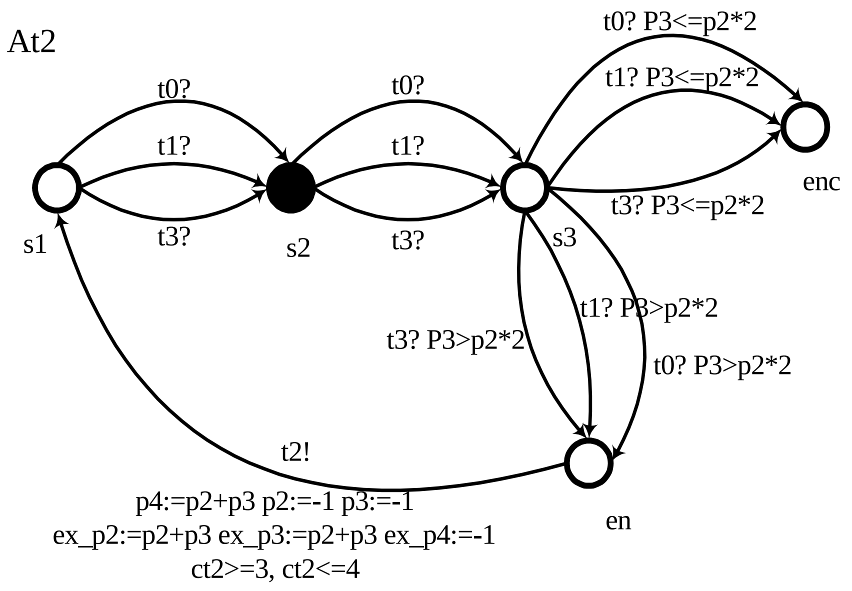


**Figure 2.7 An equivalent TA model of the simple forced safe PRES+ model in Figure 2.4**

In Figure 2.7, there are four processes At0, At1, At2 and At3, and each process corresponds to a transition of the PRES+ model, such as At0 is corresponding to transition $t_0$, At1 to $t_1$, and so on. A process defines the states of a transition and the shift between two states. Usually we use a circle to denote a state and use directed arcs to denote the state shifts. The solid circle in the Figure represents the initial state of the transition. The labels, such as "t0?" And "t0!", shared by different automata in the Figure 2.7, are called *synchronization labels*. The synchronization labels are used to indicate the synchronization among processes. For example, in Figure 2.7, transition $t_0$ is enabled. If $t_0$ fires, process At0 will shift from the state *en* to *s1* via t0!, process At1 will simultaneously shift from the state *s2* to *en* via t0?, and so on.

Let us examine process At2 corresponding to transition $t_2$. Because $t_2$ has three input places, including the duplicated shadow place, $p_2$, $p_3$ and $ex\_p_4$, $t_2$ will have four states *s1*, *s2*, *s3* and *en*, where *s1* means that there are no tokens in any input place, *s2* means that there is only one input place containing a token, *s3* means that there are two input places having tokens, and *en* means that the transition is enabled. It is clear in Figure 2.6, the equivalent standard PRES+ of the PRES+ model in Figure 2.4, that only place $ex\_p_4$ contains a token, so the initial state of $t_2$ is *s2*. In addition, transition $t_2$ has a guard. For this reason, we use the state *enc* to specify the situation that all three input places are having tokens, but the guard of $t_2$ is not satisfied. In order to change a state to another one, a transition should fire. For instance, if we want shift the state from At2.s2 to At2.s3, one of the three transitions, $t_0$, $t_1$ and $t_3$, has to fire. Finally we use "*en* → *s1*" to describe the firing of this transition.

# Chapter 3.
# Problem Formulation

In this chapter the detailed description of the requirements and problems is presented. Since the design process is not a linear process, it usually repeats many times. Therefore, here lists the collection of the requirements and problems during the whole thesis.

## 3.1 Usability Requirements Specification

As motivated in chapter 1, an integrated tool for modeling, simulation and verification of component-based PRES+ models needs to be designed and implemented. For each part, the main task is to design a graphical user interface, so that through this interface users can learn how to model, simulate or verify a PRES+ model easily and effectively. We will describe each GUI of the tool respectively.

### 3.1.1 PRES+ Modeling Interface

In this user interface, items of PRES+, such as places, transitions and tokens, can be drawn, and then connected to be a PRES+ model. Following is the list of detailed requirements.

- For items (places, transitions, tokens, etc.)
  - Items can be drawn and connected according to the standard notation of PNs;
  - Items are shown with their important properties, such as the delays, function and guard of a transition;
  - A new item, component [1], is denoted by a rectangle, around which a set of circles, denoting the ports [1] of the component, is resided;
  - The size of the place item, transition item and token item are fixed. But the size of the component item can be changed;
  - Arc items can be bent so that interleaving and overlapping of arcs is minimized.

- For actions
  - PRES+ models can be saved to files;
  - PRES+ model files can be opened and represented in graphs;
  - PRES+ models can be printed out;
  - PRES+ models can be loaded as components, that is pre-designed PRES+ models can be reused in a new PRES+ model as component items;

- Actions, such as redo, undo, cut, copy, paste, find and select, should be designed for improving the efficiency when modeling PRES+ models.

### 3.1.2 PRES+ Simulation Interface

Simulation is a good method of evaluating and validating a model. The simulation of PRES+ models is implemented in this GUI. The requirements of this part are listed below.

- The whole simulation process can be shown in a graph. In other words, when simulating a PRES+ model, the movement of tokens should be represented;
- Simulation can be both interactive and automatic. In an interactive mode, the PRES+ model will be fired after the user selects which enabled transition can fire. In an automatic mode, however, the computer will select an enabled transition randomly, and then fire it. In addition, the speed of simulation can be adjusted;
- Simulation traces can be generated when simulating, and the traces can be saved to files;
- Simulation processes can be traced by steps, and when tracing, the state of the PRES+ model should match that of the step;
- Pre-generated simulation trace files can be loaded and traced.

### 3.1.3 PRES+ Verification Interface

This GUI is used to implement the verification of PRES+ models. Since we use an existing model checking tool to perform the verification, the input of the model checker must be matched. Therefore, several translation functions are required here.

- PRES+ models can be translated into TA models, and for each TA model, a TA model file can be generated as one of the inputs of the model checker;
- CTL formulas [16], which are used to specify the verification queries, can be translated into TA terms, in order to serve as another input of the model checker;
- The model checker can be called automatically to perform the

verification;

- The verification result can be traced in PRES+ Simulation Interface.

## 3.2 Problem Formulation

According to the requirements, some problems can be forecast and will be thought much of when designing the tool.

- In PRES+ modeling
  - How to define the items of the PRES+ model. That is, how to define the data structure of the items;
  - How to update a PRES+ model if one or some components inside are modified;
  - How to save the graph to a file, and in what format.

- In PRES+ simulation
  - How to simulate into component items of a PRES+ model;
  - How to connect the simulation trace to the PRES+ model, that is how to update the state of the PRES+ model based on the step of the simulation trace;
  - How to save the simulation trace to a file, and in what format.

- In PRES+ verification
  - How to translate a PRES+ model to a TA model and save it to file;
  - How to parse the input CTL or TCTL formula, and how to translate the input formula to TA terms.

# Chapter 4.
# Related Work

In this chapter, the related work, on which this thesis is based, is presented.

## 4.1 Petri Net Class Library and Task Modules

The Petri Net Class Library [5] is an extendable Petri net class library. It defines the data structure of items that belong to Petri Net, the net structure, the data structure of the state of Petri Nets, and the changes in the net. With the library, both the users, who use the library, and the implementers, who extend the library, can build a PN, set initial marking, and simulate a PN easily. In addition, the Petri Net Class Library provides the analysis interface for the implementers, but not for users. With the analysis interface, implementers can read the content of the items and move freely around in the net.

A task module [5] corresponds to a special task, for example the task to translate a PRES+ model into a Timed Automata model. A PRES+ model specified with the Petri Net Class Library, can take a module for analysis. That means the module can use the PRES+ model or the PRES+ model is an input parameter of the module. Module-implementers can create kinds of task modules derived from the **AbstractModule** super class [5] to implement specific tasks. Many task modules have already been implemented, such as the Free Choice Module for checking if a PN is free choice, the Strongly Connectedness Module for checking if a PN is strongly connected, the Make Safe Module for making a PN safe, the Concurrency Relation Module for computing the concurrency relation of a PN, the Translation Module for translating a PRES+ model into a Timed Automata model, and so on.

## 4.2 CTL Formula Parser

To verify PRES+ models is one of the main parts in this thesis, and we use the model checking technique for the verification. For model checking, Computation Tree Logic (CTL) [16] is particular used for specifying the properties to verify. A class library for defining the data structure of a CTL formula and translating a query sentence (string) into a CTL formula has been developed [1]. In this thesis, we will use the library to parse the input query, build the corresponding data structure, and finally translate the CTL formula into a Timed Automata query.

## 4.3 UPPAAL

*UPPAAL* is a toolbox for modeling, simulation and verification of real-time systems, based on constraint-solving and on-the-fly techniques [17]. UPPAAL describes a real-time system with a Timed Automata model, and the simulator and the model-checker of UPPAAL are performed based on Timed Automata models. In this thesis, we used the model-checker, ***verifyta***, of UPPAAL to verify PRES+ models. Verifyta is designed to check invariant and bounded-liveness properties by exploring the symbolic state-space of a system. For example, with verifyta, if certain combinations of control-nodes are reachable from an initial configuration could be checked. Verifyta takes as input a Timed Automata in the *textual format* and a *formula*, and a *diagnostic trace* will be the output to report the checking results. The diagnostic trace [18] explains why the formula is satisfied or not.

# Chapter 5.
# Tool Design

This chapter presents the whole design process in detail. The whole design process includes five main parts: GUI toolkit selection, GUI design, modeling tool design, simulation tool design and verification tool design. Note, since we have defined a new item, component [1], in PRES+ nets, we use the word "item" to represent the basic component of PRES+ nets, such as place and transition. We use the word "component" to represent the new item.

## 5.1 GUI Toolkit

In this thesis, we design the integrated graphical tool based on the Petri Net Class Library (see section 4.1) and some task modules [5]. Since the Petri Net Class Library and the task modules are designed and implemented in C++, we select to use C++ language in this thesis.

As the main part of this thesis, GUIs need be designed and implemented first. Usually, when programming a GUI, programmers use a toolkit and follow the pattern of program design laid down by the toolkit vendor. In this thesis, we use the Qt toolkit [13]. The Qt toolkit is a C++ class library and a set of tools for building multiplatform GUI programs using a "write once, compile anywhere" approach. Qt lets programmers use a single source tree for applications that will run on multiple operation systems, such as Windows 95 to XP, Linux, Solaris, etc. In addition, Qt provides a powerful mechanism for seamless object communication and powerful events and event filters, which make up the C++ Object Model's inflexible static nature. Consequently, GUI programming with Qt toolkit is both runtime efficient and flexible [14].

## 5.2 Overview of the GUIs

There is a set of graphical user interfaces defined in our design. In Figure 5.1, some important interfaces are listed and the relationships among these interfaces are also illustrated. In our design, for each tool, there is a corresponding main interface. The simulation interface and the verification interface may be opened from the modeling interface. In addition, the simulation interface may be opened by the verification interface indirectly. Therefore, our tool will start with the PRES+ Modeling Interface. The figure also presents several configuration interfaces which can be produced by the modeling interface. In the verification interface, an editor may be opened for browsing files, like TA model files and verification results. We also defined some other interfaces, such as message windows, for facilitating for users.

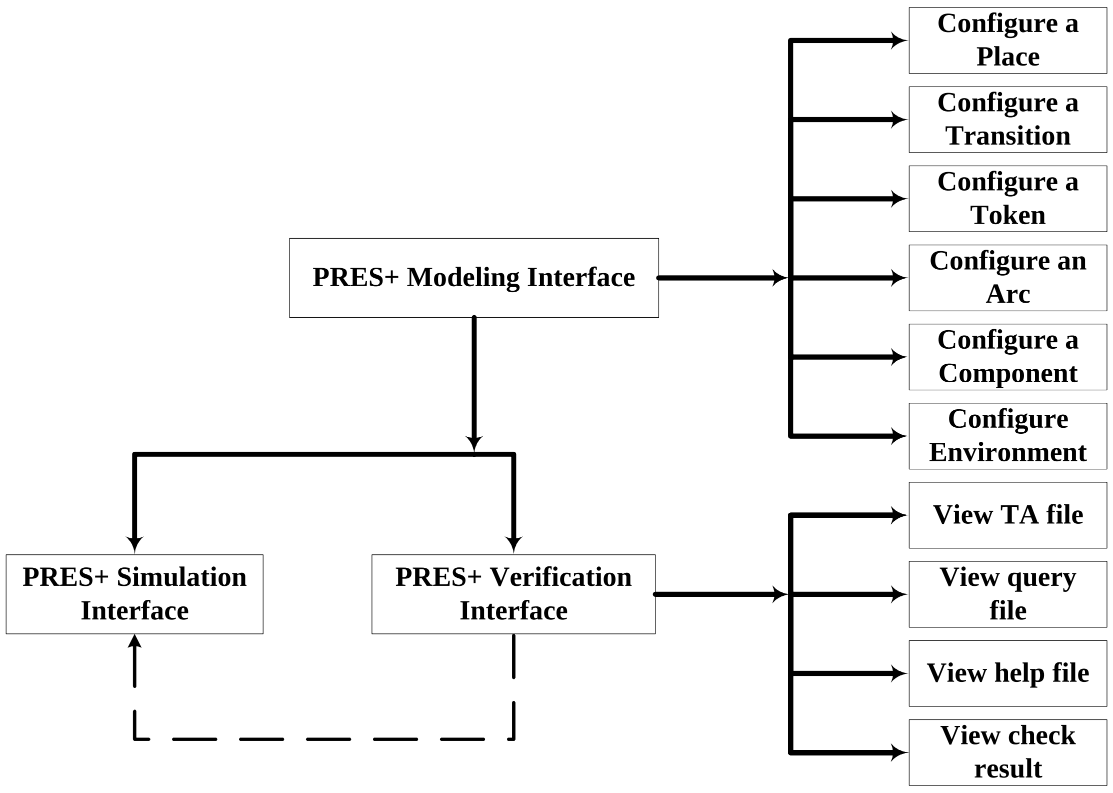


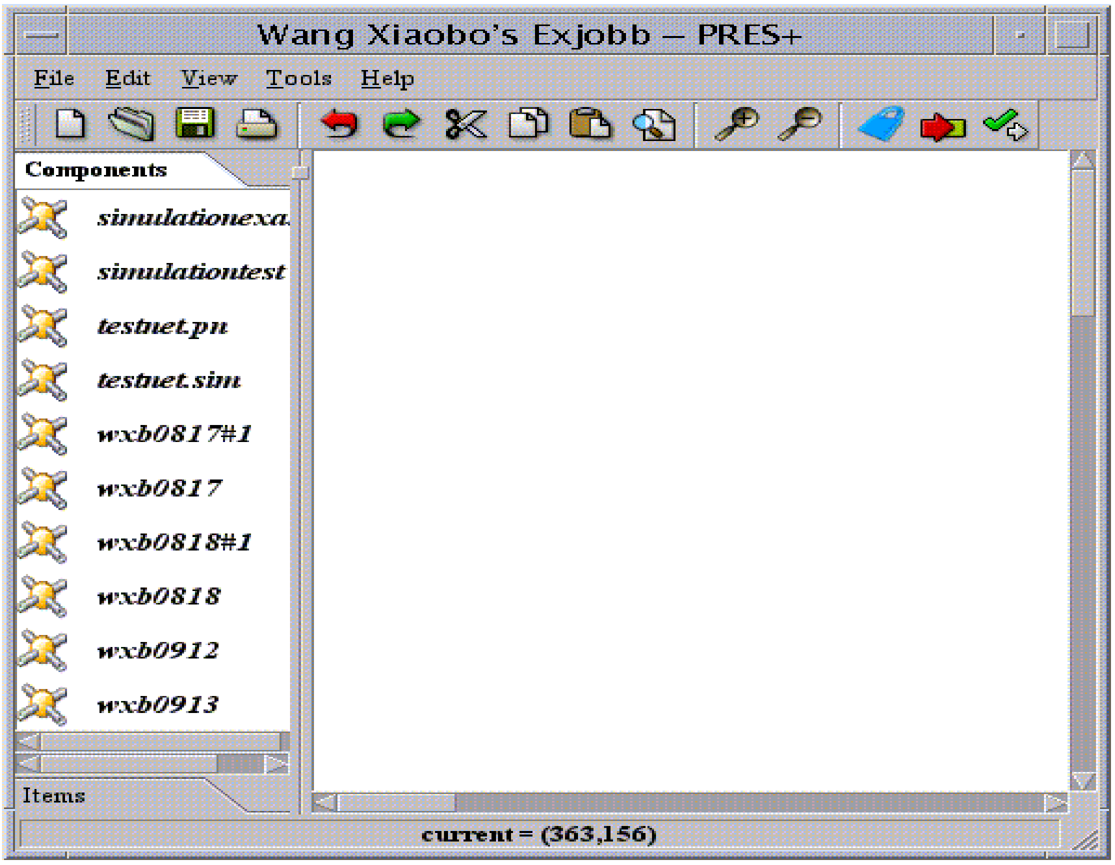
**Figure 5.1 The Relationships of Interfaces**

## 5.3 Modeling Tool Design

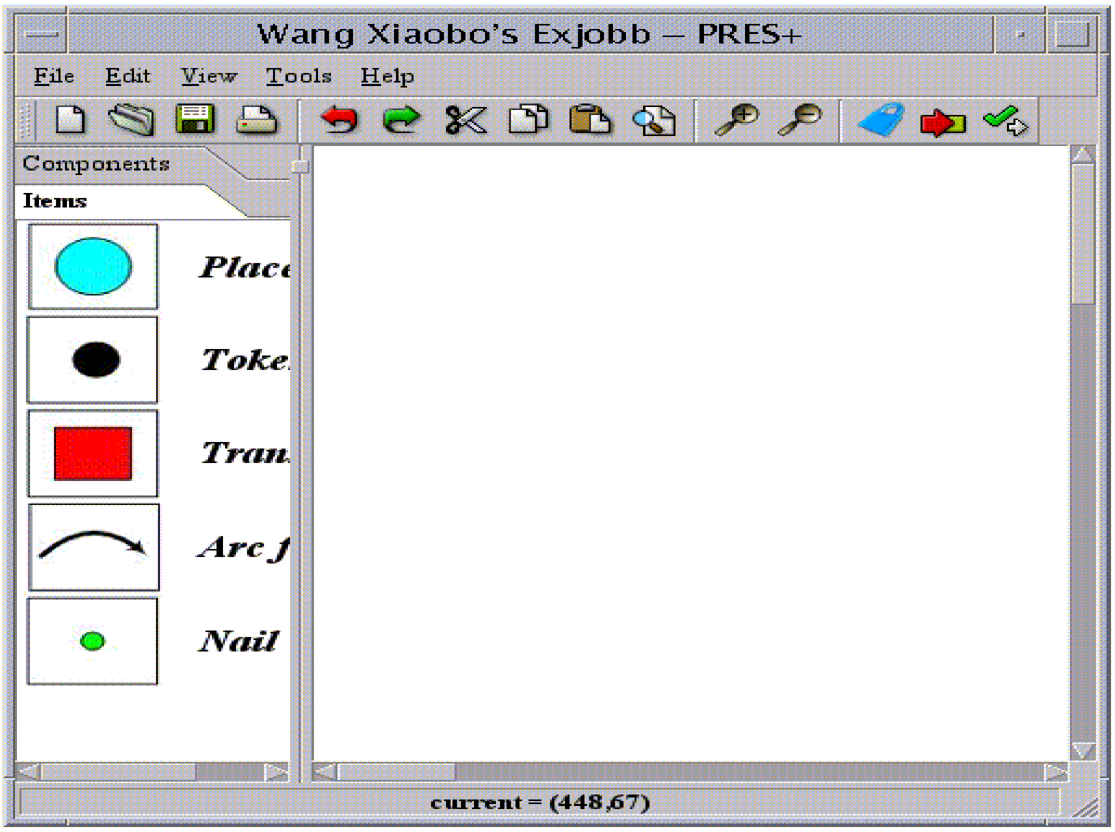
As discussed in chapter 3, the main task of this part is to design and implement a graphical user interface. Through this interface, users can draw items and then connect to a PRES+ model. Meanwhile, behind the interface, the data structure of the graphical items should be consistent with the GUI. In the following we present the design process from three aspects: user interface, graphical item structure and operations.

