

Stochastic Behavior Analysis Methods for Collaborative Business Processes (Postprint)

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Abstract

Stochastic behavior of participating organizations is a key factor in evaluating the effective implementation of business collaboration. This paper proposes a stochastic behavior analysis method for collaborative business processes by combining process algebra and Markov chains. First, finite state automata are employed to model the business process of each participating organization, and asynchronous message communication is introduced to model the collaborative business process among participating organizations. Second, the business processes of participating organizations and the corresponding collaborative business process are transformed into process algebra defined by Communication Sequential Process (CSP), and based on the operational semantics of CSP, a state transition system corresponding to the collaborative business process is constructed. Finally, the concept of normalization is introduced, and it is theoretically proven that the normalized state transition system corresponds to a homogeneous Markov chain; the steady-state probability of each state in the state transition system is obtained through balance equations. Through Markov chain analysis techniques, stochastic behavior analysis of business collaboration processes is realized. A case study demonstrates the feasibility and effectiveness of the proposed method.

Full Text

Preamble

Approach to Analyzing Random Behaviors of Collaborative Business Processes

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Abstract: Participants' random behavior is a key factor in evaluating the effective implementation of business collaboration. This paper proposes an approach to analyzing random behaviors of collaborative business processes based on process algebra and Markov chains. First, we use finite state automata to model each participant's business process and model the collaborative business process through asynchronous message communication between participants. Second, we transform each participant's business process and the corresponding collaborative business process into process algebras defined by Communicating Sequential Processes (CSP), and construct the state transition system of the collaborative business process according to CSP's operational semantics. Finally, we introduce the concept of regularization and theoretically prove that the regularized state transition system corresponds to a homogeneous Markov chain, obtaining the stability probability of each state in the state transition system according to equilibrium equations. Through Markov chain analysis techniques, we achieve random behavior analysis of collaborative business processes. A case study demonstrates the feasibility and effectiveness of the proposed method.

Key Words: collaborative business process; asynchronous message communication; random behavior; CSP; Markov chain

0 Introduction

Collaborative business processes enable participating organizations to share various capabilities (such as computing power, storage capacity, and even management capabilities) to improve computational efficiency and reduce implementation costs. In recent years, with the widespread application of information technology and the extensive 普及 of information networks, numerous industries have involved business collaboration, such as e-commerce, supply chains, and emergency response systems. However, since collaborative business processes involve multiple participating organizations with complex interactions between their processes, effective modeling and analysis during the design phase are crucial to avoid high maintenance costs due to design errors. This has become a hot research topic in the business process management (BPM) domain.

Current research on collaborative business processes primarily focuses on constructing collaborative processes that support personalized features. Most of these studies address logical structure correctness criteria based on soundness, proposing various modeling methods to determine whether a constructed collaborative business process is correct (e.g., deadlock-free, no unreceived messages). However, these works are limited to qualitative functional aspects and do not involve quantitative analysis of participants' random behaviors. In fact, participants' random behaviors affect whether collaborative business processes can achieve established business goals and constitute a key factor in evaluating effective business collaboration implementation.

To address this gap, we propose a random behavior evaluation method for collaborative business processes based on Markov chain theory. This method first transforms collaborative business processes into concurrently composed CSP processes to construct their corresponding labeled transition systems (LTS). It then builds a homogeneous Markov chain from the generated state transition system. Based on the Markov chain's probability transition matrix and equilibrium equations, we obtain the steady-state probability of each state in the transition system, thereby enabling random behavior analysis of participating organizations.

The main contributions of this paper are as follows:

- a) We propose an algorithm to automatically transform collaborative business processes into concurrently composed CSP processes and present a method for constructing the state transition system of collaborative business processes based on CSP operational semantics.
- b) We introduce the concept of state transition system regularization and theoretically prove that a regularized state transition system is equivalent to a homogeneous Markov chain. Based on this Markov chain, we propose a method for evaluating participants' random behavior using equilibrium equations.
- c) We demonstrate the effectiveness of our method through modeling and random behavior analysis of a simplified power equipment procurement process at an electric power company.

2 Basic Definitions

Building a formal model of collaborative business processes is the prerequisite and foundation for random behavior analysis. This section presents formal modeling of collaborative business processes.

A business process, as the basic unit for constructing collaborative business processes, models an organization's internal workflow. This workflow captures the execution relationships between tasks within an organization. Due to the intuitive graphical representation of automata, the ability to formally analyze task execution through state transition relationships, and other advantages, we adopt finite automata to model business processes.

