國立交通大學

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碩 士 論 文

建 立 O O M P N e t s 之 開 發 環 境

Constructing a Development Environment for OOMPNets

研 究 生：何立中

指導教授：王豐堅 教授

中 華 民 國 九 十 七 年 八 月

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摘要

著色派翠網是一種可以被用來分析許多系統的模型，而物件導向技術在近年廣泛的被使用，我們實驗室結合著色派翠網和物件的概念而發展出來一個物件導向模組化派翠網的模型。物件導向模組化派翠網減少由模型轉換為物件導向概念的時間，也正提出了一個物件導向模組化派翠網的開發環境，裡面包含了一系列的工具。本論文實作物件導向模組化派翠網的編輯器和一個相對應的發生圖的分析工具。編輯器提供了一些檢查避免不正常的現象存在於模型中，以減輕使用者的負擔。而後者，則藉著轉換演算法之轉換，利用將物件導向模組化派翠網轉換成著色派翠網，並使用已存在的分析方法做分析，再將分析的結果對應到轉換前的物件導向模組化派翠網，藉此達到分析物件導向模組化派翠網的目的。

關鍵字：著色派翠網，物件導向技術，轉換演算法，編輯器，分析，開發環境

Constructing a Development Environment for OOMPNets

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Abstract

Colored petri nets (CPNs) is a kind of model which can be used to analyze many kinds of systems. Object oriented (OO) techniques, including analysis, design and programming, are popular for years. Object oriented modular petri nets (OOMPNets), proposed by our laboratory, is a model extended from CPNs by integrating object concept into CPNs. Our laboratory is now developing the development environment which consists of a series of tools to help simplify the development of OOMPNets. This thesis implements part of the environment, including an editor named OOMPNE and a transformation tool. OOMPNE is used for constructing OOMPNets. OOMPNE provides some checks to reduce the abnormal phenomena occurring in the modeling OOMPNet. The analysis is done by transferring the modeled OOMPNets into CPNs and calling the existing analysis methods of based on occurrence graph in CPNs. We also discuss the techniques to locate the defect(s) and corresponding object/place(s) in original OOMPNets, corresponding to the defects found in above analysis.

Keywords: Colored petri nets, object oriented modular petri nets, analysis.

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本篇論文的完成，首先要感謝我的指導教授王豐堅博士不斷的指導與鼓勵，讓我在軟體工程的測試技術上，得到很多豐富的知識與經驗。另外，也非常感謝我的畢業口試評審委員朱正忠博士、留忠賢博士與黃俊龍博士，提供許多寶貴的意見，補足我論文裡不足的部分。

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List of Figures and Tables

Chapter 1 Introduction

Object Oriented Modular Petri Nets (OOMPNets) developed in our laboratory is a model which can be represented with a sequence of graphs or mathematical formulas, where the former is more readable. OOMPNets is extended from Colored Petri Nets (CPNs) with object concept. This is achieved by allowing 1) a net to be a token of another one, 2) nodes to be refined with nets and 3) nets to be combined with shared nodes. OOMPNets contains the three distinct properties: 1) For one object-net, the internal relationships of tokens encapsulated and the ripple-effect reactions caused from external firing transitions are totally represented, 2) Refineable nodes encapsulate the information with internal hierarchical presentation and 3) The nets can be combined flexibly gives a fit expression to serve developers who concern specific problems.

Currently, our laboratory is developing an environment to help the development of OOMPNets. This thesis provides two parts of the development environment: OOMPNE and OOMPOA are provided to edit and analyze OOMPNets, respectively. OOMPNE is extended from a Petri Net editor, PIPE2 [3]. OOMPNE consists of a set of edition activities to reduce the abnormal phenomena appearing in the modeled net during edit. OOMPNE also provides some simple checks to help user find the defect earlier, e.g. arc expression unbalance. In summary, OOMPNE helps user to model an OOMPNets without fundamental errors, e.g. undefined color sets used, shared node with different labels and arc expression unbalance. OOMPNE might reduce the time of modeling well-form OOMPNets, since some abnormal phenomena are prevented.

There is no analysis method developed for OOMPNets yet. An OOMPOA provided in this thesis is used to analyze OOMPNets with occurrence graph. OOMPOA analyzes OOMPNets with four steps: 1) transform OOMPNets into CPNs, 2) construct the occurrence graph of the CPNs transformed from OOMPNets, 3) investigate the dynamic properties of the occurrence graph to analyze the CPNs and 4) map the analysis results back to OOMPNets. According to the transformation information provided in OOMPOA, the dynamic properties for OOMPNets can be studied further. Besides, the information can help to develop analysis method for OOMPNets.

The rest of this thesis is organized as follows. Chapter 2 introduces CPNs and OOMPNets. The capabilities and checks of OOMPNE are described in Chapter 3. The technology of analyzing OOMPNets is introduced in Chapter 4. Chapter 5 uses an example to show how to use OOMPOA to analyze OOMPNets. Chapter 6 concludes the thesis and indicates some future works.

Chapter 2 Background

This chapter introduces Colored Petri Nets (CPNs) in Section 2.1. The Object Oriented Modular Petri Nets (OOMPNets) is introduced in Section 2.2.

2.1 Colored Petri Nets

The definition of CPNs given in Definition 2-1 is modified from the one presented in [1] with a variable tuple *V*.

Definition 2-1 (Colored Petri Net):

A Colored Petri Net is a 9-tuple $CPN = (\Sigma, V, P, T, F, C, G, A, I)$ satisfying the requirements below:

(1) Σ is a finite set of non-empty types, called color sets.

(2) V is a set of variables. Variables are used to describe the guard expressions of transitions and the expressions of arcs.

(3) P is a finite set of places.

(4) T is a finite set of transitions.

(5) F is a finite set of arcs such that:

$$P \cap T = P \cap F = T \cap F = \varnothing$$

(6) C is a color function. It is defined from P into Σ.

(7) G is a guard function. It is defined from T into expressions such that:

$$\forall t \in T : [Type(G(t)) = \text{Boolean} \wedge Type(Var(G(t))) \subseteq \Sigma]$$

where *Type(Var(G(t)))* represents the types of variables applied in *G(t)*, *Type(G(t))* represents the type of value after *G(t)* is executed.

(8) A is an arc expression function. It is defined from F into expressions such that:

$$\forall f \in F : [Type(A(f)) \subseteq C(p(f)) \wedge Type(Var(A(f))) \subseteq \Sigma]$$

where p(f) is the place node of arc f.

(9) I is an initialization function. I is defined from P into closed expressions[1] such that:

$$\forall p \in P : [Type(I(p)) = C(p)]$$

The elements defined in Definition 2-1 are illustrated with a net *CPN* one by one. Let *CPN* be $(\Sigma, V, P, T, F, C, G, A, I)$, where

(1) If place *p*, $p \in P$, holds set of tokens D, then $\bigcup_{d \in D} Type(d) \subseteq C(p)$.

(2) The variable type of *v*, $v \in V$, belongs to Σ, denoted as $Type(v) \in \Sigma$.

(3) A marking, a multi-set of net's places, of *CPN* denotes a state of the net.

(4) Firing a transition *t*, $t \in T$, changes state *m* to *m'*. *m* could equal to *m'*.

(5) $\nexists f_1, f_2$, f_1 and $f_2 \in F$, $N(f_1) = N(f_2)$[2].

(6) Color function C maps *p*, $p \in P$, to a set of types.

(7) The guard expression of transition *t*, $t \in T$, return a boolean value *b*. When *b* is true, transition *t* is enables.

(8) The variable types involved in arc expression $A(f)$ are contained in $C(p(f))$.

(9) The initial marking generated by I for $\forall p \in P$ is restricted to satisfy the types defined by all corresponding $C(p)$.

A *CPN* is a directed graph. An example net *CPN* composed if four places and two transitions is shown in Figure 2-1. The initial marking M_0 of CPN is $(p_0(a,b,1,1),p_1,p_2,p_3)$. The net is defined with two color sets (types) *U* and *V*. The value of *U* type element (variable or token) is 1, 2, or 3. The value of *V* type element is *a* or *b*. Variable *x* and *y* used in the net are declared with *U* and *V* type, respectively.

[1] An expression without variables is said to be a closed expression.

[2] *N* is a node function. It is defined from *A* into $P \times T \cup T \times P$.

Each transition or arc is associated with an expression, which is composed of variables or elements in color set above, respectively.

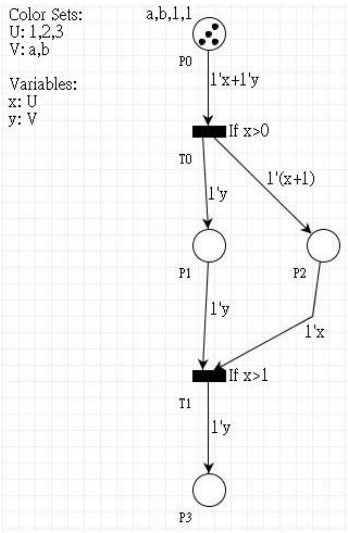


Figure 2-1 A simple example of *CPNs*.

The behaviors of *CPNs* are defined in Definition 2-3, 2-4 and 2-5:

Definition 2-2 A **token element** is a pair (p,c) where $p \in P$ and $c \in C(p)$, while a **binding element** is a pair (t,b) where $t \in T$ and $b \in B(t)$[3]. The set of all token elements is denoted by **TE** while the set of all binding elements is denoted by **BE**.

Definition 2-3 A **marking** is a multi-set over **TE** while a **step** is a non-empty and finite multi-set over **BE**. The **initial marking $\mathbf{M_0}$** is the marking which is obtained by evaluating the initialization expressions:

$$\forall (p,c) \in TE : M_0(p,c) = (I(p))(c).$$

The set of all markings and steps are denoted by M and Y, respectively.
A step Y is **enabled** in a marking M *iff* the following property is satisfied:

[3] *B(t)* is the set of all bindings for *t*.

$$\forall p \in P: \sum_{(t,b)\in Y} A(p,t)<b> \leq M(p)$$

Let the step Y be enabled in the marking M. When $(t,b) \in Y$, we say that t is **enabled** in M for the binding b. We also say that (t,b) is enabled in M, and so is t.

If a transition *t* is firable in a marking M, there are two properties needed to be satisfied: (1) The evaluation result of *G(t)* based on a binding *b* is true (2) $\forall p \in P: \sum_{(t,b)\in Y} A(p,t)<b> \leq M(p)$.

Definition 2-4 When a step Y is enabled in a marking M_1, the marking change from M_1 to M_2 can be defined as:

$$\forall p \in P: M_2(p) = (M_1(p) - \sum_{(t,b)\in Y} A(p,t)<b>) + \sum_{(t,b)\in Y} A(t,p)<b>$$

The first sum represents the tokens **removed** while the second for the token **added**. Moreover, we say that M_2 is **directly reachable** from M_1 by the occurrence of the step Y, which we also denote: $M_1[Y>M_2$.

The expressions of an input arc of a place describe that tokens are added into the place when the corresponding transition is occurred. The tokens are removed from a place are described in the expressions of the output arc of the place. When a transition *t* fires, the tokens of corresponding places are added or removed. The addition and removing tokens is basing on the corresponding arc expressions and binding of the occurring step.

Definition 2-5 A **marking** is a multi-set over P while a **step** is a non-empty and finite multi-set over T. The **initial marking M_0** is the marking which is obtained from the initialization expressions:

$$\forall p \in P: M_0(p) = I(p).$$

The sets of all markings and steps are denoted by M and Y, respectively.

CPNs can be analyzed in four different ways [10]. The first analysis method is interactive simulation. This means that user can use the simulator associated with the editor make simulation to investigate the behavior of the modeled system. The second analysis method is automatic simulation. It allows a fast simulation of thousands or millions of transitions. The purpose is to investigate the functional correctness of the system or to investigate the performance of the system, e.g. to identify bottlenecks, to predict the use of buffer space or the mean/maximal service time …, etc. The third analysis method is occurrence graphs (also called state spaces or reachability graphs). The basic idea behind occurrence graphs is to construct a directed graph which has a node for each reachable system state and an arc for each possible state change. Occurrence graph presents all possible states of the modeled system with initial parameters. All step changes of the modeled system are also recorded in the occurrence graph. User investigates the dynamic properties through the occurrence graph. The investigated results help user to find the run-time error(s) embedded in the modeled system. Obviously, such a graph may become very large, even for small CPNs. However, it can be constructed and analyzed totally automatically, and there are techniques working with condensed occurrence graphs without losing analytic power. These techniques are built upon equivalence classes. The fourth analysis method is place invariants. User constructs a set of equations which is proved to be satisfied for all reachable system states. The equations are used to prove some properties of the modeled system, e.g., absence of deadlock.

2.2 Object Oriented Modular Petri Nets

OOMPNet is an extension of CPNs. There are three extensions and two new relations in OOMPNets. OOMPNets extends 3 elements in CPNs, places, transitions and tokens. Synchronization relation (SR) and share nodes are provided in OOMPNets. Besides above three extensions and two relations, the remaining parts of OOMPNets are the same to CPNs. The extensions of places and transitions are introduced in section 2.2.1. Section 2.2.2 introduces the extension of tokens. Two new relations, SR and share nodes, are introduced in Section 2.2.3. Finally, a formal definition for OOMPNets is described in Section 2.2.4.

2.2.1 The Extensions of Places and Transitions

The places are separated into two sets, primary and abstract places in OOMPNets. The primary places are defined the same as places in CPNs. The abstract places are clarified further with refinement nets rPNet, as in Function 2-1.

Function 2-1 (refinement of abstract place):

An abstract place p can be refined as an OOMPNets $rPNet = (\Sigma', V', P', T', D', F', C', G', A', I', L')$, where:

1. $P' = \{p_{in}, p_{out}\} \cup P''$.

The input and output transitions of p are transferred to p_{in} and p_{out} respectively, where

$$In(p) = In(p_{in}) = \{t \in T \mid \exists f \in F : N(f) = (t, p)\}$$
$$Out(p) = Out(p_{in}) = \{t \in T \mid \exists f \in F : N(f) = (p, t)\}$$

2. If $P^{"} = \varnothing,\ F^{'} \subseteq (p_{in} \times T^{'}) \cup (T^{'} \times p_{out})$.

3. If $P^{"} \neq \varnothing$

   1) $T^{'} = T^{"} \cup T_1 \cup T_2$ and the intersection of each pair is $\varnothing$, and

   2) $F^{'} \subseteq (p_{in} \times T_1) \cup (T_2 \times p_{out}) \cup ((T^{"} \cup T_1) \times P^{"}) \cup (P^{"} \times (T^{"} \cup T_2))$.

4. $C(p) = \bigcup_{i=1}^{|P^{'}|} C(p_i),\ p_i \in P^{'}$

The transitions are also separated into two different sets, primary and abstract transitions in OOMPNets. The primary transitions are the same as transitions in CPNs. The abstract transitions are clarified further with refinement nets rTNet, as in Function 2-2.

Function 2-2 (refinement of abstract transition):

An abstract transition t can be refined as an OOMPNets $rTNet = (\Sigma^{'}, V^{'}, P^{'}, T^{'}, D^{'}, F^{'}, C^{'}, G^{'}, A^{'}, I^{'}, L^{'})$, where

1. $T^{'} = \{t_{in}, t_{out}\} \cup T^{"}$

The input and output places of t are transferred to t_{in} and t_{out} respectively, where

$$In(t) = In(t_{in}) = \{p \in P \mid \exists f \in F : N(f) = (p, t)\}$$

$$Out(t) = Out(t_{out}) = \{p \in P \mid \exists f \in F : N(f) = (t, p)\}$$

2. If $T^{"} = \varnothing, F^{'} \subseteq (t_{in} \times P^{'}) \cup (P^{'} \times t_{out})$

3. If $T^{"} \neq \varnothing$

   1) $P^{'} = P^{"} \cup P_1 \cup P_2$ and the intersection of each pair is $\varnothing$, and

   2) $F^{'} \subseteq (t_{in} \times P_1) \cup (P_2 \times t_{out}) \cup ((P^{"} \cup P_1) \times T^{"}) \cup (T^{"} \times (P^{"} \cup P_2))$

4. The guard expression exp attached to t is listed as $\exp_1 \wedge \exp_2 \wedge \exp_3 \cdots \wedge \exp_n, \forall t_i \in T^{'}$, t_i's guards are in the list.

