3 ANALYZING THE SAFETY OF WORKFLOW AUTHORIZATION MODELS

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Abstract: *Workflow Management Systems* (WFMS) are being widely used today by organizations to coordinate the execution of various applications representing their day-to-day tasks. To ensure that these tasks are executed by authorized users or processes (subjects), and to make sure that authorized subjects gain access on the required objects only during the execution of the specific task, granting and revoking of privileges need to be synchronized with the progression of the workflow through proper authorization mechanisms. Recently, Atluri and Huang have proposed a *workflow authorization model* (WAM) that provides such synchronization. This paper, first extends WAM to support roles and authorization constraints such as separation of duties. Second, it develops methodologies to analyze the safety of workflow authorization model when authorization constraints are imposed. The analysis is carried out by modeling WAM as a suitable Petri net (PN) and by utilizing the well-established analysis techniques of PNs.

3.1 INTRODUCTION

Workflow Management has emerged as the technology to automate the coordination of day-to-day activities (called tasks) of business processes. Today wide use of *Workflow Management Systems* (WFMS) can be found in a number of domains including office automation, finance and banking, healthcare, telecommunications, manufacturing and production. The various tasks in a workflow are executed by several users or programs according to the organizational rules relevant to the processes represented by the workflow. To ensure that these tasks are executed by authorized users or processes (subjects), proper authorization mechanisms must be in place. Moreover, to make sure that authorized

subjects gain access to the required objects only during the execution of the specific task, granting and revoking of privileges need to be synchronized with the progression of the workflow. Recently, Atluri and Huang have proposed a *workflow authorization model* (WAM) [2] that provides such synchronization.

It is common to many organizations to express security policies in terms of *roles* rather than users. For example, a nurse is authorized to administer a medication to a patient. Roles represent organizational agents intended to perform certain job functions within the organization. Users in turn are assigned appropriate roles based on their qualifications. Such role based authorization simplifies security administration. In addition, rules specifying *separation of duties* are imposed to reduce the risk of frauds by not allowing any individual to have sufficient authority within the system to perpetrate a fraud on his own. Such authorization constraints can be found in many application domains. For example, in a paper reviewing process, a person is never allowed to review his/her own paper, and a paper must be reviewed by at least three different individuals.

Although WAM is capable of providing the synchronization of authorization flow with the workflow and supports role-based authorization, it is not capable of supporting other essential requirements such as separation of duties. Although many research prototypes and commercial WFMS products are available today (e.g., Lotus Notes) that provide support for role-based authorization, they are not capable of modeling separation of duties. Since no proper support is provided, currently these constraints have to be implemented as *ad hoc* application code.

The significant work in this direction is due to Sandhu [10]. However, this research is not adequate to specify separation of duties in WFMS environment since it does not specify access control in terms of tasks. Recently, Bertino et al. [3], have identified several types of authorization constraints, including separation of duties. They have categorized constraints imposed on role and user assignments to tasks into three types: static, dynamic and hybrid constraints and have developed an approach to determine their consistency by first expressing the authorization constraints as clauses in a logic program. They have also proposed algorithms to check for the consistency of the constraints and to assign users and roles to tasks that constitute the workflow in a such a way that no constraints are violated. The primary emphasis of [3] is verification of the consistency of authorization constraints. However, since the predicates representing the constraints do not include the objects, it is not capable of distinguishing one workflow instance from the other. Thus, it is not capable of modeling inter-instance authorization constraints.

In this paper, we show how authorizations can be derived when constraints expressing separation of duties are enforced. This requires examining the current state of the set of authorizations as well as the state of the workflow. Our approach conducts a run-time evaluation of the state to authorize users to execute a task. The major distinction between our work and that proposed in [3] is that our WAM is capable of modeling separation of duties constraints on

multiple workflow instances thus is able to capture inter-instance constraints. This is because, authorization constraints are specified consisting of authorizations themselves as predicates. This will also allow enforcement of constraints based on authorizations derived by other means, but not necessarily through the workflow executions.

In this paper, we also provide a formal model based on Petri nets by enhancing the Color-Timed Petri Net proposed in [2] to model role-based access control with separation of duties. Representing WAM as a Petri net allows one to visually depict the workflow behavior through its graphical representation and to analyze its behavior through its rich set of analysis techniques. Analysis helps one to understand the implications of the authorization policies. Although each policy may appear innocent in isolation, their cumulative effect may lead to an undesirable authorization state [11]. (See section 3.3 for a definition of authorization state.) So for a given initial authorization state and a set of security policies specified by authorization rules, analysis requires determining all the reachable authorization states. This, known as the *safety problem*, first identified by Harrison, Ruzzo and Ullman [6], specifically can be stated as the following question: “Is there a reachable state in which a particular subject possesses a particular privilege for a specific object?” We develop methodologies to analyze the safety of workflow authorization model when authorization constraints such as separation of duties are imposed.

