A Reachability Verification Method Based on Pi-Calculus and Role Network Model for Cross-Organizational Business Processes

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***Abstract*—Increasingly more organizations are involved in critical cross-organizational business processes. Reachability analysis is one important way to guarantee the correctness of these processes. This paper proposes a new way of combing Role Network Model (RNM) and Pi-calculus to support reachability analysis for distributed and highly dyanmic processes. We first formally describe RNM in Pi-calculus. We then propose a reachability verification method based on RNM and μ-calculus for both structured and dynamic business processes. We evaluated our approach using a real-world government administrative permit system in China. The results show that proposed method can analyze and improve the reachability aspects of cross-organizational business processes, especially for dynamic business processes.**

***Index Terms*—cross-organizational business process, reachability verification, role network model, Pi-calculus**

I. Introduction

With the rapid development of Internet and other information technologies, cross-organizational business collaboration is becoming increasingly frequent and the boundaries of organizations are blurring. Cross-organizational business processes are the basis for organization survival and grow. How to ensure the correctness of these processes has become an important issue and reachability analysis is one of the formal ways of analyzing correctness.

Comparing with intra-organizational business processes, Jiang et al. summarized the key differentiation points of cross-organizational processes: Autonomic versus collaborative; Distributed versus interrelated; Stable versus dynamic [1]. It shows that the fundamental nature of cross-organizational business processes is the collaboration between autonomous organizations. This has caused the highly dynamic and deterministic nature of these processes.

There are often a multitude of new factors involved in these collaborations such as trust, culture, legal contract and conflict of interests due to competition. A considerable number of elements within these processes are highly human driven and not explicit or transparent due to the above new factors, at least between organizations. Such business processes often cannot be modeled accurately at design time and the precision only comes at runtime based on situational human decisions. For highly dynamic processes, Aalst pointed out that the knowledge-intensive nature of these business processes makes traditional workflow modeling methods and techniques inadequate for describing all the possible scenarios, business rules and tacit human knowledge [2]. The traditional workflow-based methods are too rigid to reflect and support runtime human decision-making.

Currently, for business processes and the web service composition, the main reachability analysis methods mainly include reachability graph [3]-[5], Petri Net based [3], [6]-[7], Polychromatic Sets based [8], conditional Pi-calculus based [9]. However, these studies don't explicit and adequately support the reachability analysis of highly dynamic cross-organizational processes.

Role Network Model (RNM) is a new way of modeling human-intensive role-based business processes [10], [11]. RNM describes a system as a network consisting of the roles (as nodes) and the collaborative relationships among them (as edges). It emphasizes the organizations and the people in the center of the system, and highlights the decision-making capacity of knowledge workers. But the behaviors of roles in RNM and their relationships with the topology of a dynamic business process could not be described formally thus making the reachability verification difficult.

Pi-calculus can formally describe a distributed, interactive and dynamic system and has strong capability in algebraic deduction. It has been widely used in business process management [12], [13]. RNM and Pi-calculus are intrinsically consistent due to their focus on

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distribution, local autonomy and dynamic process. Therefore, we combine the deduction friendly formalism of Pi-calculus with the cross-organizational modeling capability of RNM through separation of duties (SoD) and propose a reachability verification method for cross-organizational business processes.

The rest of the paper is organized as follows. The reachability verification method based on RNM and Pi-calculus is described in section II. Our evaluation case study using a government administrative permit system from China is reported in section III. Finally, section IV concludes the paper.

II. The Reachability Verification Method for Cross-Organizational Business Processes

A. RNM Based on the Pi-calculus

Organizations and the job positions within the organization are described as roles in RNM. In RNM, Roles and Business Objects are the two most important elements. State and Attribute Set are the basic elements of a Business Object.

Roles are defined as a set of standards, responsibility description, or policies of a typical organization in a particular business environment. Roles have corresponding rights and obligations. A role is formally described as a six-tuple: (*N*, *BOL*, *BOC*, *OPERL*, *OPERC*, *CHAL*), which represents the name, the business object set which can be transacted, the authority of manipulating attributes of business objects, the operation set on business objects, constraints set of operations executable by a role and the channel set owned by a role.