To handle incomplete requirements, *abstract place* and *transition* are introduced in OOMPNets. The partial specification could be encapsulated and refined with net later.

2.2.2 The Extensions of Tokens

All tokens are defined before they are used. The tokens are stated with the token's color, as *color set: name* = $[c_1,c_2,...c_n]$. They are separated into two sets, primary and complex tokens, in OOMPNets. The token of primary type is defined identically as the token in CPNs. The token of complex type is defined as an OOMPNet, called object-net. The object-net container is called the system-net. The internal interaction of a complex token is presented sufficiently by OOMPNets with a hierarchical expression and *synchronization relation (SR)* introduced in section 2.2.3. The color set of the complex token collects all reachable markings in its net after initialization.

2.2.3 Synchronization Relation and Share Node

When an application receives a request, it transits into another state. During such a transition, the application may cause some ripple-effects, such as converting the state of data objects. In the method, the data movement and state transitions are depicted in system- and object-net, respectively. Actual display of this chain-reaction employs the *SR*.

Definition 2-6 (synchronization relation):

Let $SN = (\Sigma, V, P, T, D, F, C, G, A, I, L)$ be a system net and the set of object nets which belongs to SN be denoted as $ON = COD$, $ON = \{ON_i \mid i \geq 1\}$. The intersection of T_i and T_j for corresponding object-net ON_i and ON_j is $\varnothing$, $i \neq j$. The union of all transition sets inside ON_i is named as $\tilde{T}$, $\tilde{T} = \bigcup_{i=1}^{n} T_i$. Firing a transition $t \in T$, which has an SR with $t' \in \tilde{T}$, triggers the state transition of t' concurrently. An SR belongs to $(T \times \tilde{T})$ whose transitive closure is asymmetric.

Let $P' = \{p' \mid p' \in In(t)\}$, and t and t_i belong to SN and ON_i, respectively. ON_i is defined into $P_j = \{p_j \mid j = 1...m\} \subseteq P', 1 \leq m \leq |P'|$. If $\exists (t, t_i) \in SR,\ t_i \in T_i$ and t is enabled, the following two conditions have to be satisfied 1) the value of $G(t)\langle b \rangle$ and $G(t_i)\langle b_i \rangle$ shall be true and 2) both transitions are sure to be enabled.

A use case can be categorized into classes of usage scenarios. In most cases, some actions may be defined in more than one above scenario. So, some places and transitions could be shared to reflect the dependencies between scenarios for analysis. Here, the mechanism constructs the relationships among these labelled nodes. The details are clarified as follow:

Definition 2-7 (share node):

Let set of system-nets $Net = \{Net_i \mid i = 1...n, n \geq 1\}$ and Net_i be an OOMPNet, where

1. A *NodeSet* is a set containing all the places and transitions in its *Net*. $NodeSet = (\bigcup_{i=1}^{n} P_i \cup \bigcup_{i=1}^{n} T_i)$, where P_i and T_i represent the places and transitions of the i^{th} OOMPNet respectively.
2. *R(x, y)*, the *equivalence relation* in a *NodeSet*, indicates that *x* and *y* in the

NodeSet have the same label and property (primitive or abstract), $x \neq y$, and is described as follows:

$$R(x,y) \equiv L(x) \equiv L(y).$$

3. An equivalence class for an element x in a *NodeSet* is defined as follows:

$$\hat{x} = \{y \in NodeSet \mid (x,y) \in R\}$$

OOMPNets take a *label function* which labels the place(s) and transition(s) to be applied for nets combination. The mergence(s) takes out the replications in requirement specification.

2.2.4 Formal Definition of OOMPNets

Definition 2-8 (OOMPNets):

For a character set ℓ, an OOMPNets is a 11-tuple $Net = (\Sigma, V, P, T, D, F, C, G, A, I, L)$ where

1. Σ is a finite set of non-empty types, called color sets.
2. V is a set of variables. Variables are used to describe the guard expressions of transitions and the expressions of arcs. The type of a variable belongs to Σ. In other words, $\forall v \in V, Type(v) \in \Sigma$.
3. $P = PIP \cup ABP$ is a set of places, where *PIP* is a set of primary places and *ABP* is a set of abstract places.
4. $T = PIT \cup ABT$ is a set of transitions, where *PIT* is a set of primary transitions and *ABT* is a set of abstract transitions.
5. $D = PID \cup COD$ is a set of tokens, where *PID* is a set of primary type tokens and *COD* is a set of complex type tokens. *COD* set holds the net(s) build by OOMPNets to be the token(s) of another net.
   $\forall d_c \in COD$:
   $d_c = (\Sigma_c, P_c, T_c, D_c, F_c, C_c, G_c, A_c, I_c, L_c)$
6. $F \subseteq (P \times T) \cup (T \times P)$, F represents a set of directed arcs, known as a flow

relationship.

7. $C : P \to \Sigma^*$ is a color function defined from *P* to a subset of Σ.
8. $G : T \to exp$ is a guard function to map each transition into an expression of type boolean.
9. $A : F \to \exp$ is an arc expression function. The function maps arc *f* into an expression with the token types *C(p)* located in the place *p* connected by the arc *f*.
10. I is an initialization function. It is defined from P into closed expression
11. $L : P \cup T \to \ell$ is a label function that defines a distinct string associated with node which is able to be merged with homogeneous node(s) in other net(s).

Chapter 3 An Editor for OOMPNets

The chapter presents an editor, OOMPNE, for editing OOMPNets. OOMPNE is extended from a Petri Nets editor, PIPE2 [3]. The work of editing OOMPNets in OOMPNE is easy since OOMPNE provides several tools. Figure 3-1 shows the window in OOMPNE. Section 3.1 introduces the edit functions of net elements in OOMPNE. The edit functions might cause some abnormal phenomena. These abnormal phenomena are described in Section 3.2. Section 3.3 describes the incremental analysis for the anomalies.

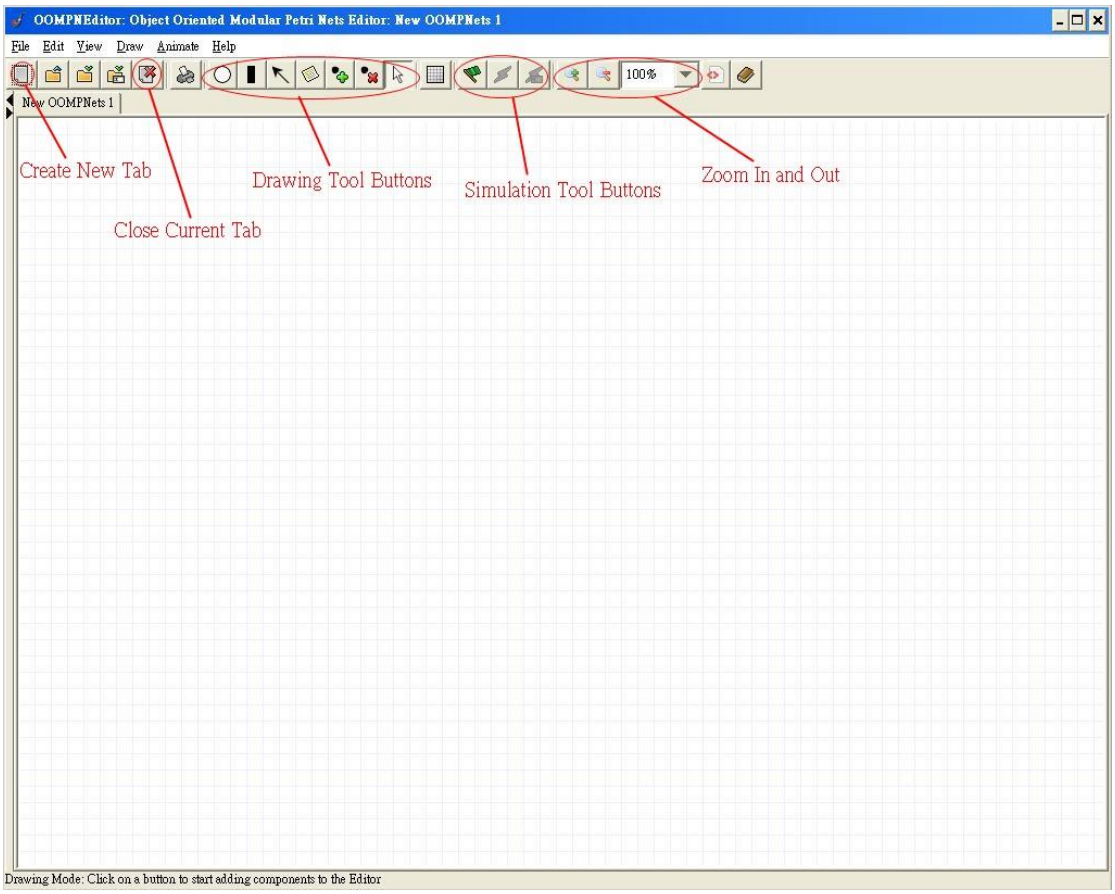


Figure 3-1 The window in OOMPNE.

3.1 Edit Functions in OOMPNE

This section describes how the elements of an OOMPNet are created and edited in OOMPNE. In OOMPNE, there are five types of edit activties:

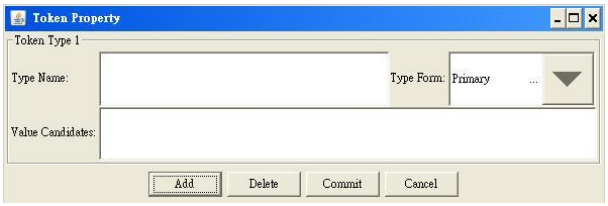
1. Insert and Delete
2. Copy and Paste
3. Move
4. Naming the Element
5. Decompose

For example, the activities of type 1 are applied to create meaningful net elements in OOMPNE. The section introduces edit functions according to their element in the followings.

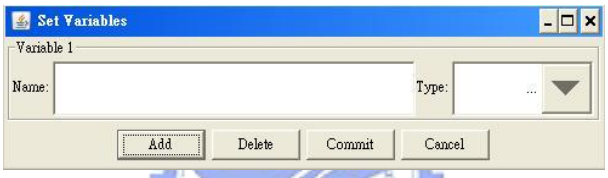
A. Color Set and Variables

In the very beginning of constructing an OOMPNet, color sets and variables need to be created. The color sets and variables of an OOMPNet are also called declarations of an OOMPNet. Figure 3-2 shows the windows in editing color sets and variables. Window “Token Property” is used to define the color set for describing the type and value of tokens. When user creates a complex type of color set, OOMPNE creates a new sheet for user to model the object-net corresponding to the type. An object-net is defined with an OOMPNet. However, a token here is dynamic, i.e., the tokens inside the OOMPNet represented by their token might be changed dynamically. I.e., different inscriptions between an object-net and its type are the initial marking and the label of elements. The other inscriptions cannot be modified. User can use operation “Delete” to delete the color sets. Operation “Delete” pops out a list for user

to select and delete the color sets. The window “Set Variables” is used to edit he/she wants variables in OOMPNets. These variables are used to edit the inscriptions of arcs or transitions. The steps of operation “Delete” in function “Set Variables” are similar to that in function “Token Property”. It also provides a list for users to select and delete the variables.



(a)



(b)

Figure 3-2 The windows in editing token properties and variables.

B. Place

Associated with a place, user can enter some special key to do the characteristics he wants. Or, he can popup a menu as in Figure 3-3 to help do the work.

1. Insert and Delete:

   The steps of creating places are described as follows. First, user selects the function “Add a place” in the drawing tool buttons. Second, user uses mouse to decide the position within the sheet. A place is now created into an OOMPNet. Then, user can edit the inscriptions of a place by using the operations in the popup menu associated with the place. In the menu, the first operation “Delete”, used to delete the target place. The rest operations will be introduced later.

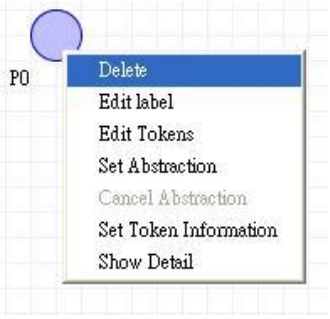


Figure 3-3 The popup menu of right click a place.

2. Copy and Paste:

   A use case can be divided into several usage scenarios. Usually, an action may be defined in more than one scenario. In order to create a share node fast, OOMPNE provides users the facility of duplicating existing nodes. Figure 3-4 shows the popup menu of duplicating operations, where the menu can be popped and each case in the menu corresponds to a distinct operation. The list shows the labels of existing places. User selects an element of the list to create the node with the same label. The operation of duplicating is to create an element with the same element type and label. Because an inscription is distinct in different scenarios, operation "duplicate" in OOMPNE does not duplicate the inscription(s).

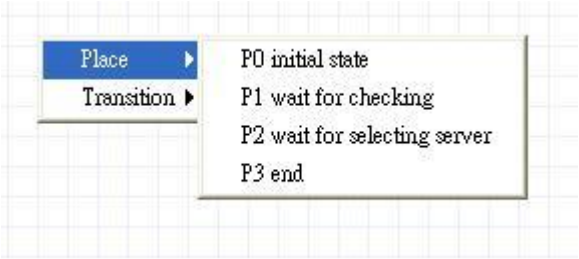


Figure 3-4 The popup menu of operation duplicate.

3. Naming the elements:

   OOMPNE provides initial name, i.e. P0, P1, …, of new created places. The operation “Edit Label” in the popup menu in Figure 3-3 is used to edit the label of the place.

4. Decompose:

   “Set Abstraction” in the popup menu, shown in Figure 3-3, is in charge of decomposing places. “Set Abstraction” can be used to refine the place. When an abstract place is generated, the refinement is started by applying “Set Abstraction”. “Cancel Abstraction” is used to change the level of a place from abstract to primary.

C. Transition

There is an associated popup menu in Figure 3-5. The operations of editing inscriptions of a transition are in the menu. These operations are introduced in the followings.

1. Insert and Delete:

   The steps of creating transitions are similar to those of creating places. The following introduces how to edit the inscriptions of a transition directly. The operations in the popup menu of transitions are: delete, edit label, set or cancel abstraction, set condition, show detail, set synchronization and rotate. Operation “Set Condition” is used to edit the guard expression(s) of a transition. On the other hand, user can use “Show Detail” to review the edited guard expression(s) of the transition. During a review, if user finds an error in the guard expression(s), he can use “Set Condition” to correct the guard expression(s). A synchronization relationship between transitions is constructed by using “Set Synchronization” operation. “Set Synchronization” provides user all transitions in corresponding

object-nets to select the synchronous transition(s). Operation “Rotate” has three candidates, 45, 90 and -45. It is used to change the angle of a transition. The operation “Delete” is similar to that in popup menu of places. Transitions can be deleted through operation “Delete” or the “delete” key in keyboard.

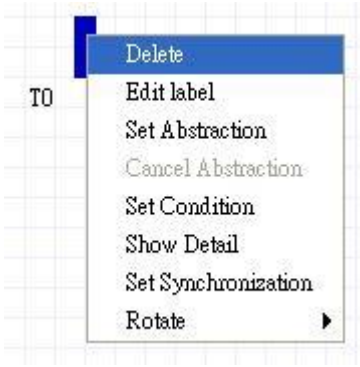


Figure 3-5 The popup menu of a transition.

2. Copy and Paste:

   In Figure 3-4, operation “duplicate” provides duplicating transitions. The steps of duplicating transitions are similar to the work for places.

