

Research Article

Cross-Organization Emergency Response Process Mining: An Approach Based on Petri Nets

Cong Liu ¹, Huiling Li,¹ Qingtian Zeng ², Ting Lu,¹ and Caihong Li¹

¹School of Computer Science and Technology, Shandong University of Technology, Zibo 255000, China

²College of Computer Science and Engineering, Shandong University of Science and Technology, Qingdao 266590, China

Correspondence should be addressed to Qingtian Zeng; qtzeng@163.com

Received 24 September 2020; Revised 16 October 2020; Accepted 26 October 2020; Published 17 November 2020

Academic Editor: Chenxi Huang

Copyright © 2020 Cong Liu et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

To support effective emergency disposal, organizations need to collaborate with each other to complete the emergency mission that cannot be handled by a single organization. In general, emergency disposal that involves multiple organizations is typically organized as a group of interactive processes, known as cross-organization emergency response processes (CERPs). The construction of CERPs is a time-consuming and error-prone task that requires practitioners to have extensive experience and business background. Process mining aims to construct process models by analyzing event logs. However, existing process mining techniques cannot be applied directly to discover CERPs since we have to consider the complexity of various collaborations among different organizations, e.g., message exchange and resource sharing patterns. To tackle this challenge, a CERP model mining method is proposed in this paper. More specifically, we first extend classical Petri nets with resource and message attributes, known as resource and message aware Petri nets (RMPNs). Then, intra-organization emergency response process (IERP) models that are represented as RMPNs are discovered from emergency drilling event logs. Next, collaboration patterns among emergency organizations are formally defined and discovered. Finally, CERP models are obtained by merging IERP models and collaboration patterns. Through comparative experimental evaluation using the fire emergency drilling event log, we illustrate that the proposed approach facilitates the discovery of high-quality CERP models than existing state-of-the-art approaches.

1. Introduction

Since the 9/11 terrorist attack, there have been considerable efforts to improve the effectiveness and efficiency to respond to emergencies. Generally speaking, an emergency is a situation that imposes immediate risk to life, property, and environment, which requires urgent disposal and intervention to prevent its worsening [1]. To support effective emergency disposal, organizations need to collaborate with each other to complete the emergency mission that cannot be handled by one single organization. In general, emergency disposal that involves multiple organizations are typically organized as a group of loosely-coupled interactive processes, known as cross-organization emergency response processes (CERPs) [2]. The construction of CERPs can improve the efficiency and effectiveness of emergency decision-making. However,

the design of CERPs is typically a time-consuming and error-prone task that requires modelers to have extensive experience and business background.

During the execution of emergency responses, event logs are recorded and stored by emergency management systems [3]. Process mining aims to construct process models by analyzing event logs collected from various information systems [4, 5]. However, existing process mining techniques cannot be applied to discover CERPs since we have to consider the complexity of various collaborations among different organizations, e.g., message exchange and resource sharing patterns. Therefore, an automated method to mine CERP models from emergency drilling event logs is urgently needed to improve the efficient model construction.

To this end, we present a CERP model mining method that takes as input an emergency drilling event log. The contributions of this paper are summarized as follows: (1)

Petri nets are extended with resource and message attributes, denoted as RMPNs, to model CERP. (2) For each organization, a novel algorithm is proposed to discover the intra-organization emergency response process (IERP) model. (3) Three kinds of collaboration patterns, including message exchange pattern, resource sharing pattern, and task synchronization pattern, are formalized based on RMPNs. In addition, the corresponding discovery techniques are presented; and (4) CERP models are discovered by merging all involved IERP models and collaboration patterns.

The remainder of the paper is organized as follows. Section 2 presents a review of the related work. Section 3 introduces some terminologies and notations used throughout the paper. A fire emergency response process case is introduced to be used as a case study in Section 4. Section 5 introduces the mining method for CERP models. Section 6 performs comparative evaluation. Finally, Section 7 concludes the paper.

