A Deadlock Detection Method for Inter-organizational Business Process Based on Role Network Model

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Abstract

In the context of inter-organizational business collaboration, structural deadlock detection is an important means of guaranteeing the correctness of an inter-organizational business process model. The existing deadlock detection methods have limitations in handling some aspects of the dynamics and uncertainty arising from inter-organizational nature of the processes. Role Network Model (RNM) was proposed to model knowledge intensive systems and can better represent the dynamic aspects of business processes using roles. But RNM is weak in the explicit description of business processes. Therefore, an extended Directed Acyclic Graph is proposed to better describe the process side complementing RNM. Second, some extended reduction rules targeting process dynamics are proposed to reduce the complexity. Third, a deadlock detection method is proposed to support highly dynamic processes. At both simulation phase and run time, deadlock detection and reduction can be performed step by step. The proposed method can not only improve the efficiency of deadlock detection but also find some deadlocks before all the uncertainties are determined. Finally, through a case study, the result demonstrates that this method can effectively achieve deadlock detection for inter-organizational business processes including dynamic and uncertain business processes.

Keywords: Business Process Management, Deadlock Detection, Inter-organizational Business Process, Role Network Model

1. Introduction

With the changing of competitive environment and the rapid development of the Internet and other information technologies, the collaborative approach of organizations has undergone tremendous changes. Inter-organizational business collaboration is becoming increasingly frequent. More and more business processes are across the boundary of organizations. A correct inter-organizational business process is becoming critical for organization survival and development. Analyzing correctness through deadlock detection and reduction has become the focus in both theoretical research and practical applications.

Many collaborative relationships of organizations are very complex due to their highly dynamic, open-ended and uncertain nature[1,2]. There exist a large number of semi-structured and unstructured inter-organizational business processes in the domain of supply chain management, E-government, emergency management and so on. In other words, the structure of these business processes cannot be completely and clearly defined at design time, and may change dynamically with the changing context at run time. Therefore, these processes are also called dynamic business processes.

Van der Aalst once pointed out the following major problems of the traditional workflow modeling methods and techniques when they were applied to knowledge intensive business systems[3]. First, these methods cannot completely describe all scenarios, business rules and human's tacit knowledge. Second, they focus more on activities and control flows so that they are too rigid and difficult to reflect and support human decision-making aspects.
In response to the characteristics of dynamics, open-endedness and uncertainty, the Role Network Model (RNM) was proposed to model knowledge intensive business application systems. Following the speech act methodology, the RNM highlights the human decision-making ability and thus suitable to more dynamic business processes. Furthermore, using roles as first-class elements, RNM can give an abstract description of the organizational roles participating in a process, which is consistent with the policy of Separation of Duties (SoD).

However, RNM does not have a strong ability to describe the process aspect explicitly. An extended directed acyclic graph (eDAG) is proposed to overcome this problem.

Further, in order to cope with large-scale and more complicated inter-organizational business processes, several extended reduction rules supporting dynamic business processes are proposed.

Finally, a deadlock detection method for inter-organizational business processes, especially highly dynamic processes, is proposed. It’s shown that the method can detect the deadlock effectively by a case study. This new method theoretically complements the existing deadlock detection methods.

The rest of the paper is organized as follows. Section 2 gives an introduction to the related studies on the forms of structural deadlock, deadlock detection methods and the RNM. Section 3 provides the representation of business process structure based on the RNM. The extended reduction rules supporting dynamic process are proposed in section 4. Further, a deadlock detection method of inter-organizational business process is proposed in Section 5. A case study is given to evaluate the proposed method in Section 6. Section 7 concludes the paper with some observations an outlook on future research.

2. Related work

2.1 The forms of structural deadlock

The structural deadlocks of any business process have two main forms\cite{4}: (1) One or more inputs of AND-join node can not be activated so that it causes a deadlock as shown in Figure 1(a), (2) Termination conditions of a loop structure can never be satisfied causing a deadlock as shown in Figure 1(b).