3. Naming the elements:

   OOMPNE provides initial name, i.e. T0, T1, …, of new created transitions. The operation “Edit label” in the menu is used to edit the label of a transition.

4. Decompose:

   “Set Abstraction” in the popup menu, shown in Figure 3-5, is in charge of decomposing transitions. “Set Abstraction” can be used to refine the transition. The operation in transitions is similar to that in places. Here omits the detail of the operation.

D. Arc

Figure 3-6 shows the popup menu associated with an arc. The operations displayed in

such a popup menu include: delete, split arc segment, set input arc expression and show detail.

1. Insert and Delete:

   Creating an arc basically include the following 3 steps: 1) selecting the "Add an arc" function in drawing tool buttons, 2) using mouse to click an element to be the source of the created arc, and 3) click another element to be the destination of the created arc. There two popup menus associated with the arc, one for the arc whose destination is a place and the other for transition. In OOMPNE, the arc is called input arc if the destination is transition; otherwise the arc is called output arc. Operation "Delete" is used to delete the target arc. An arc might cross other elements in complex models. User can create turning point to mitigate the crossing situation by using operation "Split Arc Segment" in the popup menu. "Set Input Arc Expression" is used to edit the arc expression of the targeted input arc, similarly, "Set Output Arc Expression" is used to edit the arc expression of the targeted output arc. User can review the edited arc expression by using "Show Detail" in the popup menu to help finding out error(s) to be fixed.

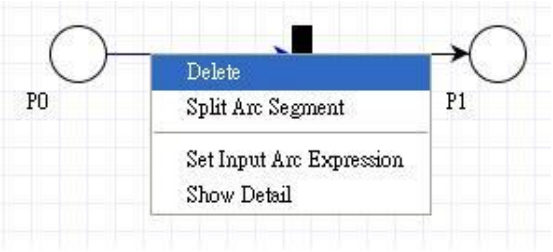


Figure 3-6 The popup menu of an input arc.

E. Token

The operations associated with tokens are list in popup menu in Figure 3-3. They contains: edit token, set token information and show detail.

1. Insert and Delete:

   User can apply the function of “Add a token” in drawing tool buttons, shown in Figure3-1. Then, he can click a place to add the token into the place. Now, the token is not defined complete yet. A token has to be added necessary inscriptions e.g. token type and token value. The work has to be done with the popup menu. Operation “Edit tokens” is another way to add or delete tokens. Deleting tokens is also achieved by using function “Delete a token” in the drawing tool buttons. The steps in “Delete a token” are similar to that in “Add a token” function. Operation “Set token information” is used to edit the inscriptions of tokens. After editing the inscriptions of tokens, user can use “Show Detail” operation to review the inscriptions of tokens. During review, user can use “Set token information” operation again to modify the inscriptions of tokens to fix his problem.

2. Naming the element:

   In OOMPNets, complex tokens are named for representing the object-nets. It is easy to describe the marking of OOMPNets. The naming operation is associated with operation “Set token information”. Figure 3-7 shows the window to edit.

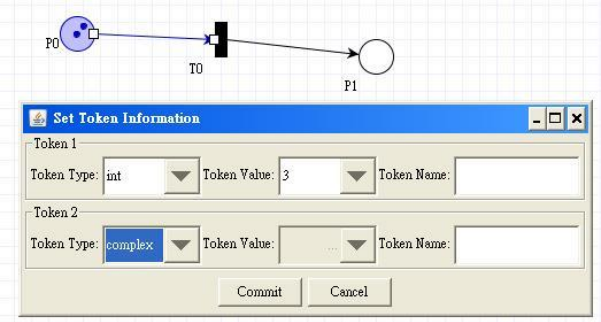


Figure 3-7 The window in editing tokens.

3. Decompose:

   After editing the inscriptions of tokens, OOMPNE can be applied to open a sheet

for user to model the object-net for a token whose type is complex. The newly created sheets are already filled in the duplication of the type object-net. User can modify the object-net to fit condition(s). It reduces the time of modeling object-nets.

3.2 Basic Abnormal Phenomena

There might be some abnormal phenomenon after an editing activity. In this section, we present the basic abnormal phenomenon right after an editing activity of modification, including “create” and “delete”. The anomalies corresponding to the activities in previous section are illustrated and discussed below:

A. Color Set and Variables

The deletion of a color set or a variable might cause a problem, loss meaning. Loss meaning means that user edits an inscription of a net element with undefined types, values or variables. For tokens, a token with deleted type cannot be removed by the corresponding arc expressions. It remains in the initial place at run time. For arcs, arc expressions with deleted data cannot consume or produce the token from or to corresponding place(s) at run time.

B. Place and Transition

(1) An arc cannot exist without source or destination. The deletion of a place or transition causes the associated arc(s) to lose source or destination.

(2) The label of share nodes is different. A place or transition is called a share node if at least one place or transition with the same label in other OOMPNets.

The label of share nodes is different when the label of a share node is changed.

C. Arc

The edition of an arc might cause some abnormal phenomena, as follows:

(1) An arc connects two nodes with the same type in OOMPNets. From the definition of OOMPNets, an arc cannot be positioned between the same type elements. In other words, the source and destination of an arc cannot both be places or transitions.

(2) A defined arc expression is combined with one or more undefined variables. It causes the corresponding transition to be fired impossibly.

(3) Unbalance arc expression is an abnormal phenomenon which causes tokens to be remained in a place or an unfirable transition. The edition of an arc expression might cause "unbalance arc expression". There are two situations to be concerned in the following:

1) For a place *p*, the union of its input arc expressions $expr s_{in}$ does not combine with a token type which is defined in the union of output arc expressions $expr s_{out}$.

$$\exists s \in C(p): \textit{the value of coefficient } n \textit{ of } s \textit{ is } 0 \textit{ in } expr s_{in}, \textit{ the value of coefficient } n' \textit{ of } s \textit{ is greater than } 0 \textit{ in } expr s_{out}.$$

During run time, firing the transitions connected with input arcs does not add any token of type *s* into place *p*. However, without the token, some transitions of the output arcs cannot be fired later. Because the tokens in p cannot satisfy with the expressions of some output arcs, the transitions of the unsatisfied output arcs are not firable even if the guard expressions of

these transitions are satisfied. The unfirable circumstances could spread to the connected transitions arrowed.

2) For a place, the union of its input arc expressions $exprs_{in}$ combines with a token type which is not defined in the union of output arc expressions $exprs_{out}$.

$$\exists s \in C(p): \textit{the value of coefficient } n \textit{ of } s \textit{ is greater than } 0 \textit{ in } exprs_{in}, \textit{ the value of coefficient } n' \textit{ of } s \textit{ is } 0 \textit{ in } exprs_{out}.$$

At the run time, a transition does not consume the tokens typed with *s* from place *p* added by input arcs. These tokens remain in place *p*. A large number of tokens remained in *p* could result in memory overhead that happens depending on the execution time of the transitions which add token of type *s* to p.

(4) The deletion of an arc might cause some unbalance arc expression(s). Each arc deletion might cause $exprs_{in}$ or $exprs_{out}$ to change. So, unbalance arc expressions might be caused by deleting arcs.

D. Token

(1) The tokens are positioned everywhere within a sheet without associated with places. Tokens cannot be positioned freely within a sheet. From the definition of OOMPNets, it is meaningless if a token is not put inside a place in an OOMPNet.

(2) Users might use undefined types or values to edit the inscriptions of tokens. It causes the token to be unconsumable, because the corresponding arc expressions are not combined with the undefined type.

(3) In an OOMPNet, a complex token has to be named necessarily. Naming a

primary token is unnecessary and then user is confused primary tokens with complex tokens.

3.3 Incremental Analysis for the Anomalies in OOMPNE

The anomalies in previous section indicate some wrong net structures potentially. This section describes how OOMPNE reminds users to prevent those anomalies. The functions for preventing each anomalies are illustrated below:

A. Color Set

To prevent loss meaning, OOMPNE checks the inscriptions of all net elements in OOMPNets whenever user deletes token type(s). OOMPNE uses message to remind user that the deletion causes some meaning loss. Figure 3-8 shows the message of deleting types, int and char. Type int is used in the OOMPNet. The message shows that type int cannot be deleted.

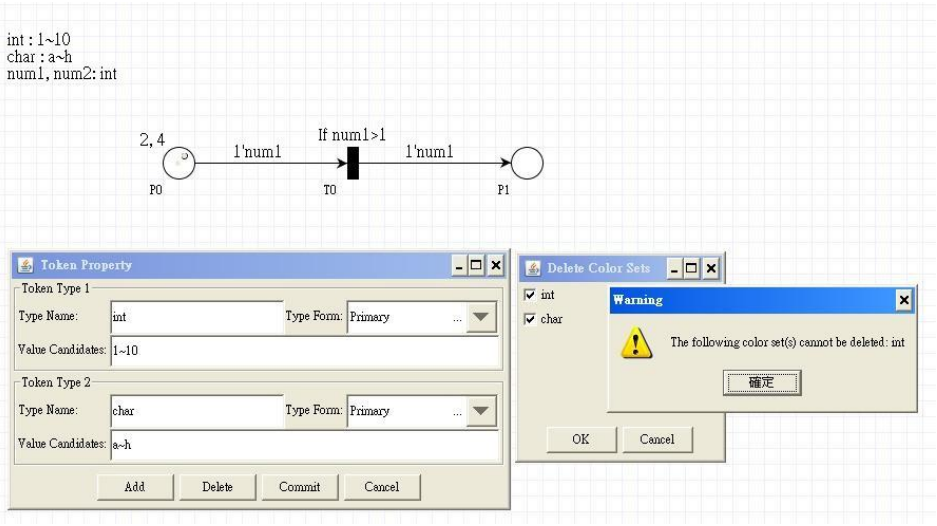


Figure 3-8 The reaction from OOMPNE of deleting used color set(s).

B. Place and Transition

(1) To prevent an arc without source or destination, OOMPNE deletes the arc(s) connected to the deleted place or transition directly. Figure 3-9 shows the net after deleting transition T0 in Figure 3-8.

(2) When user changes the label of a share node, OOMPNE synchronizes the label of the share nodes in the other OOMPNets.

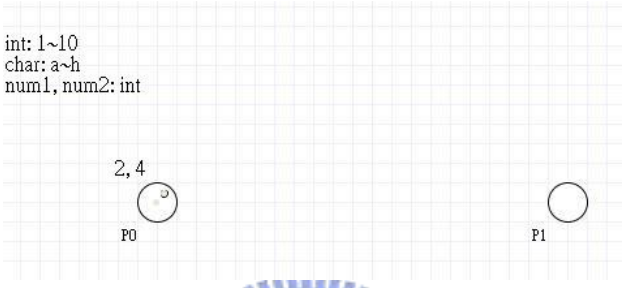
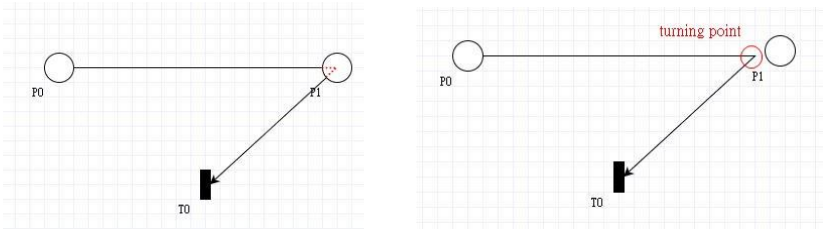


Figure 3-9 The net after deleting transition T0 in Figure 3-8.

C. Arc

(1) To prevent that the source and destination of an arc are the same type, OOMPNE changes the destination point into turning point directly. Figure 3-9(a) shows the destination changed into turning point behind place P1. Figure 3-9(b) shows the turning point by moving place P1.



(a) (b)

Figure 3-10 (a) the destination changed into turning point when user connects two places. (b) the turning point is shown by moving place P1.

(2) OOMPNE provides a defined variable list for user to edit arc expressions. Each variable in the list is associated with a blank space to be filled in an integer representing the limitation for the corresponding variable when the transition is fired. It prevents that user uses undefined variables to edit arc expressions. Figure 3-10 shows the window in editing input arc expressions from Figure 3-8.

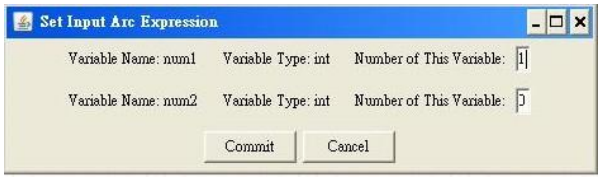


Figure 3-11 The window in editing input arc expression

(3) To prevent an unbalance arc expression below, the corresponding arc expressions will be checked when user edits an arc. The rules of detecting unbalance arc expressions are described in the followings:

$N : F \to (P \times T) \cup (T \times P)$, *N is a node function. The node function maps each arc into a pair where the first element is the source node and the second the destination node.*

$IA, OA : P \cup T \to F^*$

$IA(p) = \{ f \in F \mid \exists t \in T, N(f) = (t, p) \}$, *IA(p) is a set of input arcs of place p*

$OA(p) = \{ f \in F \mid \exists t \in T, N(f) = (p, t) \}$, *OA(p) is a set of output arcs of place p*

$Var : (F \cup T) \to Variables, Var(e) = \{ v \in Variables \mid v \text{ is used in } A(e) \text{ or } G(e) \}$

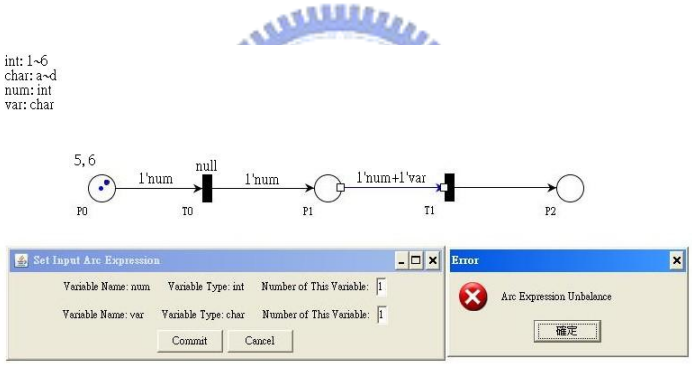
$Type : Variables \to \Sigma, Type(v) = \{ t \in \Sigma \mid \text{the type of } v \text{ is } t \}$

$Rule1 : \forall p \in P, If\ IA(p) \neq \emptyset \text{ and } OA(p) \neq \emptyset, \text{ then } \bigcup_{f_i \in IA(p)} \bigcup_{v \in Var(f_i)} Type(v) = \bigcup_{f_o \in OA(p)} \bigcup_{v \in Var(f_o)} Type(v) = C(p)$

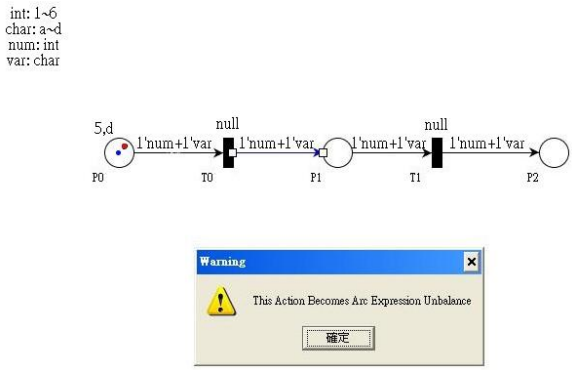
$Rule2 : \forall p \in P, If\ IA(p) = \emptyset \text{ and } OA(p) \neq \emptyset, \text{ then } \bigcup_{f_o \in OA(p)} \bigcup_{v \in Var(f_o)} Type(v) = C(p)$

$$Rule3: \forall p \in P, If\ IA(p) \neq \varnothing\ and\ OA(p) = \varnothing, then \bigcup_{f_i \in IA(p)} \bigcup_{v \in Var(f_i)} Type(v) \subseteq C(p)$$

The unbalance arc expression will be checked when user deletes an arc or edits the expression of an arc. The action of editing the expression(s) of an arc or deleting an input arc could cause the problem of case 1) in section 3.2. The action of editing expression(s) of an arc or deleting an output arc could cause the problem of case 2) in section 3.2. When an edition violates above rules, OOMPNE reminds user with a corresponding message. Figure 3-11(a) shows the message of editing an arc expression which causes an unbalance arc expression. The message of user's deleting action which causes an unbalance arc expression is shown in Figure 3-11(b).