2. Related Work

In this paper, we summarize work related to cross-organization business process modeling, process mining and cross-organization process mining, and emergency response process modeling and mining.

2.1. Cross-Organization Business Process Modeling. Van Der Aalst extended traditional workflow nets to a cross-organization scenario to model cross-organizational workflows and verify the correctness from a structure perspective in [6]. In [7], Mo et al. proposed a cross-organization business process modeling approach that applies finite state machine and asynchronous communication model. In [8], existing cross-organizational modeling methods are classified from the interorganizational angle and qualitative and quantitative analysis on the correctness and effectiveness are performed. Jiang et al. [9] described a timed colored Petri net and process-view combined approach to construct cross-organization business processes and a three-layered framework is proposed to support the interoperability.

In our previous work, we introduced four kinds of collaboration patterns, including message interaction, resource interaction, task collaboration, and service outsourcing patterns, based on which a cross-organization collaborative medical business process is modeled and its correctness is verified via reachability analysis of Petri nets in [10]. More recently, we investigated the modeling and correctness verification of cross-organizational business processes that interact through task synchronization patterns in [11].

2.2. Process Mining and Cross-Organization Process Mining. Process mining can extract useful information from event logs commonly generated by information systems. This technology provides new means for process discovery, monitoring, and improvement in various applications [12]. As an often cited example, the α -Algorithm [4] first defines four kinds of ordering relations. Then, a workflow net is derived from these task dependency relations. To further its

application for less-structured event log and overcome the spaghetti-like models which contain all details without any hierarchies, Christian and Wil proposed the fuzzy mining approach in [13]. Leemans et al. proposed the inductive miner to handle infrequency and incomplete event logs, and the discovered Petri net-based process model is guaranteed to be correct in [14].

In [5], four coordination patterns among different organizations are first defined and process mining approaches are used to discover the process model of each organization and corresponding coordination patterns based on which the whole cross-organization process is obtained by integration. In our recent work, the privacy problem of cross-organizational business process mining is investigated and a privacy-preservation mining method is proposed to construct the organization-specific cross-organization collaborative process model in [15]. In [16], a top-down process mining approach is proposed to construct the cross-organization model in service out-sourcing scenario from heterogeneous logs collected from distributed environment. Petri net refinement technique is used to merge the main process and the out-sourced ones.

2.3. Emergency Response Process Modeling and Mining. In [1, 17], we investigated the modeling and analysis methods for an emergency response process constrained by resources and uncertain durations. The number of available resources and minimum resource demand for an emergency response process is analyzed. Moreover, resource conflict detection and resolution strategies are also investigated to optimize the universal process performance. Li et al. proposed Petri net-based modeling techniques for subway station fire emergency response processes in [15]. A hierarchical Petri net that includes a logic net, a semantic net, and a set of case models is introduced for modeling and verification of emergency response processes in [18]. The applicability of this approach is validated by an emergency treatment process of highways under snow/ice weather conditions. More recently, we proposed a top-down approach for model construction and correctness verification of cross-organization emergency response processes in [19]. To support efficient emergency resource management, Zeng et al. [20] proposed an approach to support emergency resource management including both intra-organization private resource management and cross-organization public resource management.

In the emergency response process mining area, He et al. applied process mining techniques to uncover emergency rescue process of coal mine gas explosion accidents from the historical event logs in [3]. However, this approach focuses on single emergency response process and does not consider interactions and collaborations among different emergency organizations, and the resource attributes and message attributes are not considered.

3. Terminologies

Given a set S , where $|S|$ denotes the number of elements in S . $x \in S$ denotes that x is an element of S . We use \emptyset to denote

the empty set. $f: X \rightarrow Y$ is a function, i.e., $\text{dom}(f) = X$ is the domain and $\text{rng}(f) = \{f(x) | x \in \text{dom}(f)\} \subseteq Y$ is the range. If $\sigma(1) = a_1$ and $\sigma(2) = a_2, \dots, \sigma(n) = a_n$, we write $\sigma = \langle a_1, a_2, \dots, a_n \rangle$. $|\sigma| = n$ represents the length of sequence σ is n (n is a natural number). The set of all finite sequences over S is denoted as S^* .