3.2 WORKFLOW AUTHORIZATION MODEL

To ensure that authorized subjects gain access on the required objects only during the execution of the specific task, WAM synchronizes authorization flow with the workflow by synchronizing granting and revoking of privileges with the initiation and completion of the tasks. To achieve this synchronization, WAM associates an *Authorization Template* (AT) with each task, which specifies the static parameters of the authorization that can be defined during the design of the workflow. When a task starts its execution, this AT is used to derive the actual authorization. In this section, we review WAM with its extension to incorporate role based authorizations.

A workflow W can be represented as a *partially ordered* set of tasks $\{tw_1, tw_2 \dots tw_n\}$, where each task tw_i in turn can be defined as a set OP_i of a partial or total order of operations $\{op_1, op_2 \dots op_n\}$ that involve manipulation of objects [5]. Processing of a task involves accessing certain objects by certain subjects with certain privileges. To execute a task tw_i , relevant privileges on required objects have to be granted to appropriate subjects.

Let $S = \{s_1, s_2 \dots\}$ denote the set of subjects, $O = \{o_1, o_2 \dots\}$ the set of objects $\Gamma = \{\gamma_1, \gamma_2 \dots\}$ the set of objects types and $R = \{r_1, r_2 \dots\}$ the set of roles. The function $F : O \rightarrow \Gamma$. That is, if $F(o_i) = \gamma_j$, then o_i is of type γ_j . $G : S \rightarrow R$. I.e., if $G(s_i) = r_j$, then s_i is of role r_j . Let PR denote a finite set of privileges. We use S_{r_i} to denote the set of subjects that belong to role r_i and O_{γ_i} to denote the set of objects of type γ_i .

Definition 1 1. Time set $\mathcal{T} = \{\tau \in \mathcal{R} \mid \tau \geq 0\}$
 2. a time interval $\{[\tau_l, \tau_u] \in \mathcal{T} \times \mathcal{T} \mid \tau_l \leq \tau_u\}$ represents the set of all closed intervals.

According to definition 1 an interval is defined by its lower and upper bounds, τ_l and τ_u , respectively, where each of τ_l and τ_u can either be a constant or an expression.

Definition 2 A task tw_i is defined as $(OP_i, \Gamma_{IN_i}, \Gamma_{OUT_i}, [\tau_l, \tau_u])$, where OP_i is the set of operations to be performed in tw_i , $\Gamma_{IN_i} \subseteq \Gamma$ is the set of object types allowed as inputs, $\Gamma_{OUT_i} \subseteq \Gamma$ is the set of object types expected as outputs, and $[\tau_l, \tau_u]$ is the time interval during which tw_i must be executed.

Here $[\tau_l, \tau_u]$ specifies the temporal constraint stating the lower and upper bounds of the time interval during which a task is allowed to be executed.

Definition 3 A task-instance $tw-inst_i$ is defined as: $(OPER_i, IN_i, OUT_i, [\tau_{s_i}, \tau_{f_i}])$ where $OPER_i$ is the set of operations performed during the execution of tw_i , IN_i is the set of input objects to tw_i such that $IN_i = \{x \in O \mid F(x) \in \Gamma_{IN_i}\}$, OUT_i is the set of output objects from tw_i such that $OUT_i = \{x \in O \mid F(x) \in \Gamma_{OUT_i}\}$, and $[\tau_{s_i}, \tau_{f_i}]$ is the time interval during which tw_i has been executed.

Whenever a task is executed, a task-instance will be generated. Thus, a task tw_i may generate several $tw-inst_i$'s. τ_{s_i} and τ_{f_i} in the above definition indicate the time at which that particular task-instance has started and finished execution, respectively, whereas $[\tau_l, \tau_u]$ represent the time during which the task is allowed to be executed. Note that $[\tau_l, \tau_u]$ may differ from $[\tau_{s_i}, \tau_{f_i}]$. However, to ensure the temporal constraints, $[\tau_{s_i}, \tau_{f_i}]$ must be within $[\tau_l, \tau_u]$.

Definition 4 An authorization is a 4-tuple $A = (s, o, pr, [\tau_b, \tau_e])$, where subject s is granted access on object o with privilege pr at time τ_b and is revoked at time τ_e .