(a) edit expression of arc (P1,T1)



(b) delete arc (T0,P1)

Figure 3-12 (a) and (b) show the reminding ways of OOMPNE when user's action violates the rules.

D. Token

(1) The tokens are associated with places. There are two ways to create a token: 1) perform operation “Edit Tokens” in the menu associated with place and 2) perform the function “Add a token” in drawing tool buttons. The action of adding tokens through “Add a token” is valid when the clicked element is a place. The two ways of creating tokens ensure that the created token is put in places.

(2) Figure 3-8 shows the window in editing the inscriptions of a token. The combo selection of token type provides the pre-defined types for user to select. After selecting a type, the combo selection of token value provides the corresponding value candidates for user to select. Token name is unable to be filled in if the selected type is primary type. From the above functions, OOMPNE avoids using undefined token types to edit inscriptions of tokens and naming a primary token.

Chapter 4 Technology of Analyzing OOMPNets

In order to analyze OOMPNets, this chapter provides algorithms to transform OOMPNets into CPNs. The CPN transformed from an OOMPNet is called *T-CPN*. Our algorithm merges object-nets with system-net recursively till the T-CPN is generated. During the transformation, the hierarchical relationship between object-nets and system-nets are maintained in a table for indexing. The names assigned for the token types, complex tokens and variables included in the OOMPNet are unique. The mechanisms adopted in our algorithms are introduced in section 4.1. The details of the algorithms proposed in this thesis are illustrated in section 4.2.

4.1 The Mechanisms of Transformation Algorithms

The mechanisms adopted for implementing the algorithms proposed in this thesis can be separated into two parts: unfolding abstract node and generating transition. The definitions and functions included in the two parts are introduced one by one. In our methodology, all the abstract nodes of a system-net are unfolded before transformation. The transformation algorithms operate a system-net unfolded with its object-nets which have primary tokens only. The transitions of transformation result are generated by referring SRs on the condition.

The functions offered for unfolding abstract nodes are established as follows:

Function 4-1 (Unfolding an Abstract Place of an OOMPNet) :

Let an OOMPNet $N = (\Sigma, P, T, D, F, C, G, A, I, L)$ be defined with an abstract place p whose refinement is $rPNet = (\Sigma', P', T', D', F', C', G', A', I', L')$. The result of

unfolding p of N with *rPNet* is $\vec{N} = (\vec{\Sigma}, \vec{P}, \vec{T}, \vec{D}, \vec{F}, \vec{C}, \vec{G}, \vec{A}, \vec{I}, \vec{L})$, where:

(1) $\vec{\Sigma} = \Sigma \cup \Sigma'$ is the union of two sets of types (colour sets) which belongs to net N and p's refinement, respectively.

(2) $\vec{P} = P \cup P' \setminus \{p\}$ contains all places of P and P' except the abstract places p.

(3) $\vec{T} = T \cup T'$ is the union of two sets of transitions which belongs to net N and p's refinement, respectively.

(4) $\vec{D} = D \cup D'$ is the union of two sets of tokens which belongs to net N and p's refinement, respectively.

(5) The directed arcs of $\vec{N}$ are enumerated in set $\vec{F}$ which is consist of the two parts: (1) the first part holds the arcs contained in F and F' except which exist between p and a transition or vice versa and (2) the second part includes the arcs connecting the input transitions of p to the places of P' and the places of P' to the output transitions of p

$$\vec{F} = F \cup F' \setminus \{(n_1, n_2) \in F \mid n_1 = p \vee n_2 = p\} \cup$$
$$\{(t, p_{in}) \mid (t, p) \in F, t \in T, p_{in} \in P'\} \cup \{(p_{out}, t) \mid (p, t) \in F, t \in T, p_{out} \in P'\}$$

(6) The color function $\vec{C}$ is defined from $\vec{P}$ to $\vec{D}$. $\forall p \in \vec{P}, \vec{C}(p) = \begin{cases} C(p) & ,if\ p \in P \\ C'(p) & ,if\ p \in P' \end{cases}$

(7) The guard function $\vec{G}$ maps each transition to boolean expression.

$$\forall t \in \vec{T}, \vec{G}(t) = \begin{cases} G(t) & ,if\ t \in T \\ G'(t) & ,if\ t \in T' \end{cases}$$

(8) $\forall f \in \vec{F}, \vec{A}(f) = \begin{cases} A(f) & , \text{if } f \in F \\ A'(f) & , \text{if } f \in F' \\ A(f') & , \text{if } N(f) = (t, p_{in}) \vee N(f) = (p_{out}, t), t \in \vec{T} \\ & \quad \exists f' \in F, N(f') = (t, p) \vee N(f') = (p, t) \end{cases}$

(9) The initialization function $\vec{I}$ is defined from $\vec{P}$ into expressions with tokens in $\vec{D}$.

$$\forall p \in \vec{P}, \vec{I}(p) = \begin{cases} I(p) & ,\text{if } p \in P \\ I'(p) & ,\text{if } p \in P' \end{cases}$$

(10) The level function $\vec{L}$ is defined from $\vec{P} \cup \vec{T}$ into levels.

$$\forall n \in \vec{P} \cup \vec{T}, \vec{L}(n) = \begin{cases} L(n) & ,\text{if } n \in P \cup T \\ L'(n) & ,\text{if } n \in P' \cup T' \end{cases}$$

Function 4-2 (Unfolding abstract transition) :

Let an OOMPNet, $O = (\Sigma, V, P, T, D, F, C, G, A, I, L)$ with an abstract transition t, and the refinement is $rTNet = (\Sigma', V', P', T', D', F', C', G', A', I', L')$. Then we define the unfolded N to be $\vec{O} = (\vec{\Sigma}, \vec{V}, \vec{P}, \vec{T}, \vec{D}, \vec{F}, \vec{C}, \vec{G}, \vec{A}, \vec{I}, \vec{L})$ where:

(1) $\vec{\Sigma} = \Sigma \cup \Sigma'$ is the union of two sets of types (color sets) which belongs to net *O* and *t*'s refinement, respectively.

(2) $\vec{V} = V \cup V'$ is the union of two sets of variables which belongs to net *O* and *t*'s refinement, respectively.

(3) $\vec{P} = P \cup P'$ is the union of two sets of places which belongs to net *O* and *t*'s refinement, respectively.

(4) $\vec{T} = T \cup T' \setminus \{t\}$ contains all transitions of *T* and *T*' expect the abstract transition *t*.

(5) $\vec{D} = D \cup D'$ is the union of two sets of tokens which belongs to net *O* and *t*'s refinement, respectively.

(6) The directed arcs of $\vec{O}$ are enumerated in set $\vec{F}$ which is consist of the two parts: (1) the first part holds the arcs contained in *F* and *F*' except which exist between *t* and a place or vice versa and (2) the second part includes the arcs connecting the input places of *t* to the transitions of *T*' and the transitions of *T*' to the output places of *t*

$$\vec{F} = F \cup F' \cup \{(p, t_{in}) \mid (p,t) \in F, p \in P, t_{in} \in T'\} \cup$$
$$\{(t_{out}, p) \mid (t, p) \in F, p \in P, t_{out} \in T'\} \setminus \{(n_1, n_2) \mid n_1 = t \vee n_2 = t\}$$

(7) The color function $\vec{C}$ is defined from $\vec{P}$ to $\vec{D}$.

$$\forall p \in \vec{P}, \vec{C}(p) = \begin{cases} C(p) & ,if\ p \in P \\ C'(p) & ,if\ p \in P' \end{cases}$$

(8) The guard function $\vec{G}$ maps each transition to boolean expression.

$$\forall t \in \vec{T}, \vec{G}(t) = \begin{cases} G(t) & ,if\ t \in T \\ G'(t) & ,if\ t \in T' \end{cases}$$

(9) $$\forall f \in \vec{F}, \vec{A}(f) = \begin{cases} A(f) & ,\ if\ f \in F \\ A'(f) & ,\ if\ f \in F' \\ A(f') & ,\ if\ N(f) = (p, t_{in}) \vee N(f) = (t_{out}, p), p \in \vec{P} \\ & \quad \exists f' \in F, N(f') = (p,t) \vee N(f') = (t, p) \end{cases}$$

(10) The initialization function $\vec{I}$ is defined from $\vec{P}$ into expressions with tokens in $\vec{D}$.

$$\forall p \in \vec{P}, \vec{I}(p) = \begin{cases} I(p) & ,if\ p \in P \\ I'(p) & ,if\ p \in P' \end{cases}$$

(11) The label function $\vec{L}$ is defined from $\vec{P} \cup \vec{T}$ into labels.

$$\forall n \in \vec{P} \cup \vec{T}, \vec{L}(n) = \begin{cases} L(n) & ,if\ n \in P \cup T \\ L'(n) & ,if\ n \in P' \cup T' \end{cases}$$

In addition, for the complex token(s) located in the input place(s) of transition *t*, the binding function *bct* of *t* (defined in Definition 4-1) selects a set of complex tokens from *t*'s input places for consuming. The notations used for defining *bct* are introduced here:

(1) $\forall n \in P \cup T : S(n) = \{ f \in F \mid \exists n' \in P \cup T : [N(f) = (n, n') \vee N(f) = (n', n)] \}$

Function S maps node n to the set of n's incoming and outgoing arcs, i.e., n is at one of the end of these arcs.

(2) $\forall t \in T : Var(t) = \{ v \mid v \in Var(G(t)) \vee \exists f \in S(t) : v \in Var(A(f)) \}$

The set of variables in the guard expression of transition t is denoted by $Var(t)$.

(3) $\forall t \in T : CTVar(t) = Var(t) \setminus \{ v \mid v.type\ is\ prime \}$

Set $CTVar(t)$ contains all variables typed with complex in $Var(t)$.

Definition 4-1 (Complex Tokens Binding):

A **complex tokens binding** of a transition *t* is a function *bct* defined on $CTVar(t)$, such that:

$$\forall v \in CTVar(t) : bct(v) \in Type(v)$$

we denote the set of all complex tokens bindings for *t* by $BCT(t)$.

Complex token bindings are usually written in the form $\langle ctv_1 = ct_1, ctv_2 = ct_2, ..., ctv_n = ct_n \rangle$ where $ctv_i \in CTVar(t)$ and $ct_i \in COD$, $1 \le i \le n$. When an element $ctv_i = ct_i$ belongs to a binding generated by *bct*, we use

$ctv_i = ct_i \triangleright bct$ to denote the relation. *bct* is used as $\langle ctv_1 = ct_1, ..., ctv_n = ct_n \rangle$ in the followings because, for each $\langle ctv_1 = ct_1, ..., ctv_n = ct_n \rangle$, there is a corresponding binding function. The relationship is defined by the *binding element* given in Definition 4-2.

Definition 4-2 (Binding Element of Complex Tokens):
A **binding element** of complex token(s) is a pair (t, bct) where $t \in T$ and $bct \in BCT(t)$. The set of all binding elements of complex tokens is denoted by $BECT$.

An OOMPNet can be represented to a tree structure $G = (V, E)$ as the example net_o shown in Figure 4-1. The case is applied for demonstrating the concepts proposed in the thesis. In the figure, a rectangle depicts a net and a directed arc connects two nets. The head of an arc is net $n_{i.j}$ located at the *i*th level and the tail is net $n_{i-1.k}$ located at one level higher which takes $n_{i.j}$ as a part. The node *r* having no superior is the root of the tree, denoted the system-net of the OOMPNet net_o. The child nodes of *r* are object-nets, $n_{2.1}$, $n_{2.2}$ and $n_{2.3}$, representing the complex tokens of *r*. A system-net holds the object-net(s) built by OOMPNets to be its complex token(s) and the complex token can be unfolded further to another system-net and object-net(s), e.g. $n_{2.1}$ is a system-net of object-net $n_{3.1}$ and $n_{3.2}$. The belonging relationships are kept by the nets located in adjacent levels for all levels lower than r. Therefore, for all descendants of *r*, a net $n_{i-1.k}$ is a system-net of another net $n_{i.j}$ if $n_{i-1.k}$ is a parent node of $n_{i.j}$ in the hierarchy.

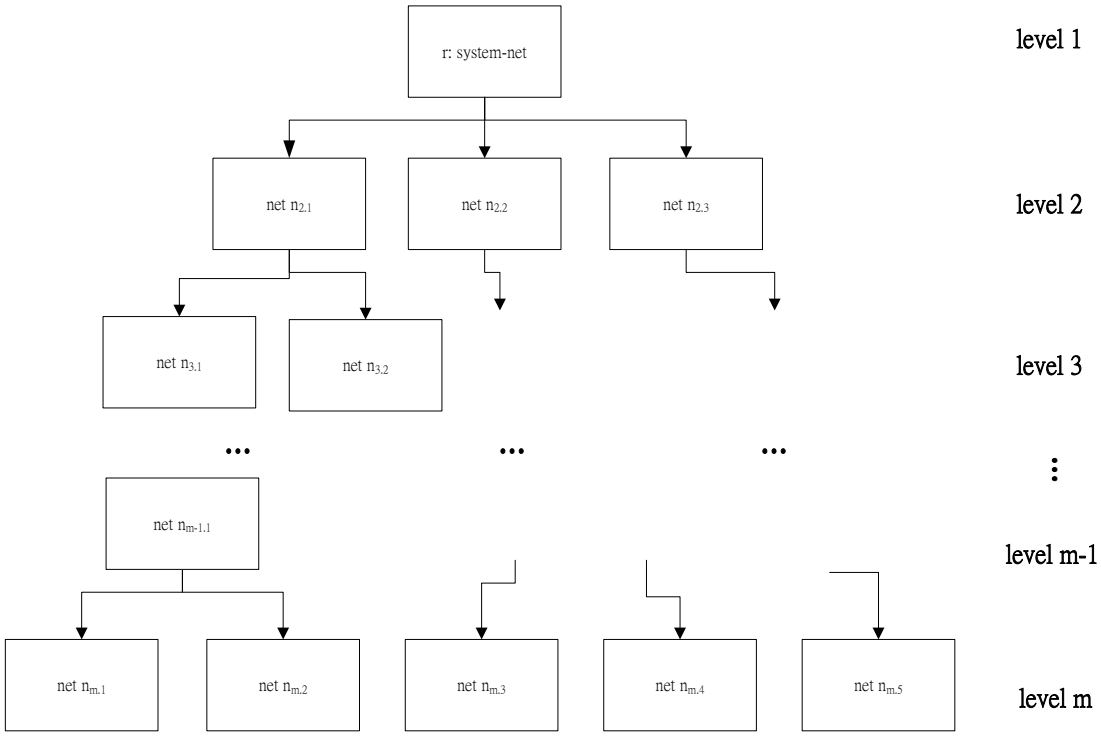


Figure4-1 the hierarchical tree structure of an OOMPNet net_o

The transformation algorithm provided in the thesis transforms an OOMPNet into a T-CPN by the *bottom-up transformation procedure*. The procedure traverses the tree of net_o from leaves at the bottom to r at the top. One step progress of the transformation is proceeded by reconstructing the system-net $n_{i\text{-}1.k}$ with it object-nets $n_{i.1},\ldots,n_{i.n}$. The net obtained replaces the sub-tree depicted for $n_{i\text{-}1.k}$ and $n_{i.1},\ldots,n_{i.n}$. The four operations: (1) combining the variables and color sets belonging to $n_{i\text{-}1.k}$ and $n_{i.1},\ldots,n_{i.n}$, (2) duplicating the places and tokens of $n_{i.1},\ldots,n_{i.n}$ into $n_{i\text{-}1.k}$, (3) generating transitions based on the complex token bindings and the synchronization relationship(s) of $n_{i\text{-}1.k}$ and (4) connecting the nodes generated in (2) and (3) by arcs according to net $n_{i\text{-}1.k}$ and $n_{i.1},\ldots,n_{i.n}$ are performed for accomplishing the reconstruction.