![Figure 1. The forms of structural deadlock of any business process](image)

2.2 Deadlock detection method

There have been research works on deadlock detection methods for business processes. Some studies detect deadlocks by comparing with a set of specific deadlock patterns \cite{5-7}. There are certain advantages for such types of method relying on well-known deadlock patterns. But some deadlocks may be missed if the deadlock pattern catalogue is incomplete and difficult to compare with. In addition, Tan proposed a deadlock detection method based on minimal structural deadlock detection algorithm and reachability graph\cite{8}. Sha suggested a deadlock verification method using a Collaboration Guideline\cite{9}. Wang proposed a deadlock detection method based on reachability graph in grid workflow\cite{10}. Hu described business processes using Pi-calculus and thus can detect deadlocks using existing tools\cite{11}. Although these methods have a formal foundation to a certain extent, they are weak in supporting highly dynamic processes in the context of inter-organizational processes.

When a business process model is large and complex, state space explosion may occur. Therefore, it is necessary to reduce the scale of a model as far as possible while maintaining the deadlock property of the business process model. Sadiq and Lin proposed some reduction rules to reduce the scale of models\cite{12,13} and their formal foundation is directed acyclic graph(DAG). However, the method does not support highly dynamic business processes.
Overall, these methods mentioned above can not meet the requirements of deadlock detection of high dynamic process.

2.3 Role Network Model (RNM)

The Role Network Model (RNM) was proposed to model knowledge intensive business application systems\(^{[14,15]}\). In the RNM, Business Object and Role are two main elements. Positions and organizations and their related rights, duties and obligations (interpreted as business rules) are abstracted as roles. Thus, a system can be considered as a network consisted of roles and their collaborative relationships.

A Role is defined as a nine-tuple: \((N, TYP, ORG, SUP, BOL, BOC, OPERL, OPERC, RES)\) where \(N\) represents the name, \(TYP\) represents the type of a role, \(ORG\) represents the affiliated organization of a role, \(SUP\) represents the superior role, \(BOL\) represents the business object set which can be transacted by a role, \(BOC\) represents the authorized set of the role dealing with the attributes of a business object, \(OPERL\) represents the operation set which can be performed by the role, \(OPERC\) represents the constraint condition set of operations executable by corresponding roles and each constraint condition is signed as \(o_{ij,c}\), and \(RES\) represents the materials assigned to a role.

The control mechanism of a business process based on RNM can be described as follows. At different time points, the corresponding roles execute operations if the constraint conditions on the state of a business object are satisfied, and then update the state of the business object. Thus, this achieves the control of the business object moving among roles as well as the business process. RNM allows space for uncertainties within a system (such as the dynamic behaviors of a role) through grasping the certainties within a system (such as the rights and obligations of a role). In this regard, RNM is suitable for the control of dynamic business processes.

In addition, for inter-organizational business collaboration, Hierarchical Role Network Model (HRNM) was proposed in order to abstract a whole organization as a role at the macro level of horizontal organizational collaboration\(^{[16]}\). Four interfaces of the role and corresponding channels of roles were proposed for inter-organizational business collaboration\(^{[16]}\).

The RNM related research results are the basis of this paper. We propose a new model reduction and deadlock detection method for inter-organizational business processes based on the RNM.

3. The representation of inter-organizational business processes based on the RNM

For an inter-organizational business process model based on RNM, let \(s^*_ij\) represents the possible state set of the business object after the \(j\)th operation have been executed by \(Role_i\), and \(o_{ij,c}\) represents the constraint condition that discriminate whether \(Role_i\) can or can not execute the \(j\)th operation based on the state of business object. \(o_{ij,c}\) can also be called as a discrimination function. If the result of discrimination is true, the corresponding operation can be executed. The basic structures of collaborative relationships of roles include sequence, split and join which are shown in Figure 2 where the oval denotes the role and the solid circle denotes the operation.