An *authorization base* $AB = \{A_1, A_2 \dots\}$ is a finite set of authorizations. As workflow execution progresses, all authorizations that have been generated are added to the set AB .

Definition 5 Given a task tw_i , an authorization template $AT(tw_i)$ is defined as a 4-tuple $AT(tw_i) = ((r_i, -), (\gamma_i, -), pr_i, [\tau_l, \tau_u])$ where

- (i) $(r_i, -)$ is a *subject hole* which can be filled by a subject s_i where $G(s_i) = r_i$,
- (ii) $(\gamma_i, -)$ is an *object hole* which can be filled by an object o_i where $F(o_i) = \gamma_i$,
- (iii) pr_i is the privilege to be granted to s_i on object o_i .
- (iv) $[\tau_l, \tau_u]$ is the time interval during which the task must be executed.

In the definition for $AT(tw_i)$ (i) says that only subjects belonging to role r_i is allowed to execute tw_i thus the subject hole $(r_i, -)$ allows only subjects that belong to role r_i , (ii) dictates that only objects of type γ_i can be processed by

tw_i , thus the object hole $(\gamma_i, -)$ allows objects of only type γ_i , (iii) says that a subject requires a privilege pr_i on the objects that arrive at tw_i for processing, and (iv) says the default interval for the authorization template will be the valid time interval for the task.

Authorization templates are attached to the tasks in a workflow. A task tw_i may have more than one authorization template associated with it. More AT s are required in cases where there are more than one type of object to be processed, or more than one subject is required to perform the processing. To distinguish the privileges in AT from those in A , we often use $pr(AT)$ to denote the privilege component of an authorization template AT . An authorization template enables one to specify rules such as “Only a clerk is allowed to perform check preparation during time 10 and 50.” These can actually be stated during the design process by the workflow designer.

Definition 6 [Authorization Derivation Rule]

Given an authorization template $AT(tw_i) = ((r_i, -), (\gamma_i, -), pr_i, [\tau_{li}, \tau_{ui}])$ of task tw_i , an authorization $A_i = (s_i, o_i, pr_i, [\tau_{bi}, \tau_{ei}])$ is derived as follows:

Grant Rule: Suppose object x is sent to subject y at τ_{ai} to start tw_i .

If $x \in O_{\gamma_i}$ and $y \in S_{r_i}$ and $\tau_{ai} \leq \tau_{ui}$,

$s_i \leftarrow y, o_i \leftarrow x, pr_i \leftarrow pr(AT)$;

$\tau_{ei} \leftarrow \tau_{ui}$,

if $\tau_{ai} \leq \tau_{li}$, $\tau_{bi} \leftarrow \tau_{li}$; otherwise $\tau_{bi} \leftarrow \tau_{ai}$.

Revoke Rule: Suppose tw_i ends at τ_{fi} at which point x leaves tw_i .

If $\tau_{fi} \leq \tau_{ui}$, $\tau_{ei} \leftarrow \tau_{fi}$.

Example 1 We explain now how authorizations are derived from the authorization templates with an example. Considering a check processing example [2] consisting of three tasks tw_1, tw_2 and tw_3 denoting prepare check, approve check and issue check, respectively. They can be expressed as follows:

$tw_1 = (\{\text{prepare check}\}, \{\text{check}\}, [10, 50])$

$tw_2 = (\{\text{approve check}\}, \{\text{check}\}, \{\text{check}\}, [20, 60])$

$tw_3 = (\{\text{issue check}\}, \{\text{check}\}, \{\text{check}\}, [40, 80])$

Suppose the associated roles for performing these processes are clerk, manager and clerk, respectively. Assume Mary and John are clerks and Peter is the only manager. We define the following authorization templates.

$AT(tw_1) = ((\text{clerk}, -), (\text{check}, -), \text{prepare}, [10, 50])$

$AT(tw_2) = ((\text{manager}, -), (\text{check}, -), \text{approve}, [20, 60])$

$AT(tw_3) = ((\text{clerk}, -), (\text{check}, -), \text{issue}, [40, 80])$

Now suppose the check $ck1$ for payment arrives at time 40 and John starts tw_1 . Both subject and object are filled into the authorization template $AT(tw_1)$, generating an authorization (John, $ck1$, prepare, [40, 50]). Suppose John finishes tw_1 at 47, then the authorizations on $ck1$ are revoked for John by replacing the upper bound with 47, thus forming the authorization (John, $ck1$, prepare, [40, 47]). Similarly, other authorizations will be derived as approve and issue tasks are executed.