The concept of the algorithm moves the object-nets into the corresponding

system-net. So, the first two steps of the transformation algorithm collect the color sets, variables, tokens and places of the object-nets. Then, these elements are putted into the corresponding system-net directly. Before transformation, the complex tokens in system-net reference to object-nets respectively. After the two steps, a complex token references to the transformed places corresponding to the object-net which is referenced by the complex token before. It is because that the marking of object-net is also needed in T-CPN when builds occurrence graph.

In order to maintain the behaviors of OOMPNets in T-CPN, the third step of transformation concerns about the *BCT* of each transition and SR set. Here, this chapter defines the term Synchronous Transition Groups (*STG*), as Definition 4-3. Each group in *STG* defines which transitions are merged together. Each synchronous transition group is a set of transition(s) represented by a new transition in T-CPN. The transformation of transitions has three activities: First, creating transitions corresponding to the elements of *BECT* from each transition in the transforming OOMPNet. Second, the algorithm bases on the transitions from *BECT* and *SR* set to construct the *STG* and create the transition(s) representing the group(s) in *STG*. Third, the algorithm deletes the transition(s) which is(are) not representing the group(s) in *STG*. In a transformation, each transition t in the system-net is replaced by the transitions of the corresponding elements in set *BECT* if the $BCT(t)$ is not empty. The guard expressions of a transition corresponding to $BCT(t)$ are the primary guard expressions of the transition t. Then, the algorithm bases on the *BECT* and *SR* set to collect which transitions are merged together. If the $BCT(t)$ is empty, the transition t is added into the T-CPN directly. If a transition in system-net has synchronization relationship with a transition in object-net, its *BCT* is not empty. The transition mergence is according to *SR* set and the *bct* of each element in *BECT*. For

example, a transition t' in the object-net and a transition (t, bct) are merged together if (t, t') belongs to *SR* set and the *bct* contains the complex token representing the object-net in the system-net.

Definition 4-3 (Synchronous Transition Groups, STG):
A set of transitions form a synchronous transition group *iff* they fulfill the follows:

1. If the transition's BCT is empty or the transition in an object-net without SR with a transition in system-net, it constitutes a synchronous transition group of its own.
2. For each transition in a synchronous transition group has synchronization relation with another transition in the synchronous transition group.
3. Each synchronous transition group contains one transition from the system-net and the other transitions from object-nets which are contained in *bct* of the system-net transition are not grouped from the same transition.

For example, an OOMPNet *SN* with two object-nets, *ON1* and *ON2*, is shown in Figure 4-2. The *SR* of *SN* is $(SN:T0, ON1:T0)$. The *BECT* of the *SN* contains binding element $(SN:T0, <ctv=ON1>)$ and $(SN:T0, <ctv=ON2>)$. The synchronization transition set of $SN:T0$ holding elements $((SN:T0, <ctv=ON1>), ON1:T0)$ and $(SN:T0, <ctv=ON2>)$ is generated by the binding elements. Moreover, the STG set $\{(ON2:T0,)\}$ generated for $ON2:T0$ denotes that there is no complex token consumed when the transition is fired.

If *SN* is an object-net of another OOMPNet *USN* and transition *T0* of *USN* has a synchronization relation with *SN:T0*, the *SR*s of *USN* is adapted by the STG set of $SN:T0$. Thus, the adaption results are $(USN:T0, ((SN:T0, <ctv=ON1>), ON1:T0))$ and $(USN:T0, (SN:T0, <ctv=ON2>))$. The synchronization relations are kept by this way during net transformation.

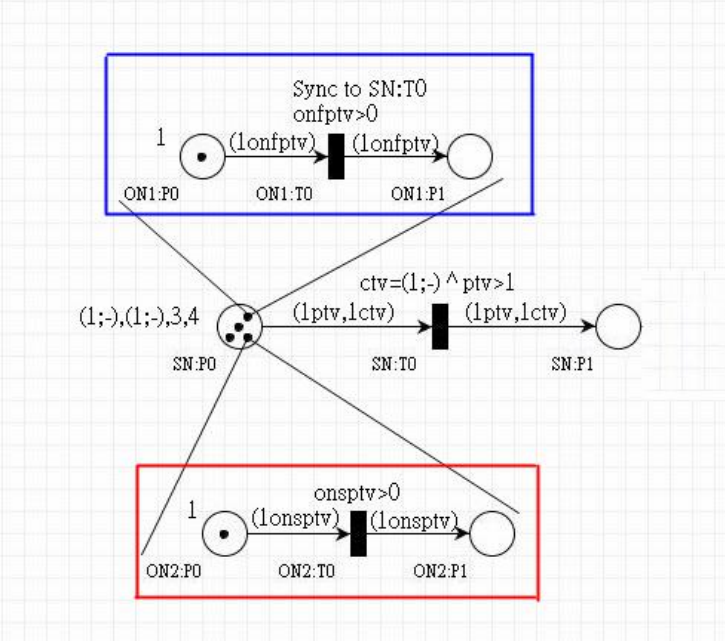


Figure.4-2. An OOMPNet *SN* contains two object-nets.

For each synchronous transition group, here defines the guard expression of the transition which represents the synchronous transition group. The synchronous guard function SGF is defined from the set of transition groups, STG, into boolean expressions:

$\forall T \in STG:$

$$SGF(T) = \wedge_{t \in T}\left(\begin{cases} G(t) \backslash \{ g \in G(t) \mid Type(g) \text{ is complex} \} & \text{,if } t \text{ in system-net and } G \text{ is the guard function of system-net} \\ G_i(t) & \text{,if } t \text{ in the } i^{th} \text{ object-net and } G_i \text{ is the guard function of } i^{th} \text{ object-net} \end{cases} \right)$$

The transformation of an arc is according to transitions and places in the *T-CPN*. Arcs in OOMPNet are duplicated, created or modified to ensure that the behavior of the T-CPN could be similar to its corresponding behavior in the OOMPNet. In order to maintain the guard expressions of transitions about object-nets, this chapter defines OOT-Property Arcs (*OOTPA*). The format of guard expression about object-nets is $ctv = m$ where ctv is a complex type variable and m is a marking of the

corresponding object-net. During a transformation, *OOTPA* is created according to the marking(s) in the guard expression(s). OOT-Property arcs are created in pairs. For example, Figure 4-2 shows a transition *SN:T0* has a complex guard expression *ctv=(1;-)*. Because the marking *(1;-)* has empty part, the corresponding places can be omitted the OOT-Property arcs. There are four OOT-Property arcs, *(ON1:P0,SN:T0)*, *(SN:T0,ON1:P0)*, *(ON2:P0,SN:T0)* and *(SN:T0,ON2:P0)*, existed in the *T-CPN*. *(ON1:P0,SN:T0) and (SN:T0,ON1:P0)* is a pair of OOT-Property arcs. Similarly, *(ON2:P0,SN:T0)* and *(SN:T0,ON2:P0)* is a pair of OOT-Property arcs. In this example, *SN:T0* has synchronization relation with *ON1:T0*, so the arc *(ON1:P0,SN:T0)* is already existed in *T-CPN* before creating OOT-Property arcs. Here discusses the arc expression of OOT-Property arcs. The creation of arc expression(s) of OOT-Property arcs is called OOT-Property arc function (OOTPAF). It contains two situations: 1) The OOT-Property arc can be added into the *T-CPN* directly. 2) There is an arc existed in the position where is the OOT-Property arc created. In the situation 1), the arc expression of the arc is multi-set of the marking described in the guard expression corresponding to the place. For example, arc expression of OOT-Property arc *(ON2:P0,SN:T0) and (SN:T0,ON2:P0)* in *T-CPN* of Figure 4-2 is *1'1*. In the situation 2), it can be separated into two kinds: i) the destination of the existed arc is a transition and ii) the destination of the existed arc is a place. The algorithm uses the existed arc to be an OOT-Property arc by modifying the arc expression(s). Concerning i), algorithm bases on the arc expression of the existed arc and the marking in the guard expression to edit the arc expression of pair OOT-Property arcs. The arc expression of the existed arc is changed into the multi-set of marking in the guard expression corresponding to the place. And, the arc expression(s) of the matched OOT-Property arc is a function. Input of the function is the multi-set of the original arc expression of the existed arc. The output of the function is subtracting the

multi-set of the original arc expression of the existed arc from the multi-set of the marking in the guard expression corresponding to the place. In Figure 4-2, the arc expressions of *(ON1:P0,SN:T0)* and *(SN:T0,ON1:P0)* are *1'1* and *f(exp)=1'1-exp* respectively. If the arc expression of OOT-Property arc is empty, the OOT-Property arc can be omitted. Concerning ii), the arc expression of the existed arc is adding the multi-set of the marking in the guard expression corresponding to the place and the original arc expression of the existed arc. And, the arc expression(s) of the matched OOT-Property arc is(are) the multi-set of the marking in the guard expression corresponding to the place.

Function 4-3 (2-levels OOMPNet transformed into CPN):

Let an OOMPNet $O = (\Sigma, V, P, T, D, F, C, G, A, I, L)$, where there is no abstract place or transition. A T-CPN $T - Net = (\vec{\Sigma}, \vec{V}, \vec{P}, \vec{T}, \vec{F}, \vec{C}, \vec{G}, \vec{A}, \vec{I})$ generated by transformation algorithm where:

1 *If* $COD = \varnothing$, *then O is a Colored Petri Net*.

1−1. The *COD* is empty, so there is no complex type color set. $\vec{\Sigma} = \Sigma$.

1−2. There is no complex type variable existed in V. So, $\vec{V} = V$.

1−3. There is no complex token, so the place set of objct-nets is empty. Then, $\vec{P} = P$.

1−4. There is no complex token, so the transition set of objct-nets is empty. Then, $\vec{T} = T$.

1−5. There is no complex token, so the arc set of objct-nets is empty. Then, $\vec{F} = F$.

1−6. The input of $\vec{C}$ is the places in $\vec{P}$. Because $\vec{P} = P$, $\vec{C} = C$.

1−7. The input of $\vec{G}$ is the transitions in $\vec{T}$. Because $\vec{T} = T$, $\vec{G} = G$.

1−8. The input of $\vec{A}$ is the arcs in $\vec{F}$. Because $\vec{F} = F$, $\vec{A} = A$.

1−9. The input of $\vec{I}$ is the places in $\vec{P}$. Because $\vec{P} = P,\ \vec{I} = I$.

2 *If* $COD \neq \varnothing, and\ |COD| = m, then$

$\forall d_{c_i} \in COD, d_{c_i} = (\Sigma_{c_i}, V_{c_i}, P_{c_i}, T_{c_i}, D_{c_i}, F_{c_i}, N_{c_i}, C_{c_i}, G_{c_i}, A_{c_i}, I_{c_i})\ and\ COD_{c_i} = \varnothing$

2−1. $\vec{\Sigma} = \Sigma \cup (\bigcup_{i=1...m} \Sigma_{c_i})$

2−2. $\vec{V} = V \cup (\bigcup_{i=1...m} V_{c_i})$

2−3. $\vec{P} = P \cup (\bigcup_{i=1...m} P_{c_i}); \forall i = 1...m, P \cap P_{c_i} = \varnothing$

2−4. $\vec{T} = STG$

2−5. $\vec{F} = \{(f, \vec{t}) \in (F \cup \bigcup_{i=1...m} F_{c_i}) \times \vec{T} \mid t(f) \in \vec{t}\} \cup OOTPA$

2−6. $\forall p \in \vec{P}, \vec{C}(p) = \begin{cases} C(p) & ,if\ p \in P \\ C_{c_i}(p) & ,if\ p \in P_{c_i} \end{cases}$

2−7. $\forall f = (f', \vec{t}) \in \vec{F}, \vec{A}(f) = \begin{cases} A(f') & ,if\ f' \in F \\ A_{c_i}(f') & ,if\ f' \in F_{c_i} - OOTPA \\ OOTPAF(f) & ,if\ f \in OOTPA \end{cases}$

2−8. $\forall t \in \vec{T}, \vec{G}(t) = SGF(t)$

2−9. $\forall p \in \vec{P}, \vec{I}(p) = \begin{cases} I(p) & ,if\ p \in P \\ I_{c_i}(p) & ,if\ p \in P_{c_i} \end{cases}$

4.2 Transformation Algorithm

An algorithm, named OOMPNetToCPN, for transforming an OOMPNet to a CPN is presented in this section. The algorithm involves three sub-algorithms, ProduceElement, CreateSTG and CreateTransition, sequentially to achieve its goal. The ProduceElement algorithm is utilized to duplicate elements of the original net to

result. The CreateSTG algorithm is used to generate synchronize transition set(s) for keeping the dependent relations between transitions. The CreateTransition algorithm is applied to create transition(s) according to the BCTs of the system-net and the synchronization transition sets generated by CreateSTG.

Let OOMPNet N be a source net of a series of transformations. A hierarchical representation of N is $G=(V,E)$. Depth-first search [11] is applied to traverse graph G. The OOMPNetToCPN algorithm is executed on object-net $n_{i.j}, n_{i,j} \in V$, and its system-net $n_{i\text{-}1.k}$ when the algorithm finishes examining $n_{i.j}$'s adjacent nodes. Let $n_{i-1,k}=(\Sigma,V,P,T,D,F,N,C,G,A,I,L)$ and $n_{i,j} \in COD$.