![Figure 2. Sequence, Split and Join structure of business process based on RNM](image)

1. Sequence structure. It is a sequence structure when \(o_{ij,c}(s^*_ij)\equiv true\) and \(\forall s^*_ij \in s^*_ij\).
2. Split structure. It is an AND-split structure only when \(o_{ij,c}(s^*_ij)\cap \ldots \cap o_{ij,c}(s^*_ij)\equiv true\), \(\forall s^*_ij \in s^*_ij\). When \(o_{ij,c}(s^*_ij)\cup \ldots \cup o_{ij,c}(s^*_ij)\equiv true\) and \(o_{ij,c}(s^*_ij)\cap \ldots \cap o_{ij,c}(s^*_ij)\equiv false\),
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∀s_{ij,t} ∈ S_{ij,y}. It is an XOR-split structure if only one value of o_{ij,c} is true for all possible situations, and it is an OR-split structure if there are one or more o_{ij,c} of which the value is true for different situations.

3) Join structure. It is an AND-join structure only when \(o_{ij,c}(s_{ij,t} \ldots s_{xy,t})=true\), \(∀s_{ij,t} ∈ S_{ij,y} \ldots S_{xy,t} ∈ S_{xy}\). When \(o_{ij,c}(s_{ij,t}) ∪ \ldots ∪ o_{ij,c}(s_{xy,t})=true\) and \(o_{ij,c}(s_{ij,t}) \cap \ldots \cap o_{ij,c}(s_{xy,t})=false\), \(∀s_{ij,t} ∈ S_{ij,y} \ldots S_{xy,t} ∈ S_{xy}\). It is an XOR-join structure if only one value of o_{ij,c} is true for all possible situations, and it is an OR-join structure if there are one or more o_{ij,c} of which the value is true for different situations.

RNM allows space for the uncertainty within a system when it describes the certainties of the system using rights, duties and obligations of a role. The uncertainty refers to the dynamic nature of a business process that is reflected in the partial order relationship of business operations of some roles at run time. There are two main reasons resulting in dynamic business processes: (1) there are a large number of business object state values and the combination of discriminant functions’ values of the multiple operations are different at different time at run time. And determination of values of discriminant functions is based on a business rules repository. (2) According to the context, the knowledge worker may specify a set of preceding or succeeding operations dynamically at run time following the constraints of the rights and responsibilities of an acting role.

The business collaborative channels are introduced to describe the partial order relationship among operations explicitly. From the certainty perspective of a partial order relationship, the business collaborative channel in RNM can be divided into two categories. One is the structured business collaborative channel, which reflects the certain part of a partial order relationship among operations. And this kind of channel corresponds to the partial order relationship among sequence, AND-split, XOR-split, AND-join, XOR-join and other structural process structures. The other one is called the dynamic business collaborative channel reflecting the dynamic business collaborative relationship among roles. It is identified by \(δ_{ij,t}\) which corresponds to \(o_{ij,c}(s_{ij,t})\) where \(S_{ij,t} ∈ S_{ij,y}\). At run time, whether the value of \(δ_{ij,t}\) is true or not can be determined based on the results generated by the business rules engine or decided by a knowledge worker. If the value of \(δ_{ij,t}\) is true in the simulation phase or at run time, the corresponding dynamic business collaborative channel is changed to a structured business collaborative channel for a business process instance. Otherwise, the channel is deleted.

Furthermore, the operation and the sub-process are considered as tasks, and the structured business collaborative channels of a role are considered as edges. The logical relations in XOR-split/ XOR-join structure can be represented by Choice/Merge Coordinator. Thus, the structured business process based on RNM can be expressed as the Dag used by [12,13], and some process structures of basic control flow patterns such as sequence, AND-split, XOR-split, AND-join, XOR-join can also be described.

But the DAG cannot explicitly describe the OR-split and OR-join process patterns as well as the dynamic business processes. Therefore, the dynamic business collaborative channel is introduced into the DAG and the extended DAG can now explicitly describe inter-organizational dynamic business processes based on RNM.

eDAG is defined as \(G=(N,E)\). Where, \(N\) is a finite set of nodes. And for each \(n ∈ N\), nodeType(n) ∈ \{task, choice coordinator, merge coordinator\}. \(E\) is a finite set of directed edges representing transitions between two nodes. And for each \(e ∈ E\), edgeType(e) ∈ \{structured business collaborative channel, dynamic business collaborative channel\}. The graphic symbols of eDAG are shown in Figure 3.