3.3 WAM WITH SEPARATION OF DUTIES

Separation of duties can be expressed as constraints. In [3], Bertino et al. have identified several types of authorization constraints, including separation of duties. Similarly, we also express separation of duties as rules.

Definition 7 Given an authorization template $AT(tw_i) = ((r_i, -), (\gamma_i, -), pr_i, [\tau_i, \tau_{u_i}])$, we define a set of *potential authorizations*, PA_i , representing all possible authorizations that can be potentially derived from $AT(tw_i)$. Each potential authorization pa in PA_i is a triple (s_i, o_i, pr_i) such that $s_i \in S_{r_i}, o_i \in O_{\gamma_i}$.

Definition 8 Given an authorization $A = (s, o, pr, [\tau_b, \tau_e])$ in AB , we define a *non-temporal projection* A_{NT} of A as $A_{NT} = (s, o, pr)$. The non-temporal projection of AB , $AB_{NT} = \{A_{NT1}, A_{NT2} \dots\}$.

In our formalism, we assume each constraint c_i is a logical expression of the form: $q \leftarrow p$ where p is any logical expression consisting of A_{NT} as literals and q is a single literal which is always either pa or $\sim pa$ such that $pa \in PA_i$ of some tw_i . We also denote $s(p)$ (or $s(q)$) as the set of subjects that are specified in $pa \in PA_j$ (or $pa \in PA_i$). Enforcement of a constraint would either force or prohibit assignment of a specific user to a task. Therefore, separation of duties constraints fall into two categories. Note that this categorization is different from that of [3].

- *Exclusive type*: In this type, q is always of the form $\sim pa$ where $pa \in PA_j$ for some tw_j .
- *Assertive type*: In this type, q is always of the form pa where $pa \in PA_j$ for some tw_j .

As an example of an exclusive constraint, consider once again the check processing example introduced in section 3.2. Suppose the business policy of the bank is such that it does not allow any single individual to both prepare and issue a check. This policy can be expressed as constraint c_1 : A clerk who prepares a check cannot issue the same check. Formally, c_1 can be expressed as follows.

$$c_1: (\forall x \in S_{clerk}, y \in O_{check}) \cdot (\sim (x, y, issue) \leftarrow (x, y, prepare))$$

On the other hand, if the business policy states that a check can be issued only by an individual who prepares it. This can be formally stated as:

$$c_2: (\forall x \in S_{clerk}, y \in O_{check}) \cdot ((x, y, issue) \leftarrow (x, y, prepare))$$

Thus c_2 is an assertive type constraint. Based on whether a constraint is either assertive or exclusive type, certain users in the role of clerks are not eligible to execute the task of issuing a check. Thus, the set of eligible users for each task changes dynamically based on the current state of the authorization base. Moreover, the eligible users vary from one task-instance to another. Furthermore, only certain constraints play a role in deciding the eligibility of subject to execute a task. For example, c_1 affects the eligible set of subjects of tw_3 but not of tw_1 or tw_2 in our check processing example. Therefore we determine first the set of relevant constraints for each task tw_i , denoted as C_{tw_i} .

Definition 9 We define C_{tw_i} as follows: $C_{tw_i} = \{c_j \mid c_j \in C \text{ which is of the form } q_i \leftarrow p_j \text{ and } q_i \in PA_i\}$.

Then, for each task, we define a set of eligible subjects, denoted as $S_i^e(o)$ with respect to object o .

Definition 10 Given an authorization template $AT(tw_i), ((r_i, -), (\gamma_i, -), pr_i, [\tau_i, \tau_{u_i}])$, we define the set of eligible subjects $S_i^e(o)$ as follows:

1. $S_i^e(o) = S_{r_i}$ if $C_{tw_i} = \emptyset$
2. $S_i^e(o) = S_{r_i} - s(q_i)$ if $c_i : q_i \leftarrow p_j \in C_{tw_i}$ is an exclusive constraint and p_j is true with respect to AB_{NT}
3. $S_i^e(o) = s(q_i)$ if $c_i : q_i \leftarrow p_j \in C_{tw_i}$ is an assertive constraint and p_j is true with respect to AB_{NT}

The above definition says that if the constraint specifying the separation of duties is of exclusive type, the set of eligible subjects is obtained by subtracting the disallowed subjects from the set of subjects playing the role assigned to execute the task. On the other hand, if the constraint is of assertive type, the set of eligible subjects is simply the set of subjects specified in $pa \in q$. If no constraints affect the task, then the set of eligible subjects is same as the set of subjects playing the role. An appropriate authorization must be generated from the authorization template at run time in such a way that the subject to execute the task must be chosen from the set of eligible subjects and only when the task receives an object with type specified in the authorization template. The following authorization derivation rule ensures this requirement.