This work is based on Petri nets, and some basic concepts are reviewed below [21–24].

Definition 1 (Petri nets). A Petri net is defined as a 4-tuple $\Sigma = (P, T, F, M_0)$, such that (1) $P \cap T = \emptyset$ and $P \cup T \neq \emptyset$, where P is a finite set of places and T is a finite set of transitions; (2) $F \subseteq (P \times T) \cup (T \times P)$ is a finite set of arcs; and (3) $M_0: P \rightarrow \{0, 1, 2, 3, \dots, n\}$ is the initial marking.

For any $x \in P \cup T$, $\bullet x = \{y | (y, x) \in F\}$ is the preset of x and $x^\bullet = \{y | (x, y) \in F\}$ is its postset. M_0 denotes the initial marking, and $R(M_0)$ is the set of reachable markings of Σ . For any $t \in T$, t is enabled under M , denoted as $(\Sigma, M)t >$, if $\forall p \in \bullet t: M(p) \geq 1$. If $(\Sigma, M)t >$ holds, t may fire, resulting in a new marking M' , denoted as $(\Sigma, M)[t > (\Sigma, M')]$ such that $M'(p) = M(p) - 1$ if $p \in \bullet t/t^\bullet$, $M'(p) = M(p) + 1$ if $p \in t^\bullet/t^\bullet$, and otherwise $M'(p) = M(p)$.

A Petri net that describes a process is called workflow net (or WF-net). Its definition is reviewed below [25].

Definition 2 (workflow nets). A Petri net $\Sigma = (P, T, F, M_0)$ is a WF-net if the following conditions hold: (1) there exists a source place $i \in P$ such that $\bullet i = \emptyset$; (2) there exists a sink place $o \in P$ such that $o^\bullet = \emptyset$; and (3) each node is on a path from i to o ; and (4) for each $p \in P$, $M_0(p) = 1$ if $p = i$, and otherwise $M_0(p) = 0$.

Because a process is created once it enters the workflow engine and destroyed when completed, we use a source place and a sink place to explicitly denote the initial and final states. Transitions are used to represent tasks in a process.

4. A Fire Emergency Response Process Case

When a fire emergency occurs, its disposal usually involves multiple emergency organizations. A typical fire emergency response process usually involves the following organizations: police station, emergency command center (ECC), explosive ordnance disposal (EOD) team, fire brigade, and hospital. Figure 1 shows the overall cross-organization fire emergency response process and an overview of the main emergency tasks for each organization.

This emergency response scenario includes the following steps. (1) The police station first receives a fire alarm and then reports the information to ECC. (2) The police rushes to the fire site and performs its detailed disposal missions and then reports the site conditions to ECC. (3) After receiving the fire information, ECC first establishes the temporary emergency command group and then makes and issues emergency plans to its subordinate organizations, i.e., medical rescue instruction to the hospital, search EOD instruction to the EOD team, and fire rescue instruction to the fire brigade. (4) The EOD team rushes to the site once it receives the search EOD instruction from ECC, conducts its specific disposal tasks according to the emergency plan, and

finally reports the EOD search results. (5) The fire brigade rushes to the site once it receives the fire rescue instruction from ECC, conducts its specific disposal tasks according to the emergency plan, and finally reports the fire rescue results. (6) The hospital personnel rushes to the site once it receives the medical rescue instruction from ECC, conducts its specific disposal tasks according to the plan, and finally reports the results. (7) After receiving all the feedback information from the hospital, EOD team, and fire brigade, ECC makes a summary and finally does the file archive. (8) ECC arranges the media coverage for this emergency response; and (9) Finally, ECC, hospital, and the fire brigade do the media coverage together.

During the execution of the fire emergency response processes, emergency drilling event logs are recorded and stored by the emergency management systems. In general, the collected fire emergency drilling event log, denoted as firelog^1 , contains 126 cases, 3528 events, and 28 emergency tasks in total. This log will be used in the next sections to explain our concepts and techniques, and every event in the emergency drilling event logs have the resource attributes, message attributes, and timestamp.