Figure 3. The graphic symbols of eDAG
4. The extended reduction rules supporting dynamic business process

For reducing the complexity of the structural deadlock detection of a business process, extended reduction rules supporting dynamic business process are proposed based on eDAG and the reduction rules proposed by Sadiq and Lin\cite{12,13}.

**Definition 1: Terminal Reduction Rule**

If the total number of the input edges and the output edges of a node is less than or equal to 1, and the type of a possible edge is not a dynamic-business-collaborative-channel type, the node and the channel can be removed. The Figure 4 shows an example when an operation of Role3 only has one input edge and the type of the edge is a structured business collaborative channel.

![Figure 4. An example applying terminal reduction rule](image)

**Definition 2: Sequential Reduction Rule**

If a node has exactly one input edge and one output edge and one of the following two conditions is satisfied, the Sequential Reduction Rule can be applied.

(1) When both edges are the structured-business-collaborative-channel type.

(2) When only one of the two edges is the dynamic-business-collaborative-channel type, if the preceding node of the current node has only one output edge or the succeeding node has only one input edge.

The reduction process is as follows. One edge of the structured-business-collaborative-channel type and the current node are removed, and the other edge is taken as the output edge of its preceding node and the input edge of its succeeding node. One example of applying the sequential reduction rule is shown in Figure 5.

![Figure 5. An example applying sequential reduction rule](image)

**Definition 3: Adjacent Reduction Rule**

There may exist one type of scenarios described as follows. A node has one input (or output) edge and more than one output (or input) edges. The type of the node is the same with its preceding (or succeeding) node, and the input/output edge set can not contain the dynamic-business-collaborative-channel type at the same time. For this situation, the current node is removed and its preceding and succeeding nodes are connected. If the input edge set or output edge set of the removed node contain edges of dynamic-business-collaborative-channel type, the corresponding identifications of the dynamic-business-collaborative-channel type is reserved. One example applying adjacent reduction Rule is shown in Figure 6.

![Figure 6. An example applying adjacent reduction rule](image)

**Definition 4: Closed Reduction Rule**

If there are several edges with the same direction between two nodes both of which are the type of task or the type of choice/merge coordinator, and one of the following two conditions is satisfied, one edge is reserved and others are removed.

(1) When all these edges are not the dynamic-business-collaborative-channel type.
(2) When all the edges are the dynamic-business-collaborative-channel type and their identifications are the same.

An example of Closed Reduction Rule is shown in Figure 7.

![Figure 7. An example applying closed reduction rule](image)

Similar to definition 1, the type of all edges involved in application conditions of the Choice-convergence Reduction Rule, the Synchronizer-Convergence Reduction Rule and the Merge-Fork Reduction Rule proposed in [13] must be the structured-business-collaborative-channel type. Otherwise, the three rules above cannot be applied. Due to space limitation and the consideration that the three rules are not used frequently, discussions on these rules are not included.

5. The deadlock detection method

A deadlock detection method is proposed to support dynamic inter-organizational business processes as shown in Figure 8. At design time, an eDAG is generated from a system model based on RNM to describe its business process structure. Then, reduction and deadlock detection are performed based on the eDAG. If there are no dynamic-business-collaborative-channel type edges in the eDAG, then we can reach on conclusion on whether there are deadlocks. Otherwise, we need to determine the uncertainties in the simulation phase or at run time. The value of $\delta_{ijkl}$ is determined based on business rules or knowledge workers. Then the eDAG is revised correspondingly. This process maybe conducted iteratively to detect deadlock. When a deadlock is found, exception handling or model revision needs to be done.