Definition 1 (Business Process). A business process is a five-tuple $BP = (S, i, o, R, Org)$, where: a) S is a finite set of states; b) i and o are two special states representing the start and termination states of the business process, respectively; c) R is a set of state transition relations. For any state transition relation $r \in R$, it can be formally defined as a 3-tuple $r = (sb, a, se)$, where: (a) sb is the source state of the transition; (b) a is the task that triggers the transition; (c) se is the target state of the transition. d) Org denotes the organization to which the business process belongs, used to uniquely identify an organization.

When an organization's business activities extend beyond its internal boundaries, collaborative business processes emerge. Based on asynchronous message communication, task interactions and collaborations between different participating organizations constitute collaborative business processes. Collaborative business processes are built upon business process definitions. Before presenting the formal definition, we first define asynchronous communication relations.

Definition 2 (Asynchronous Communication Relation). An asynchronous communication relation is a 3-tuple $ac = (ti, tj, msg)$, where: a) ti and tj are two tasks with a message passing relationship; b) Let Org_i and Org_j be the organizations where ti and tj reside, respectively, and $Org_i \cap Org_j = \emptyset$; c) msg is the message passed between ti and tj ; d) ti is the task that generates message msg , while tj is the task that receives message msg .

Essentially, an asynchronous communication relation specifies the message passing relationship between tasks distributed across different organizations in a cross-organizational environment, characterizing the interaction process of business collaboration. To simplify analysis, we assume that if a task requires receiving an external message before execution, it receives exactly one message; similarly, if a task sends a message after execution, it sends exactly one message.

Given the business processes of each participating organization, we can define a collaborative business process by defining the set of asynchronous communication relations.

Definition 3 (Collaborative Business Process). A collaborative business process is a 2-tuple $CBP = (BPS, AC)$, where: a) $BPS = \{BP_1, \dots, BP_n\}$ is the set of n business processes participating in collaboration; b) AC is the set of asynchronous message communication relations.

Specifically, the initial state of a collaborative business process is denoted as $ci = (i_1, \dots, i_n)$, where $i_j \in \{1, \dots, n\}$ and i_j is the start state of business process BP_j . The termination state is denoted as $co = (o_1, \dots, o_n)$, where $o_j \in \{1, \dots, n\}$ and o_j is the termination state of business process BP_j .

From the asynchronous message communication relation set AC in a collaborative business process, we can define the set of all messages in CBP , the set of messages each task needs to receive before execution, and the set of messages each task sends after completion.

Definition 4 (Message Set of Collaborative Business Process). Let $CBP = (BPS, AC)$ be a collaborative business process. The message set contained in CBP is $MS = \{msg \mid ac = (ti, tj, msg) \in AC\}$.

Definition 5 (Task Receive Message Set). Let $CBP = (BPS, AC)$ be a collaborative business process. The set of messages that task t needs to receive before execution is $RM = \{msg \mid ac = (ti, tj, msg) \in AC \wedge tj = t\}$.

Definition 6 (Task Send Message Set). Let $CBP = (BPS, AC)$ be a collaborative business process. The set of messages that task t sends after execution

is $SM = \{msg \mid ac = (ti, tj, msg) \in AC \wedge ti = t\}$.

Based on Definition 3, we present Algorithm 1 to transform each participating organization' s business process into a CSP process.

Algorithm 1: Generate CSP Process for Business Process

Input: business process $BP = (S, i, o, R, Org)$;

Output: CSP process Pro for BP;

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put i into queue Q;
put i into visited queue VQ;
while Q.size > 0 do
    elem = Q.poll;
    for each r in R do // Get state transitions from elem
        if elem = r.sb then
            S.add(r);
        end if
    end for
    if S.size == 0 then // If elem is a termination state, skip
        continue;
    end if;
    if S.size == 1 then // Directly build CSP process sb() and add to Pro
        r = (sb, a, se) = S.get(0);
        generate CSP process sb() = a → se() and add sb() to Pro;
        if VQ does not contain se then
            add se to Q;
            add se to VQ;
        end if
    end if
    if S.size > 1 then // If multiple branches, build choice relation process sb() and add to Pro
        get S = {r = (sb, a, se), ..., r = (sb, a, se)};
        generate sb() = a → se() [] ... [] a → se() and add sb() to Pro;
    end if
end while
return Pro;

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The basic idea of Algorithm 1 is to recursively generate the CSP process expression for each business process $BP \in BPS$ using a breadth-first search strategy. The process expression is represented by a process identified by the start state i . Each event in the process expression corresponds to a task. Let l and k be the maximum depth and number of state transitions of business process BP , respectively. The worst-case time complexity of Algorithm 1 is $O(l \times k)$.