5. Cross-Organization Emergency Response Process Mining

This section details the cross-organization emergency response process (CERP) model mining from emergency drilling event logs.

5.1. Emergency Drilling Event Logs. The event logs captured during the execution of emergency response processes are essentially a collection of events such that each event refers to an emergency task and includes a group of attributes, such as timestamp, resources, and sent and received messages. Formal definition of events and attributes are given below.

Definition 3 (events and attributes). Let ξ be the event universe, i.e., the set of all possible event identifiers and N be the attribute universes, i.e., the set of all possible event attributes. For any event $e \in \xi$ and $n \in N$, $\#_n(e)$ represents the value of attribute n for e .

For an arbitrary event $e \in \xi$, the following attributes are involved in the emergency drilling event logs:

- (i) $\#_{\text{case}}(e)$ represents the case to which e belongs to, and each event belongs to only one independent case
- (ii) $\#_{\text{act}}(e)$ represents the task name of e
- (iii) $\#_{\text{mR}}(e)$ represents the messages received by e
- (iv) $\#_{\text{mS}}(e)$ represents the messages sent by e
- (v) $\#_{\text{rR}}(e)$ represents the resource set of e
- (vi) $\#_{\text{org}}(e)$ represents the organization name of e
- (vii) $\#_{\text{time}}(e)$ represents the timestamp of e

Definition 4 (case, event log). A case over some event universe ξ is a finite sequence of events $\sigma \in \xi^*$ such that each

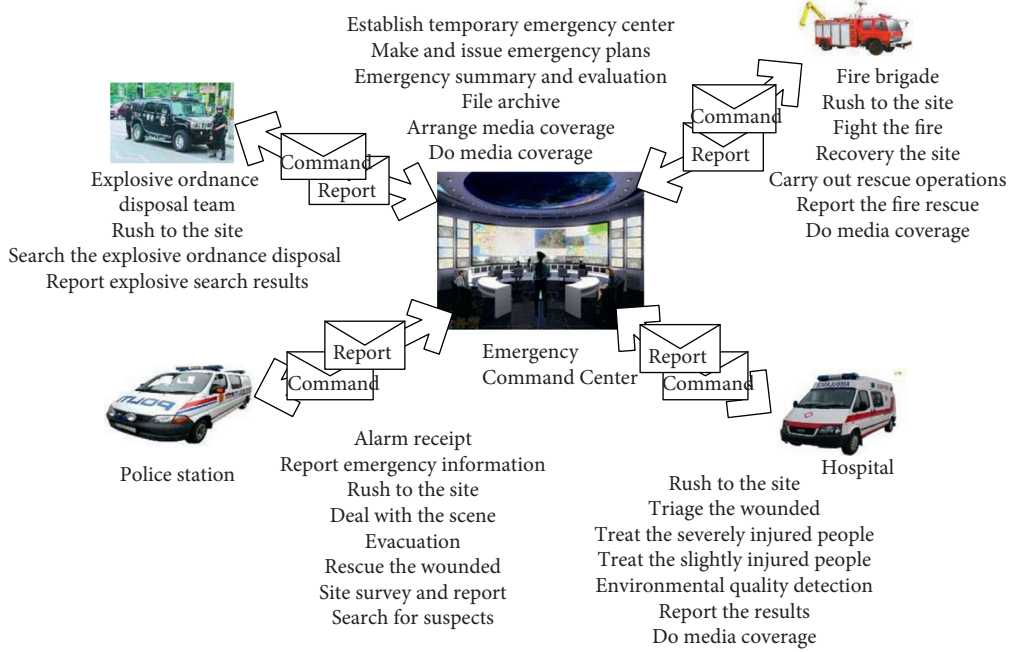


FIGURE 1: Cross-organization fire emergency response collaboration diagram.

event appears only once and all events have the same case id, i.e., $1 \leq i < j \leq |\sigma|$: $\sigma(i) \neq \sigma(j) \wedge \#_{\text{case}}(\sigma(i)) = \#_{\text{case}}(\sigma(j))$. An event log is defined as a finite set of cases, i.e., $L \subseteq \xi^*$.