A channel describes the collaborative relationship of related organizations. Roles share a channel if there is a collaborative relationship. Roles can transmit information over the channel, and then execute the appropriate operations to complete the interaction and collaboration.

Name and Process are two basic concepts in Pi-Calculus. The communication between processes is achieved by sending and receiving Names. The main elements in RNM are described by Pi-calculus as shown in Table I.

TABLE I. Main Elements of RNM Described by Pi-Calculus

RNM	Pi-calculus
Role	Process: *Role*
Business object and its state	Name: *bo, st*
Operation	Name: *op*
Constraints on operations executable by a Role	Judge expression
Cooperation relationship	Name: *ch*

Some basic expressions are defined based on the syntax of Pi-calculus [13] as follows.

1) 0 represents the nil-process.

2) Prefix: $ch(x)$ means that the name x is received along the channel ch by a role. $\overline{ch}<x>$ means that name x is sent along the channel ch by a role. The silent τ means that role's internal operation that cannot be observed by other roles.

3) *a.Role* means prefix *a* is executed and then behaves like *Role*. The "." represents sequential execution in Pi-calculus.

4) $\sum_{i \in I} Role_i$ behaves like one or other of $Role_i$, where I is the finite index set.

5) $Role_1|Role_2$ means that $Role_1$ and $Role_2$ are acting in parallel.

6) [x=y] *Role* behaves like *Role* if *x* and *y* are the same name, otherwise like 0.

7) (*Yx) Role* means that name *x* is declared as a *Role*'s local name and bounded in *Role*. It is not visible outside of *Role* until it is sent outside of *Role*.

B. The Reachability Verification Method

In RNM, the reachability of a process is mainly described as the reachability between the states of one or multiple business objects.

A cross-organizational business process can be divided into two categories: structured and dynamic. Structured business processes are those whose partial order relationships of operations (namely, collaboration channels of roles in RNM) are determined at design time. While dynamic business processes, including semi-structured and unstructured business processes, are those whose partial order relationships of operations cannot be fully determined at design time. Some process fragments should be determined at runtime based on the decisions made by organizations or people in a situational manner.

Aiming to support both types of business processes, we propose the reachability verification method by combining RNM and μ-calculus in the way shown in Fig. 1.

C. The Reachability Verification Method for Structured Business Processes

A model should obtain all the possible transitions of business objects' states at first. Then, reachability analysis of the business process can be conducted based on μ-calculus and Role behavior deduction. If it is unreachable between two states, the method can identify the incorrect part of the RNM through Role behavior deduction and produce detailed information for analysis.

(1) Reachability verification based on μ-calculus

All possible state transitions of business objects can be described as μ-calculus formulas. And then the RNM can be verified whether it satisfies the corresponding μ-calculus formulas. The verification can be conducted based on theoretical analysis; and also by means of some tools, such as the check command of Mobility Workbench (MWB) [14].

(2) Role behavior deduction

A role's own behavior and the interaction of the roles can be deducted to determine whether two states are reachable using the reduction rules, the transition rules and others of Pi-calculus.