Algorithm 4.1: OOMPNetToCPN(OOMPNet oonet, HashMap hierarchy){

```
1.    //Input: oonet=(Σ, P, T, D, F, N, C, G, A, I, L): an OOMPNets with complex tokens
2.    //        hierarchy: a hashmap to store the hierarchical level of the transformed net
3.    //Output: net: 1-level OOMPNet
4.    for each apNet∈oonet.P.AP.net{
5.        oonet = UnfoldAbstractPlaces(oonet, apNet);
6.    }
7.    for each atNet∈oonet.T.AT.net{
8.        oonet = UnfoldAbstractTransitions(oonet, atNet);
9.    }
10.   //Unfolding all abstract places and transitions in oonet
11.   if(oonet.D.COD.size > 0){
12.     //oonet.D.COD.size means the complex token number of oonet
13.     for each d∈oonet.D.COD {
14.         //recursively transforms OOMPNets into T-CPNs
15.         OOMPNet cpn = OOMPNetToCPN(d.net, hierarchic);
16.         //integrate color sets, variables and places of object-net into correspond system-net
17.         oonet = ProduceElement(oonet, cpn, d, hierarchic);
18.     }
19.     //create the BECT transitions into net
20.     oonet=CreateTransition(oonet);
21.     ArrayList STGroup = CreateSTG(oonet.T, oonet);
22.     //the creation of synchronous transition groups is according to Def 4-3
23.     ArrayList STGTransition = new ArrayList();
```

```
24.     //store the transitions correspond to each group in STGroup
25.     for each g∈STGroup{
26.         Transition newTransition = new Transition();
27.         newTransition.stg = g;
28.         oonet.addPlaceTransition(newTransition);
29.         STGTransition.add(newTransition);
30.     }
31.     //collect arcs existed in object-nets of oonet
32.     Arc[] F' = new Arc[];
33.     for each d∈oonet.D.COD{
34.         F' = F'∪d.net.F;
35.     }
36.     for each stgt∈STGTransition{
37.      for each t∈stgt.stg{
38.         stgt.guardExpres = stgt.guardExpres ∧ t. guardExpres;
39.         for each f∈oonet.F∪F'{
40.           if(t(f)==t){
41.               Arc newArc = new Arc();
42.               if(f.source == t){
43.                   newArc.source = stgt;
44.                   newArc.target = p(f);
45.               }
46.               else{
47.                   newArc.source = p(f);
48.                   newArc.target = stgt;
49.               }
50.               newArc.expres = f.expres;
51.               oonet.addArc(newArc);
52.           }
53.         }
54.      }
55.      //create the arcs of OOTPA
56.     if(t∈T && (complex guard expressions of t is not empty)){
57.           for each m∈M{
58.           //M is the set of the markings in the complex guard expressions of t
59.           OOMPNets on = getCorrespondObjectNet(m);
60.           //getCorrespondObjectNet is used to find the object-net
61.           //corresponds to the marking m
```

```
62.                 for each p∈on.pt.p{
63.                     if(m(p)!=null){
64.                         if((p,t)∉F && (t,p)∉F){
65.                             Arc newInputArc = new Arc();
66.                             Arc newOutputArc = new Arc();
67.                             newInputArc.addExpres(multi-set of M(p));
68.                             newOutputArc.addExpres(multi-set of M(p));
69.                             newInputArc.source = p;
70.                             newOutputArc.target = p;
71.                             newInputArc.target = stgt;
72.                             newOutputArc.source = stgt;
73.                             net1.addArc(newInputArc);
74.                             net1.addArc(newOutputArc);
75.                         }
76.                         else if(f==(p,t)∈F){
77.                             Arc newArc = new Arc();
78.                             newArc.addExpres(f(exp)= multi-set of M(p) – f.guardExpres);
79.                             newArc.source = t;
80.                             newArc.target = p;
81.                             f.guardExpres = null;
82.                             f.addExpres(multi-set of M(p));
83.                             net1.addArc(newArc);
84.                         }
85.                         else if(f=(t,p)∈F){
86.                             Arc newArc = new Arc();
87.                             newArc.addExpres(multi-set of M(p));
88.                             newArc.source = p;
89.                             newArc.target = t;
90.                             net1.addArc(newArc);
91.                             f.guardExpres = f.guardExpres+multi-set of M(p);
92.                         }
93.                     }
94.                 }
95.             }
96.         }
97.         for each t∈oonet.T{
98.             if(t∉STGTransition){
99.                 oonet.deletePlaceTransition(t);
```

```
100.                }
101.            }
102.            return oonet;
103.        }
104.        else if(oonet.D.COD.size == 0){
105.            //oonet without complex token
106.            return oonet;
107.        }
108. }
```

This algorithm is the main recursive algorithm to transform OOMPNets into T-CPN. Inputs of the algorithm are one OOMPNet and a hashmap which is an index table described in Sec. 4.1. 1-level OOMPNet is an output of the algorithm. The final output is a T-CPN conform the description in Sec. 4.1.

Lines 4 to 9 in the algorithm unfold the abstract nodes in the OOMPNet. Lines 11 to 107 separate the input OOMPNet into two situations according to the number of complex token. An OOMPNet is 1-level if its complex token number is 0. Lines 104 to 107 return the inputted OOMPNet which is 1-level originally. Lines 11 to 105 concern the number of complex token is bigger than 0. Lines 8 to 13 find out the object-net which is 1-level OOMPNet by calling itself. Then, function ProduceElement in line 17 integrates the declarations, places and tokens of the object-net into its system-net. For a 2-level OOMPNet, the declarations, places and tokens of all object-nets are integrated into the system-net after the for-loop in line 13 to 18 finish. Then, lines 20 to 101 realize the third and forth steps in transformation. Lines 20 to 30 transform transitions and lines 31 to 101 transform arcs. Line 20 calls function CreateTransition for creating the transitions corresponding to BCT of all transitions in oonet and put these new created transitions into oonet. Lines 21 to 30, like STG described in Def. 4-3, create STG and transitions correspond to the group of

STG. These transitions corresponding to the groups in STG are the final result of transforming transitions. The other transitions will be deleted in lines 97 to 101. Lines 39 to 53, like set $\{(f,\vec{t}) \in (F \cup \bigcup_{i=1...m} F_{c_i}) \times \vec{T} \mid t(f) \in \vec{t}\}$ in Function 4-3, transform the original arcs. Lines 56 to 96 create the arcs of OOTPA described in Sec. 4.1.

Algorithm 4.2: CreateTransition(OOMPNet sn){

1. //**Input**: sn=(Σ, P, T, D, F, N, C, G, A, I): is a 2-level OOMPNet without the transitions created based on BCT.
2. //**Output**: rn: an OOMPNet with the transitions created based on BCT.
3. **for each** t∈T{
4. T' = the set of transitions corresponding to BCT(t)
5. **for each** t'∈T'{
6. //edit the initial data of transition t'
7. t'.correspond=t;
8. //store the t' is corresponding to which original transition
9. t'.addGuardExpres(IGE);
10. //t' corresponds to bct, IGE=bct∪{primary type guard expression of transition t}
11. **if**(sn not contain t'){
12. sn.addPlaceTransition(t');
13. //add the t' transition into sn
14. }
15. }
16. }
17. **for each** t∈T{
18. **if**(t.correspond == null && BCT(t)≠∅){
19. sn.deletePlaceTransition(t);
20. }
21. }
22. rn=sn;
23. **return** rn;
24. }

Lines 3 to 16 in the algorithm create transition(s) corresponding to the *BCT* of all transition(s) in the inputted *OOMPNet*. Lines 5 to 13 add new created transition(s)

into the inputted *OOMPNet*. In order to recognize the new created transition from which transition, a transition associates with a tag correspond. Line 7 let the new created transition store the transition which it corresponds to into the tag. Line 9 adds the guard expression into the new created transition. The guard expression(s) are the corresponding *bct* and primary guard expression(s) from the transition which the new crated transition corresponds to. After above activities, the new crated transition is added into the inputted *OOMPNet* in line 12. Lines 17 to 21 delete the transitions which are replaced by their *BCT*.

Algorithm 4.3: ProduceElement (OOMPNet net1, OOMPNet net2, ComplexToken ct, HashMap hierarchy){

```
1.    //Input: net1=(Σ, P, T, D, F, N, C, G, A, I): the system-net corresponds to net2
2.    //        net2=(Σ', P', T', D', F', N', C', G', A', I'): the object-net corresponds to net1
3.    //        ct: a complex token in net1 represents net2
4.    //        hierarchy: store the hierarchical level of transformed OOMPNet
5.    //Output: resultNet: after merging net2 into net1
6.    net1.Σ = net1. Σ ∪ net2. Σ';
7.    //unite declarations of net1 and net2
8.    ArrayList integratedPlaces = new ArrayList();
9.    for each p∈net2.P{
10.   //Add all places of net2 into net1
11.   Place clonePlace = p.clone();
12.   net1.addPlaceTransition(clonePlace);
13.   integratedPlaces.add(clonePlace);
14.   }
15.   hierarchy.put(ct.name, integratedPlaces);
16.   //store the representation relation of net2 in net1
17.   resultNet=net1;
18.   return resultNet;
19. }
```

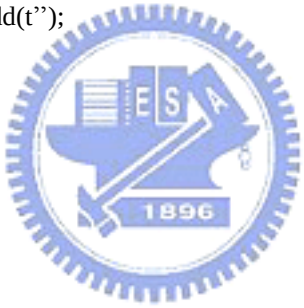
This algorithm integrates the color sets, variables and places of the object-net into the corresponding system-net. Line 6 integrates the color sets and variable of net2

into net1. Lines 9 to 14 integrate the clones of places in net2 into net1. The complex token references to the clones of places in net2 in net1 and store the relation into index table in line 15.

Algorithm 4.4: CreateSTG(OOMPNet sn){

```
1.    //Input: sn: the system-net which is needed to transform
2.    //Output: ArrayList: groups, the transitions are grouped into synchronous transition group
3.    ArrayList STG = new ArrayList();
4.    ArrayList totalAdded = new ArrayList();
5.    for each t∈sn.T{
6.     if(t.correspond≠null){
7.       //concerning the transition created from function CreateTransition
8.       OOMPNets[] ON = getObjectNetsInbct(t);
9.       //get all object-nets contained in the bct where t is corresponding to bct
10.      ArrayList[] syncTransitions = new ArrayList[ON.size+1];
11.      int count = 0;
12.      for each on∈ON{
13.            ArrayList addedTransition = new ArrayList();
14.            // used to record the collected transitions
15.            for each t'∈on.T{
16.                  //on.T is the transition set in on
17.                  ArrayList tempArray = new ArrayList();
18.                  // used to collect the synchronous transitions which are
19.                  //created from the same transition into to an array
20.                  if((t.correspond, t')∈sr && t'∉addedTransition){
21.                        //t and t' have synchronization relation and t' is not collected
22.                        tempArray.add(t');
23.                        addedTransition.add(t');
24.                        for each t''∈on.T{
25.                              if(t''.stg and t'.stg≠∅ have transitions representing the BCT
                                        from the same transition){
26.                                 tempArray[count].add(t'');
27.                                 addedTransition.add(t'');
28.                              }
29.                        }
30.                        if(tempArray is not empty){
```

```
31.                                 syncTransition[count].add(tempArray);
32.                             }
33.                         }
34.                     }
35.                     totalAdded.addAll(addedTransition);
36.                     count++;
37.                 }
38.                 syncTransition[count].add(t);
39.                 STG.addAll(Combination(syncTransition));
40.                 //Combination is used to create the stgs containing transition t.
41.                 //the function Combination collects different groups from the arrays in syncTransition
42.                 //each group is created from pick up exactly one transition from
43.                 //each array in syncTransition
44.                 for each d∈sn.D.COD{
45.                     for each t''∈d.net.T{
46.                         if(t''∉totalAdded){
47.                             STG.add(t'');
48.                         }
49.                     }
50.                 }
51.             }
52.             else{
53.                 STG.add(t);
54.             }
55.         }
56.         return STG;
57.     }
```



This algorithm creates *STG* described in Def. 4-3. The input of the algorithm is the transition set of the corresponding system-net. The *STG* is the output of the algorithm. This algorithm separates the inputted transition set into two situations. One is the original transitions where the *BCT* of the transition is empty. The other is the transitions corresponding to *BCT*. Lines 6 to 51 deal the transition corresponding to *BCT*. The other transitions are dealt at lines 52 to 54. Line 8 calls function getObjectNetsInbct to get the object-nets which are related to the input transition.

Lines 12 to 37 is a *for* loop which concerns the transitions in related object-nets to collect transitions into corresponding arrays. In the *for* loop, it concerns the transitions in related object-nets where the transitions have synchronous relationship with current transition in system-net. An array collects the transitions which are transformed from the same transition. If transitions are transformed from the same transition, the groups which are represented by the transitions contain elements representing the elements of *BCT* from the same transition. Lines 24 to 29 collect the transitions which are transformed from the same transition into the same array. And, the transition in system-net is represented an array and putted into the arrays. The arrays of each transition in system-net are input of function Combination to generate synchronous transition groups in line 39. The way of grouping synchronous transition groups in function Combination is that each array is picked one transition to be a group. The output of function Combination is different groups from the input arrays. After grouping all synchronous transition groups of transitions in system-net, the ungrouped transitions in system-net or object-nets are grouped respectively and putted into the group set from above activities at lines 44 to 55. Line 56 return the finial group set to the calling function.

Chapter 5 Example

To demonstrate the usages of *OOMPNE* and *OOMPOA*, this section introduces a scenario "transfer account successfully" in use case "Transfer Account". The scenario is modeled as an *OOMPNet* by using *OOMPNE*. The modeling process of using *OOMPNE* is introduced step by step as the following. Then, OONPOA is applied in this example to illustrate the steps of transforming *OOMPNets* into *T-CPN*, and the corresponding analysis.

5.1 Edit OOMPNets with OOMPNE

Table 5-1 shows the specification of use case "Transfer Account" and Table 5-2 shows a scenario "Transfer Account Successfully" of the use case.

Use Case
Title: Transfer Account **Goal**: ATM supports user to transfer money from one account to another. **Related Actors**: User, System Manager **Primary Actors**: User **Trigger:** User **Precondition**: ATM is turned on and the ATM is idle. **Primary Scenario**: Steps: Pre: ATM is turned on and the ATM is idle. 1. User provides card and information to identify his identity. Pre: User identity has no problem. 2. User transfers money. **Alternatives**: 1a. User doesn't pass the identity verification within 1 times. 1a1. ATM shows an "invalid identity" message.

Pre: The message is shown. 1a2. GO TO step 1. 1b. User doesn't pass the identity verification 2 times. 1b1. ATM terminates the transaction. 2a. The transaction is fail. 2a1. ATM terminates the transaction. **Exceptions: could happen at any time** 1. The power supply is cut off suddenly. (1) Maintainer turns on ATM's power supply. (2) System manager turns on ATM system. **Postcondition**: A transfer of money is executed successfully.

Table 5-1 The specification of "Transfer Account".

Scenario: Transfer Account Successfully
Pre: ATM is closed. 1. System manager turns on ATM. Pre: ATM is turned on and the ATM is idle. 2. User provides card and information to identify his identity. Pre: User identity has no problem. 3. User transfers money.

Table 5-2 The scenario of "Transfer Account Successfully"

In the process of modeling scenario "transfer account successfully", the first step declares the color sets and variables needed. Figure 5-1 shows the window of declaring four color sets. The declared color sets are ATM, Information, Customer, and Management. Color set ATM belongs to complex type and the others belong to primary type. Because color set ATM is complex, OOMPNE creates a new sheet for the user to model the type of the complex color set after user declares color sets. Figure 5-2 shows the net of the color set ATM. The details of modeling ATM are similar to modeling scenario "transfer account successfully", so it is described later. Figure 5-3 shows the activities of declaring variables. Here, this OOMPNet needs be

declared five variables, e.g. controller, user, machine, password, and account.

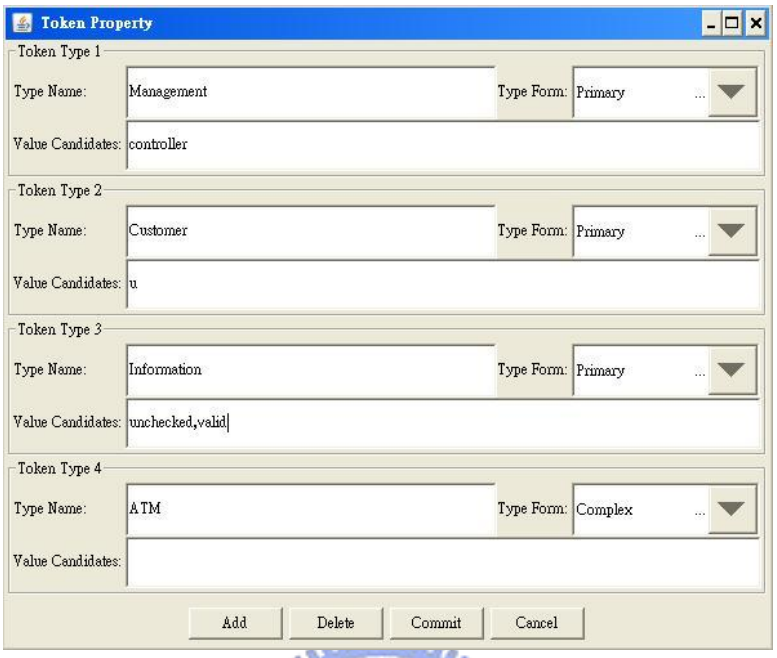


Figure 5-1 The window of declaring color sets.

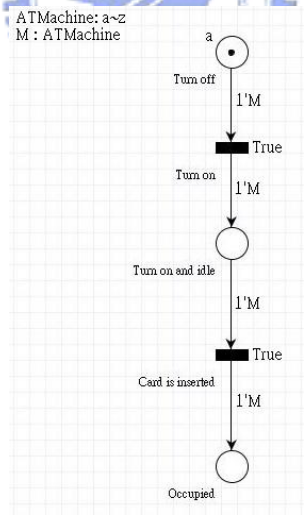


Figure 5-2 The OOMPNet of color set ATM.