Definition 11 [Authorization Derivation Rule for extended WAM] Given an authorization template $AT(tw_i) = ((r_i, -)(\gamma_i, -), pr_i, [\tau_i, \tau_{u_i}])$ of task tw_i , an authorization $A_i = (s_i, o_i, pr_i, [\tau_{b_i}, \tau_{e_i}])$ is derived as follows:

Grant Rule: Suppose object x is sent to subject y at τ_{a_i} to start tw_i .

If $x \in O_{\gamma_i}$ and $y \in S_i^e(x)$ and $\tau_{a_i} \leq \tau_{u_i}$,

$s_i \leftarrow y, o_i \leftarrow x, pr_i \leftarrow pr(AT);$

$\tau_{e_i} \leftarrow \tau_{u_i},$

if $\tau_{a_i} \leq \tau_{l_i}, \tau_{b_i} \leftarrow \tau_{l_i}$; otherwise $\tau_{b_i} \leftarrow \tau_{a_i}$.

Revoke Rule: Suppose w_i ends at τ_{f_i} at which point o_i leaves tw_i .

If $\tau_{f_i} \leq \tau_{u_i}, \tau_{e_i} \leftarrow \tau_{f_i}$.

Note that the only difference between the above definition and earlier derivation rule in definition 6 is the set from which a subject is chosen. Without the separation of duties constraints, a subject is chosen from the set of subjects playing the specified role, whereas with separation of duties constraints, a subject is chosen from the set of *eligible* subjects which may be a subset of the previous set.

Definition 12 Given a workflow W , we define a *workflow authorization state* $A^s(W)$ as the set of current non-temporal projection of authorizations derived during the execution of W .

For instance, in example 1, a workflow authorization state $A^s(W)$ could be $\{(John, ck2, prepare), (Peter, ck1, approve)\}$, meaning that an authorization is granted to John for preparing $ck2$ and to Peter to approve $ck1$. In the following, we explain the process of deriving authorizations by taking an example.

Example 2 Consider once again example 1. Suppose a separation of duties constraint is specified as $(\forall x \in S_{clerk}, y \in O_{check}) \cdot (\sim (x, y, issue) \leftarrow (x, y, prepare))$. Since $S_1^e(ck1) = subject(clerk) = \{John, Mary\}$, $Mary \in S_1^e(ck1)$, and $ck1 \in O_{check}$, after the execution of task tw_1 , an authorization $(John, ck1, prepare, [40,47])$ is generated. Similarly, after the execution of task tw_2 , an authorization $(Peter, ck1, approve, [47,54])$ is generated. As a result of the constraint, the eligible set of subjects authorized to execute tw_3 are evaluated as follows: $S_3^e(ck1) = S_{clerk} - \{s(John, ck1, prepare)\} = \{Mary, John\} - \{John\} = \{Mary\}$. In other words, only Mary is allowed to execute tw_3 . Thus the separation of duties constraint is satisfied.

3.4 SAFETY ANALYSIS OF WAM

In this section, we first present the Petri net representation of WAM through which we perform the safety analysis. Then we present the algorithm to test for the safety of WAM. We also report the implementation status of this module.

3.4.1 Color Timed Petri Net (CTPN) - A Model to Represent Workflow Authorization Model

In this section, we present the *Color Timed Petri Net* (CTPN) Model [2] to represent the WAM proposed in the previous section. Our CTPN is an extension of *colored* and *timed* Petri nets [7], which in turn are extensions of an ordinary Petri net.

Definition 13 A Color Timed Petri Net (CTPN) is a tuple $CTPN = (PN, \Sigma, CR, E, IN, D, ts)$ where

1. $PN = (P, T, F, M)$ is an ordinary Petri net.
2. $\Sigma = \{\sigma_1, \sigma_2, \dots\}$ is a finite set of colors (or types),
3. CR is a color function such that $CR(p) \subseteq \Sigma$, and $CR(m(p)) \subseteq CR(p)$,
4. E , the arc function such that: $\forall f(p, t), f(t, p) \in F, E_f \subseteq CR(p)_{MS}$,
5. IN is an interval function associated with a transition, i.e., $IN : T \rightarrow \mathcal{T} \times \mathcal{T}$ such that $IN(t_i) = [\tau_{ti}, \tau_{ui}]$ where $[\tau_{ti}, \tau_{ui}] \in \mathcal{T} \times \mathcal{T}$ and $t_i \in T$,
6. D is a delay function associated to a place. i.e., $D : P \rightarrow \mathcal{T} \times \mathcal{T}$ such that $D(p_j) = [\delta_j^m, \delta_j^M]$, where $[\delta_j^m, \delta_j^M] \in \mathcal{T} \times \mathcal{T}$ and $p_j \in P$, and
7. ts is a timestamp function such that $ts(m(p_k)) = \alpha_k \in \mathcal{T}$, which denotes the arrival time of the token to p_k .