### 5.3.1 User Interface

In figure 5.2, the user interface of the PRES+ modeling tool is shown. This interface includes five parts: a menu bar, a toolbar, a toolbox, a canvas and a status bar. The menu bar consists of five popup menus: File, Edit, View, Tools and Help. For each popup menu, there are several actions. For example, the File menu includes the **New** action for creating a new file, the **Open** action for opening an existing file, the **Save** action for saving the edited PRES+ model, the **Save As** action for saving the edited PRES+ model into a specified file, the **Print** action for printing the edited PRES+ model and the **Exit** Action for exiting from the application. Every action corresponds to a command, which can be invoked via the menu option. In our design, actions also contain an icon and a menu text that are represented in popup menus and in the toolbar.



**a ) Components List**



**b ) Items List**

**Figure 5.2 PRES+ Modeling Interface**

The toolbar is a movable panel that contains a set of controls (actions) for quick access to frequently used commands and options. In the PRES+ Modeling Interface, only one toolbar is created for frequently used commands, and all these commands correspond to actions in the popup menus.

In the middle of the PRES+ Modeling Interface, there is a splitter widget. The splitter divides the main part of the interface into two sides. The left side is a toolbox that contains two list boxes, and the right side is a canvas for modeling PRES+ models. Toolbox is a widget that displays a column of tabs one above the other, with the current item displayed below the current tab. In our design, we build two tabs to put into the toolbox. The two tabs are two list boxes that list components and items respectively. Items are the basic items of Petri Nets, which are place, token, transition, arc and nail (a part of arcs for making arc inflexed, usually denoted with a small circle). Components are PRES+ models that are already built as reusable IP blocks [1] and exist in the module library, an appointed directory in the file structure. Canvas provides a 2D area, on which PRES+ models can be drawn.

The status bar, in bottom of the PRES+ Modeling Interface, is a horizontal bar suitable for displaying status information, such as information of the option user makes and of the mouse position.

In order to implement the PRES+ Modeling Interface, we first create a main application window which is derived from the QMainWindow class of Qt. Then we insert the menu bar, toolbar and status bar into the main application window. In the third step, we defined our own actions through the abstract interface provided by QAction class of Qt, and add these actions into menus and the toolbar. Next, we insert the main part, a splitter widget, into the main application window. As the left part of the splitter widget, the components list box is a dynamic list, when the components list is selected the contents of the list box will be update automatically. And the items list box is a statistic list with the fixed contents. As the right part, a Qt canvas is put into the splitter widget, and a view is defined derived from the QCanvasViwe class of Qt to provide an on-screen view of the canvas.

### 5.3.2 Graphical Item Structure

Since items are the basic element of PRES+ models, it is necessary to define the data structure for each item. According to the properties of items, the Petri Net Class Library [5] gives a general structure for each item. However, in our design, as graphic objects, items also have some graphical attributes. Therefore, the data structures of items are re-defined in our tool.

First, in order to be shown on the canvas, items should be canvas items defined by Qt. And based on the different shape of items, we use some basic graph to define them. For example we select QCanvasEllipse class to be derived for building place and token item, and QCanvasRectangle class for building transition item. Moreover, for unique identifying items, each item is arranged a name (Id) when it is constructed and cannot be changed. Second is to add the general properties to each item's data structure. For example, the transition item has two bounds of delay, a guard, an associated function, and etc. In order to make the graphical PRES+ models more expressive, some important attributes of items need be shown in the graph. So finally, several tags with the important information are inserted into the item's data structure and these tags are created by deriving from the QCanvasText class.

In our design, there are two complex graphical items. One is arc, and the other is component. Both of them are an assembled graph. The arc item consists of a set of lines, a set of nails and an arrow, or an arrow directly. Therefore we used QCanvasLine class, QCanvasEllipse class, and QCanvasLine class to be derived for defining line, nail and arrow item respectively, and then combine them into an arc item. It is necessary to note that the arc item is not a canvas item. Furthermore, since an arc item contains at least an arrow, we use the arrow to uniquely identify the arc.

A component item is an abstract representation of a PRES+ model, and we only focus on its interface [1], but not the detail inside. A component item is often drawn as a box surrounded by its ports [1], and a port is a kind of place, denoted by a small circle. So we use QCanvasRectangle class and QCanvasEllipse class for building a component item.

The detailed items' data structures are specified in Appendix A.

### 5.3.3 Operations

Operations are a set of controls that users can operate via the PRES+ Modeling Interface. As introduced in 5.3.1, each control corresponds to an action. In our design, the controls in PRES+ Modeling Interface can be divided into two classes. One is the kind of controls that are invoked via a menu option or a toolbar button, such as Redo and Undo. And the other class is the kind of controls that are triggered by a set of events. For example, when a user selects the place item in items list, and clicks the mouse at any position in the canvas, then the control for drawing a place will be called and a place will appear at the position where the mouse was clicked. In Table 5.1 all operations in the PRES+ Modeling Interface are listed.

| Name | Description | Class |
|---|---|---|
| fileNewAction | Create a new file with a blank canvas | 1 |
| fileOpenAction | Open a new file | 1 |
| fileSaveAction | Save the current model | 1 |
| fileSaveAsAction | Save the current model into a specified file | 1 |
| filePrintAction | Print the current model | 1 |
| fileExitAction | Quit the application | 1 |
| editUndoAction | Undo the most recent operation | 1 |
| editRedoAction | Redo the most recent undo operation | 1 |
| editCutAction | Cut a set of items from canvas (set unvisible) | 1 |
| editCopyAction | Copy a set of selected items | 1 |
| editPasteAction | Paste a set of copied items to canvas | 1 |
| editFindAction | Find an visible item in canvas and select it | 1 |
| editSelectAllAction | Select all visible items in canvas | 1 |
| viewZoomInAction | Zoom in the canvas | 1 |
| viewZoomOutAction | Zoom out the canvas | 1 |
| simulationFireAction | Open the current PRES+ net in the simulation window | 1 |
| verificationVerifyAction | Open the current PRES+ net in the verification window | 1 |
| toolConfigurationAction | Configure the tool | 1 |
| toolUpdateAction | Update the current PRES+ net | 1 |
| helpContentsAction | Popup the help window with all contents | 1 |
| helpIndexAction | Popup the help window with the index | 1 |
| helpAboutAction | Messages about the tool | 1 |
| ListSelected | Operate if the list is selected | 2 |
| LibrarySelected | Operate if the item in components list is selected | 2 |
| LibraryHighlighted | Operate if the item in components list is highlighted | 2 |
| ComponentSelected | Operate if the item in items list is selected | 2 |
| ComponentHighlighted | Operate if the item in items list is highlighted | 2 |
| PaintModule | Operate when drawing a component, a place or a transition | 2 |
| PaintLine | Operate when drawing a line | 2 |
| PaintArrow | Operate when drawing an arrow | 2 |
| PaintNail | Operate when drawing a nail | 2 |
| PaintIOArc | Operate when drawing an arc | 2 |
| PaintToken | Operate when drawing a token | 2 |
| MoveItems | Operate when moving an item | 2 |
| ReShapeComponent | Operate when re-shaping a component item | 2 |
| SelectItems | Operate when selecting an item | 2 |
| ConfigureItems | Operate when configuring an item, except component item | 2 |
| EditComponents | Operate when editing a component item | 2 |
| | | |
| | | |

**Table 5.1 Operations List of PRES+ Modeling Interface**

For the controls of the first class, Qt provides many useful objects that can help to design some actions. For instance, the QFileDialog class provides dialogs that allow users to traverse their file system in order to select one or many files or a directory. With this class, we defined our fileOpenAction, fileSaveAction and fileSaveAsAction easily. But some actions need be designed based on our own algorithms and rules, such as RedoAction and UndoAction.

The controls of the second class, are implemented using a major mechanism of Qt, named *meta-object system* [13]. The basic idea of this mechanism is to create independent software components that can be bound together without any component knowing anything about the other components it is connected to. As a key service of this mechanism, signals and slots is a fundamental mechanism used to bind up two objects. For example, in one object, called sender, a signal is declared, and in the other object, called receiver, a slot is declared and implemented. When the sender emits the signal, then the receiver will automatically performs the slot if the slot and the signal have been connected.

In the following we will describe the solutions for some particular problems that we met in the design.

- **Redo and Undo**

  Redo and Undo are a pair of reverse functions. Undo is the operation that reverses the last editing action, and Redo restores the last editing action that was canceled by Undo. Therefore, before designing these two operations, it is necessary to define the rule to limit the operating scope of Redo and Undo. The rule here includes two dimensions. One is if the Undo and Redo operations can be done infinitely? The other is which action can be Undone or Redone? Below, we list the rule and then present the mechanism behind Undo and Redo.

  - **The rule of Redo and Undo**
    - Both Undo and Redo can record maximum 10 actions;
    - The editCutAction operation can be Undone and Redone;
    - The editPasteAction operation can be Undone and Redone;
    - The PaintModule operation can be Undone and Redone;
    - The PaintNail operation can be Undone and Redone;
    - The PaintIOArc and PaintToken operations can be Undone and Redone;
    - The ConfigureItems operation can be Undone and Redone.

  - **The underlying mechanism**

    We define two stacks to record the undoable edits. The maximum depth of the stacks is 10 units. When an undoable edit is executed, we push the edit onto the undo stack. When the Undo action is activated, the edit on the top of the undo stack will be popped up, executed reversely, and pushed onto the redo stack. If the Redo action is executed, the edit on the top of the redo stack will be popped up, executed and moved onto the undo stack. However, if there is any action executed since the last Undo, the redo stack will be cleared. In Figure 5.3, an example of operating Undo and Redo is given. In the example, at first there are four undoable commands (denoted by circles) having been executed and recorded on the undo stack, and there is no command in redo stack (shown in Figure 5.3 a)). After an undoable command executed, the two stacks are changed to the situation in Figure 5.3 b). The Figure 5.3 c) represents the Undo action has activated twice sequentially, and the two undoable commands move from the undo stack onto the redo stack. When the Redo action executes, the top item of the redo stack will be popped and pushed onto the undo stack (represented in Figure 5.3 d)).

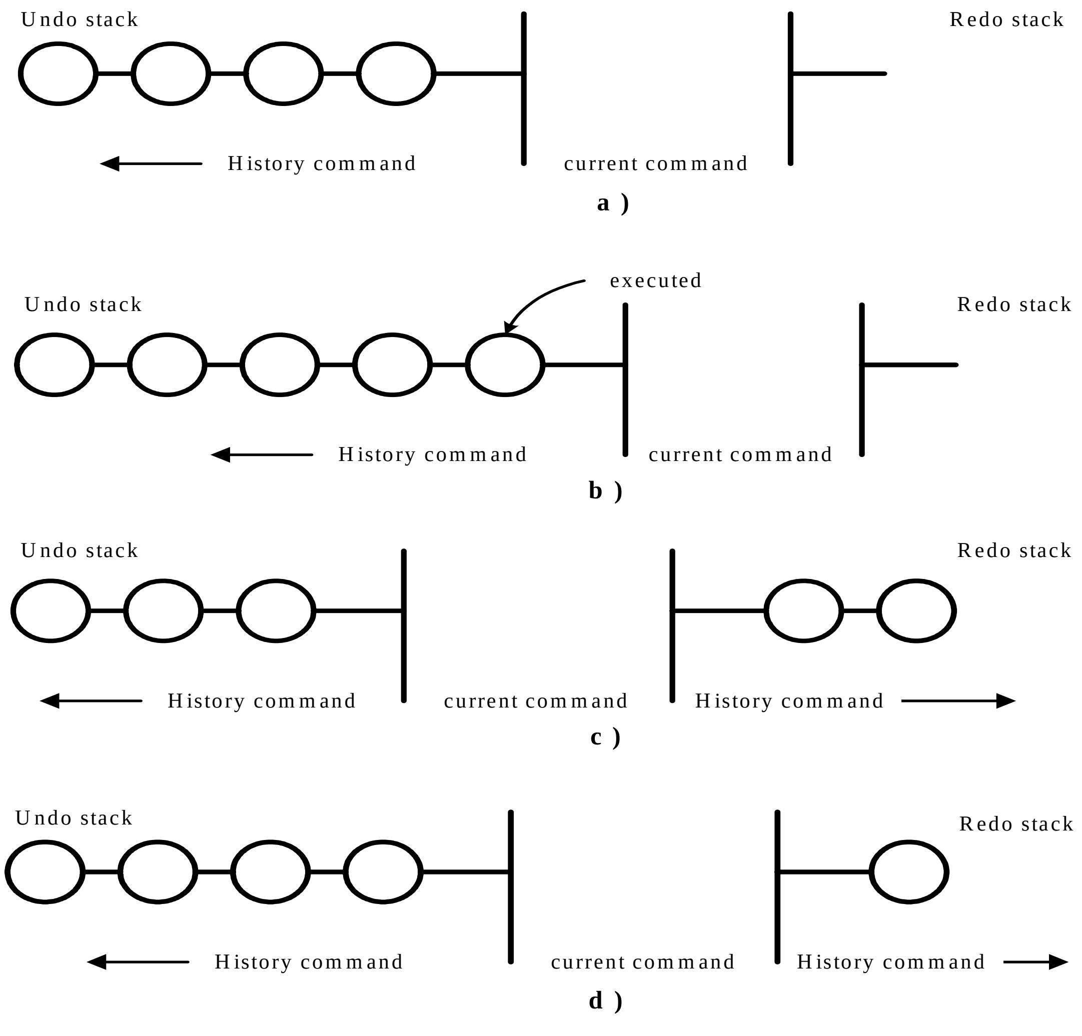


**Figure 5.3 An Example of Operating Undo and Redo**

- **Input format of the graphical PRES+ model**

  As explained in [5], an input format of PRES+ models is needed. However, different from the input format defined in [5], in our design, we add some attributes into the format to specify the graphical properties and the component items. Meanwhile, we also define the GUI schema PresGUIPlus.xsd to extend the PresPlus.xsd [5]. The detail of the GUI schema is given in Appendix B.

  In the input format of graphical a PRES+ model, a header must be specified at the beginning of the format. Following is the detail of the header.

```
<?xml version="1.0" encoding="iso-8859-1"?>
<petriNet xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
   xsi:noNamespaceSchemaLocation='PresGUIPlus.xsd'>
```

  Following the header, all the places are list. We will explain the syntax of the specification of a place based on the example below.

```
<place id = "p" x = "100" y = "100"/>
```

  In this example, the place is named p and drawn on the canvas with the center at position (100, 100). A place can also have a token, and the following example will show the syntax of this case.

```
<place id = "p" x = "100" y = "100">
      <token time = "0.0" value = "1"/>
</place>
```

  In this example, the place p has a token with the timestamp ‘0.0’ and value ‘1’.

  After the places, all the transitions are list. All properties of a transition will be specified. The specification of a transition has the following syntax.

```
<transition id = "t" assignment = "p-1" guard = "p>1" x = "150" y = "150">
      <interval start = "0" stop = "2"/>
</transition>
```

  This is a transition named t. It is an output transition of place p with the associated function $f$ = p – 1, and the guard $G$ = p > 1. The minimum bound delay of t is ‘0’ and the maximum bound delay is 2. Further more, the transition’s center is drawn at the position (150, 150).

  If a PRES+ model contains component items, all component items should be specified following transitions.

```
<component id = "com" x = "200" y = "200" width = "100" height = "50">
    <inport id = "ip" x = "190" y = "225"/>
    <outport id = "op" x = "310" y = "225"/>
</component>
```

In this example, the component item, named com, which corresponds to an existing PRES+ model file named com in the module library, contains an in-port ip and an out-port op. This component item will be drawn at position (200, 200) with width is 100 and height 50. And the ports of this component item will be drawn at positions (190, 225) and (310, 225) respectively.

Next, the input arcs, arcs from places or ports to transitions, are specified.

```
<inputArc id = "in1" placeId = "p" transitionId = "t"/>
<inputArc id = "in2" portId = "ip" transitionId = "t"/>
```

These two input arcs are in1 and in2. in1 is from the place p to transition t, whereas in2 starts from the port ip and ends at the transition t.

At the end, the output arcs, arcs from transitions to places or ports, are specified similar with the input arcs.

```
<outputArc id = "out1" placeId = "p" transitionId = "t"/>
<outputArc id = "out2" portId = "op" transitionId = "t"/>
```

This example lists two output arcs, out1 and out2.

After the whole definition, there should be an end tag.

```
</petriNet>
```

- **Update the PRES+ net**
  The component item is a new item that we have introduced in this thesis. Like the two sides of a coin, on one hand, by using the component item, we can reduce the design complexity [1]; On the other hand, as an abstract interface of a reusable PRES+ model, when the PRES+ model is changed, the corresponded component item should be modified simultaneously. Therefore how to update a PRES+ model currently being edited if one of its component items has been modified, is a problem which faced us during the design.

  Before going into detail, let us first define the concept of a useful port.
  **Definition 5.1: Useful Port.** A useful port is a port that is connected to a transition in the PRES+ model. If a useful port is an in-port, so it is called

a useful in-port. And a useful out-port means that a useful port is an out-port.