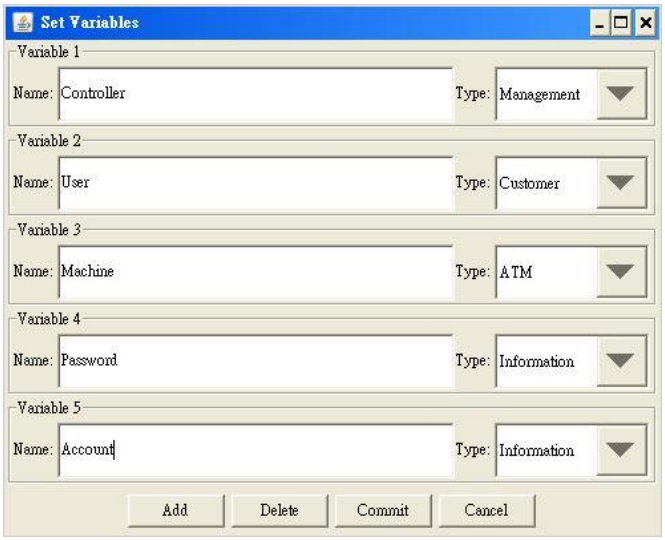


Figure 5-3 The window of declaring variables.

The second step is based on Table 5-2 to model the net structure of scenario "transfer account successfully" and edit the inscriptions of the net elements. The process of creating and editing net elements are described in Section 3.1. When user edits the inscription of arcs, OOMPNE will remind user of his/her error edition. Figure 5-4 shows the reaction of OOMPNE if user edits an inscription which might cause some abnormal phenomena. After creating and editing net elements, the modeled OOMPNet of scenario "transfer account successfully" is shown in Figure 5-5. The top-left is the declared color sets and variables. And, transition "System manager turns on ATM" synchronizes with the transition "turn on" in object-net atm.

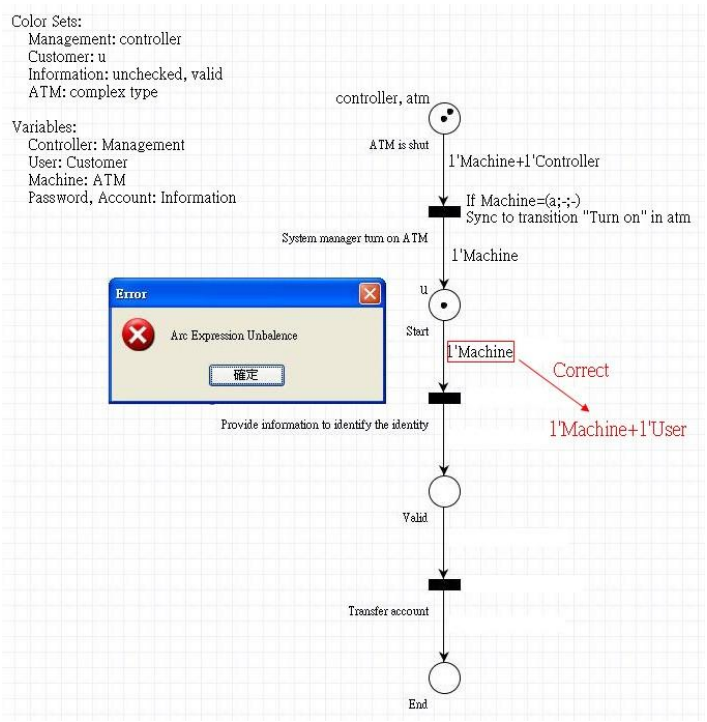


Figure 5-4 The warning message of editing unbalance inscriptions of arc (Start, Provide information to identify the identity).

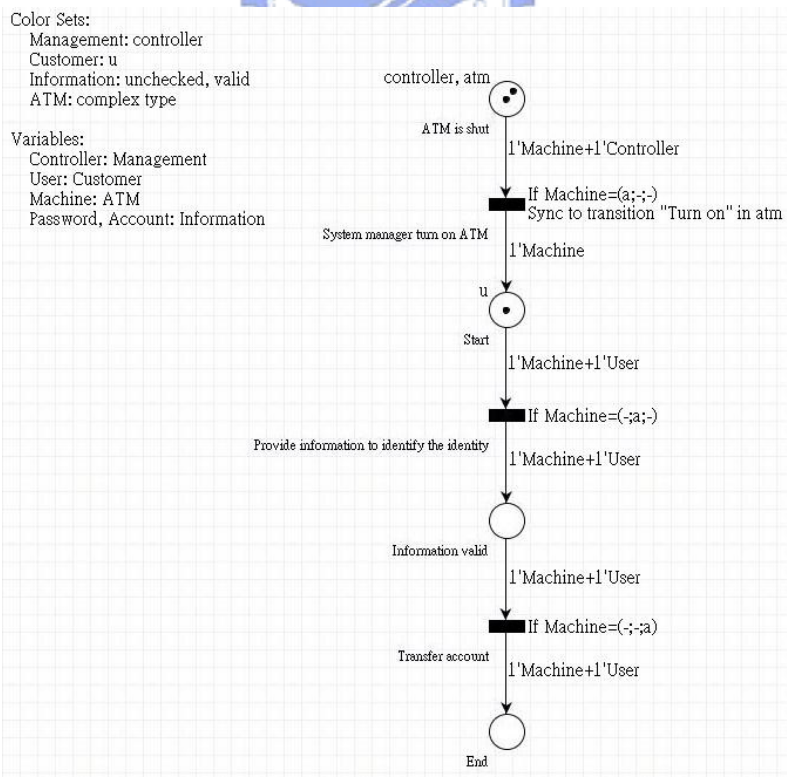


Figure 5-5 The OOMPNet of scenario “transfer account successfully”.

The final step of the modeling process refines the nodes which are needed to be refined. In current status of the modeled OOMPNet, transition “provide card and information to identify the identity” need be refined. Table 5-3 shows the refinement of transition “provide card and information to identify the identity”, and user uses the popup menu associated with transition to set the transition to be abstract. OOMPNE creates new sheet for user to model the refinement in Table 5-3. Figure 5-6 shows the OOMPNet of the refinement. Transition “Insert ATM card” in the refinement synchronizes with transition “Card is inserted” in object-net atm. Similarly, transition “transfer account” in Figure 5-5 need be refined. The refinement of transition “transfer account” is shown in Table 5-4. The modeled OOMPNet of the refinement is shown in Figure 5-7.

Refinement of transition “provide card and information to identify the identity”
Pre: ATM is turn on and idle 1. User inserts the ATM cash card. Pre: ATM is occupied 2. User enters the password. Pre: ATM is occupied and password is unchecked. 3. ATM verifies password.

Table 5-3 The refinement of transition “provide card and information to identify the identity”

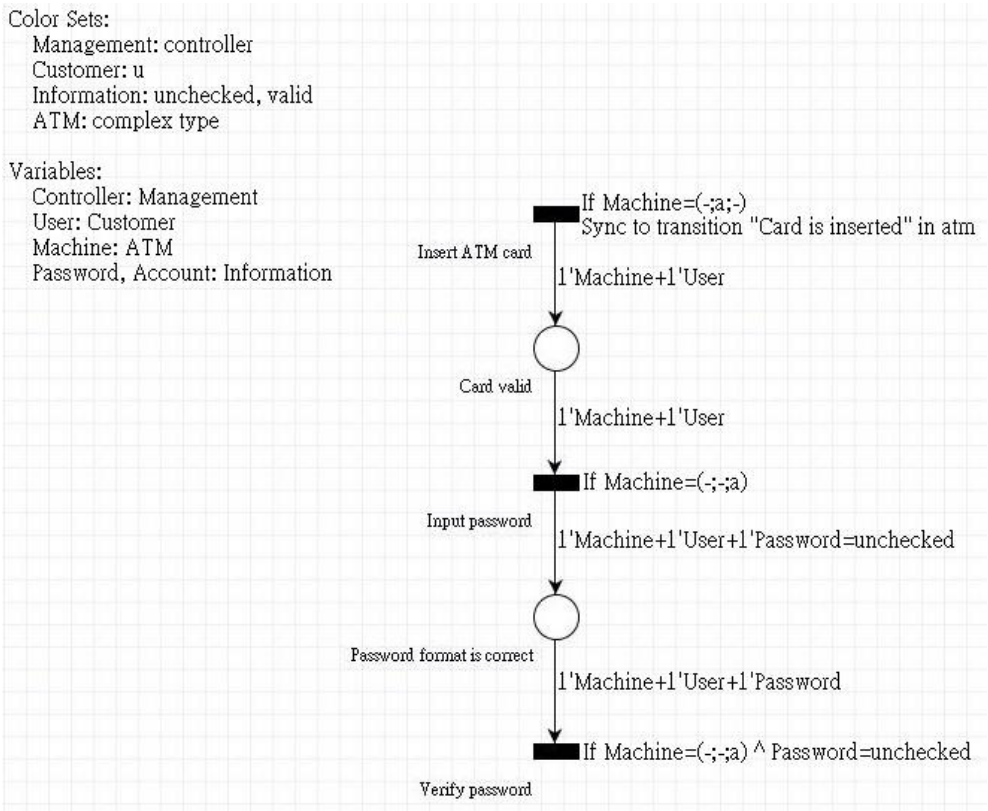


Figure 5-6 The OOMPNet of refinement described in Table 5-3

Refinement of transition “transfer account”
Pre: ATM is occupied.
1. User selects function “transfer account”.
Pre: ATM is occupied.
2. User enters account number.
Pre: ATM is occupied and account is unchecked.
3. ATM checking account number format.
Pre: ATM is occupied and account is valid.
4. User enters the amount of money.
Pre: ATM is occupied.
5. User rechecks transfer information.

Table 5-4 The refinement of transition “transfer account”.

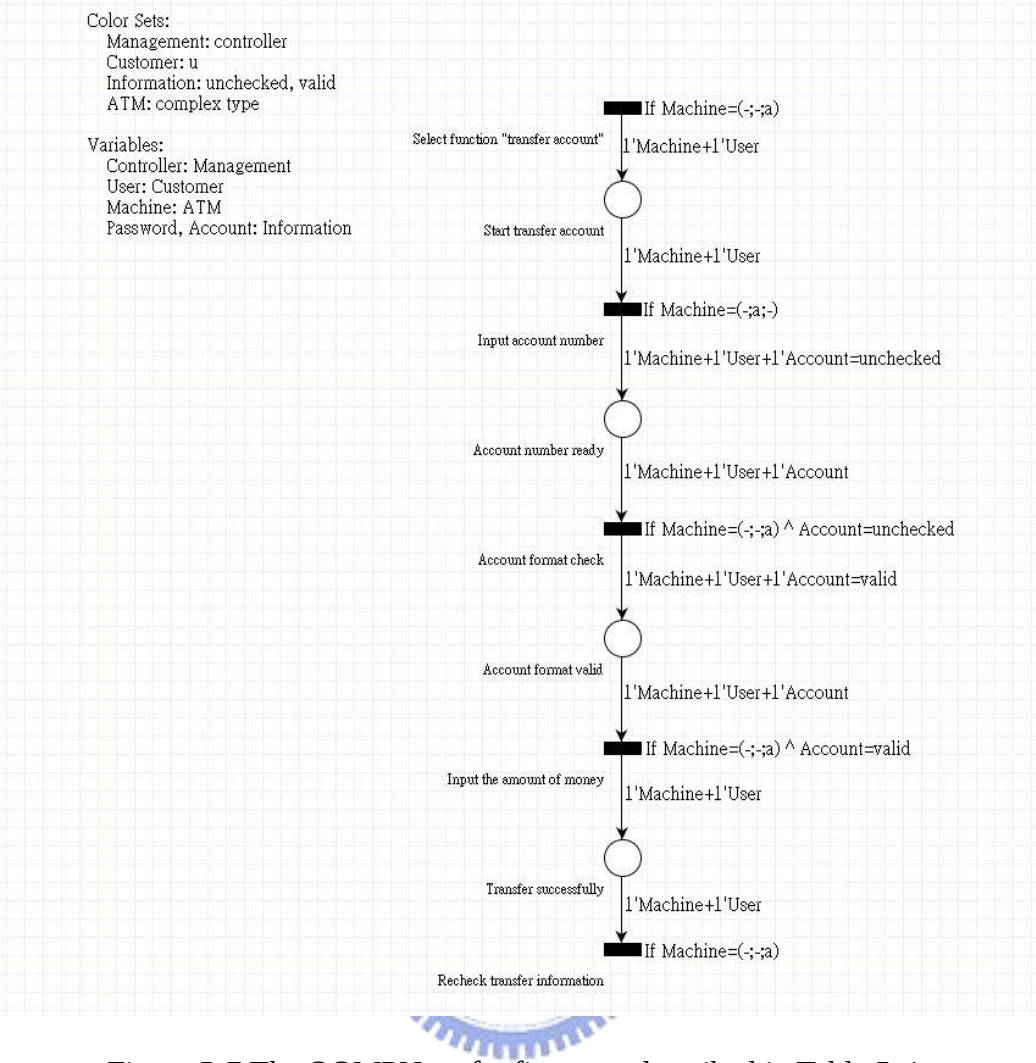


Figure 5-7 The OOMPNet of refinement described in Table 5-4.

From the above three steps, a scenario can be modeled as an OOMPNet by using OOMPNE. User can use function “Merge abstract nodes” to unfold the abstract node. After unfolding abstract nodes, user can see the whole OOMPNet of scenario “transfer account successfully” without aligning. Figure 5-8 shows the whole OOMPNet of scenario “transfer account successfully”. The two abstract transitions are replaced by their OOMPNets of refinements respectively. The inscriptions in above figure are the same as those in latter Figures. They will be omitted then.

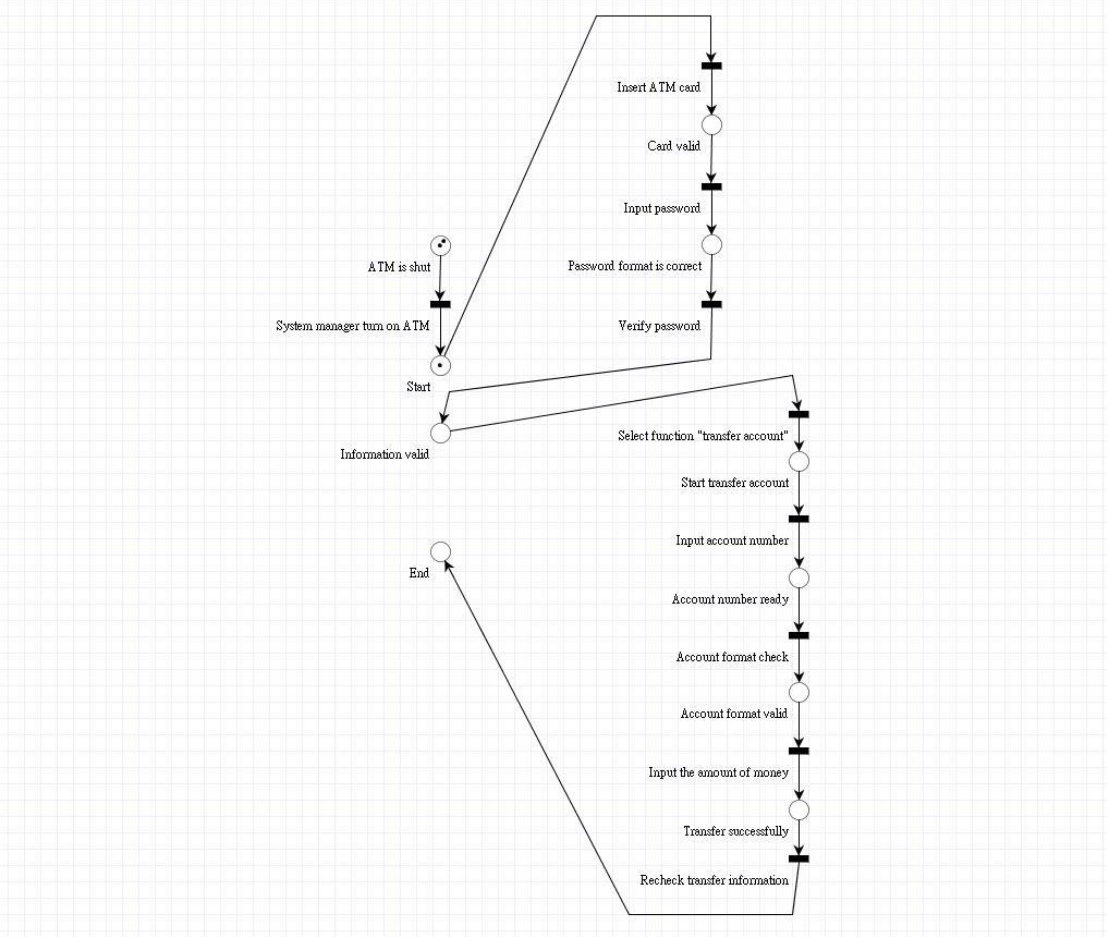


Figure 5-8 The OOMPNet of scenario “transfer account successfully”.