We represent a token as (v, x) where v is the color of the token and x the timestamp. Whenever a token moves from one place to another through a fired transition, its timestamp is modified to the firing time of the transition.

We use $m(p)$ to denote the marking of place p . $m(p)$ is expressed as a multi-sets of tokens with respect to distinct colors. For example, $m(p) = g + r$ represents place p containing a token of color g and a token of color r , i.e., $CR(m(p)) = \{g, r\}$.

The above definition dictates that each token has a color which is defined in the color set Σ . Each place has a color set (i.e., denoted as $CR(p)$) attached to it which specifies the set of allowable colors of the tokens to enter the place. For a token to reside in a place, it must satisfy that the color of token is a member in the color set of the place. Each arc $f(p, t)$ or $f(t, p)$ is associated with a color set such that this set is contained in the multi-sets of $CR(p)$. A transformation of colors may occur during firing of a transition. The firing of a transition is determined by the firing rules and the transformation by the arc function E . The firing rules can be formally stated as follows:

Definition 14 Given a transition t_i such that $IN(t_i) = [\tau_{li}, \tau_{ui}]$, $\forall p_j \in \bullet t_i$ and $\forall p_k \in t_i \bullet$, for any p_j marked with tokens $(v_{j1}, x_{j1}), (v_{j2}, x_{j2}) \dots (v_{jn}, x_{jn})$,

1. (v_{jl}, x_{jl}) is said to be *available* only during the interval $[\delta_j^m + x_{jl}, \delta_j^M + x_{jl}]$,
2. t_i is said to be *enabled* at time x if $E_{f(p_j, t_i)} \leq m(p_j)$ and all tokens in p_j are available at time x .
3. an enabled t_i is *firable* if $\max \{(\delta_j^m + x) \mid p_j \in \bullet t_i\} \leq \tau_{ui} \wedge \min \{(\delta_j^M + x \mid p_j \in \bullet t_i\} \geq \tau_{li}$ is true. A firable transition may fire any time during the *firable interval*, $[\max\{\tau_{li}, \max\{\delta_j^m + x \mid p_j \in \bullet t_i\}\}, \min\{\tau_{ui}, \min\{\delta_j^M + x \mid p_j \in \bullet t_i\}\}]$.
4. Suppose t_i fires at τ_i . Firing of t_i results in a new marking M' as follows: $m'(p_k) = m(p_k) + E_{f(t_i, p_k)}$ and $m'(p_j) = m(p_j) - E_{f(p_j, t_i)}$ and the timestamp of each element in $m'(p_k)$ is τ_i .

A transition t_i is enabled only if all of its input places p_j contain at least as many available tokens of the type as that specified in the arc function $E_{f(p_j, t_i)}$ of the corresponding $f(p_j, t_i)$.

The delay associated with a place represents minimum $\delta^m(p)$ and maximum $\delta^M(p)$ delay a token is required to remain in that place after its arrival. The delay can be a constant d where $\delta^m(p) = \delta^M(p) = d$. A token is said to be available only after the delay $D(p_j)$ has elapsed. On the other hand, the time interval associated with a transition states that it can fire only during this interval, irrespective of the tokens' timestamps in its input places. A transition is said to be enabled only if each of its input places has an available token.

A transition t_i fires only if its enabling time falls within the specified time interval $IN(t_i)$. When more than one input place exists, the transition fires after the maximum delay of all the input places has elapsed. Both the time interval and the delay can be specified as variables instead of fixed values. Upon firing, a transition t_i consumes as many tokens of colors from each of its input places p_j as those specified in the corresponding $E_{f(p_j, t_i)}$ and deposits as many tokens with specified colors into each output place p_k as those specified in the corresponding $E_{f(t_i, p_k)}$. That is, the arc function of $f(p_k, t_i)$ specifies the number of tokens of specified colors to be removed from p_j when t_i fires,

and the arc function $f(t_i, p_k)$ specifies the number of tokens of specified colors to be inserted into p_k when t_i fires.