Let $CBP = (BPS, AC)$ be a collaborative business process. After generating the CSP process for each participating organization' s business process BP_i ($0 \leq i < n$) using Algorithm 1, we concurrently compose these generated CSP processes to obtain the CSP process corresponding to CBP .

Definition 7 (CSP Process for Collaborative Business Process). Let $CBP = (BPS, AC)$ be a collaborative business process, where $BPS = \{BP_1, \dots, BP_n\}$ and Pro_i is the CSP process corresponding to any business process BP_i ($0 \leq i < n$). The CSP process for CBP is $CBP-Pro = Pro_1 \parallel \dots \parallel Pro_n$, where “ \parallel ” is the CSP concurrency operator.

After determining the CSP process for CBP, we need to clarify the interactions between tasks of participating organizations to generate the corresponding state transition system. Since CSP does not explicitly support message send and receive actions, for any asynchronous message communication $ac = (tik, tj, msg)$ $AC = \{ac_1, \dots, ac_n\}$ ($0 \leq k < n$), we treat tik and tjk as the same event. According to CSP operational semantics, tik and tjk will synchronize during interaction, simulating the interaction between tik and tjk . This can be achieved through action renaming in CSP processes.

Definition 8 (CSP Process Renaming). Let Pro be a CSP process. We denote $Pro[b \rightarrow a]$ ($0 \leq i < n$) as renaming any event b in process Pro to a .

From AC in CBP , we can determine the renaming set for each participating organization.

Definition 9 (Renaming Set for Participating Organization). Let Pro be the CSP process of a participating organization BP . Denote $fn(Pro)$ as the set of all events in process Pro . The renaming set required for Pro is $RN = \{t \mid ac = (t, t, msg) \in AC \wedge t \in fn(Pro)\} \cup \{t \mid ac = (t, t, msg) \in AC \wedge t \notin fn(Pro)\}$.

Definition 10 (Renamed Name). Let Pro be the CSP process corresponding to a participating organization BP , and RN be Pro 's renaming set. For $t \in RN$, let the corresponding asynchronous message communication be $ac = (t, t, msg)$. The renamed name for t is msg .

After determining the renaming set RN for the participating organization and the renamed name for each action in RN , we replace each action to be renamed in RN with its corresponding renamed name to obtain the CSP process that can describe task interaction relations, denoted as $CBP-Prof$. Based on $CBP-Prof$ and CSP operational semantics, we can generate the state transition system for the collaborative business process.

Definition 11 (State Transition System for Collaborative Business Process). Let CBP be a collaborative business process with interaction-describing CSP process $CBP-Prof$. The state transition system for CBP is represented as a labeled transition system $LTS = (S, s, Act, R)$, where: a) S is a finite set of states; b) s is the initial transition state; c) Act is the set of transition actions; d) $R \subseteq S \times Act \times S$ is the set of transition relations, representing state transitions caused by task execution.

After generating the state transition system for the collaborative business process, we present the method for constructing its corresponding homogeneous Markov chain.

Definition 12 (Regularization of State Transition System). Let CBP be a collaborative business process with state transition system $LTS = (S, s, Act, R)$. Let $\Sigma : R \rightarrow \mathbb{R}$ be a mapping from transition relations to positive real numbers. If Σ satisfies the following three conditions: a) For all $r \in R$, $0 < \Sigma(r) \leq 1$; b) For all $r \in R$, $\sum_{r'} \Sigma(r') = 1$; c) For all $s \in S$, $\sum_{r \in R} \Sigma(r) = 1$ where $r \in R$ and r' 's source state is s , then we say LTS is regularized by function Σ , denoted as the regularized state transition system LTS_{reg} .

Theorem 1. Let CBP be a collaborative business process. The regularized state transition system LTS_{reg} obtained by applying function Σ to LTS is a homogeneous Markov chain.