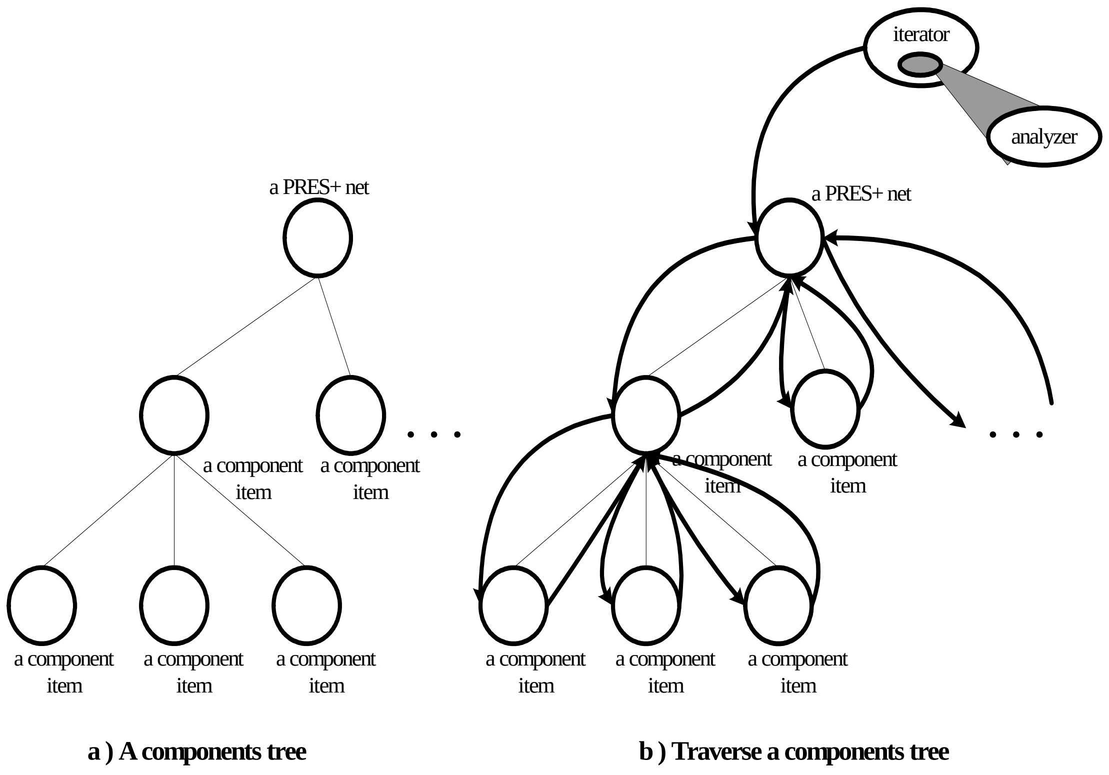


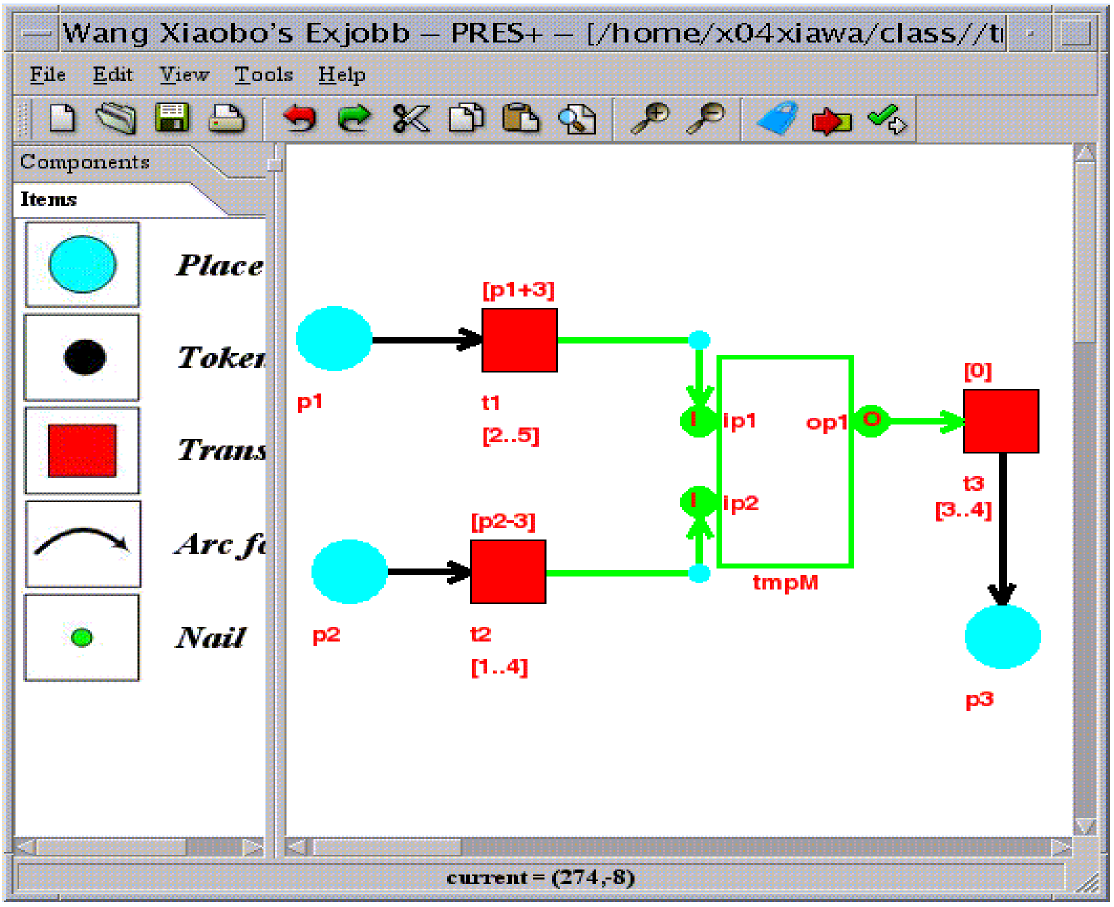
**Figure 5.4 Tree structure of a PRES+ model**

There are two situations in which a PRES+ model needs to be updated. One is when we open a PRES+ model and the component items inside have been changed. The other is when a component item of the PRES+ model currently being edited has been modified.

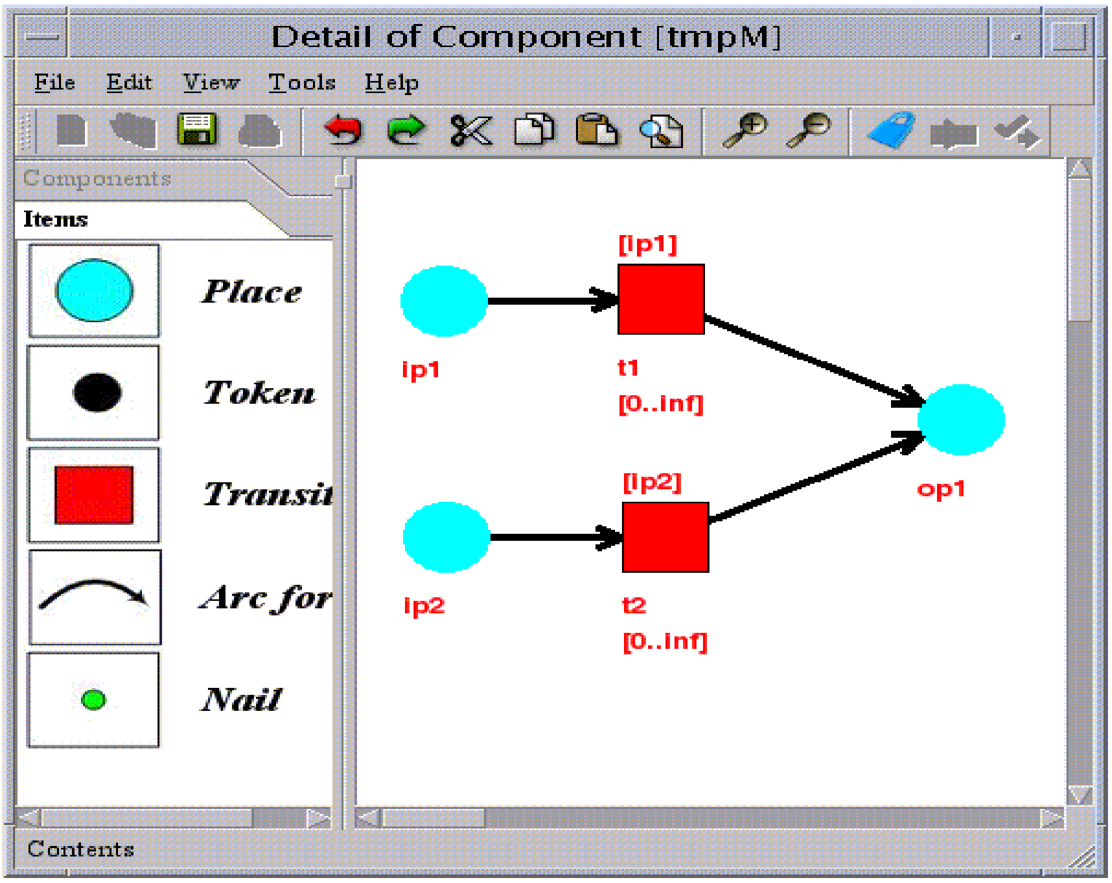
In the first situation, in order to check if the current interface of each component item is correct, we go through the corresponding PRES+ model to get its correct interface and compare it with the current specified interface. Due to the fact that PRES+ models can contain nested component items, we can use a tree data structure to represent a PRES+ model, named a ***component tree***. In a component tree, we call the root node PRES+ net, and other nodes the component items or PRES+ modules. If a PRES+ model is represented in this way, the task to check the PRES+ model can be implemented with a recursive algorithm for traversing a components tree. In Figure 5.4, the components tree of a PRES+ net is presented. Figure 5.4 a) shows that the PRES+ model has three levels. That means that this PRES+ model contains some component items, and some of them also contain component items. Figure 5.4 b) shows the process of traversing the components tree, and the arrows in b) represent the traversing steps. In order to check each component item, we design an iterator to traverse the component tree. Moreover, we add an analyzer function into the iterator to check if the interface of each component item in the tree is correct. For the example in Figure 5.4 b), the iterator goes through the components tree from the root node, the most outside PRES+ net, and reaches the most left component item in the second level. The iterator finds this PRES+ module also contains component items. Then the iterator goes deeply to the component items in the third level. Since the PRES+ modules corresponding to the component items in the third level do not contain any component items, the analyzer function starts to check the interface of each PRES+ module and returns back the check result to their father node, the component item in the second level. The check result can be divided into four classes and for each class the return value will be 0, 1, 2, or 3 respectively. For the first class, the return value is 0, which means that the current interface of the PRES+ module is correct. If the return value equals to 1, the interface of the PRES+ module has been changed, but all the useful ports of the interface were not modified. The analyzer function will in this case emit a warning message to notice the user. If the return value is 2, the interface of the PRES+ module has been changed, and some of the useful ports of the interface were modified. The analyzer function will emit a critical message. In the case that the return value is 3, which means that the analyzer function cannot parse the input format file of the PRES+ model, the analyzer function will emit another critical message. In the father node, the PRES+ module in the second level, if it receives the check result 0, the iterator will continue to traverse the component tree. If it receives 1, the input format file of it will be modified and the iterator will continue to traverse the components tree. And if it receives 2 or 3, it will return the check result to its father node, the root node of the components tree, and the iterator will stop to traverse. Finally, if the iterator reaches back to the root node, the input format file of the PRES+ net will be modified and the updating process will be finished. It is worthy to note that it is efficient to model a PRES+ net with some component items, but once any component items are modified, the updating process of the PRES+ net is time-consuming. Therefore, it is a trade-off the designers need to think over before they model a PRES+ net.

The second situation is not so complex as the first one. When a user models a PRES+ net with our tool, the user could scan and edit the details of any component items. In Figure 5.5, an example of updating the editing PRES+ net is presented. Figure 5.5 a) gives a PRES+ net, and in this net there is a component item, named tmpM. The interface of tmpM consists two in-ports, ip1 and ip2, and one out-port, op1. When double clicked the component item, a new window will pop up to show the details of the component item (in Figure 5.5 b)). The PRES+ module corresponding to the component item contains three places and two transitions. In the new window, users may edit the PRES+ module. Figure 5.5 c) is the detail of the PRES+ module after edited. It is clear that the interface of the PRES+ module is modified. After saving the modifications of tmpM and closing the window, users can be back to the window in which the PRES+ net is being edited. In this window, users could update the PRES+ net by click the icon, the one with a lock image. Since the useful in-port of the interface of the component item has been modified, the PRES+ net needs to be updated. Further more, the useful in-port ip2 has been deleted, the connection between transition t2 of the PRES+ net and ip2 will not exist any more. Therefore, the old component item (in Figure 5.5 a)) will be erased, and a new component item with the correct interface will be drawn instead. In addition, the arcs connected with the component item will be removed. Figure 5.5 d) presents the PRES+ net after updating process.

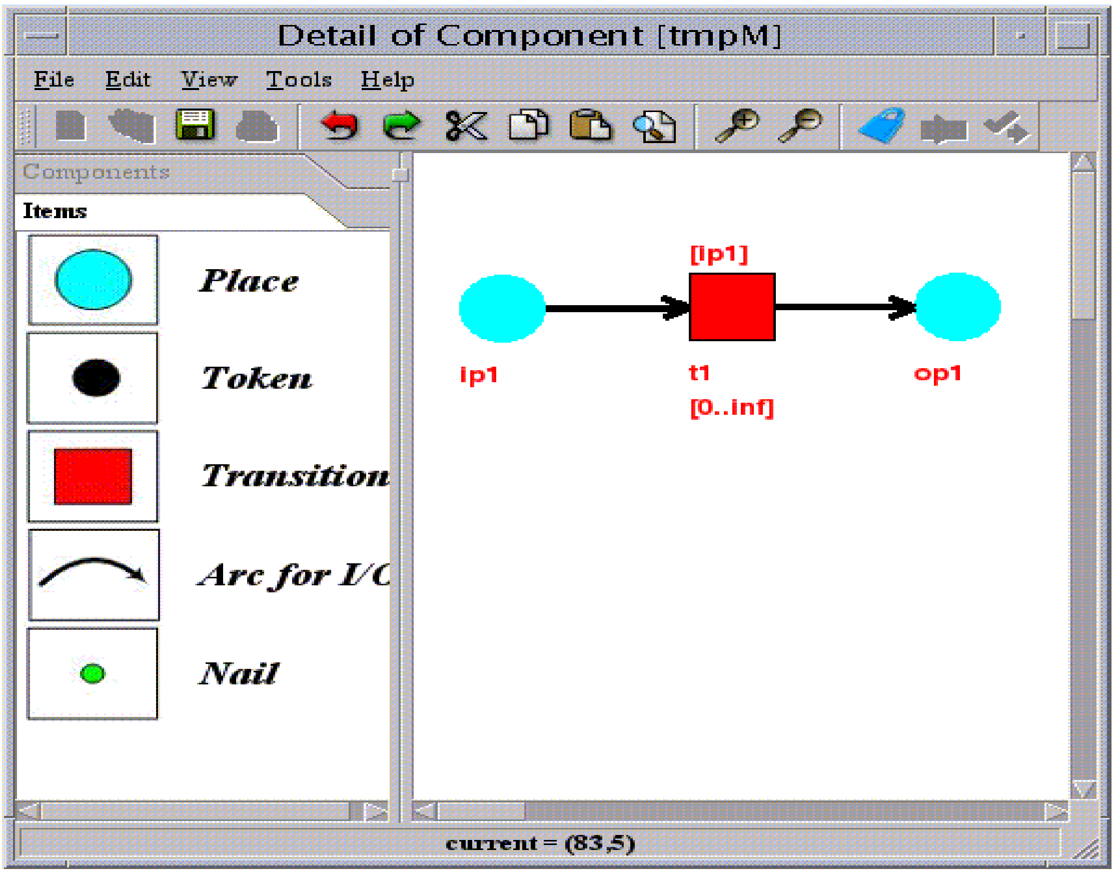
It is necessary to note that the input format of a graphical PRES+ net is saved in an XML file. In our design, we build a class derived from the class QXmlDefaultHandler to parse the input format XML file and get the interface of the PRES+ net defined in the XML file. With the interface we can judge if the PRES+ net being edited needs to be updated.



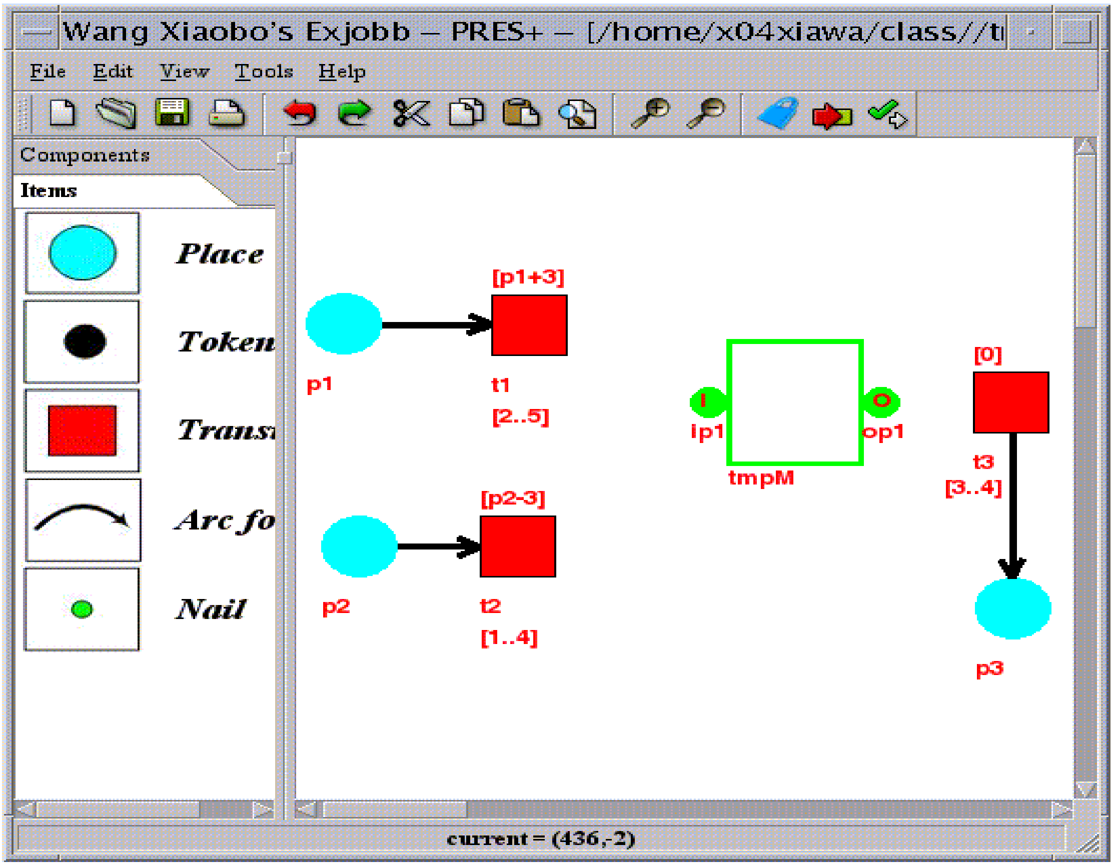
**a ) An editing PRES+ model contains a component item**



b ) Details of the component item



c ) After modifying the component item



**d ) After updating the PRES+ model**

**Figure 5.5 An example of updating a PRES+ model**

- **Translate the graphical PRES+ model into Petri Net**
  The Petri Net Class Library [5] is an extendable Petri net class library. It defines the structure of the PRES+ net and provides some useful task modules. Therefore, in order to simplify our tasks, we translate a graphical PRES+ model into a simple timed Petri Net. To achieve the translation, we use the interface defined in the SimpleTimedPetriNet class. The class has the functions createPlace, createTransition, createToken, createInputArc, and createOutputArc to create the places, transitions, tokens, input arcs and output arcs respectively. After creating all items of a simple timed PN, the net will be created spontaneously. With the simple timed Petri Net model, we can easily simulate the net by calling the function fire, and translate the net into a TA model by using the task module, Translation Module. However, the component item of a PRES+ model is not defined in the Petri Net Class Library. When translating, we have to translate the component item first. In our design, a PRES+ model may contain several component items and in each component item, there may also have some component items, like the representation of a components tree. So we design to expand every component item in every level of the component tree to the root node level. In other words is to present all items in every component item in a PRES+ model. For

example, the PRES+ net shown in Figure 5.5 a), has three places, three transitions, one component item and six arcs. And the details of the component item is represented in Figure 5.5 b), which has three places, two transitions and four arcs. If we expand all the items inside the component item to a PRES+ model, the equivalent PRES+ model could be represented with six places, five transitions and ten arcs, and shown in Figure 5.6. In order to ensure the uniqueness of the Ids of all items, we add a prefix to all the Ids. The prefix consists of the component item id and a symbol "_". In Figure 5.6, the places tmpM_ip1, tmpM_ip2 and tmpM_op1, and the transitions tmpM_t1 and tmpM_t2 are the items extracted from the component item tmpM.