![Figure 8. The process of deadlock detection method](image)

(1) System modeling based on RNM

A system is modeled based on the RNM and its extended model. At the micro level, every organization can be seen as one Role Network composed of internal roles and their collaborative relationships. But at the macro-level of cross-organizational collaboration, the specific business can be abstracted as business objects; an organization can be seen as one abstract role; and then the global Role Network is constructed at macro-level. In a macro-level Role Network, one role only has the operation set related to cooperation with other organizations and the corresponding discriminant function set. And they are sub-sets of related operations and the corresponding discriminant function set of corresponding Role Network at micro-level.
(2) Structure description of inter-organizational business process based on eDAG

A. The generation of eDAG

eDAG is constructed to describe the structure of business process explicitly according to the method mentioned in Section 3 at first. eDAG should meet the basic requirements of DAG. If there exists a loop structure, then determine whether there are conditions to meet the need of exiting the loop at first. If there is, then the loop-body can be abstracted as a sub-process. Otherwise, there exists a deadlock due to the loop structure.

In addition, same as the DAG, there should be only one start and one end node. A virtual start or end node need to be introduced to the eDAG if the initial eDAG has more than one start or end nodes.

B. The revision of eDAG

The eDAG is revised according to the value of certain $\delta_{ijkl}$ at first. If the value of $\delta_{ijkl}$ is true, the type of corresponding edge should be changed to a structured-business-collaborative-channel type. Otherwise, this channel should be removed.

If there are some nodes that there is no path from them to the end node and from the start node to them, the nodes and corresponding edges should be removed.

(3) Reduction

Following the reduction algorithm proposed by [13], the extended reduction rules proposed in section 4 can be selectively applied for reduction according to the two following conditions:

A. If eDAG satisfies the basic requirements of DAG, all rules can be used to reduce the model.

B. If there are more than one start or end node, all rules but Terminal Reduction Rule can be used to reduce the model.

(4) Deadlock detection

Using the reduced eDAG, the steps of deadlock detection are proposed as follows.

Step 1: If the reduced eDAG is empty, it shows there is no deadlock. Otherwise, go to Step 2.

Step 2: If there is no path from the start to the end node, there must exist one or more deadlocks and the deadlocks are caused by a dynamic process. Otherwise, go to Step 3.

Step 3: If there are more than one start node, let the set of all start nodes except the former start node as $N_s$. For each $n \in N_s$, if (1) there does not include any node of the merge coordinator type and any edge of the dynamic-business-collaborative-channel type, and (2) there is an AND-join structure in the path from node $n$ to the end node, it shows that there are deadlocks and the deadlocks are caused by the dynamic business process. Otherwise, go to Step 4.

Step 4: If the reduced eDAG doesn’t contain any dynamic-business-collaborative-channel-type edge, it shows that there are structural conflicts within the business process. In this case, whether there is any deadlock is discriminated according to the basic forms of deadlock. Otherwise, if there are edges of the dynamic-business-collaborative-channel type, the existence of deadlocks cannot be determined and needs further determine the uncertainties.

6. Case study

There are dozens of independent organizations participated in China’s administrative permit system. These organizations handle hundreds of administrative permits that belong to different organizations. And there are a great number of semi-structured, dynamic business processes. The business process of administrative permit system is typical of inter-organizational business process. Considering page limitation, some administrative permits related to registration of "Company Limited" are taken as a case to illustrate deadlock detection for inter-organizational business processes using the proposed method.

At first, a company applies to the Administration for Industry & Commerce bureau for the administrative permit named “enterprise name pre-registration approval”. After the application is approved, the company need apply for other related administrative permits following the corresponding business rules or the instructions from the Administration for Industry & Commerce or others at run time. And there are a large number of choices for succeeding administrative permits, which constitutes a highly dynamic business process. For example, the company may need to apply to Public Security Bureau for “security permits”, or apply to Health Bureau for “Engaged in food production and operation”. In other words, before a company can further apply to Administration for Industry & Commerce for “Limited registration and annual inspection”, related pre-permits must be applied to corresponding government departments and corresponding applications are approved. After the
“Limited registration and annual inspection” is approved, company should apply to Bureau of Quality and Technical Supervision, State Administration of Taxation and Local Taxation Bureau for related administrative permits.