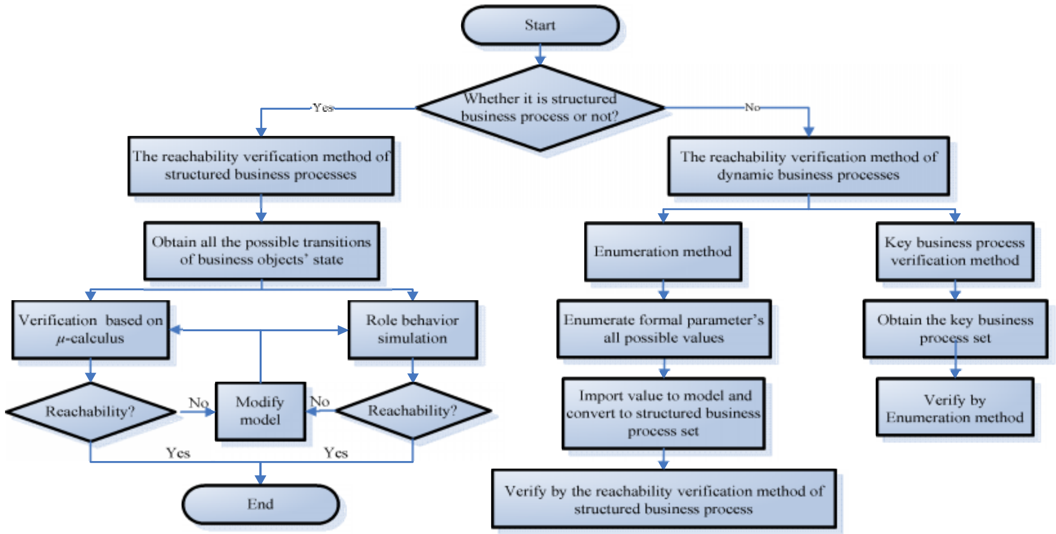


Figure 1. The reachability verification method

In comparison with the verification method based on μ-calculus, role behavior deduction cannot determine reachability directly. However, it is able to give transitions between the two states. And some previously missing transitions could be identified using role behavior deduction. Therefore, it is a necessary complement to the verification method based on μ-calculus. Analysis tools, such as the step command of MWB, can also assist this method to reduce the effort.

D. The Reachability Verification Method for Dynamic Business Processes

The uncertainties of any business process, which is due to the runtime decisions made on the spot by an organization or person, can also be represented as formal parameters in a RNM model. Such a dynamic business process will be instantiated into more deterministic structured process after all formal parameters are replaced by actual value. Then the reachability verification method for structured business processes can be used to check these instance processes.

Some decisions made by organizations or people can be abstracted as channels, in which case the topology of a dynamic business process will change through the channel's transfer among roles.

Considering the above-mentioned factors, two verification approaches for dynamic business processes are proposed depending on the context as shown in Table II.

TABLE II. THE SUITABLE SCENCE AND RELIABILITY OF TWO METHODS

Method	The suitable scence	Reliability
Enumeration method	There is little uncertainty in the process, and it can enumerate all possible values of uncertainty.	Complete Reliability
Key process verification method	There is a lot uncertainty in the process and difficult to predict all possible values.	Partially Reliability

III. CASE STUDY

There are dozens of independent but collaborative departments handling hundreds of administrative permits in China' administrative permit system. And there are a number of semi-structured, dynamic cross-organizational business processes in this system. The authors led the implementation of one such system for a local government and the case study is based on this real-world system.

The company registration process is taken as an example. At first, a company must apply for the administrative permit named Enterprise Name Preregistration Approval (ENPA) to the Industrial and Commercial Bureau (ICB). After the application is approved, ICB will decide and notify what related administrative permits should be applied depending on the information provided by the company from dozens of possible permits. Then the company will apply for these related administrative permits to the corresponding departments based on the notification from ICB. For example, ICB will inform the company to apply for the Permit of Special Sensitive Area Construction Project (PSSACP) permit to Environment Protect Bureau (EPB) if ICB believes that the proposed activities of the company may cause pollution to the environment. The process mentioned above is the type of dynamic cross-organizational business processes. And the process can be verified by the enumeration method or the key process verification method according to different situation.

In addition, the handling processes of all administrative permits are actually similar and can be considered as a structured business process from the macro level.

Due to space limitation, we only use the part of company registration process, that the company applies for ENPA to ICB (which is recorded as bo_1) and PSSACP (which is recorded as bo_2) to the EPB, as an example to illustrate the effectiveness of the proposed reachability verification method.

A. System Modeling

Let bo_1 and bo_2 denote the administrative permit ENPA and PSSACP respectively. And the related roles and operations are shown in Table III.

TABLE III. RELATED BUSINESS ROLES AND THEIR OPERATIONS

Organization	Role	Operation
Company	$Role_1$	Apply and Modify materials of bo_1 Apply and Modify materials of bo_2
ICB	$Role_2$	Pre-approve and approve of bo_1
EPB	$Role_3$	Pre-approve and approve of bo_2

The state vector of each business object contains a state variable, respectively, $st_{11}$and st_{21}. Their value set can be described as $\{st_{i1}v_1,\ st_{i1}v_2,\ st_{i1}v_3,\ st_{i1}v_4,\ st_{i1}v_5\}$ (i=1,2), corresponding to "applied", "refused", "accepted", "not approved", "approved".