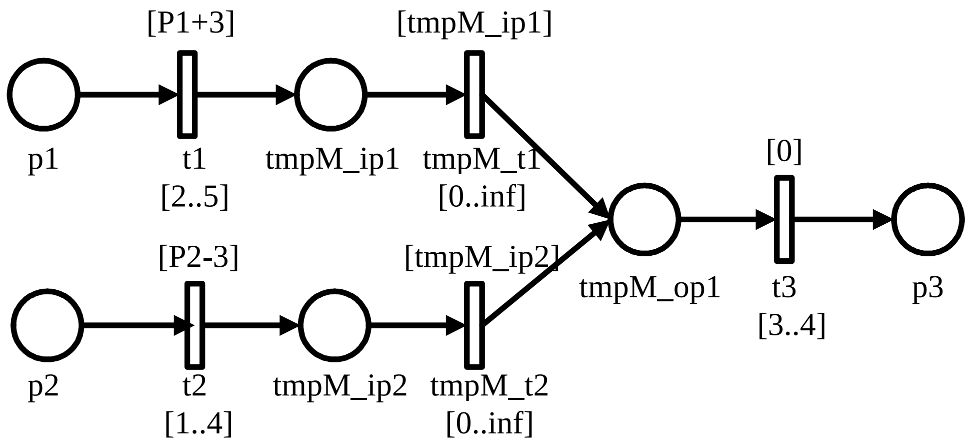


**Figure 5.6 The equivalent PRES+ model of the model in Figure 5.5 a)**

After building the equivalent PRES+ model, we can create a simple timed Petri Net by using the functions of the SimpleTimedPetriNet class with the item's properties as the input attributes.

## 5.4 Simulation Tool Design

The simulation tool is used to simulate a PRES+ model and present the simulation process graphically. Simulation is a method for validating if a specified state of a PRES+ net is reachable, and is implemented by firing enabled transitions of the PRES+ model. When an enabled transition is fired, the tokens in the PRES+ model will move and the state of the PRES+ net will be changed. Usually we use the **token game**, which is an interactive simulation of the model behaviour, to present the simulation process. In this section, we will introduce the user interface first, and then some important algorithms will be given.

### 5.4.1 User Interface

Figure 5.7 shows the simulation window. The simulation window is derived from QMainWindow class provided by Qt, and consists of two parts. The left part is a control panel, via which users can simulate a PRES+ model interactively. The right part is a view, created by deriving from QCanvasView class, in which the simulation process will be illustrated.

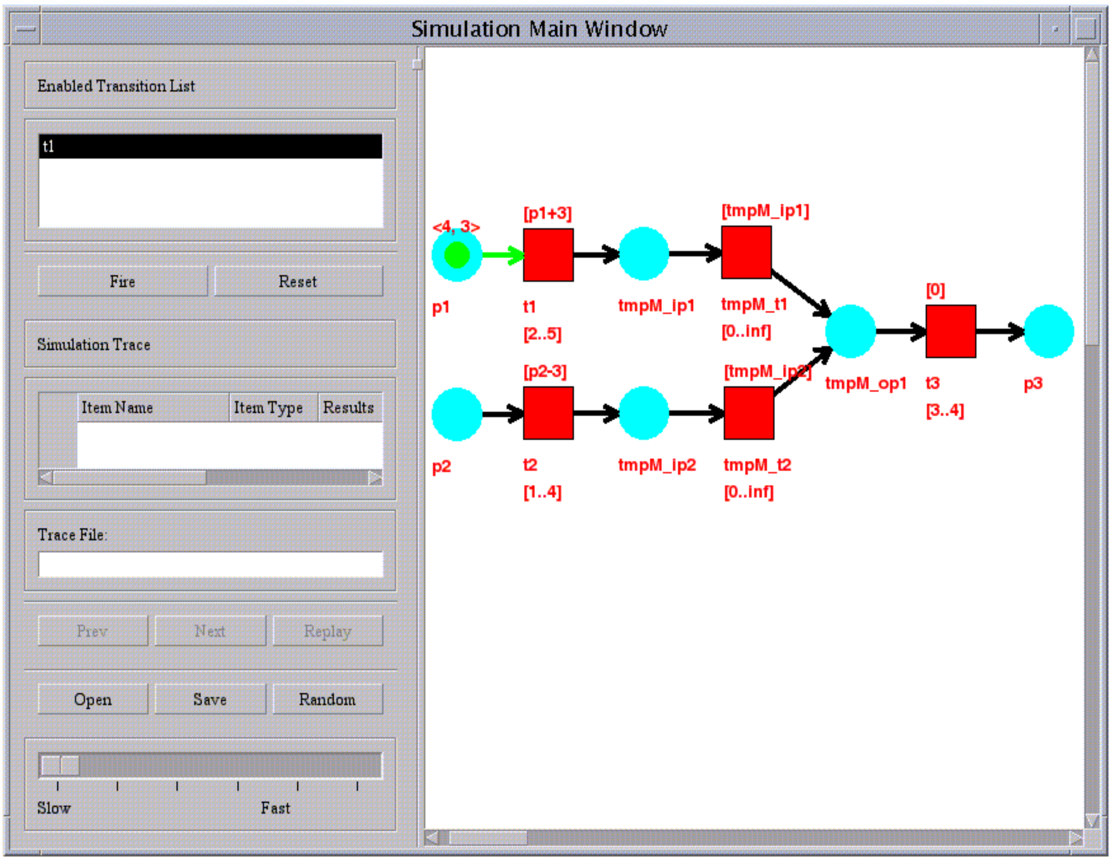


**Figure 5.7 PRES+ Simulation Interface**

In the control panel, the “Enabled Transition List”, “Simulation Trace”, “Trace File” and “Control Buttons Group” are widgets enumerated in this order from top. The part “Enabled Transition List” has a list box, derived from QListBox, used to list the current enabled transitions ids, and two control buttons, “Fire” and “Reset”. The “Fire” button is corresponding to firing the transition that selected in the list box. The “Reset” button is used to reset the marking of the PRES+ model back to its initial marking. We display the simulation result in a trace table, which is derived from QTable class, in the part “Simulation Trace”. The “Trace File” is a line text editor used to display the trace file. In the “Control Buttons Group”, there are six control buttons and a horizontal slider. The buttons “Prev”, “Next” and “Replay” are used to trace the simulation trace. And the buttons “Open” and “Save” are corresponding to operating the trace file. When the button “Random” is pressed, the simulation will be performed automatically. During the random simulation, if there are several enabled transitions at a time, the tool will select an enabled transition randomly and fire it. In order to adjust the speed of the random simulation, we design a slider, derived from QSlider class, at the bottom of the control panel. The right part of the PRES+ Simulation Interface, a canvas is provided in order to display the PRES+ model and the token game.

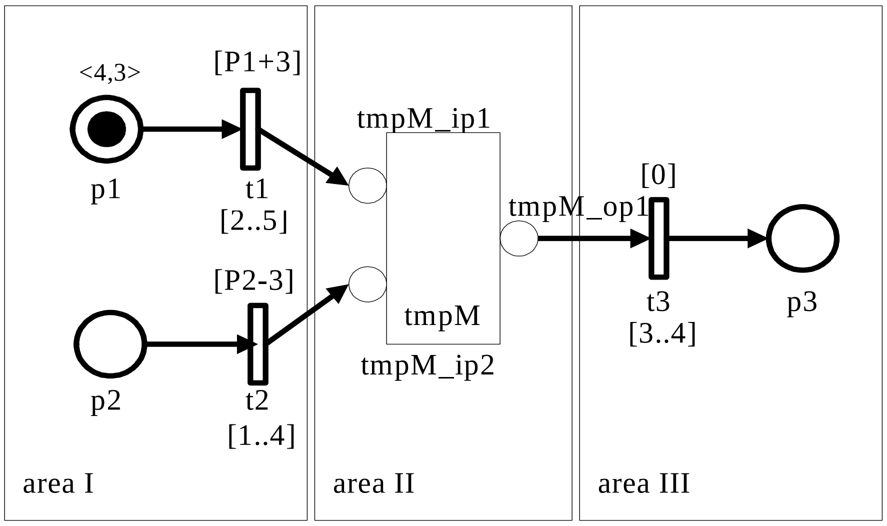
Figure 5.7 gives out the simulation of the PRES+ model shown in Figure 5.5 a). Before we simulate the PRES+ model, we add a token into place p1, and the token has the value is 4 and time stamp is 3. In Figure 5.5 a), the PRES+ model contains a component item. But when we simulate the model, we expand the component item, and for each item inside the component item we add a prefix, “tmpM_”, to its id. In Figure 5.7, the PRES+ model is in its initial state, and the transition t1 is enabled and is list in the “Enabled Transition List”. Therefore, if the “Fire” button is pushed, the transition t1 will be fired, and the state of the net will be changed, the token will disappear from place p1 and a token will be appear in place tmpM_ip1. In initial state, the “Simulation Trace” is empty, and the buttons “Prev”, “Next” and “Replay” are disabled.

### 5.4.2 Expand Component Items

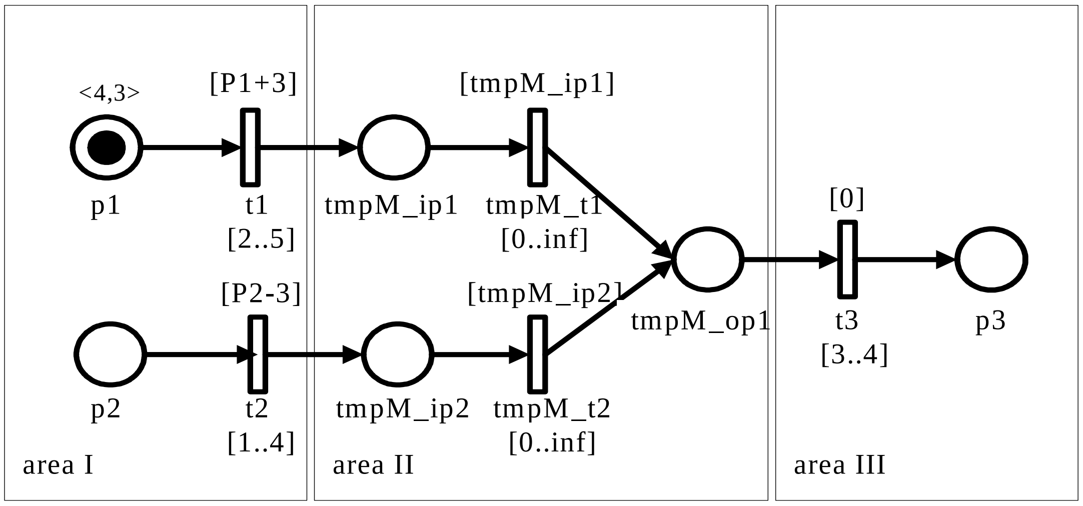
As mentioned before, a PRES+ model may contain component items. But, when it is simulated, tokens may move inside a component item and the transitions in a component item may be enabled and fired. In order to show the simulation clearly, therefore, the details of component items are displayed to users. There are two possible methods to display the contents of component items. One method is to open a new window to show the details of a component item when firing a transition inside the component item. Another method is to expand all component items to a PRES+ model, like in Figure 5.7. In the first solution, there will be many simulation windows open at the same time, and users need to switch simulation windows frequently. So it is hard for users to operate simulation and check the simulation results. In addition, if simulation in this way, it is also hard to us to implement the trace function. Therefore, we select the second method. However, how to guarantee there is no any items overlapped after we expand all component items, is a hard nut to crack. In our design, we make a naïve algorithm to expand component items of a simple PRES+ model. But for expanding the component items of a complex PRES+ model, we have not found an intelligent method yet.

In the following, we give a simple PRES+ model in Figure 5.8 a) to show how the expanding algorithm works. Firstly we divide the canvas into three areas based on the left and right borders of the component item tmpM. It is clear that in area II the component item will be expanded and the right border of this area will be changed. The items in area I will not be moved after expanding, and the items in area III should be moved rightwards after expanding. In Figure 5.8 b), it presents the three areas after expanding. Like translating a graphical PRES+ model into a simple timed Petri Net, in order to ensure all items' id unique, we add a prefix to all items' id. The prefix consists of the component item id and a symbol "_".

It should be mentioned that for certain complex PRES+ models, this algorithm may not create nice graphs after expanding component items, but it will not affect the simulation.



**a) Before Expanding**



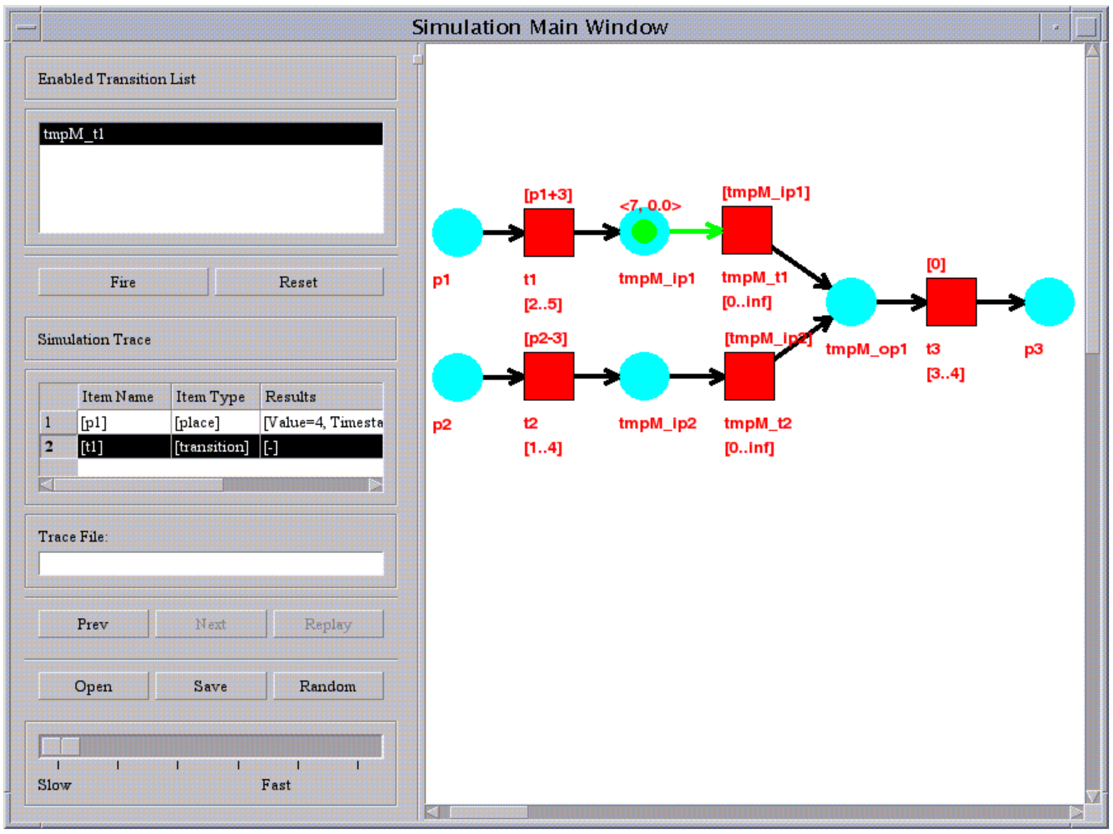
**b) After Expanding**

**Figure 5.8 Expanding a PRES+ model**

### 5.4.3 The Token Game

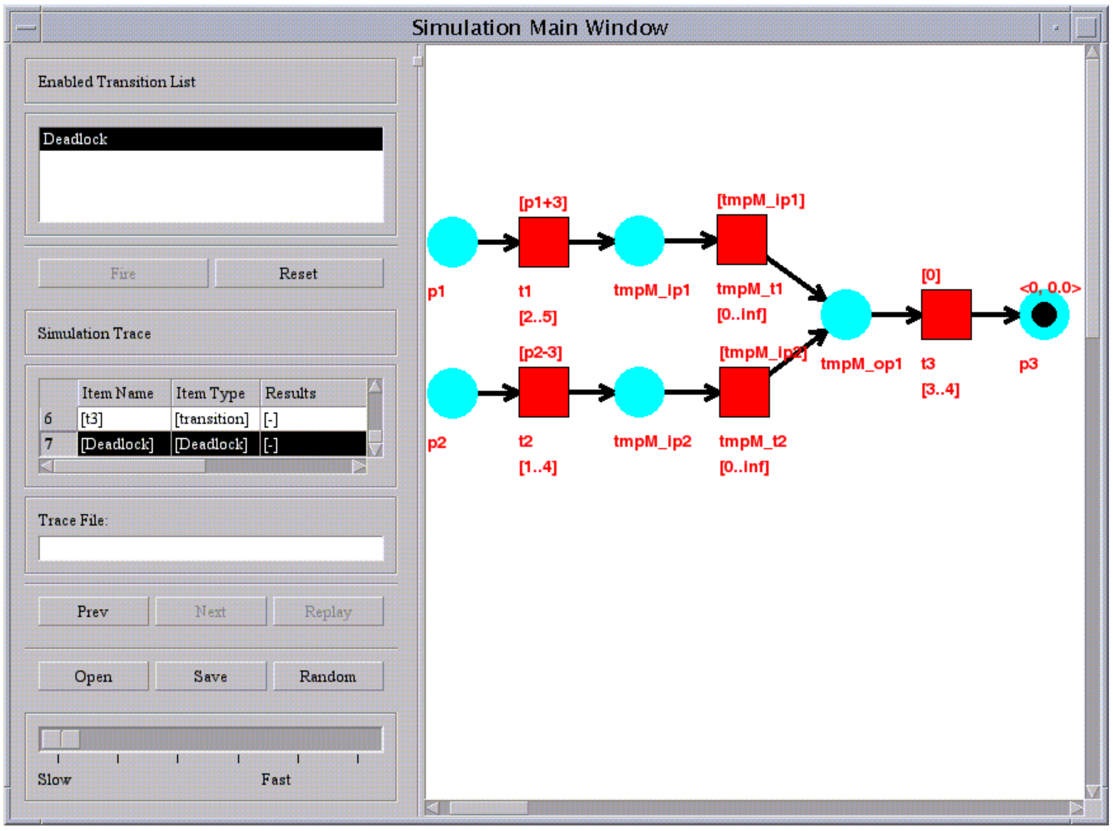
The token game is an interactive firing of transitions in subsequent markings, and usually is used to present the simulation process via displaying the movement of tokens. In our PRES+ Simulation Interface, we execute the token game in the canvas when we simulate a PRES+ model.