Proof. To prove that LTS_{reg} is a homogeneous Markov chain, the key is to show that a probability transition matrix $M = [m_{ij}]$ can be constructed from LTS_{reg} , satisfying conditions a)-c) in Definition 12. From Definition 12, we know that LTS_{reg} has a corresponding probability transition matrix M , which implies that LTS_{reg} is a homogeneous Markov chain MC, and M is the probability transition matrix of MC.

After determining the probability transition matrix of the Markov chain, we can obtain the steady-state probability of each state in LTS_{reg} according to equilibrium equations. Let the state set in LTS_{reg} be $S = \{s_1, \dots, s_n\}$ with probability transition matrix M , and $P = \{p_1, \dots, p_n\}$ be the steady-state probability vector corresponding to S . Then P can be obtained from the following equilibrium equation (1):

$$\begin{aligned} p_1 + \dots + p_n &= 1 \\ P &= MP \end{aligned}$$

The steady-state probability p_i ($0 \leq i < n$) obtained from the equilibrium equation (1) is a function of certain probabilities p_j ($0 \leq j < n$) in $\{p_1, \dots, p_n\}$. Based on this function, we can analyze the random behavior of participating organizations.

3 Random Behavior Analysis of Collaborative Business Processes

The analysis of random behavior in collaborative business processes consists of four steps: a) constructing the corresponding state transition system based on the collaborative business process definition; b) constructing the corresponding homogeneous Markov chain from the state transition system; c) obtaining the probability transition matrix of the Markov chain; and d) calculating the steady-state probability of each state in the state transition system using equilibrium equations.

Regarding how to construct the state transition system corresponding to a collaborative business process, considering that collaborative business processes are a typical type of open system whose behavior is determined by the business processes of participating organizations and task interactions between different processes, while traditional finite automata can only model closed systems

(where system behavior is completely controllable and fully determined by system states), we first model the behavior of each participating organization's business process as a CSP process. The collaborative business process behavior can then be represented by the concurrent composition of CSP processes corresponding to each participating organization. Based on CSP operational semantics, we construct the state transition system for the collaborative business process.

4 Case Study

Supply chains are typical collaborative business systems. We illustrate the effectiveness of our method through modeling and random behavior analysis of a simplified power equipment procurement process at an electric power company. This procurement process involves three participating organizations: the power grid company, the electrical equipment manufacturer, and the electrical equipment parts supplier. The interaction flow is described as follows:

- a) The power grid company first sends a product order request (reqOrder) to the electrical equipment manufacturer. The manufacturer determines that the ordered product consists of self-made part A and outsourced part B. The manufacturer then decides whether to accept the order based on its current situation, which involves randomness.
- b) If the manufacturer rejects the order (refOrder), the interaction ends. Otherwise, the manufacturer notifies the grid company that the order is accepted (acpOrder) and sends a parts procurement request (reqBOrder) to the parts supplier. The supplier decides whether to accept the parts order based on its current situation, which also involves randomness.
- c) If the supplier rejects the parts order (refBOrder), the manufacturer notifies the grid company that the product order fails due to parts B order rejection (orderFailByBRef). Otherwise, the supplier accepts the order (acpBOrder). However, in actual production, whether the supplier can complete parts B on time involves randomness.
- d) If the supplier fails to complete parts B on time, it notifies the manufacturer of the production failure (mafBFail). The manufacturer then notifies the grid company that the product order fails due to parts B production failure (orderFailByBMaf), and the interaction ends. Otherwise, the supplier notifies the manufacturer that the parts B order can be completed (doneB). Although the supplier can deliver parts B, whether the manufacturer can assemble self-made part A and outsourced part B to complete the product involves randomness.
- e) If the manufacturer fails to assemble the product, it sends an assembly failure message (orderFailByAsm) to the grid company, and the interaction ends. Otherwise, it notifies the grid company that the order is completed successfully (orderSucc), and the interaction ends.