In general, when a company submits an application to a department or modifies its submitted materials, the corresponding value of the state of the business object is $st_{i1}v_1$. Relevant department can execute the operation "pre-approve" when the value of state is $st_{i1}v_1$, and execute the operation "approve" when the value of the state is $st_{i1}v_3$. st_{i10} and st_{i11} can be used to represent the state after pre-approve and approve are executed in the same role because these two operations should be executed at different times. And the value range of st_{i10} and st_{i11} are $\{st_{i1}v_2, st_{i1}v_3\}$ and $\{st_{i1}v_4, st_{i1}v_5\}$ respectively. A company need modify its materials when state's value is $st_{i1}v_2$ or $st_{i1}v_4$.

Let $\overrightarrow{st_1} = (st_{11}v_1, st_{11}v_2, st_{11}v_3, st_{11}v_4, st_{11}v_5)$ and $\overrightarrow{st_2} = (st_{21}v_1, st_{21}v_2, st_{21}v_3, st_{21}v_4, st_{21}v_5)$, then related roles are modeled as below.

$$\begin{aligned} Role_1(ch_{12n},ch_{12},ch_{13},\overrightarrow{st_1}) = {} & \overline{ch_{12}} < st_{11}v_1 > .Role_1(ch_{12n},ch_{12},ch_{13},\overrightarrow{st_1}) \\ & + ch_{12}(st_{11}).[st_{11} = st_{11}v_2]\overline{ch_{12}} < st_{11}v_1 > .Role_1(ch_{12n},ch_{12},ch_{13},\overrightarrow{st_1}) \\ & + ch_{12}(st_{11}).[st_{11} = st_{11}v_4]\overline{ch_{12}} < st_{11}v_1 > .Role_1(ch_{12n},ch_{12},ch_{13},\overrightarrow{st_1}) \\ & + ch_{12n}(ch).[ch = ch_{13}](\overrightarrow{st_2})Role_{11}(ch_{12n},ch_{12},ch_{13},\overrightarrow{st_2}) \end{aligned}$$

$$\begin{aligned} Role_{11}(ch_{12n},ch_{12},ch_{13},\overrightarrow{st_2}) = {} & \overline{ch_{13}} < st_{21}v_1 > .Role_{11}(ch_{12n},ch_{12},ch_{13},\overrightarrow{st_2}) \\ & + ch_{13}(st_{21}).[st_{21} = st_{21}v_2]\overline{ch_{13}} < st_{21}v_1 > .Role_{11}(ch_{12n},ch_{12},ch_{13},\overrightarrow{st_2}) \\ & + ch_{13}(st_{21}).([st_{21} = st_{21}v_4]\overline{ch_{13}} < st_{21}v_1 > .Role_{11}(ch_{12n},ch_{12},ch_{13},\overrightarrow{st_2}) \\ & + (v\overrightarrow{st_1})[st_{21} = st_{21}v_5]Role_1(ch_{12n},ch_{12},ch_{13},\overrightarrow{st_1})) \end{aligned}$$

$$\begin{aligned} Role_2(ch_{12n},ch_{12},ch,st_{110},st_{111},\overrightarrow{st_1}) = {} & ch_{12}(st_{11}).[st_{11} = st_{11}v_1]\overline{ch_{12}} < st_{110} > \\ & .[st_{110} = st_{11}v_3]\overline{ch_{12}} < st_{111} > .[st_{111} = st_{11}v_5]\overline{ch_{12n}} < ch > \\ & .Role_2(ch_{12n},ch_{12},ch,st_{110},st_{111},\overrightarrow{st_1}) \end{aligned}$$

$$\begin{aligned} Role_3(ch_{13},st_{210},st_{211},\overrightarrow{st_2}) = {} & ch_{13}(st_{21}).[st_{21} = st_{21}v_1]\overline{ch_{13}} < st_{210} > \\ & .[st_{210} = st_{21}v_3]\overline{ch_{13}} < st_{211} > .Role_3(ch_{13},st_{210},st_{211},\overrightarrow{st_2}) \end{aligned}$$

$$\begin{aligned} Sys(ch_{12n},ch_{12},ch_{13},\overrightarrow{st_1},\overrightarrow{st_2},ch,st_{110},st_{111},st_{210},st_{211}) = {} & Role_1(ch_{12n},ch_{12},ch_{13},\overrightarrow{st_1}) \\ & \mid Role_{11}(ch_{12n},ch_{12},ch_{13},\overrightarrow{st_2}) \mid ole_2(ch_{12n},ch_{12},ch,st_{110},st_{111},\overrightarrow{st_1}) \\ & \mid Role_3(ch_{13},st_{210},st_{211},\overrightarrow{st_2}) \end{aligned}$$