The simulation starts with the initial state of the PRES+ model, and the existence of enabled transitions determines if the simulation may continue. In Figure 5.7, a PRES+ model is in its initial state, and transition t1 is enabled and consequently listed in the "Enabled Transition List". After firing t1, the state of the PRES+ model is changed accordingly, and the simulation step is recorded in the "Simulation Trace". At this time the transition tmpM_t1 is enabled and list in the "Enabled Transition List". In the canvas, the PRES+ model is in the new state, with a token in the output place tmpM_ip1 of transition t1. Since transition t1 has an associated function *f* = p1 + 3, the value of the token in place tmpM_p1 is 7, which is shown in Figure 5.9. We can imagine if the transitions tmpM_t1 and t3 are fired sequentially, the token will arrive place p3 and at that time no transition is enabled. The simulation will be therefore stopped when a token is in place p3. We present the end of the simulation with the symbol "Deadlock" list in "Enabled Transition List", which is shown in Figure 5.10.



| | Item Name | Item Type | Results |
|---|---|---|---|
| 1 | [p1] | [place] | [Value=4, Timesta |
| 2 | [t1] | [transition] | [-] |

Figure 5.9 An Example of Firing a Transition



| | Item Name | Item Type | Results |
|---|---|---|---|
| 6 | [t3] | [transition] | [-] |
| 7 | [Deadlock] | [Deadlock] | [-] |

Figure 5.10 An Example of the End of Simulation

### 5.4.4 Trace the Simulation

The simulation trace will be generated while simulating PRES+ models. We display the simulation trace in a trace table, which contains three attributes, “Item Name”, “Item Type”, and “Results”. In the “Item Name” field, an item’s id is saved. And in the “Item Type” field, we record the type of the item that corresponding to the name in “Item Name” field. To trace a simulation, in theory, we only need the order of the transitions that were fired during simulation. However, in order to make the simulation trace clear and detailed, we also record the input places of the fired transitions to the simulation trace. Due to the fact that the essence of the dynamic behaviour of a PRES+ model is its state shifting, and that the state of a PRES+ model mainly consists of the information of tokens in places, we record the “Results” field corresponding to a place item with the value and time stamp of the token in this place item, and the global time of the PRES+ model. But transitions cannot contain tokens, so in the “Results” field corresponding to a transition, nothing will be recorded.

With the simulation trace, we could recur the movement of a PRES+ model. To trace a simulation means that when any row in the trace table is selected, the PRES+ model drawn in the canvas will reflect the corresponding state. In order to synchronize the selecting action and the redraw operation, a mechanism to quickly get the corresponding state of a PRES+ model is needed. Clearly, the fast way to get a particular state is to get it from a list that saved all states that have occurred during the simulation. Therefore, if the simulation trace is generated during the simulation, we append the states of the PRES+ model to another list in sequence, so that each state uniquely corresponds to a row of the trace table, in which a particular transition is recorded. Thus, when any row in the trace table is selected, it will search downward from the selected row for finding the first transition. The state corresponding to this transition can easily be retrieved from the list. Similarly, if the simulation trace is loaded from a trace file, the list of recorded states will be created and filled during the loading process.

### 5.4.5 Automatic Event

In the PRES+ Simulation Tool, we defined two automatic events: the automatic simulation event, which is used to simulate a PRES+ model automatically, and the automatic replay event, which is used to replay the simulation trace automatically.

In the PRES+ Simulation Interface, when users press the “Random” button, the automatic simulation event will be invoked. This event is a fast simulation event, used to fire transitions continuously. During simulation, if there is one transition enabled, the transition will be fired. If there are several transitions enabled at same time, this event will select an enabled transition randomly and fire it. This automatic event will stop when two situations occur. One situation is when users press the “Random” button the second time. The other situation is when there is no enabled transition and the simulation stops. In order to control the executing speed of this automatic event, we create a slider in the PRES+ Simulation Interface. Users could drag the slider to set the executing speed of the automatic simulation event, before they press the “Random” button.

The automatic replay event can be invoked when users press the “Replay” button. This event will stop in two situations. One situation is when users press the “Replay” button the second time. The other is when the tracing process is at the end of the simulation trace. Similarly as with the automatic simulation event, users can control the speed of this even via adjusting the position of the slider in the PRES+ Simulation Interface.

The automatic events are implemented by deriving from timer events. A timer event is a kind of event that will be fired when the control’s preset timer interval expires. In the PRES+ Simulation Tool, we start the timer event by pressing the button, “Random” or “Replay”. The timer interval is connected to the slider. When the position of the slider is changed, the value of the timer interval will be modified accordingly.

## 5.5 Verification Tool Design

The verification tool in this thesis is used to verify a PRES+ model by using the existing tool verifyta [17].

### 5.5.1 User Interface

According to the usability requirements specified in chapter 3, the underlying model checker should be transparent for the user. The verification tool verifyta may be accessed from UPPAAL’s graphical interface, or in command line. In our design, we place verifyta behind the PRES+ Verification Interface, and our program performs the verification via a system call to verifyta. Figure 5.11 shows the PRES+ Verification Interface.

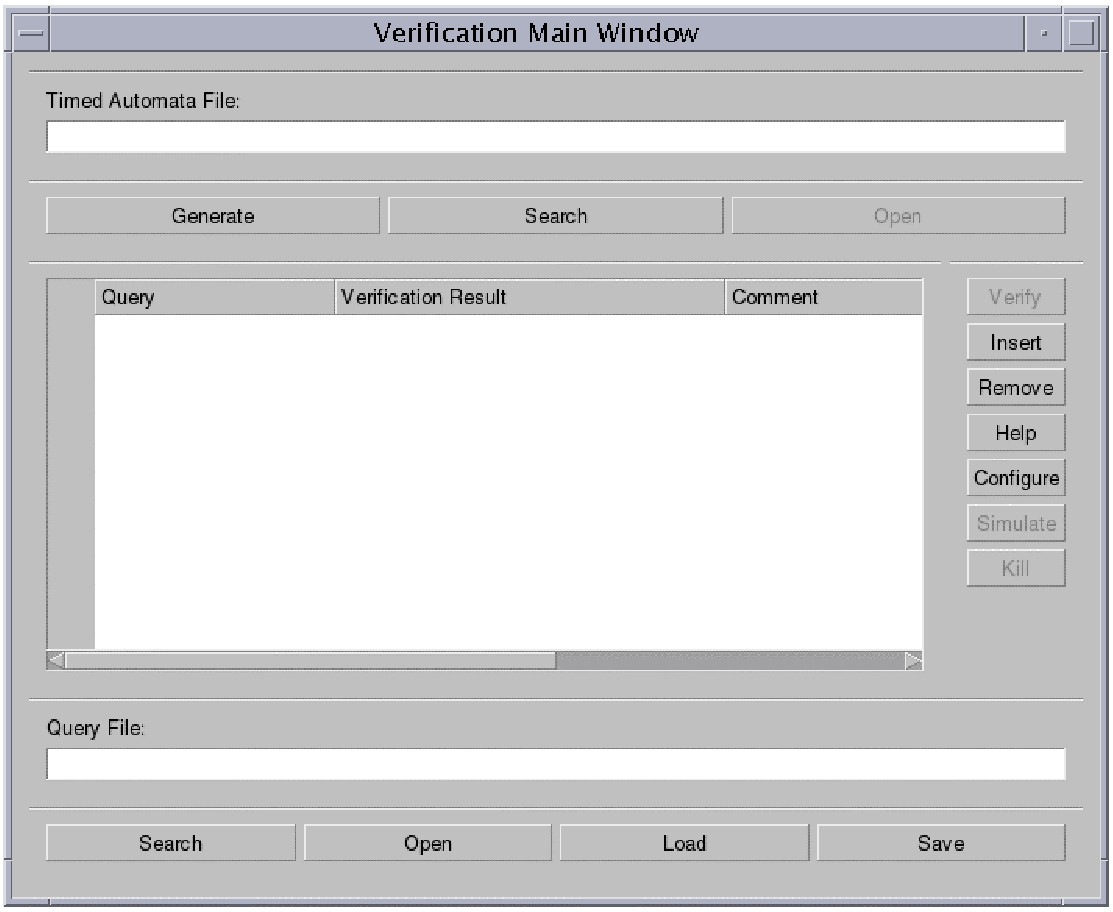


**Figure 5.11 PRES+ Verification Interface**

This interface is made up of three parts. The upper part of the interface deals with the underlying TA representation, which is the input language of verifyta. In the line editor, users can input an existing Timed Automata file, whose name normally ends with ".xta". A temporary file "translatortext.xta" can be generated corresponding to the PRES+ model being edited in PRES+ Modeling Interface, when the "Generate" button is pressed. After the Timed Automata file is selected, user can view the details of the file by clicking the "Open" button, thus a rich text editor with the contents of the Timed Automata file will be activated. For the structure of a timed automata file, which is defined in UPPAAL, we gave an example in 2.3.

The middle part of the PRES+ Verification Interface is a control area mainly for editing the query formulas, executing the verification and simulating the *diagnostic trace* of the verification. This part consists of a table for displaying the query formulas, the verification results and the comments user marked corresponding to the verification results, and a group of buttons. The table has three columns, "Query", "Verification Result" and "Comment", in which the "Verification Result" column cannot be edited, but the others are editable. User can edit a CTL query formula in the "Query" column, and then push the "Verify" button for verifying the query. The verification result will appear in the “Verification Result” column after verification. Then the user could give some comments to the result in column “Comment”. Initially, the table is empty without any rows. If user wants to input a query, the “Insert” button should be pushed to insert an empty row into the table. Oppositely, when the “Remove” button is pushed, the currently selected row will be erased from the table. The “Help” button will give users a brief introduction for how to use the PRES+ Verification Tool, and the “Configure” button is used to set the path of the verification tool verifyta. The button, “Simulate”, provides a very useful function for simulating the *diagnostic trace* in the PRES+ Simulation Interface. Sometimes, a verification procedure may go on for quite long times. For this reason, the “Kill” button is designed for terminating the current verification process. It is worth to mention that the “Verify” button is disabled unless there exists a Timed Automata file existent and a query formula input in the current row of the table. The “Simulate” button will be enabled when a query is verified.

At the bottom of the PRES+ Verification Interface, the line editor is used to display an existing query file. A query file encloses a set of query formulas, and for each formula, there may have a comment. Usually a query file’s name is end with a suffix “.q”. In this area, there are four control buttons used to operate the query file. The “Search” button is used to select an existing query file, the “Open” button is used to open the selected query file in a rich text editor, the “Load” button is used to parse the query file and load the set of query formulas into the table above, and the “Save” button is used to save the queries and comments in the table into a query file. For the structure of a query file, we will give an example in the Appendix C.

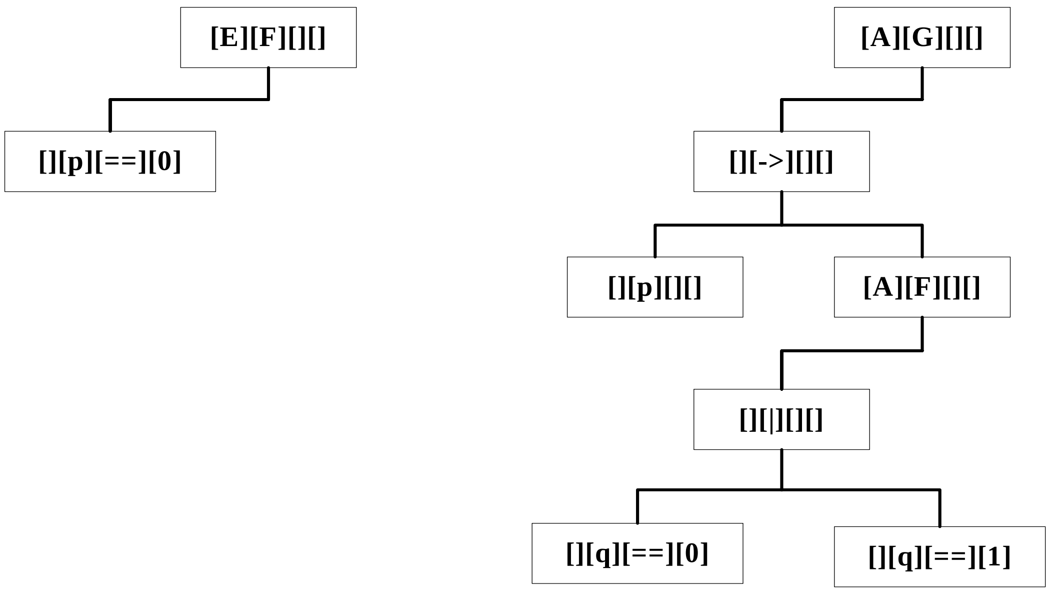
### 5.5.2 Translate a PRES+ model into a Timed Automata model

When verifying a PRES+ model, we use the available tool, verifyta. Verifyta is a model checking tool used to verify Timed Automata models. Therefore, before we make a call to verifyta, we must translate a PRES+ model into a Timed Automata model. Fortunately, the Petri Net Class Library [5] provides a task module – Translation Module – to translate a PRES+ model into a Timed Automata model and save the Timed Automata model into a file. Thus our task is to translate a graphical PRES+ model into a simple timed Petri Net model. The translation work is described in section 5.3.3. When we start the PRES+ Verification Interface, we transfer a PRES+ model to the PRES+ Verification Tool. When the “Generate” button in PRES+ Verification Interface is pressed, the translation procedure is called to translate the simple timed Petri Net model into a Timed Automata model and save the Timed Automata model into a temporary file “translatortext.xta”.

### 5.5.3 Parse a query formula into a CTL formula

To describe a query formula, in our design, we have designed a particular data structure. Usually a CTL formula consists of atomic propositions, boolean connectives, temporal operators and quantifiers. In our design, the atomic propositions are expressions related to places. For example, p==2 means the place p has a token and the value of the token is 2. The temporal operators of a CTL formula are **G** (globally), **F** (future), **X** (next step), **U** (until) and **R** (release). And a quantifier, **A** (all) or **E** (exists), is always set before a temporal operator. The details of CTL formulas are presented in [1]. In this thesis, we focus on how to parse a query formula into the CTL data structure.

The CTL formula parser, introduced in 4.2, defines the structure of a CTL formula and implements the translation from a query formula into a CTL data structure. First, let us introduce the data structure of CTL formulas. A binary tree structure is used to describe a CTL formula, and the number of levels of the tree is based on the complexity of the structure of the CTL formula. Each node of the tree represents a CTL unit and consists of a quantifier, an operator, a relation and a relation value. In Figure 5.12, two examples are presented. Figure 5.12 a) shows a simple CTL formula, EF(p == 0), which means that there exists a future where place p has a token with value is 0. In the root node of the tree, the quantifier is “E” and operator is “F”. This node contains in turn another CTL unit, and the operator of that CTL unit is “p”, the relation is “==” and the relation value is “0”. The CTL formula, shown in Figure 5.12 b), is much more complex than the one in Figure 5.12 a). This CTL formula contains seven CTL units and arranged in five layers.



**a ) EF(p==0)** **b ) AG([p -> AF([q==0 | q==1])])**

**Figure 5.12 Two CTL Formulas examples**

The parser of the available tool can translate an input query into a CTL formula. In order to parse an input query, the parser limits the format of the input. An input query should be arranged in the order of propositions, operators and quantifier. To the two CTL formulas in Figure 5.12, the input queries should be “0 == p E F” and “p 0 == q 1 == q | A F → A G” respectively. When the parser catch an input query, the parser traverses every characters of the input query sequentially and build a binary tree to represent the translation CTL formula.

In PRES+ Verification Interface, users could input queries into the “Query” column of the table. When the “Verify” button is pushed down, the CTL Formula parser will be invoked to translate the query formula into a CTL formula, and after translation, the CTL formula will be displayed in the area where the input query was input.

### 5.5.4 Translate a CTL formula into a Timed Automata Query

After translating an input query into a CTL data structure, we must translate the CTL formula into a Timed Automata query, which will be one of the input attributes of verifyta. In order to translate, the relationship between the CTL formulas and Timed Automata queries must first be defined. In our design, we implement several basic translations, which are shown in Table 5.2.

| Name | CTL Formula | Timed Automata Query |
|---|---|---|
| Possibly | EF p | E<> $p'$ |
| Invariantly | AG p | A[] $p'$ |
| Potentially always | EG p | E[] $p'$ |
| Eventually | AF p | A<> $p'$ |
| Leads to | AG(p -> AF q) | $p'$ --> $q'$ |

**Table 5.2 Some Relationships between CTL formulas and TA queries**

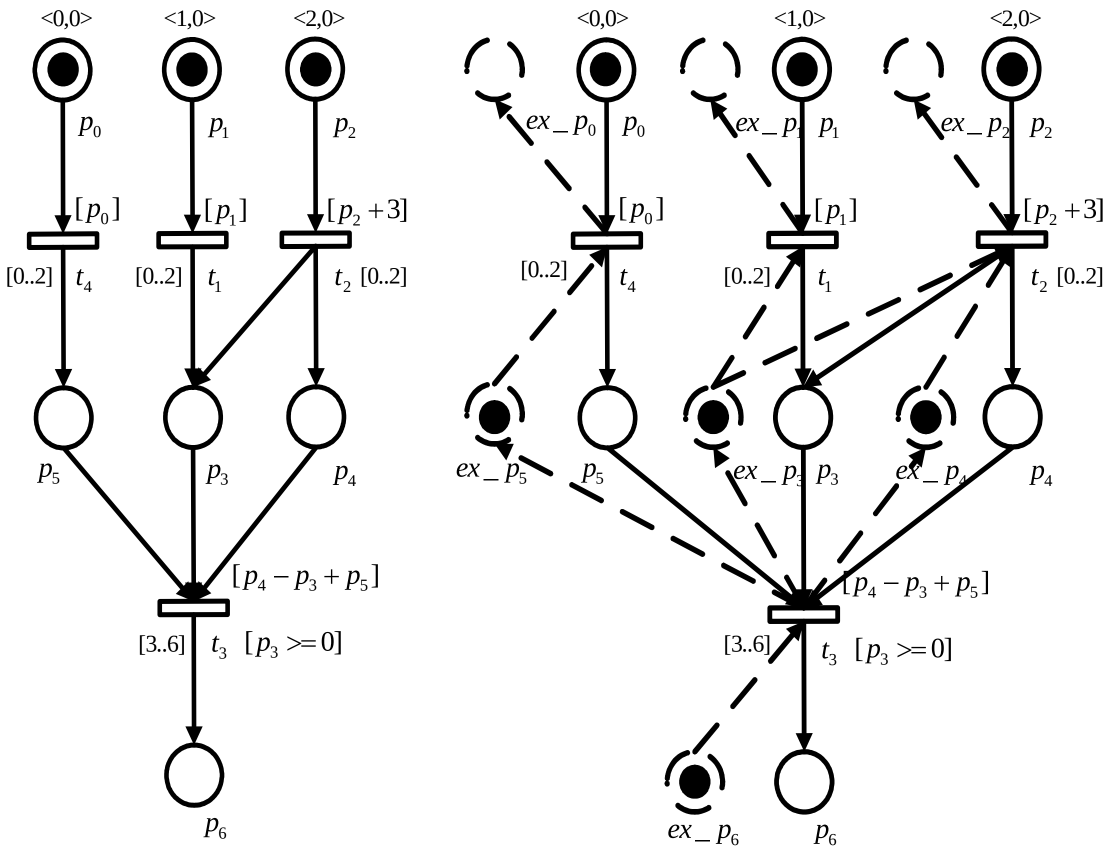
The symbols p and q in the table 5.2 are the propositions of CTL formulas, and the $p'$ and $q'$ are the state properties of Timed Automata queries corresponding to p and q respectively. Below the meaning of each CTL formula in table 5.2 is listed.

“EF p”: it is possible in the future that p is satisfied;
“AG p”: p is always satisfied;
“EG p”: p is potentially always satisfied;
“AF p”: p will always be satisfied in the future;
“AG(p -> AF q)”: once p is satisfied, q must be satisfied in the future.

According to the relationships in table 5.2, we can implement the translation with two steps. First is to translate the quantifier and operators into Timed

Automata queries properties, such as translating “EF” into “E<>”. The second step is to translate the propositions of CTL formulas into the state properties of Timed Automata queries, that is to translate p to p' and q to q'. The symbol p or q of a CTL formula is an expression of places of a particular PRES+ model. Usually it may be an id of a place, or relations among places. For example, if the expression is “p”, it means that the place p has a token. And if the expression is “p == 3”, it means that the value of the token in place p is 3. Just as its name implies, Timed Automata query is used to describe a Timed Automata model. Therefore, to translate p to p' and q to q', we must translate a PRES+ model into a Timed Automata model, which is represented in 5.5.2. In the following we will give an example to illustrate the translation from a PRES+ model into a Timed Automata model and the translation from a CTL formula into a Timed Automata query. In Figure 5.13 a), a Forced Safe PRES+ model is illustrated.