(1) System modeling based on RNM

The roles and business objects are the most important elements of RNM. They can be abstracted as follows at first.

Companies and government departments can be abstracted as roles. The companies, Administration for Industry & Commerce, Health Bureau, Environmental Protection Bureau, Public Security Bureau, Construction Administration Bureau, Bureau of Agriculture, Bureau of Culture, Bureau of Quality and Technical Supervision, State Administration of Taxation and Local Taxation Bureau can be represented respectively as \( \{ \text{Role}_i \mid i = 1, 2, \ldots, 11 \} \).

The related administrative permits can be abstracted as business objects. "Enterprise name Pre-registration approval", "Engaged in food production and operation", "Below 10 million Yuan investment and special sensitive area construction projects under a municipal district", "Security permits", "Housing rental registration", "Non-main crop seed business license", "Books, newspapers, magazine sale licensed", "Limited registration and annual inspection", "Organization Code Certificate", "State Tax registration", "Region Tax registration" can be represented respectively as \( \{ \text{bo}_j \mid j = 1, 2, \ldots, 11 \} \), and can be handled by corresponding \( \text{Role}_i \).

Then we assume there is no structural deadlock for business process in any organization. And based on RNM, every role only has the operation set related to the cooperation with other organizations and the corresponding discriminant function set.

Through careful analysis and domain expert feedback, we validate the models for administrative permit application and handling by \( \text{Role}_i \) and the corresponding handling by \( \text{Role}_j \) are shown in Table 1.

<table>
<thead>
<tr>
<th>Role</th>
<th>Business object</th>
<th>Related business operation interface</th>
<th>Discriminant functions</th>
<th>Post state</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{Role}_1 )</td>
<td>( b_{sop_{11}} )</td>
<td>Apply for an item or Modify project application materials</td>
<td>(( bo_j, \text{state}= ) empty or received refused message or received not approved message) and pre-items.state=approved</td>
<td>( bo_j, \text{state}=) applied</td>
</tr>
<tr>
<td>( \text{Role}_j ) (&lt;1)</td>
<td>( b_{sop_{1i+1}} )</td>
<td>Receive handling result</td>
<td>( bo_j, \text{state}=) sent refused message or sent approved message or sent not approved message</td>
<td>( bo_j, \text{state}=) received refused message or received approved message or received not approved message</td>
</tr>
<tr>
<td>( \text{Role}_i ) (&gt;1)</td>
<td>( b_{sop_{i1}} )</td>
<td>Pre-approve</td>
<td>( bo_j, \text{state}=) applied</td>
<td>( bo_j, \text{state}=) accepted or refused</td>
</tr>
<tr>
<td>( \text{Role}_i ) (&gt;1)</td>
<td>( b_{sop_{i+1}} )</td>
<td>Feedback after pre-approval</td>
<td>( bo_j, \text{state}=) refused</td>
<td>( bo_j, \text{state}=) sent refused message</td>
</tr>
<tr>
<td>( \text{Role}_i ) (&gt;1)</td>
<td>( b_{sop_{i+2}} )</td>
<td>Approve</td>
<td>( bo_j, \text{state}=) accepted</td>
<td>( bo_j, \text{state}=) approved or not approved</td>
</tr>
<tr>
<td>( \text{Role}_i ) (&gt;1)</td>
<td>( b_{sop_{i+3}} )</td>
<td>Feedback after approval</td>
<td>( bo_j, \text{state}=) approved or not approved</td>
<td>( bo_j, \text{state}=) sent approved message or sent not approved message</td>
</tr>
</tbody>
</table>

(2) The generation of eDAG

The business processes of companies applying for the administrative permit and the corresponding government departments’ processing can be roughly shown graphically in Figure 9(a). Although this process fragment contains a loop structure, it can exit the loop structure when “\( bo_j, \text{state}=\) received approved message”. Thus, there is no deadlock and the process fragment can be abstracted as the sub
process shown as in Figure 9(b).