B. The Reachability Verification of Structured Business Process

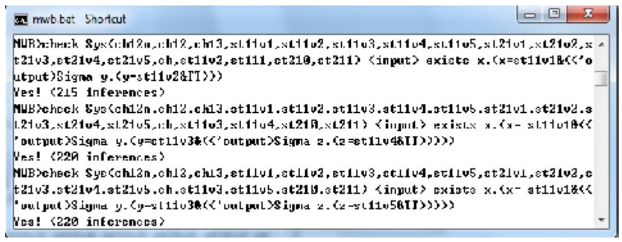
The application and handling process of each administrative permit can be seen as an interactive behavior between the company and the relevant government department. And it can be considered as a structured business process. Due to space limitation, only the part of process about bo_1 is taken as an example to illustrate the reachability verification method based on μ-calculus.

State transitions from $Role_1$ to $Role_2$ and corresponding μ-calculus formulas are shown in Table IV.

TABLE IV. STATE TRANSITIONS FROM ROLE1 TO ROLE2 AND CORRESPONDING M-CALCULUS FORMULAS

State transition	μ-calculus formula
$st_{11}v_1 \rightarrow st_{11}v_2$	*<input>exists x.(x=st11v1&(<'output>Sigma y. (y=st11v2&TT)))*
$st_{11}v_1 \rightarrow st_{11}v_3 \rightarrow st_{11}v_4$	*<input>exists x.(x=st11v1&(<'output>Sigma y. (y=st11v3&(<'output>Sigma z.(z=st11v4& TT)))))*
$st_{11}v_1 \rightarrow st_{11}v_3 \rightarrow st_{11}v_5$	*<input> exists x.(x= st11v1&(<'output>Sigma y.(y=st11v3&(<'output>Sigma z.(z=st11v5 &TT)))))*

The verification results based on MWB are shown as follows.



The verification results show that the all transitions from $Role_1$ to $Role_2$ are reachable.

C. The Reachability Verification of Dynamic Business Process

As mentioned above, the dynamic process type can be verified by the enumeration method or the key process verification method according to different situation. Due to space limitation, only the following scenario is considered. If $role_2$ believes the company may cause environmental pollution, $role_2$ will notify the company that it needs to apply for bo_2 to $role_3$. Thus, in the model, channel ch_{13} is instead of the formal parameter ch and sent to $role_1$ along the channel ch_{12n}. Then $role_1$ transforms to $role_{11}$ which is another form of $role_1$. And then, the cooperation relationship between $role_1$ and $role_3$ is arranged dynamically because they both share the channel ch_{13}. At this time, $role_1$ can apply for bo_2 to $role_3$ along ch_{13}. The transition from $st_{11}v_1$ to $st_{21}v_1$ can be described by μ-calculus as follows.

<input> exists x.(x=st11v1&(<'output>Sigma y. (y=st11v3&(<'output>Sigma z.(z=st11v5& (<'ch12n>Sigma o.(o=ch13&(<'ch13>Sigma p. (p=st21v1&TT))))))))

The verification result is shown as follows. It is reachable.

IV. CONCLUSION

In order to better analyze and guarantee the correctness of highly dynamic cross-organizational business processes, a reachability verification method based on Pi-calculus and RNM is proposed. Pi-calculus based RNM has the capability of stronger algebraic deduction and analysis. Especially, the channel is introduced to improve RNM to explicitly describe cooperation relationships among roles. A dynamic business process can be described formally through sending and receiving the channel by roles. Furthermore, detailed reachability verification mechanisms are proposed for both structured and dynamic cross-organizational business processes. The proposed method can avoid potential state space explosion problems in other reachability graph methods because it limits its verification of reachability between two states at any given time.

In the future, we will further explore runtime reachability verification to guarantee the correctness of dynamic cross-organizational business processes with lots of uncertain factors.

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