As explained in 2.3, before we translate a PRES+ model into a TA model, we should make the PRES+ model safe. In Figure 5.13 b), it shows the equivalent standard PRES+ model of the forced safe PRES+ model in Figure 5.13 a). Figure 5.14 shows the corresponding Timed Automata model of the PRES+ model.



**a ) A Forced Safe PRES+ model** **b ) An equivalent standard PRES+ model**

**Figure 5.13 A Forced Safe PRES+ model example**

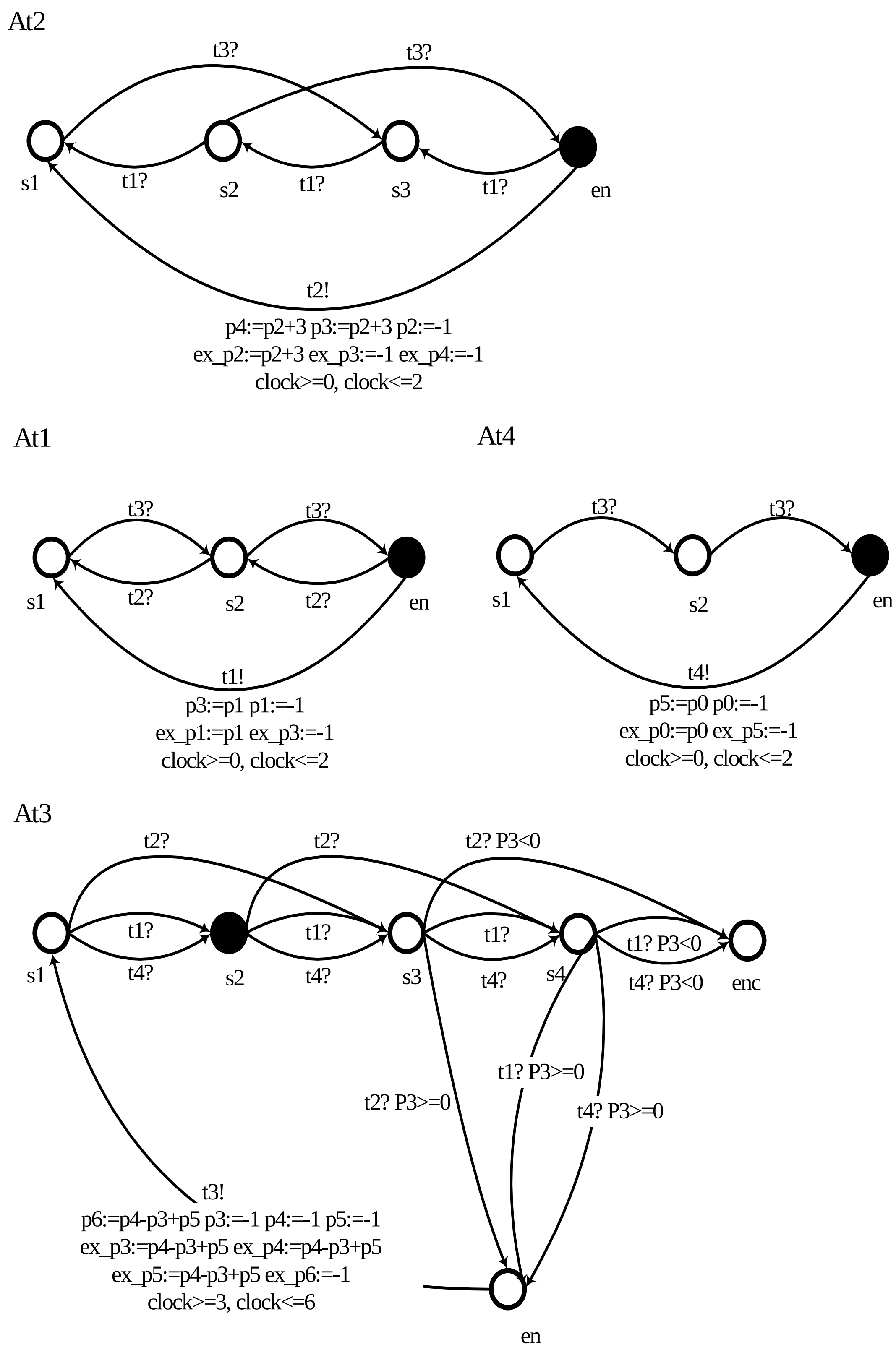


**Figure 5.14 Graphical representation of a TA model**

In the forced safe PRES+ model, if the input query presented in CTL formula is “EF p3”, which means that a token will possibly reach the place p3 in the future, the corresponding Timed Automata query should be “E<> p”, where p is the expression, with an equivalent meaning that there is a token in place p3. We can split that expression into two parts first, and then connect the two parts into the whole expression with “or” operator.

The first part states that place p3 must have a token. From the Figure 5.13 a) and according to the enabling rule of Forced Safe PRES+ models, we can get, that if transition t3 is enabled or t3 is not enabled only because its guard is not satisfied, then place p3 must have a token. Therefore, corresponded to the TA model in Figure 5.14, this part can be written as “At3.en or At3.enc”. In addition, it is clear that this part is based on the output transitions of place p3.

The second part describes that a token will reach place p3. In Figure 5.13 a), we can guarantee that a token will arrive at p3 by firing any one of the transitions t1 and t2. If we fire transition t1, the token in place p1 will move to place p3 and t1 will be disabled. In this case, according to the TA model in Figure 5.14, transition t1 is in state s1, denoted by “At1.s1”, and transition t3 may be in state s2, s3, s4, en or enc. So we can use “(At1.s1 and At3.s2) or (At1.s1 and At3.s3) or (At1.s1 and At3.s4) or (At1.s1 and At3.en) or (At1.s1 and At3.enc)” to describe that a token reach p3 after t1 firing. However, since “At3.en” and “At3.enc” have been expressed in the first part, we delete the redundancy and get “(At1.s1 and At3.s2) or (At1.s1 and At3.s3) or (At1.s1 and At3.s4)”. If we fire the transition t2, the token in place p2 will move into place p3 and place p4 and t2 will be disabled. Same as the t1 firing, in this case, we can get the description “(At2.s1 and At3.s3) or (At2.s1 and At3.s4)”. In order to simplify the algorithm, which is used to generate a TA query, we add a redundant formula into this description and get “(At2.s1 and At3.s2) or (At2.s1 and At3.s3) or (At2.s1 and At3.s4)”. Therefore the second part of the expression p is “(At1.s1 and At3.s2) or (At1.s1 and At3.s3) or (At1.s1 and At3.s4) or (At2.s1 and At3.s2) or (At2.s1 and At3.s3) or (At2.s1 and At3.s4)”. In addition, it can be seen that this part is based on all transitions connecting to place p3.

Finally, we connect the two parts to get the whole expression, which is “At3.en or At3.enc or (At1.s1 and At3.s2) or (At1.s1 and At3.s3) or (At1.s1 and At3.s4) or (At2.s1 and At3.s2) or (At2.s1 and At3.s3) or (At2.s1 and At3.s4)”

Figure 5.15 presents the flow chart of the algorithm for generating this type of expressions. The algorithm starts with getting the lists of the input transitions and the output transitions of the specified place. If the place has output transitions, the algorithm will deal with the output transitions list to generate the first part of the expression and insert it into the expression. For each output transition ti, if it has a guard, the algorithm will produce “Ati.en or Ati.enc”. Otherwise, the algorithm will generate “Ati.en”.

After operating all output transitions, the algorithm will deal with the input transitions of the place to generate the second part of the expression and insert it into the expression. For each input transition tj, first the algorithm will judge if tj is an output transition. If tj is an output transition, the algorithm will skip tj and operate the next input transition (The reason will be explained below). If tj is not an output transition, the algorithm will calculate the number n of input places of each output transition ti, which equals to the number of the states of ti. Then the algorithm the description “(Atj.s1 and Ati.s2) or … or (Atj.s1 and Ati.sn)”. (That is why we add a redundant formula into the second part of the above example)

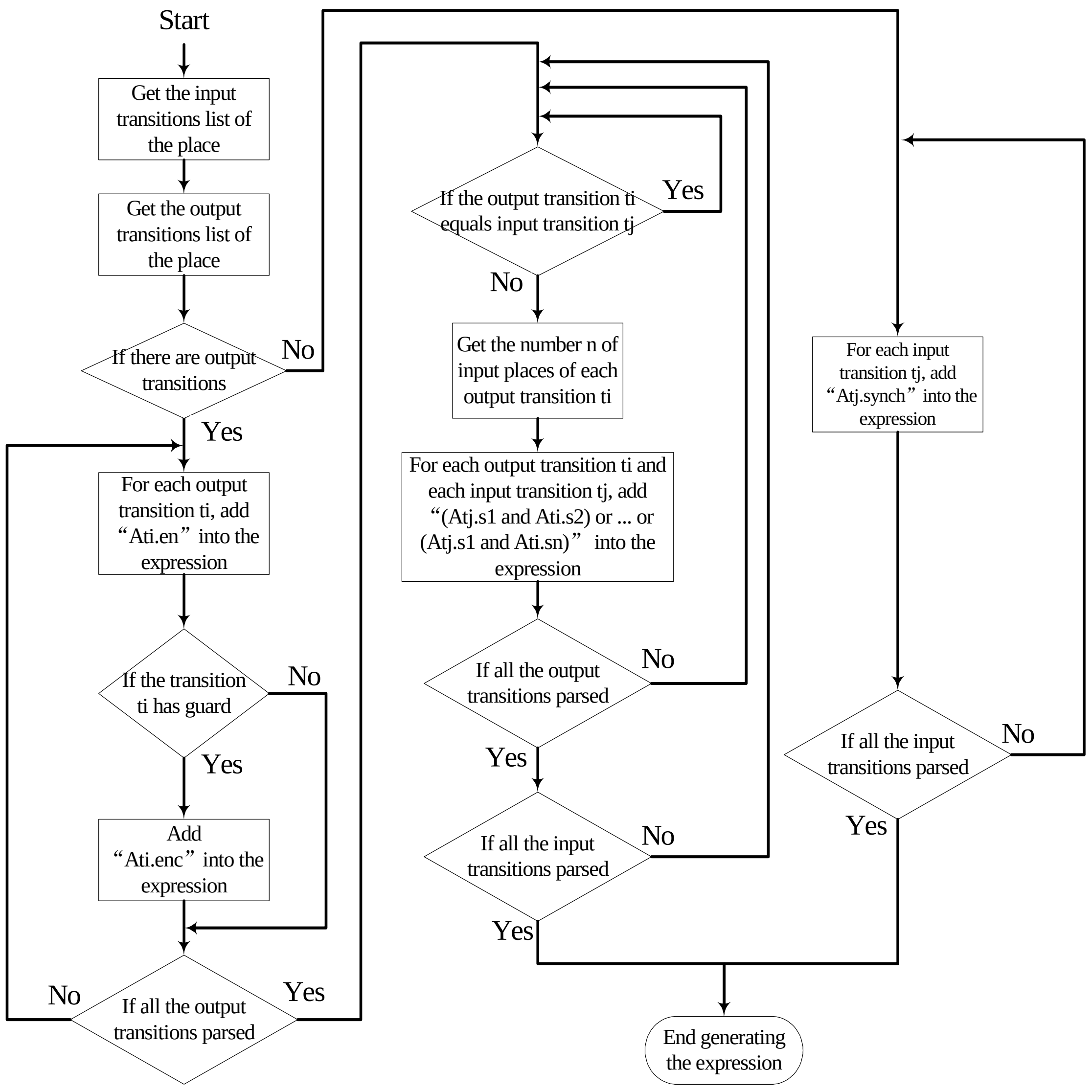

Start
Get the input transitions list of the place
Get the output transitions list of the place
If there are output transitions
No
Yes
For each output transition ti, add “Ati.en” into the expression
If the transition ti has guard
No
Yes
Add “Ati.enc” into the expression
No
If all the output transitions parsed
Yes
If the output transition ti equals input transition tj
Yes
No
Get the number n of input places of each output transition ti
For each output transition ti and each input transition tj, add “(Atj.s1 and Ati.s2) or ... or (Atj.s1 and Ati.sn)” into the expression
If all the output transitions parsed
No
Yes
If all the input transitions parsed
No
Yes
For each input transition tj, add “Atj.synch” into the expression
If all the input transitions parsed
No
Yes
End generating the expression

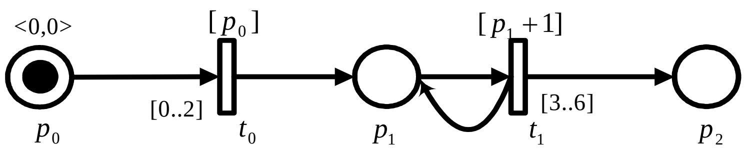
**Figure 5.15 The flow chart of the algorithm for generating TA query expression**

If there is no output transition of the specified place, for each input transition tj of the place, the algorithm inserts “Atj.synch” into the expression. Then the algorithm finishes generating the TA query expression. The reason for this part will be explained below.

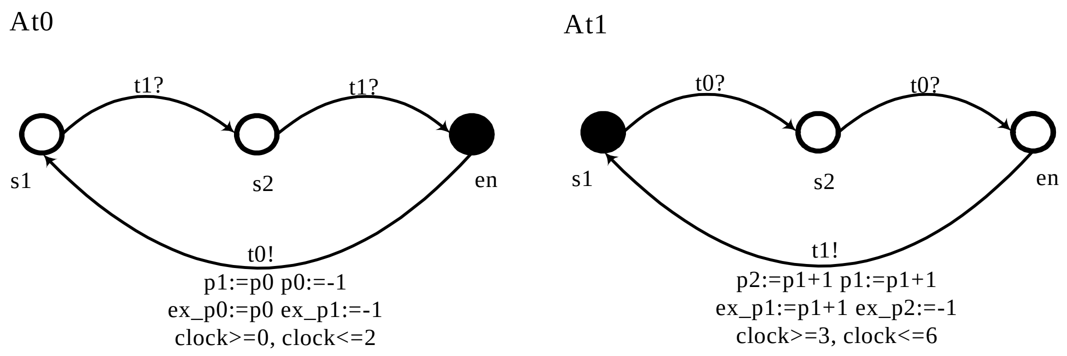
In PRES+ models, a place may be both the input place of a transition and the output place of the transition, such as place p1 shown in Figure 5.16. Furthermore, a place may have no any output transitions, such as place p2 in Figure 5.16.

If we want check if the place p1 will be possibly reached, we give the CTL formula “EF p1”. After translation, the first part of the TA query is “At1.en”. And the second part is “(At0.s1 and At1.s2) or (At1.s1 and At1.s2)”, because t1 is both the input transition and output transition of p1. However “At1.s1 and At1.s2” will never be satisfied. For this reason, in our algorithm, the logical module “if the output transition ti equals the input transition tj” is used to exclude this kind of description from a TA query.

If we want check if the place p2 will be possibly reached, we give the CTL formula “EF p2”. Since p2 does not have any output transitions, both the first part and the second part of the TA query cannot be generated, and we need another method to represent that transition t1 fires. In a TA model, we use the state “synch” to express the firing process of a transition. Therefore, in our algorithm, the module “For each input transition tj, add Atj.synch into the expression” is used for this case.



a ) A Forced Safe PRES+ model

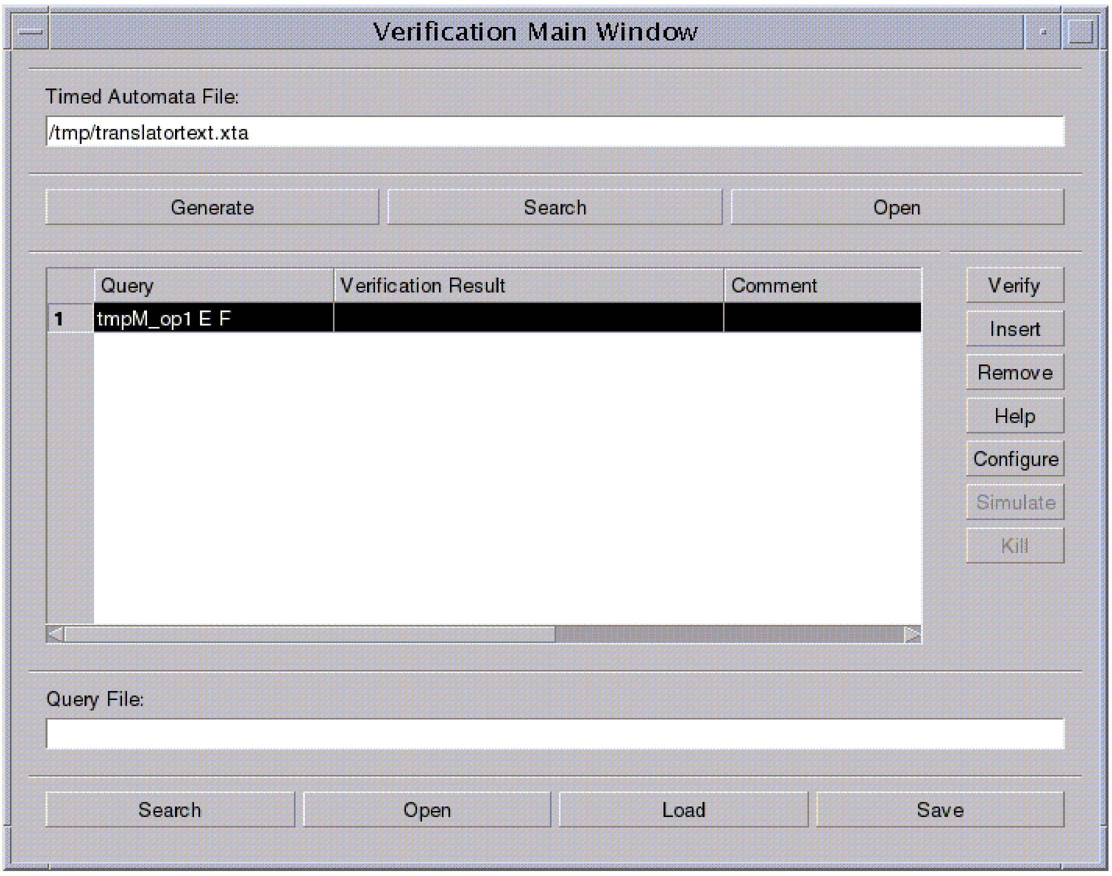


b ) The equivalent TA model

**Figure 5.16 A special Forced Safe PRES+ model and the equivalent TA model**

### 5.5.5 Verification

After having translated a PRES+ model into a Timed Automata model and saved the TA model into a file, parsed the input query and generate a CTL formula, and translated the CTL formula into a Timed Automata query and saved the TA query into a file, we can call verifyta to perform the model checking. The command line of calling verifyta is "verifyta –s –t 0 [TA model file] [TA query file]", and since our verification tool is a graphical tool, the procedure for calling verifyta will be behind the interface. In Figure 5.17, a query is input for verifying the PRES+ model shown in Figure 5.5 a), Figure 5.18 shows the situation after the verification, and in Figure 5.19, the verification result shown in a text editor is presented.