**Figure 9.** The transformation of business process fragment about application and handling of one administrative permit

Based on the analysis and the reduction, the application and the handling processes of the 11 business objects can be converted into 11 sub processes and they are denoted by \( \{ Sp_j \mid j = 1, 2, \ldots, 11 \} \). In addition, considering the relationship of related business objects, it is certain that there are edges of dynamic-business-collaborative-channel type from \( Sp_1 \) to \( Sp_2 \ldots Sp_7 \) as well as \( Sp_2 \ldots Sp_7 \) to \( Sp_8 \). Moreover it is an AND-split structure from \( Sp_8 \) to \( Sp_9, Sp_{10}, Sp_{11} \). Furthermore, a virtual end node is introduced and the process structure based on eDAG is shown in Figure 10 (a).

(3) **The first reduction**

The first reduction result after applying the sequential reduction rule, the closed reduction rule and the terminal reduction rule is shown in Figure 10(b).

(4) **The first deadlock detection**

Detecting deadlock is based on the deadlock detection method proposed in section 5. When Step 4 is executed, it is unable to determine whether there is a deadlock due to the existence of edges of the dynamic-business-collaborative-channel type. We need to further determine some uncertainties.

(5) **Determination of uncertainty**

If one company’s type is "Company Limited" and it’s business scope is "food processing" and so on, Administration for Industry & Commerce requires the pre-permits of \( bo_2 \) are \( bo_2, bo_3 \) and \( bo_5 \). That means the values of corresponding \( \delta \) of the edges of dynamic-business-collaborative-channel type from \( Sp_2, Sp_3, Sp_5 \) to \( Sp_8 \) are true, while the values from other sub processes to \( Sp_8 \) are false. If the company only applies for \( bo_2 \) and \( bo_3 \) due to some reasons, that is, the values of corresponding \( \delta \) from \( Sp_1 \) to \( Sp_2 \) and \( Sp_3 \) are true, while the values from \( Sp_1 \) to other sub processes are false, then the modified eDAG is shown in Figure 10(c).

**Figure 10.** The business process structures during the deadlock detection process based on eDAG

(6) **The second reduction**

As the revised eDAG has two start nodes, the sequential reduction rule and the closed reduction rule are used and the second reduction result is shown in Figure 10(d).

(7) **The second deadlock detection**
When Step 3 is executed, there is a start node in addition to the former start node in eDAG which is \( Sp_5 \). And it doesn't contain any Merge coordinator and edge of the dynamic-business-collaborative-channel type from \( Sp_5 \) to the end node \( Sp_8 \). And there exists also an AND-join structure. This indicates there are deadlocks in the model. In this situation, exception handling needs to be done. For example, remind the company to apply for \( bo_5 \).

7. Conclusion

In this paper, a deadlock detection method for inter-organizational business process based on RNM is proposed. And the method is evaluated through a case study. The main contributions of this paper are summarized as follows.

1. An extended DAG is proposed for explicitly representing the structure of inter-organizational dynamic business process based on RNM.
2. Using existing reduction rules, several reduction rules amenable to dynamic business processes are proposed to reduce the complexity of inter-organizational business processes. These rules can better meet the dynamics and uncertainties inter-organizational business processes.
3. A deadlock detection method of inter-organizational business processes, especially for dynamic processes, is proposed. The method reduces the complexity of such a business process at the design time. In the simulation phase or at run time, with further determination of uncertainties, model reduction and deadlock detection are conducted step by step. In this way it can not only improve the efficiency of deadlock detection, but also find some deadlocks before all the uncertainties are determined.

We have evaluated the methods for administrative permit system. And we plan to apply it more widely in the domain of E-commerce and emergency management to further verify and improve the proposed methods. In addition, virtual nodes need to be added when the last three reduction rules are applied. This changes the original structure of the process, making it difficult to pinpoint the location of a deadlock. However, complete deadlock detection cannot be guaranteed if these three rules are not used. For solving this problem, we will try to further combine RNM and pi-calculus to improve the deadlock detection method for inter-organizational business processes with the ability of formalized algebraic deduction of Pi-calculus and related analysis tools.

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