3.4.2 CTPN Representation of WAM

In the following, we illustrate how each component of WAM is represented in the CTPN. Given a task tw with $AT(tw) = ((r, -), (\gamma, -), pr, [\tau_l, \tau_u])$, execution of tw generates an authorization $A = (s, o, pr, [\tau_b, \tau_e])$.

(1) A role r is represented as a place with an associated color set that contains all subjects. (2) A object type γ is represented as a place with a color set that contains all objects. (3) A subject, an object and a (subject, object) pair are represented by a token with respective color. (4) A subject assigned to a role r is represented as a token deposited in a place r . (5) An object of type γ is represented as a token in place γ . (6) A privilege pr to perform the task is represented by a place with a color set expecting tokens of (subject, object) type. An arc is connected from grant transition to the privilege place and another from the privilege place to the revoke transition with the arc function of expected (subject, object) pair. (7) The grant and revocation processes are represented as input (grant) and output (revoke) transitions of the place representing the privilege, respectively. (8) A subject hole $(r, -)$ is represented as an input arc from place r to the grant transition with an arc function specifying the subjects of role r . (9) An object hole $(\gamma, -)$ is represented as an input arc from place γ to the grant transition with an arc function specifying the objects of type γ . (10) The time interval $[\tau_l, \tau_u]$ associated with the grant or revoke transitions denotes the specified interval during which the authorization is valid. (11) An authorization corresponds to a filled privilege place. (12) The time interval $[\tau_b, \tau_e]$ in an authorization is the time interval during which a token resides in place pr (the difference between τ_b and τ_e is the duration for executing tw , denoted as $D(pr)$). (13) A constraint $c : q_i \leftarrow p_j \in C_{tw_i}$ can be represented by a subnet as follows: For each A_j in p_j create a place C with an input arc (f_1) from the grant transition of pr_j in p_j and an output arc (f_2) to the grant transition of pr_i in q_i , both with arc function (x, o) where x and o are two variables. If c_i is of assertive type, the arc function from the place representing r_i is same as x in f_2 , otherwise if c_i is of exclusive type, it will be a different variable than x . (14) A relative time constraint d between two tasks can be associated as a delay d at the constraint place.

Figure 3.1 shows the CTPN representation of the authorization model for a workflow consisting of role r , object type γ and a task tw . $s_1 \dots s_m$ are subjects assigned to role r and $o_1 \dots o_n$ denote objects of type γ . Ensuring that only objects of specified type and subjects of specified role are assigned a privilege pr is reflected by the input arc functions to the grant transition of pr . The granting of an authorization is represented by the firing of t_s when an object of type γ arrives with an authorized subject from role r , thereby starting the execution of tw . Then a token of color (x, o) is placed in pr . The authorization is thus derived based on the value (or color) and timestamp of the input tokens. Also note that the privilege pr is not granted for x on o until t_s fires and a token

Figure 3.1 A CTPN representation of WAM for a Workflow with one task

Figure 3.2 A CTPN representation of the check processing example

with (x, o) is deposited in *pr*. The token resides in *pr* until t_f fires (i.e., as long as the task is executed). This firing removes the token from *pr* thereby revoking the authorization from the subject. Figure 3.2 shows the CTPN representation for the check processing example. The *start* and *finish* transitions represent the initiation and completion of each workflow instance.

3.4.3 Approach to Conduct Safety Analysis

In this section, we demonstrate how CTPN representation lends itself to address the safety problem of WAM. Our CTPN representation of WAM is such that the safety problem in authorization models is equivalent to the reachability problem in Petri nets. Reachability is a fundamental property for studying the dynamic properties of any system. It can be formally defined as follows.

Definition 15 [9] A marking M is said to be *reachable* from a marking M_0 if there exists a sequence of firings that transforms M_0 to M .

Since in our model, authorizations are represented as a marked place pr with token (s, o) , the safety question whether s possesses pr on o can simply

be answered by conducting a reachability analysis on the corresponding CTPN which answers whether a place pr will ever be marked by a token (s, o) . Thus,

$$\text{Safety of WAM} \equiv \text{Reachability of its CTPN representation}$$

since workflow authorization state in WAM is equivalent to marking of its corresponding CTPN.

Therefore, existing reachability analysis techniques, methods and results can be directly adopted to WAM. One may use one of the following three approaches to conduct safety analysis:

1. Simulation: Simulation is a technique to analyze a system by conducting controlled experiments. However, sometimes it is expensive and also it is not possible to use simulation to prove that the system has the desired properties because it is not a formal analysis technique.