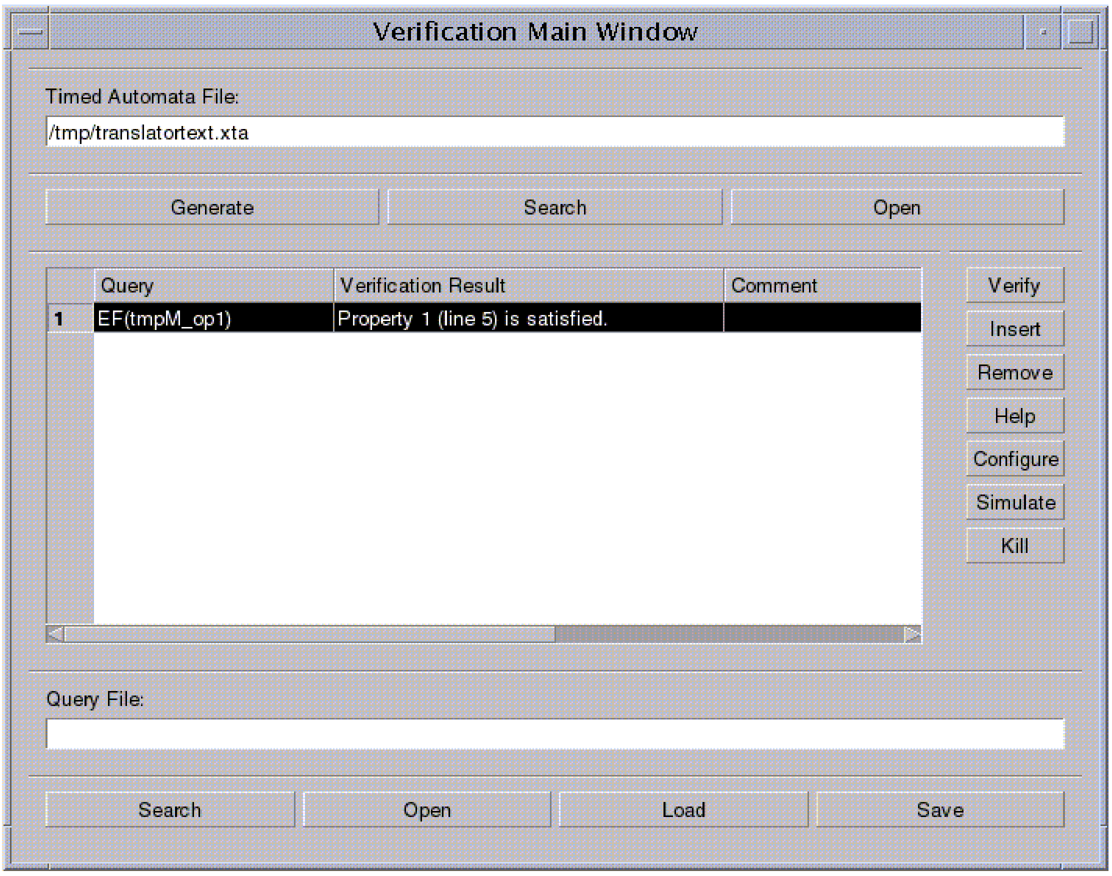

Verification Main Window

Timed Automata File: /tmp/translatortext.xta

| | Query | Verification Result | Comment |
|---|---|---|---|
| 1 | tmpM_op1 E F | | |

Query File:

**Figure 5.17 Input a query for verification**



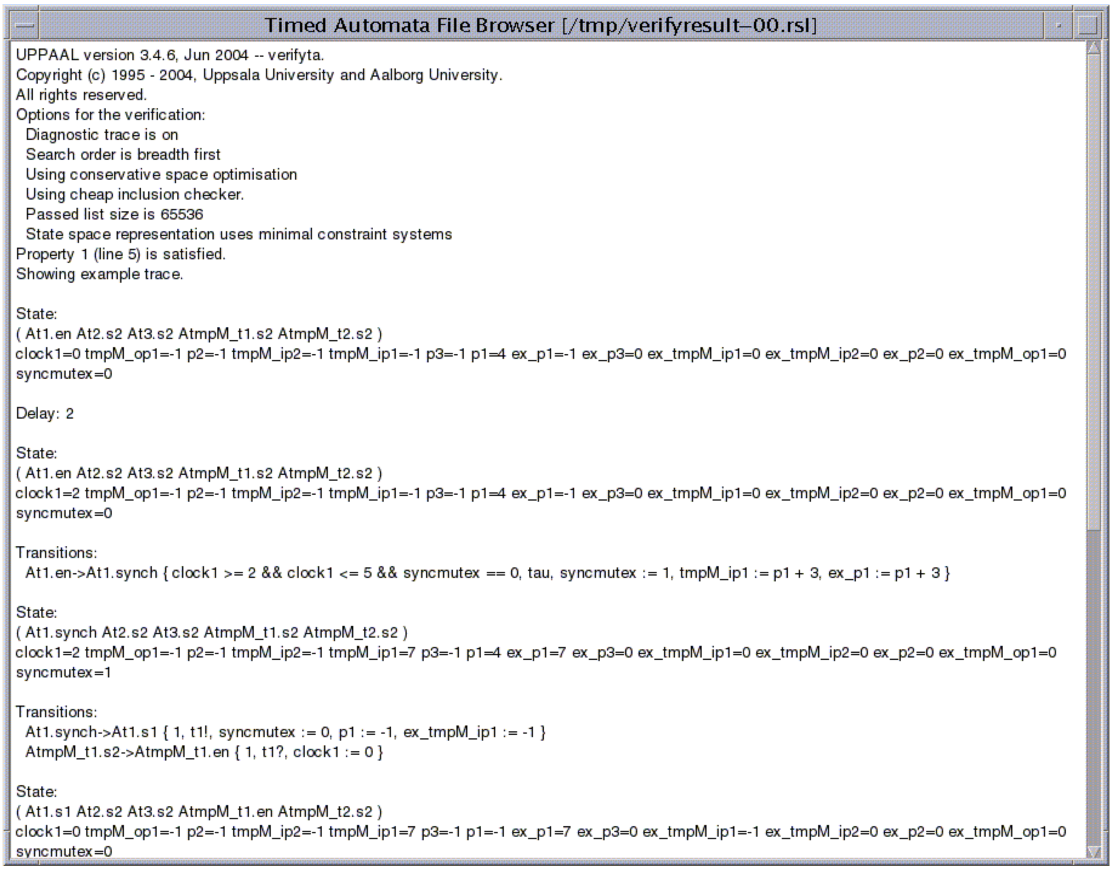
Timed Automata File:

/tmp/translatortext.xta

| | Query | Verification Result | Comment |
|---|---|---|---|
| 1 | EF(tmpM_op1) | Property 1 (line 5) is satisfied. | |

Query File:

**Figure 5.18 After verify the query**



```
UPPAAL version 3.4.6, Jun 2004 -- verifyta.
Copyright (c) 1995 - 2004, Uppsala University and Aalborg University.
All rights reserved.
Options for the verification:
  Diagnostic trace is on
  Search order is breadth first
  Using conservative space optimisation
  Using cheap inclusion checker.
  Passed list size is 65536
  State space representation uses minimal constraint systems
Property 1 (line 5) is satisfied.
Showing example trace.

State:
( At1.en At2.s2 At3.s2 AtmpM_t1.s2 AtmpM_t2.s2 )
clock1=0 tmpM_op1=-1 p2=-1 tmpM_ip2=-1 tmpM_ip1=-1 p3=-1 p1=4 ex_p1=-1 ex_p3=0 ex_tmpM_ip1=0 ex_tmpM_ip2=0 ex_p2=0 ex_tmpM_op1=0
syncmutex=0

Delay: 2

State:
( At1.en At2.s2 At3.s2 AtmpM_t1.s2 AtmpM_t2.s2 )
clock1=2 tmpM_op1=-1 p2=-1 tmpM_ip2=-1 tmpM_ip1=-1 p3=-1 p1=4 ex_p1=-1 ex_p3=0 ex_tmpM_ip1=0 ex_tmpM_ip2=0 ex_p2=0 ex_tmpM_op1=0
syncmutex=0

Transitions:
  At1.en->At1.synch { clock1 >= 2 && clock1 <= 5 && syncmutex == 0, tau, syncmutex := 1, tmpM_ip1 := p1 + 3, ex_p1 := p1 + 3 }

State:
( At1.synch At2.s2 At3.s2 AtmpM_t1.s2 AtmpM_t2.s2 )
clock1=2 tmpM_op1=-1 p2=-1 tmpM_ip2=-1 tmpM_ip1=7 p3=-1 p1=4 ex_p1=7 ex_p3=0 ex_tmpM_ip1=0 ex_tmpM_ip2=0 ex_p2=0 ex_tmpM_op1=0
syncmutex=1

Transitions:
  At1.synch->At1.s1 { 1, t1!, syncmutex := 0, p1 := -1, ex_tmpM_ip1 := -1 }
  AtmpM_t1.s2->AtmpM_t1.en { 1, t1?, clock1 := 0 }

State:
( At1.s1 At2.s2 At3.s2 AtmpM_t1.en AtmpM_t2.s2 )
clock1=0 tmpM_op1=-1 p2=-1 tmpM_ip2=-1 tmpM_ip1=7 p3=-1 p1=-1 ex_p1=7 ex_p3=0 ex_tmpM_ip1=-1 ex_tmpM_ip2=0 ex_p2=0 ex_tmpM_op1=0
syncmutex=0
```

**Figure 5.19 The verification result**

### 5.5.6 Simulate a *diagnostic trace*

After verification, we will get a *diagnostic trace*, and the trace contains an example trace for explaining why the property is satisfied or not. Therefore, we can go through the trace and extract useful information to generate a simulation trace file, with which the PRES+ Simulation tool could display the example to debug the PRES+ model. In Figure 5.19, in the verification result, the *diagnostic trace* is shown. And following we will present the whole *diagnostic trace* shown in Figure 5.19 and the simulation trace based on the *diagnostic trace.*

```
State:
( At1.en At2.s2 At3.s2 AtmpM_t1.s2 AtmpM_t2.s2 )
clock1=0 p2=-1 p3=-1 tmpM_ip1=-1 tmpM_op1=-1 tmpM_ip2=-1 p1=4 ex_p1=-1
ex_tmpM_ip2=0 ex_tmpM_op1=0 ex_tmpM_ip1=0 ex_p3=0 ex_p2=0 syncmutex=0
Delay: 2
State:
( At1.en At2.s2 At3.s2 AtmpM_t1.s2 AtmpM_t2.s2 )
clock1=2 p2=-1 p3=-1 tmpM_ip1=-1 tmpM_op1=-1 tmpM_ip2=-1 p1=4 ex_p1=-1
ex_tmpM_ip2=0 ex_tmpM_op1=0 ex_tmpM_ip1=0 ex_p3=0 ex_p2=0 syncmutex=0
Transitions:
   At1.en->At1.synch { clock1 >= 2 && clock1 <= 5 && syncmutex == 0, tau, syncmutex := 1,
tmpM_ip1 := p1 + 3, ex_p1 := p1 + 3 }
State:
( At1.synch At2.s2 At3.s2 AtmpM_t1.s2 AtmpM_t2.s2 )
clock1=2 p2=-1 p3=-1 tmpM_ip1=7 tmpM_op1=-1 tmpM_ip2=-1 p1=4 ex_p1=7
ex_tmpM_ip2=0 ex_tmpM_op1=0 ex_tmpM_ip1=0 ex_p3=0 ex_p2=0 syncmutex=1
Transitions:
   At1.synch->At1.s1 { 1, t1!, syncmutex := 0, p1 := -1, ex_tmpM_ip1 := -1 }
   AtmpM_t1.s2->AtmpM_t1.en { 1, t1?, clock1 := 0 }
State:
( At1.s1 At2.s2 At3.s2 AtmpM_t1.en AtmpM_t2.s2 )
clock1=0 p2=-1 p3=-1 tmpM_ip1=7 tmpM_op1=-1 tmpM_ip2=-1 p1=-1 ex_p1=7
ex_tmpM_ip2=0 ex_tmpM_op1=0 ex_tmpM_ip1=-1 ex_p3=0 ex_p2=0 syncmutex=0
Delay: 1
State:
( At1.s1 At2.s2 At3.s2 AtmpM_t1.en AtmpM_t2.s2 )
clock1=1 p2=-1 p3=-1 tmpM_ip1=7 tmpM_op1=-1 tmpM_ip2=-1 p1=-1 ex_p1=7
ex_tmpM_ip2=0 ex_tmpM_op1=0 ex_tmpM_ip1=-1 ex_p3=0 ex_p2=0 syncmutex=0
Transitions:
   AtmpM_t1.en->AtmpM_t1.synch { clock1 > 0 && syncmutex == 0, tau, syncmutex := 1,
tmpM_op1 := tmpM_ip1, ex_tmpM_ip1 := tmpM_ip1 }
State:
( At1.s1 At2.s2 At3.s2 AtmpM_t1.synch AtmpM_t2.s2 )
clock1=1 p2=-1 p3=-1 tmpM_ip1=7 tmpM_op1=7 tmpM_ip2=-1 p1=-1 ex_p1=7
ex_tmpM_ip2=0 ex_tmpM_op1=0 ex_tmpM_ip1=7 ex_p3=0 ex_p2=0 syncmutex=1
Transitions:
   AtmpM_t1.synch->AtmpM_t1.s1 { 1, tmpM_t1!, syncmutex := 0, tmpM_ip1 := -1,
ex_tmpM_op1 := -1 }
   At1.s1->At1.s2 { 1, tmpM_t1?, 1 }
   At3.s2->At3.en { 1, tmpM_t1?, clock1 := 0 }
   AtmpM_t2.s2->AtmpM_t2.s1 { 1, tmpM_t1?, 1 }
State:
( At1.s2 At2.s2 At3.en AtmpM_t1.s1 AtmpM_t2.s1 )
```

```
clock1=0 p2=-1 p3=-1 tmpM_ip1=-1 tmpM_op1=7 tmpM_ip2=-1 p1=-1 ex_p1=7
ex_tmpM_ip2=0 ex_tmpM_op1=-1 ex_tmpM_ip1=7 ex_p3=0 ex_p2=0 syncmutex=0
```

In the *diagnostic trace*, the state and transition expressions appear alternately, and each state expression presents the state of the TA model and each transition expression presents the state shift of a particular transition. In addition, since in TA model, the "At.en → At.synch → At.s1" is used to present the firing of the transition t, according the *diagnostic trace* shown above, we can generate the simulation trace as follow:

```
[p1]--[place]--[-]--[Value=4, Timestamp=0, Globaltime=0.0.]
[t1]--[transition]--0--[-]
[tmpM_ip1]--[place]--[-]--[Value=7, Timestamp=0, Globaltime=0.0.]
[tmpM_t1]--[transition]--0--[-]
[tmpM_op1]--[place]--[-]--[Value=7, Timestamp=0, Globaltime=0.0.]
```

This simulation trace means if we fire the transitions t1 and tmpM_t1 in turn, a token with the value is 7 will reach the place tmpM_op1.

In the PRES+ Verification Interface, when the "Simulate" button is pressed, the simulation trace file will be generated and the PRES+ Simulation Interface will be opened with the simulation trace.

# Chapter 6.
# User Manual

This chapter represents briefly how to use the tool.

## 6.1 Introduction

This software is a graphical tool for modeling, simulation and verification of PRES+ models, and can be run on multiple operation systems, such as Windows 95 to XP, Linux, Solaris, etc. This graphical tool consists of three main parts, a graphical editor for modeling PRES+ models, a simulator for simulating PRES+ models, and a verifier for verifying PRES+ models. Following we will represent how to use these three parts.

## 6.2 Graphical Editor

The graphical editor is the main window of this graphical tool, and both the simulator and verifier could be opened from this editor. The GUI of this editor is shown in Figure 5.2.

### 6.2.1 Menu Bar

The menu bar is fixed in the upper of the editor. It contains the following popup menus.

- **File** – to manage PRES+ model description files
  - **New**: re-initiates the editor
  - **Open**: loads an existing graphical PRES+ model from file
  - **Save**: saves the editing graphical PRES+ model into files
  - **Save As**: saves the editing graphical PRES+ model into a specified files
  - **Print**: prints the editing graphical PRES+ model out from printer
  - **Exit**: exits this tool

- **Edit** – to control the editions during modeling PRES+ models
  - **Undo**: undo the recent operations
  - **Redo**: redo the operations that just undone
  - **Cut**: deletes a set of selected items and saves them into memory
  - **Copy**: saves a set of selected items into memory
  - **Paste**: draws items which are in memory on the canvas
  - **Find**: finds and selects a specified item
  - **Select All**: selects all items on the canvas

- **View** – to change the appearance of the editor
  - **Zoom In**: magnifies the granularity of the canvas
  - **Zoom Out**: shrink the granularity of the canvas

- **Tool** – contains tools to operate PRES+ models
  - **Simulation**: invokes and opens the simulator
  - **Verification**: invokes and opens the verifier
  - **Update Module**: updates a component item of the editing PRES+ model, if the component item has been changed
  - **Configuration**: opens a separate window for setting the path of the modules library and the path of the verification tool, varifyta.

- **Help** – to show the help pages
  - **Contents**: opens a separate window for showing the help pages
  - **About**: opens a separate window for showing the information about the version and copyrights of this tool

### 6.2.2 Tool Bar

The tool bar is normally located just below the menu bar but can be moved to other positions. The tool bar is divided into four groups, which are corresponding to the File, Edit, View and Tool popup menu respectively, and each group provides quick access to some of the most frequently used menu items.

### 6.2.3 Components List

The components list, located the leftmost of the main window, lists the names of the components that exist in the module library. Users can change the contents of the components list by changing the path of the module library.

### 6.2.4 Items List

The items list, also located the leftmost of the main window as an alternative to the components list, fixedly lists the basic items of PRES+ net, such as place, transition, token, arc and nail.

### 6.2.5 Drawing

The main function of the graphical editor is to draw a PRES+ model on the canvas, which is located in the right part of the main window. A PRES+ model consists of a set of places, a set of tokens, a set of transitions, a set of components and a set of arcs. And for each arc, it may contain a set of lines, a set of nails and an arrow.

- **Drawing Rules**
  - Tokens must belong to places, and each place contains at most one token. Therefore, a token can be drawn if there is at least one place without token on the canvas
  - An arc, used to connect a place, a transition and a component, can be drawn from a place to a transition, from a transition to a place, from a port of a component to a transition, or from a transition to a port. In addition, there is at most one arc from an item to another item
  - Nails must belong to arcs. Therefore, a nail can be drawn if there is at least one arc on the canvas
  - For the items with same type, the Id (name) of an item must be unique in a PRES+ model. For a new drawing item, the editor will arrange an un-replicative id for it, and the id may be modified by users unless ensuring the uniqueness
  - Every item may be moved directly except arcs and tokens. A token could be moved together with the place that contains the token, and an arc could be moved together with the two items which are connected by the arc. In addition, the ports of a component could be moved only along the border of the component
  - The shape of an item is fixed except components

- **Draw a place** – first select the place item in the items list. Second click on a blank area of the canvas. Then a place will be added into the canvas at the position where the mouse was clicked.

- **Draw a transition** – first select the transition item in the items list. Second click on a blank area of the canvas. Then a transition will be added into the canvas at the position where the mouse was clicked.

- **Draw a token** – first select the token item in the items list. Second click on a place, which has no token, on the canvas. Then a token will appear in the center of the place.

- **Draw an arc** – first select the arc item in the items list. Then starting an arc by clicking on an item, which should be a place, a transition or a port, and this item is the source of the arc. For every click on the blank area, a nail will be added, and a line between the source and a nail, or between two nails will be drawn too. Finally click should be on another item, a place, a transition or a port, and this item is the target of the arc.