[Figure 1: see original paper] Participating organizations' business processes

- (a) Based on the above analysis of the power equipment procurement process, we can model the business processes of the grid company, electrical equipment manufacturer, and parts supplier, as shown in Figure 1.
- (b) Based on the business processes of these three organizations, the collaborative business process for the entire procurement is defined as $CBP = (BPS, AC)$, where:
 - $BPS = \{BP_pow, BP_maf, BP_sup\}$, with BP_pow , BP_maf , and BP_sup representing the business processes of the grid company, manufacturer, and supplier as finite automata, respectively (shown in Figure 1);
 - $AC = \{(sendReqOrder, recReqOrder, reqOrder), (sendRefOrder, recRefOrder, refOrder), (sendAcpOrder, recAcpOrder, acpOrder), (sendReqBOrder, recReqBOrder, reqBOrder), (sendRefBOrder, recRefBOrder, refBOrder), (sendOrderFailByBRef, recOrderFailByBRef, orderFailByBRef), (sendAcpBOrder, recAcpBOrder, acpBOrder), (sendMafBFail, recMafBFail, mafBFail), (sendOrderFailByBMaf, recOrderFailByBMaf, orderFailByBMaf), (sendDoneB, recDoneB, doneB), (sendOrderFailByAsm, recOrderFailByAsm, orderFailByAsm), (sendOrderSucc, recOrderSucc, orderSucc)\}$.
- (c) According to Algorithm 1, we transform each participating organization's business process in CBP into CSP processes and rename each send and receive action according to Definition 10. The CSP process for the parts supplier is as follows (the CSP processes $G()$ and $M()$ for the grid company and manufacturer are omitted due to space limitations):

$S() = reqBOrder \rightarrow S();$
 $S() = acpBOrder \rightarrow S();$
 $S() = mafBFail \rightarrow S() \quad [] \quad doneB \rightarrow S();$

The concurrent composition of the CSP processes for the grid company, manufacturer, and parts supplier, along with their operational semantics, generates the state transition system LTS shown in Figure 2.

[Figure 2: see original paper] State transition system of the collaborative business process

Regarding the randomness in the collaborative business process interactions, let the probabilities of successful execution for $acpOrder$, $acpBOrder$, $doneB$, and $orderSucc$ in the LTS be p , p , p , and p , respectively. This yields the following probability transition matrix M for the LTS:

$M = [\text{matrix representation}]$

According to the equilibrium equation (1), the probability of node p is $p = [\text{expression}]$, which represents the probability of successful procurement by the grid company. Based on p , we discuss how to analyze the impact magnitude

of the manufacturer and parts supplier on the grid company' s procurement success.

Since probabilities p and p reflect the manufacturer's behavioral characteristics, while p and p reflect the supplier' s characteristics, we group p and p together and p and p together. First, we fix p and p (let $p = p = C$, where C is a constant) and vary p and p in the interval $[0.1, 1]$ to obtain a set of values for node p . Then, we fix p and p (let $p = p = C$) and vary p and p in $[0.1, 1]$ to obtain another set of values for p . By comparing these two sets, we can determine which organization has greater impact on procurement success.

Figures 3 and 4 show the impact curves of the manufacturer and parts supplier on grid company procurement success when $C = 0.2$ and $C = 0.8$, respectively.

[Figure 3: see original paper] Impact relationship between participating organization processing capability and procurement success rate

[Figure 4: see original paper] Impact relationship between participating organization processing capability and procurement success rate

From Figures 3 and 4, we observe: When both the manufacturer and parts supplier have strong processing capabilities ($C = 0.8$, where larger C indicates stronger capability), the parts supplier has greater impact on procurement success than the manufacturer, suggesting that improving the supplier' s capability should be prioritized. When both have weak processing capabilities ($C = 0.2$), the manufacturer has greater impact than the supplier, indicating that improving the manufacturer' s capability should be prioritized.

This case analysis yields the following conclusion: With clear understanding of each organization' s impact on order procurement, measures can be taken to improve the corresponding nodes' business processing capabilities, thereby enhancing the reliability and robustness of business collaboration.

5 Conclusion

This paper proposes a random behavior analysis method for collaborative business processes based on stochastic process theory. The method first transforms each participating organization' s business process into CSP processes, then obtains the CSP process for the collaborative business process through their concurrent composition, and generates the corresponding state transition system. We present a method for mapping the state transition system of collaborative business processes to a homogeneous Markov chain, enabling the calculation of steady-state probability formulas for each state through equilibrium equations. Based on these formulas, we can analyze the impact of participating organizations on business collaboration and adopt corresponding measures to improve node processing capabilities, thereby enhancing collaboration reliability and robustness.

Our work currently focuses only on behavioral characteristics of collaborative

business processes. In fact, reliable execution of business collaboration also depends on other factors such as demand uncertainty. Future work will first consider constructing an indicator system for uncertainties affecting business collaboration, then integrate these indicators to evaluate collaborative business process reliability more accurately and comprehensively.

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