5.2 Analyzer in OOMPNets, OOMPOA

To analyze OOMPNets, there are four steps to achieve. The first one transforms the OOMPNet into T-CPN with a transformation algorithm. Secondly, user constructs the occurrence graph of the T-CPN. This step can be done automatically, too. The third step uses the built occurrence graph to investigate dynamic properties, e.g. liveness property, home property and so on. According the results of the investigated dynamic properties, the error(s) embedded in the T-CPN can be found. The forth step maps the found errors to the original OOMPNet. Figure 5-9 and 5-10 show the T-CPN transformed from the OOMPNet of scenario “transfer account successfully” and the

occurrence graph respectively. The T-CPN contains an index table which maps the transformed complex token in OOMPNet to the transformed places of the corresponding object-net. The red arcs in the T-CPN are arcs of OOTPA described in Sec. 4.1. The transitions in the T-CPN are corresponding to the groups of STG. So, the label of each transition in the T-CPN is the format of the groups in STG. For example, the transition $\{(System\ manager\ turn\ on\ ATM, < Machine = atm >), Turn\ on\}$ in the T-CPN is generated by grouping the *bct* of transition *System manager turn on ATM* and the transition *Turn on* in the object-net atm. The *bct* is $< Machine = atm >$ where *Machine* is complex type variable and *atm* is the name of the complex token. The occurrence graph in Figure 5-10 is a direct graph. Vertices in occurrence graph are representing the reachable markings of the T-CPN. The format of markings is (multi-set of tokens in place 1; multi-set of tokens in place 2; …; multi-set of tokens in place n) where n is the number of places in the T-CPN. A complex token is represented by the marking of the corresponding object-net according to the index table. Because the format of markings is too long, the code names are used to represent markings instead. For example, *(1)* in Figure 5-10 represents the marking $((a;-;-), controller; u;-;-;-;-;-;-;-;-)$ and so on. An edge in occurrence graph means a transition fired associated with a binding. The format of steps is $(transition, binding\ element)$. For example, step3 $(\{(Input\ password, < Machine = atm >)\}, < User = u >)$ fires the transition *Input password* and the binding element is <*User*=*u*>.

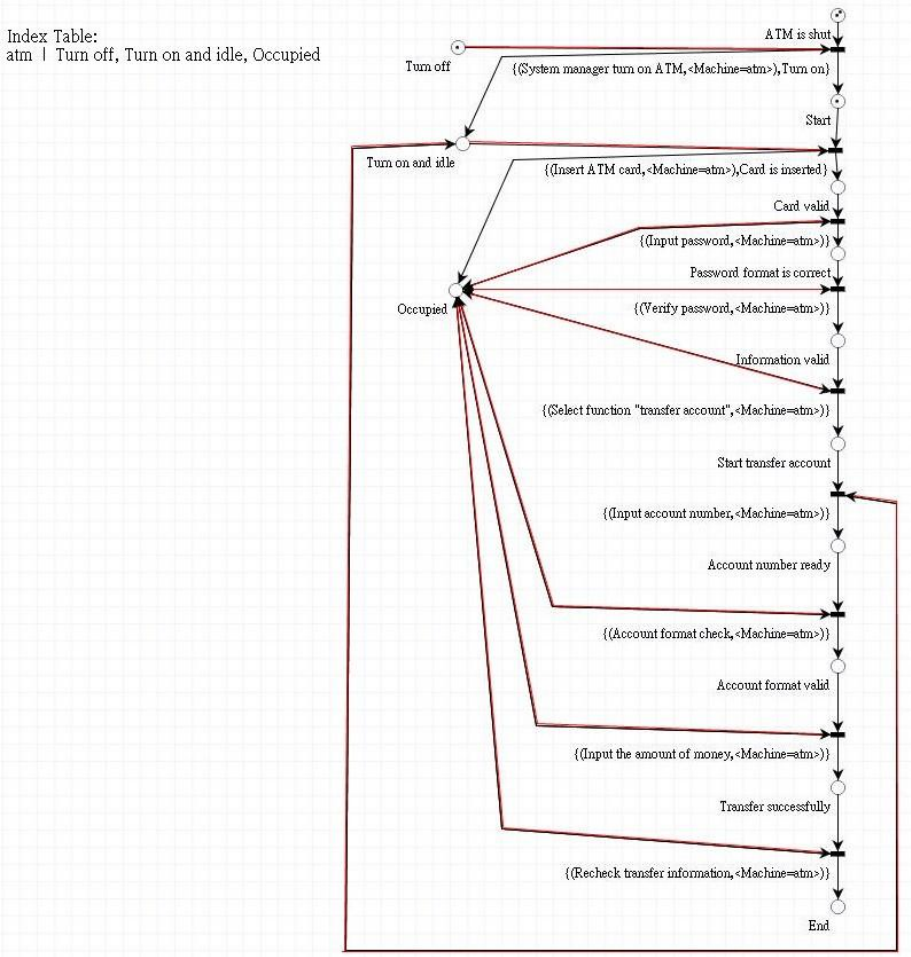
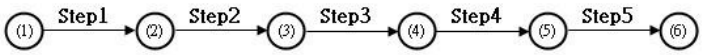


Figure 5-9 T-CPN of OOMPNet in Figure 5-5.



Marking:

(1) : ((a ; - ; -),controller ; u ; - ; - ; - ; - ; - ; - ; - ; -)
(2) : (- ; (- ; a ; -),u ; - ; - ; - ; - ; - ; - ; - ; -)
(3) : (- ; - ; (- ; - ; a),u ; - ; - ; - ; - ; - ; - ; - ; -)
(4) : (- ; - ; - ; (- ; - ; a),u,unchecked ; - ; - ; - ; - ; - ; -)
(5) : (- ; - ; - ; - ; (- ; - ;),u ; - ; - ; - ; - ; -)
(6) : (- ; - ; - ; - ; - ; (- ; - ; a),u ; - ; - ; - ; -)

Steps:

Step1 : ({(System manager turn on ATM, <Machine=atm>), Turn on}, <Conyroller=controller>)
Step2 : ({(Insert ATM card, <Machine=atm>), Card is inserted}, <User=u>)
Step3 : ({(Input password, <Machine=atm>)}, <User=u>)
Step4 : ({(Verify password, <Machine=atm>)}, <Password=unchecked, User=u>)
Step5 : ({(Select function "transfer account", <Machine=atm>)}, <User=u>)

Figure 5-10 The occurrence graph of T-CPN in Figure 5-9.

Now the occurrence graph is analyzed to calculate four dynamic properties, best integer bounds, best multi-set bounds, liveness and home properties. According to the dynamic properties described in [1] and [2], Figures 5-11~5-14 show the results of the investigated dynamic properties.

Best Integer Bounds	Upper	Lower
ATM is shut	2	0
Start	2	0
Card valid	2	0
Password format is correct	3	0
Information valid	2	0
Start transfer account	2	0
Account number ready	3	0
Account format valid	3	0
Transfer successfully	2	0
End	2	0
Turn off	1	0
Turn on and idle	1	0
Occupied	1	0

Figure 5-11 The best integer bounds of the T-CPN.

Figure 5-11 shows the best integer bounds of the T-CPN. It contains two kinds, best upper integer bounds and best lower integer bounds. The best upper integer bound of a place specifies the maximum number of tokens associated with the place in any reachable markings. The upper integer bound of place *Start* is 2 which means place *Start* has at most 2 tokens, and there is at least one reachable marking whose place *Start* has 2 tokens too. Similarly, the lower integer bound of a place specifies the minimum number of tokens associated with the place in any reachable markings. The lower integer bound of place *Start* is 0 which means that there is at least zero token associated with place *Start* and there exists a reachable marking where there is no

token associated with place *Start*. A similar remark applies to other places.

Best Upper Multi-set Bounds	
ATM is shut	1’atm+1’controller
Start	1’atm+1’u
Card valid	1’atm+1’u
Password format is correct	1’atm+1’u+1’unchecked
Information valid	1’atm+1’u
Start transfer account	1’atm+1’u
Account number ready	empty
Account format valid	empty
Transfer successfully	empty
End	empty
Turn off	1’a
Turn on and idle	1’a
Occupied	1’a
Best Lower Multi-set Bounds	
ATM is shut	empty
Start	empty
Card valid	empty
Password format is correct	empty
Information valid	empty
Start transfer account	empty
Account number ready	empty
Account format valid	empty
Transfer successfully	empty
End	empty
Turn off	empty
Turn on and idle	empty
Occupied	empty

Figure 5-12 The best multi-set bounds of the T-CPN.

Above paragraph describes the best integer bounds of a place which ignores the token colors. Figure 5-12 shows the best upper and lower multi-set bounds of places.

It considers not only the number of tokens but also the colors of tokens. The best upper multi-set bound of a place specifies all possible multi-sets of token colors associated with the place where the sum of the coefficient of colors in each multi-set is equal to the best upper integer bound of the place. For example, the best upper multi-set bound of place *Start* has only one possible multi-set, 1'atm+1'u, where the sum of coefficient of colors in the multi-set is equal to the best upper integer bound of the place. It means that there exist reachable markings where one *atm* and one *u* are associated with place *Start*. Similarly, the best lower multi-set bound of a place specifies all possible multi-sets of token colors associated with the place where the sum of the coefficient of colors in each multi-set is equal to the best lower integer bound of the place. For example, the best lower multi-set bound of place *Start* is empty where the sum of coefficient of colors is 0 equal to the best lower integer bound of place *Start*. It means that there exists a reachable marking where there is no token associated with place *Start*. A similar remark applied to other places.

Home Properties	
Home Markings:	*(6)*

Figure 5-13 The home properties of the T-CPN.

Figure 5-13 shows the home properties of the T-CPN. The home properties show that there exists a single home marking, *(6)*. Home marking means that all reachable markings can reach to the home marking. In other words, it is impossible to have an occurrence sequence which cannot be extended to reach the home marking [1].

Liveness Properties	
Dead Markings:	*(6)*
Dead Transitions:	$\{(Input\ account\ number, < Machine = atm >)\}$,
	$\{(Account\ format\ check, < Machine = atm >)\}$,
	$\{(Input\ the\ amount\ of\ money, < Machine = atm >)\}$,
	$\{(\mathrm{Re}check\ transfer\ \mathrm{inf}ormation, < Machine = atm >)\}$
Live Transitions:	None

Figure 5-14 The liveness properties of the T-CPN.

The liveness properties specify three items which are dead markings, dead transitions and live transitions. A marking is dead if and only if it is impossible to enable a transition in the marking. A transition is a dead transition if and only if the transition cannot be enabled in any reachable markings. A transition is a live transition if and only if the transition is enabled in any reachable markings. The liveness properties of the T-CPN above are shown in Figure 5-14. There is a single dead marking (6) specified in Figure 5-14. There are four dead transitions in the T-CPN. Finally, there are no live transitions.

According to the above investigated dynamic properties, developer traces to find out errors which are embedded in net elements. The OOT-Property arcs connect to transition $\{(Input\ account\ number, < Machine = atm >)\}$ cause transition $\{(Input\ account\ number, < Machine = atm >)\}$ to be unfirable. OOT-Property arcs are transformed from the complex type guard expression of transitions. And, transition $\{(Input\ account\ number, < Machine = atm >)\}$ corresponding to the group in STG is grouped from the transition *Input account number* in original OOMPNet. So, developer can check the guard expression of transition *Input account number* to find out errors. It finds that the guard expression $Machine = (-; a; -)$ in transition *Input account number* is an error inscription. The error inscription causes the transition and the following transitions to be dead transitions.

Chapter 6 Conclusion and Future Work

The major contribution of this thesis is to develop OOMPNE and OOMPOA of the development environment for OOMPNets. OOMPNE is an editor for user to model a well-form net structure OOMPNets. During the editing, OOMPNE provides some checks to prevent abnormal phenomena appearing in the OOMPNet being modeled. After modeling an OOMPNet, the net is analyzed to find out error(s). Besides, the thesis provides an analysis tool, OOMPOA, to analyze OOMPNets based on CPN and occurrence graph. OOMPOA transforms an OOMPNet into CPNs and calls the analysis methods of CPNs to analyze the results.

The future works are listed as follows:

1. Most editors for modeling CPNs have a simulator to validate the net modeled by finding some anomalies related to the net's behaviors. A simulator for OOMPNE is an extension in the future.
2. The dynamic properties are applied to analyze CPN. Current dynamic properties found in transformed CPNs might be transformed back as the dynamic properties for OOMPNets for analysis.

Reference

[1] Kurt Jensen, “Coloured Petri Nets: Basic Concepts,” Springer, 1992.

[2] Kurt Jensen, “Coloured Petri Nets: Analysis Methods,” Springer, 1995.

[3] PIPE2, http://pipe2.sourceforge.net/.

[4] Ching Huey Wang, Feng Jian Wang, “An Object-Oriented Modular Petri Nets for Modeling Service Oriented Applications”, International Computer Software and Applications Conference (COMPSAC 2007).

[5] Anne Vinter Ratzer, Lisa Wells, Henry Michael Lassen, Mads Laursen, Jacob Frank Qvortrup, Martin Stig Stissing, Michael Westergaard, Søren Christensen, Kurt Jensen, “CPN Tools for Editing, Simulating, and Analysing Coloured Petri Nets”, Applications and Theory of Petri Nets 2003: 24th International Conference, ICATPN 2003, pages 450-462, Springer-Verlag, Berlin, 2003.

[6] Kurt Jensen, Lars Michael Kristensen and Lisa Wells, “Coloured Petri Nets and CPN Tools for Modelling andValidation of Concurrent Systems”, International Journal on Software Tools for Technology Transfer, vol. 9 (2007), Springer Verlag, 213-254.

[7] Glenn Lewis, Charles Lakos, “Incremental State Space Construction for Coloured Petri Nets”, Applications and Theory of Petri Nets 2001: 22nd International Conference, ICATPN 2001, pages 263-282, Springer-Verlag, Berlin, 2001.

[8] Søren Christensen, Niels Damgaard Hansen, “Coloured Petri Nets Extended with Channels for Synchronous Communication”, Applications and Theory of Petri Nets 1994: 15th International Conference, ICATPN 1994, pages 159-178, Springer-Verlag, Berlin, 1994.

[9] Charles Lakos, “From Coloured Petri Nets to Object Petri Nets”, Applications and Theory of Petri Nets 1995: 16th International Conference, ICATPN 1995, pages 278-297, Springer-Verlag, Berlin, 1995.

[10] Colored Petri Nets, http://www.daimi.au.dk/CPnets/.

[11] Thomas H. Cormen, Charles E. Leiserson, Ronald L. Rivest, Clifford Stein, “Introduction to Algorithms” Second Edition, The MIT Press, 2001.