- **Draw a nail** – first select the nail item in the items list. Second click on an arc, to which a nail is to be added.

- **Draw a component –** first select the component that you want add to the editing PRES+ model in the components list. Second click on a blank area of the canvas. Then a component will be added into the canvas at the position where the mouse was clicked.

- **Select an item** – simply click on the item.

- **Multi-select** – first click on a blank area of the canvas. Then move the mouse with the button pressed. A rectangle will be drawn and the items inside the rectangle will be selected.

- **Move an item** – click on the item, and move the mouse with the button pressed. When the mouse button is released, the item will move to the current mouse position.

- **Configure an item** – double click on the item except component items, a separate window will be opened. In this window, a number of properties of the item could be edited.

- **Configure a component** – double click on a component item, a new editor will be opened. In the new editor, the PRES+ model, which corresponds to this component item, will be presented and may be edited.

## 6.3 Simulator

The simulator is a validation tool for checking the PRES+ model that is being edited in the graphical editor via simulation and also used to visualize executions generated by the verifier. The simulator interface consists of two parts, the left part is a controller for controlling the simulation and the right part is a viewer for displaying the simulation process (token game). The GUI of the simulator is shown in Figure 5.7.

- **Interactive Simulation** – means that during the whole simulation procedure, users and simulator operate alternately. In detail, users will select an enabled transition to fire, and the simulator will fire the transition, move the token, list the enabled transitions for next firing and record the simulation trace. To choose one enabled transition, users should highlight the transition in the list, the upper part of the controller, and then click on the "Fire" button for activating the simulator process

- **Automatic Simulation –** means that the simulator takes charge of the whole simulation procedure. The simulator will randomly choose one enabled transition for firing, fire the selected transition, move the token, list the enabled transitions and record the simulation trace. To invoke the automatic simulation, the “Random” button should be pushed down. And when the “Random” button is released, the automatic simulation will stop

- **Buttons**
  - **Fire**: fires the highlighted transition in “Enabled Transitions List”.
  - **Reset**: resets the PRES+ model into the initial state.
  - **Prev**: sets the PRES+ model into the state immediately preceding the current state according to the simulation trace, and highlights the corresponding element in the “Simulation Traces”.
  - **Next**: sets the PRES+ model into the state immediately following the current state according to the simulation trace, and highlights the corresponding element in the “Simulation Traces”.
  - **Replay**: replays the trace starting from the current selected element automatically.
  - **Open**: opens and loads an existed simulation trace file.
  - **Save**: saves the simulation trace into a simulation file.
  - **Random**: starts the automatic simulation.

- **Slider –** is used for controlling the speed used when the simulation trace is replayed and the automatic simulation is executed

## 6.4 Verifier

The verifier provides the functions for checking invariant and liveness properties of a PRES+ model. The verifier GUI, given in Figure 5.11, consists the following three parts.

- **Timed Automata Model description –** the upper part of the verifier interface, is used to represent a PRES+ model with a Timed Automata model.
  - **Timed Automata File**: a file containing a Timed Automata model. In the editor, users can input an existing Timed Automata file as an input parameter of the verification process.
  - **Generate button**: creates a temporary Timed Automata file corresponding to the PRES+ model in the graphical editor.
  - **Search button**: opens a file selector window for a specified Timed Automata file corresponding to the editing PRES+ model in the graphical editor.
  - **Open button**: opens a rich text editor for displaying the detail of the Timed Automata file.

- **Verification controller –** the middle part of the verifier interface, is used to edit queries, execute verification and invoke the simulator for simulating the verification results.

- **Table**: consists of three columns. In the “Query” column, a query described in a specified format may be input; In “Verification Results” column, the information if the query is satisfied or not will be filled; And in the “Comment” column, users can edit some description about the query and verification results.
- **Verify button**: executes the verification process only if a Timed Automata file is provided and a query is input to the current selected row of the table. After verification, the verification results will be filled into the table.
- **Insert button**: adds a new row in the table for editing a new query.
- **Remove button**: deletes the current selected row of the table.
- **Help button**: opens a separate window for displaying the help pages about the verifier.
- **Configure button**: opens a file selector window for the verification tool, verifyta.
- **Simulate button**: creates a temporary simulation trace file according to the verification results of the current selected row in the table, and opens the simulator with the simulation trace for tracing the verification results.

- **Batch queries description** – the bottom part of the verifier interface, is used to operate the query file.
  - **Query File**: a file containing a set of queries. In the editor, users can input an existent pre-edited Query file.
  - **Search button**: opens a file selector window for a Query file.
  - **Open button**: opens a rich text editor for displaying the detail of the Query file.
  - **Load button**: loads the queries and comments in the Query file into the above table.
  - **Save button**: opens a file selector window for saving the queries and comments in the above table into a specified Query file.

# Chapter 7.
# Conclusions and Future Work

This chapter presents a summary of this thesis, and also points out some interesting future works.

## 7.1 Conclusions

In this thesis, an implementation of an integrated graphical tool for modeling, simulation and verification of PRES+ models has been presented. PRES+ is an extended timed Petri Net model used to represent the embedded systems. The designers and analyzers of component-based embedded systems could use this tool when they build and check a system.

This tool consists of three main sub-tools, PRES+ modeling tool, PRES+ simulation tool and PRES+ verification tool. By using the PRES+ modeling tool, users can create PRES+ models and design the properties of each item in PRES+ models. In addition, we introduced the component item, which is an abstract interface of a pre-edited PRES+ model, in PRES+ models so that it becomes simpler and more efficient to build a big and complex PRES+ model. We also defined an input format of a graphical PRES+ model, which is presented in XML with the graphical attributes.

The PRES+ simulation tool provides a way to validate PRES+ models. With this sub tool, users can simulate PRES+ models interactively or automatically. During the simulation, the simulating process is visualized via displaying the token game, and can be traced from the simulation trace.

The PRES+ verification tool is used to check invariant and liveness properties of PRES+ models. Two inputs are needed for the verification process, one is a query formula, and the other is a Timed Automata model. A particular CTL data structure is selected to describe the query. The second input, a textural format file of a Timed Automata model is used, which may be generated automatically by translating a PRES+ model into a Timed Automata model. The verification result will be presented in the GUI of this sub-tool, and may be validated by the PRES+ simulation tool.

## 7.2 Future Work

The main contribution of this thesis is to implement an integrated graphical tool for modeling and analyzing component-based embedded systems. Future work could be aimed to improve the usability of this tool and make better the

GUIs of this tool.

This tool includes the fundamental functions for modeling, simulating and verifying PRES+ models. Improvements may be found in each part. For example, for the PRES+ modeling tool, a better Undo and Redo rule is necessary to be defined for making the modeling process more efficient. For the PRES+ simulation tool, a better algorithm needs to be found for expanding the component items of a PRES+ model. And for the PRES+ verification tool, the parser for analyzing the CTL formula can only recognize the postfix formulas. Therefore, it is better if a new parser could be designed for recognizing the normal CTL formulas directly.

The GUIs of this tool are designed mainly based on the functionalities of the tool. So the improvers could think more about the end-users' feeling on these GUIs.

# Appendix A

In this section, the definition of each graphical item is presented.

## Place Item

PlaceItem class, derived from QCanvasEllipse, provides an interface of a graphical place.

| | |
|---|---|
| QPtrList<ArcItem> inList; | //input arcs list |
| QPtrList<ArcItem> outList; | //output arcs list |
| int selfno; | //the no. of a place |
| static int placenum; | //the unique no. of places |
| QString tagtext; | //the ID (name) of a place |
| TagItem *tag; | //the tag item to show the ID (name) of a place |
| TokenItem *token; | //the token item of a place, initially equals 0 |
| bool visible; | //if a place is visible, true is visible and false is unvisible. |
| bool selectflag; | //if a place is selected, true is selected and false is unselected. |

## Transition Item

TransitionItem class, derived from QCanvasRectangle, provides an interface of a graphical transition.

| | |
|---|---|
| QPtrList<ArcItem> inList; | //input arcs list |
| QPtrList<ArcItem> outList; | //output arcs list |
| int selfno; | //the no. of a transition |
| static int transitionnum; | //the unique no. of transitions |
| QString tagtext; | //the ID (name) of a transition |
| TagItem *tag; | //the tag item to show the ID (name) of a transition |
| TagItem *tag1; | //the tag item to show the delays of a transition |
| TagItem *tag2; | //the tag item to show the assignment of a transition |
| QString lowerBound; | //the minimum delay of a transition |
| QString upperBound; | //the maximum delay of a transition |
| QString triggerTime; | //the trigger time of a transition |
| QString firingTimeProposal; | //the firing time proposal of a transition |
| QString assignment; | //the associated function of a transition |
| QString guard; | //the guard of a transition |
| bool guardExists; | //if a transition has a guard |
| bool infinite; | //if a transition has the maximum delay |
| bool visible; | //if a transition is visible |
| bool selectflag; | //if a transition is selected |

## Token Item

TokenItem class, derived from QCanvasEllipse, provides an interface of a graphical token.

```
QcanvasItem *fatherplace;          //the (place or port) item that contains the token
int selfno;                        //the no. of a token
static int tokennum;               //the unique no. of tokens
QString value;                     //the value of a token
QString timestamp;                 //the timestamp of a token
TagItem *tag;                      //the tag item to show the value and a timestamp of a token
bool visible;                      //if a token is visible
bool fatherisplace;                //if the item that contains the token is a place
```

## Port Item

PortItem class, derived from QCanvasEllipse, provides an interface of a graphical port.

```
QPtrList<ArcItem> inList;          //input arcs list
QPtrList<ArcItem> outList;         //output arcs list
TagItem *tag;                      //the tag item to show the ID (name) of a port
TagItem *tag1;                     //the tag item to show the type of a port
TokenItem *token;                  //the token item of the port, initially equals 0
ComponentItem *fatherbox;          //the component item that contains the port
bool porttype;                     //if the port is an input port
bool visible;                      //if the port is visible
bool selectflag;                   //if the port is selected
```

## Component Item

ComponentItem class, derived from QCanvasRectangle, provides an interface of a graphical component.

```
QCanvasItemList inportlist;        //in-ports list
QCanvasItemList outportlist;       //out-ports list
TagItem *tag;                      //the tag item to show the name of a component
bool visible;                      //if the component is visible
bool selectflag;                   //if the component is selected
```

## Line Item

LineItem class, derived from QCanvasLine, provides an interface of a graphical line, a part of an arc.

| | |
|---|---|
| QCanvasItem *fromitem; | //one item that the line connected |
| QCanvasItem *toitem; | //the other item that the line connected |
| ArcItem *fatherarc; | //the arc that contains the line |
| int connecttype; | //the type of the line according to the items it connected. 0 means from a nail to a nail, 1 means from a place to a nail, 2 means from a port to a nail, and 3 means from a transition to a nail |
| bool visible; | //if the line is visible |

## Arrow Item

ArrowItem class, derived from QCanvasLine, provides an interface of a graphical arrow, a part of an arc.

| | |
|---|---|
| QCanvasItem *fromitem; | //one item that the arrow connected |
| QCanvasItem *toitem; | //the other item that the arrow connected |
| ArcItem *fatherarc; | //the arc that contains the arrow |
| QCanvasLine *arrowline1; | //used for drawing the arrow |
| QCanvasLine *arrowline2; | //used for drawing the arrow |
| int connecttype; | //the type of the arrow according to the items it connected. 0 means from a nail to a place, 1 means from a nail to a transition, 2 means from a nail to a port, 3 means from a place to a transition, 4 means from a transition to a place, 5 means from a port to a transition, and 6 means from a transition to a port. |
| bool visible; | //if the arrow is visible |

## Nail Item

NailItem class, derived from QCanvasEllipse, provides an interface of a graphical nail, a part of an arc.

| | |
|---|---|
| QCanvasItem *prelink; | //one link that the nail is connected |
| QCanvasItem *nextlink; | //the other link that the nail is connected |
| QCanvasItem *preitem; | //the other item the prelink is connected |
| QCanvasItem *nextitem; | //the other item the nextlink is connected |
| ArcItem *fatherarc; | //the arc that contains the nail |
| bool visible; | //if the nail is visible |

## Arc Item

ArcItem class provides an interface of a graphical arc.

| | |
|---|---|
| QCanvasItem *fromitem; | //one item that the arc connected |
| QCanvasItem *toitem; | //the other item that the arc connected |
| int selfno; | //the no. of an arc |
| static int arcnum; | //the unique no. of arcs |
| QString tagtext; | //the ID (name) of an arc |
| TagItem *tag; | //the tag item to show the ID (name) of an arc |
| QPtrList<NailItem> nailList; | //the nails list |
| ArrowItem *arrowitem; | //the arrow that the arc contains |
| int connecttype; | //the type of the arc according to the items it connected. 0 means from a place to a transition, 1 means from a transition to a place, 2 means from a port to a transition, and 3 means from a transition to a port. |
| bool visible; | //if the arc is visible |
| bool selectflag; | //if the arc is selected |

# Appendix B

In this section, the GUI schema PresGUIPlus.xsd is presented.

```
<?xml version="1.0" encoding="UTF-8"?>
<xs:schema xmlns:xs='http://www.w3.org/2001/XMLSchema'>

    <!-- Here starts the content of the petri net definition.-->
    <xs:element name="petriNet">
        <xs:complexType>
            <xs:sequence>
                <xs:element ref="place" minOccurs='0' maxOccurs='unbounded'/>
                <xs:element ref="transition" minOccurs='0' maxOccurs='unbounded'/>
                <xs:element ref="component" minOccurs='0' maxOccurs='unbounded'/>
                <xs:element ref="inputArc" minOccurs='0' maxOccurs='unbounded'/>
                <xs:element ref="outputArc" minOccurs='0' maxOccurs='unbounded'/>
            </xs:sequence>
        </xs:complexType>

        <xs:unique name="uniquePlaces">
            <xs:selector xpath="./place"/>
            <xs:field xpath="@id"/>
        </xs:unique>

        <xs:unique name="uniqueTransitions">
            <xs:selector xpath="./transition"/>
            <xs:field xpath="@id"/>
        </xs:unique>

        <xs:unique name="uniqueComponents">
            <xs:selector xpath="./component"/>
            <xs:field xpath="@id"/>
        </xs:unique>

        <xs:unique name="uniqueInputArcs">
            <xs:selector xpath="./inputArcs"/>
            <xs:field xpath="@id"/>
        </xs:unique>

        <xs:unique name="uniqueOutputArcs">
            <xs:selector xpath="./outputArc"/>
            <xs:field xpath="@id"/>
        </xs:unique>
        <xs:key name='placeKey'>
            <xs:selector xpath="./place"/>
            <xs:field xpath="@id"/>
        </xs:key>
        <xs:keyref name="inputArcRefPlaces" refer='placeKey'>
            <xs:selector xpath="./inputArc"/>
            <xs:field xpath="@placeId"/>
        </xs:keyref>
        <xs:keyref name="outputArcRefPlaces" refer='placeKey'>
            <xs:selector xpath="./outputArc"/>
        <xs:field xpath="@placeId"/>
        </xs:keyref>

        <xs:key name='transitionKey'>
            <xs:selector xpath="./transition"/>
            <xs:field xpath="@id"/>
        </xs:key>
        <xs:keyref name="inputArcReferTransitions" refer='transitionKey'>
            <xs:selector xpath="./inputArc"/>
            <xs:field xpath="@transitionId"/>
        </xs:keyref>
        <xs:keyref name="outputArcReferTransitions" refer='transitionKey'>
            <xs:selector xpath="./outputArc"/>
            <xs:field xpath="@transitionId"/>
        </xs:keyref>
    </xs:element>

    <xs:element name="interval">
        <xs:complexType>
            <xs:attribute name="start" use='required'>
                <xs:simpleType>
                    <xs:restriction base='xs:int'>
                        <xs:minInclusive value="0"/>
                    </xs:restriction>
                </xs:simpleType>
            </xs:attribute>
            <xs:attribute name="stop">
                <xs:simpleType>
                    <xs:restriction base='xs:int'>
                        <xs:minInclusive value="0"/>
                    </xs:restriction>
                </xs:simpleType>
            </xs:attribute>
        </xs:complexType>
</xs:element>

<xs:element name="token">
        <xs:complexType>
                <xs:attribute name="time" use='required'>
                        <xs:simpleType>
                                <xs:restriction base='xs:decimal'>
                                        <xs:minInclusive value="0"/>
                                </xs:restriction>
                        </xs:simpleType>
                </xs:attribute>
                <xs:attribute type='xs:int' name="value" use='required'/>
        </xs:complexType>
</xs:element>

<xs:element name="inport">
        <xs:complexType>
                <xs:attribute name="id" type="xs:ID" use='required'/>
        </xs:complexType>
</xs:element>

<xs:element name="outport">
        <xs:complexType>
                <xs:attribute name="id" type="xs:ID" use='required'/>
        </xs:complexType>
</xs:element>

<xs:element name="place">
        <xs:complexType>
                <xs:all>
                        <xs:element ref="token" minOccurs='0' maxOccurs='1'/>
                </xs:all>
                <xs:attribute name="id" type="xs:ID" use='required'/>
                <xs:attribute name="x" type='xs:string' use='required'/>
                <xs:attribute name="y" type='xs:string' use='required'/>
        </xs:complexType>
</xs:element>

<xs:element name="transition">
        <xs:complexType>
                <xs:all>
                        <xs:element ref="interval"/>
                </xs:all>
                <xs:attribute name="id" type="xs:ID" use='required'/>
                <xs:attribute name="x" type='xs:string' use='required'/>
                <xs:attribute name="y" type='xs:string' use='required'/>
                <xs:attribute name="assignment" type='xs:string' use='required'/>
                <xs:attribute name="guard" type='xs:string' use='optional'/>
            </xs:complexType>
        </xs:element>

        <xs:element name="component">
            <xs:complexType>
                <xs:all>
                    <xs:element ref="inport"/>
                    <xs:element ref="outport"/>
                </xs:all>
                <xs:attribute name="id" type="xs:ID" use='required'/>
                <xs:attribute name="x" type='xs:string' use='required'/>
                <xs:attribute name="y" type='xs:string' use='required'/>
                <xs:attribute name="width" type='xs:string' use='required'/>
                <xs:attribute name="height" type='xs:string' use='required'/>
            </xs:complexType>
        </xs:element>

        <xs:element name="inputArc">
            <xs:complexType>
                <xs:attribute name="id" type="xs:ID" use='required'/>
                <xs:attribute name="placeId" type="xs:IDREF" use='optional'/>
                <xs:attribute name="portId" type="xs:IDREF" use='optional'/>
                <xs:attribute name="transitionId" type="xs:IDREF" use='required'/>
            </xs:complexType>
        </xs:element>

        <xs:element name="outputArc">
            <xs:complexType>
                <xs:attribute name="id" type="xs:ID" use='required'/>
                <xs:attribute name="placeId" type="xs:IDREF" use='optional'/>
                <xs:attribute name="portId" type="xs:IDREF" use='optional'/>
                <xs:attribute name="transitionId" type="xs:IDREF" use='required'/>
            </xs:complexType>
        </xs:element>

</xs:schema>
```

# Appendix C

In this section, an example is presented for giving out the structure of an input query file.

Following is the contents of an input query file for verifying the PRES+ net shown in Figure 5.13 a).

```
/*
  * EF(p3) - in the future, a token will possibly reach p3.
  */
p3 E F

/*
  * AG(p3->EF(p6)) - once a token reaches p3, then a token will possibly reach p6 in the future.
  */
p3 p6 E F -> A G
```

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