2. Reachability tree: The basic idea behind the reachability tree is to construct a graph which contains a node for each reachable state and an arc for each possible change of the state. This is similar to unfolding the maximal state in [11] for analyzing TAM (The Typed Access Matrix Model). Since this represents all possible states, we can answer all safety questions. However, this tree can grow infinitely large even for a small PN (if they are unbounded). It has been shown in [8] that the reachability problem although decidable, has at least exponential space and time complexity.

3. Matrix-equations: In this approach, the dynamic behavior of a PN is captured in algebraic equations that can be represented as a matrix. Given an initial state, this technique allows us to determine whether a specific state is reachable. However, this requires the PN to be acyclic.

Fortunately, for our CTPN representation of workflow, we can adopt the less expensive matrix equation approach. Before we present our approach, we first recognize that our CTPN representation of an consistent workflow specification is acyclic in its structure, referred to as *acyclic Petri net*, which does not contain cycles.

Definition 16 [1] A workflow specification W is said to be *inconsistent* if either of the following is true: (1) the set of dependencies impose a cyclic execution order among some of the tasks in W (2) the set of dependencies specify that a set of complementary states (e.g., cm and ab) have to be reached for at least one task in W .

In the above definition, the first condition specifies an inconsistent precedence relationship among the tasks. For example, a set of two dependencies where one dependency states task tw_1 can begin only after task tw_2 completes the execution, and the other dependency states tw_1 has to be executed before tw_2 , would form an inconsistent precedence ordering between tw_1 and tw_2 . The second requirement specifies inconsistent logical relationships among the task dependencies. For example, if we consider a set of dependencies where one states if tw_1 aborts, tw_2 has to abort and the other dependency specifies tw_2 has to commit if tw_1 aborts. There is an obvious inconsistency for tw_2 if tw_1

aborts. Refer to [1] for a detailed discussion on consistency checking. It has been shown in [1] that if the workflow specification is consistent then there does not contain any cycle in the corresponding CTPN representation. This leads to the following proposition.

Proposition 1 *If the workflow specification W is consistent, then the corresponding CTPN is acyclic.*

Our approach to conducting safety analysis relies on the following theorem.

Theorem 1 [9] *In an acyclic Petri net, a marking M_i is reachable from an initial marking M_0 , iff there exists a nonnegative integer solution U satisfying*

$$M_i = M_0 + AU, \quad (3.1)$$

where A is the corresponding incidence matrix that can be derived from the Petri net as follows: A is an $(m \times n)$ matrix such that m and n are the number of places and transitions, respectively, and each $a_{ij} = a_{ij}^+ - a_{ij}^-$ where a_{ij}^+ (a_{ij}^-) is the number of arcs from transition j to its output (input) place i . (See [9] for a proof.)

Algorithm 1 [Safety Analysis of WAM]

Given a workflow specification W , an initial state of authorization and the final state of authorization,

1. Construct $CTPN$ of W according to the mapping in section 3.4.1.
2. Obtain the initial marking M_0 of $CTPN$ by marking $CTPN$ according to the given initial authorization state.
3. Obtain the final marking M_i of $CTPN$ by marking $CTPN$ according to the given final authorization state.
4. Solve $M_i = M_0 + AU$. If U is a non-negative integer, output **Yes** and stop; otherwise output **No**.

The above algorithm presents the approach to test for the safety of WAM. The complexity of this algorithm is nothing but that of solving m equations with n variables where m and n represent the number of places and transitions, respectively.

3.4.4 Implementation

We have implemented a *Workflow Specification and Analysis Software* (WSAS) in Visual Basic. WSAS consists of two parts: The first part is to test whether the specification of the workflow is correct or not. The second part tests the safety of workflows, i.e., given an initial state of the workflow, it tests whether a specified state is reachable or not. WSAS has been built on top a prototype, called *IDEF/System Dynamics Evaluation Software*, developed by Boucher and Jafari [4], which assumes the underlying Petri net model is an ordinary Petri net. Currently we are working on enhancing WSAS to handle CTPN. Our approach is as follows. If the number of subjects is finite, the color sets associated with each place in a CTPN can be converted into a finite number of parallel arcs represented by an ordinary PN. By doing so, our WSAS can be utilized for conducting the analysis.

3.5 CONCLUSIONS

In this paper, we have shown how authorization constraints representing separation of duties can be incorporated into workflow authorization models. We have proposed a methodology to conduct safety analysis of workflow authorization models. We are currently extending the tool which we have developed to test for safety of workflows to address the safety of WAM. Since our software tool can only analyze ordinary Petri nets, we are currently investigating translating the CTPN to an ordinary PN so that our tool can be directly used to analyze WAM.

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