Table 1 depicts a fragment of the fire emergency drilling event log firelog. It contains one case that records all events generated during one run of the process. In total, 30 events are included and they are fully ordered by the timestamp. For example, we have the following observation for e_2 : (1) $\#_{\text{case}}(e_2) = 1$ means that the event belongs to case with ID 1; (2) $\#_{\text{act}}(e_2) = t_2$ means that the task name of this event is t_2 ; (3) $\#_{\text{mr}}(e_2) = \{\emptyset\}$ means that no message is sent after the event finished; (4) $\#_{\text{ms}}(e_2) = \{p_{m1}\}$ means that this event needs to receive message p_{m1} before execution; (5) $\#_{\text{r}}(e_2) = \{\emptyset\}$ means that the event does not use resources; and (6) $\#_{\text{time}}(e_2) = 14: 21 \text{ Jan } 02 \text{ } 2014$ is the time that this event ends.

5.2. Intra-Organization Emergency Response Process Model Mining. Different from traditional business processes, CERPs are more complex and typically involve various elements, e.g., messages and resources. Therefore, we first extend classical Petri nets with message and resource attributes as follows.

Definition 5 (RMPN). $\Sigma = (P, T, F, M_0)$ is a RMPN if (1) $P = P_L \cup P_R \cup P_M$, $P_L \cap P_R = \emptyset$, $P_L \cap P_M = \emptyset$, $P_M \cap P_R = \emptyset$, and $P_L \subseteq P$ represent the logic place set, $P_M \subseteq P$ represents the message place set, and $P_R \subseteq P$ represents resource place set; (2) $F = F_L \cup F_R \cup F_M$, where F_L represents the control-flow, F_R represents the resource flow, and F_M represents the message flow; and (3) $\forall p \in P$ if $p \in P_R \cup \{i\}$, $i \in P_L \wedge i = \emptyset$, and $M_0(p) = 1$, and otherwise $M_0(p) = 0$.

RMPNs are used to represent CERPs, and the mining methods are all based on this model. We first introduce how

to mine IERP models. To this end, we need to obtain the emergency drilling event logs of each organization by projecting the whole event log based on the organization attribute. Taking event log in Table 1, the emergency drilling event log of the police station includes $e_1, e_2, e_3, e_4, e_5, e_6, e_7$, and e_8 .

Then, the following algorithm is presented to discover the IERP model represented by an RMPN by taking as input the event log of single organization.

Algorithm 1 extends the existing inductive miner [14] that mines the control-flow model with message sending and receiving information as well as resource accessing information and finally returns an RMPN. Considering the police station as an example, task t_2 sends message p_{m1} and task t_7 sends message p_{m2} when finished. By taking as input the firelog, the obtained RMPN for each organization is shown in Table 2.

5.3. Cross-Organization Collaboration Pattern Mining. After obtaining the RMPN for each emergency organization, we introduce how to discover collaboration patterns. To this end, three kinds of patterns, including message exchange pattern, resource sharing pattern, and task synchronization pattern, are formalized as follows.

Definition 6 (message exchange pattern). Let $\Sigma_1 = (P_1, T_1, F_1, M_{01})$ and $\Sigma_2 = (P_2, T_2, F_2, M_{02})$ be the RMPNs of two emergency organizations. Message exchange pattern exists between them if (1) $P_{L1} \cap P_{L2} = \emptyset$; (2) $P_{M1} \cap P_{M2} \neq \emptyset$; (3) $P_{R1} \cap P_{R2} = \emptyset$; and (4) $T_1 \cap T_2 = \emptyset$.

Definition 7 (resource sharing pattern). Let $\Sigma_1 = (P_1, T_1, F_1, M_{01})$ and $\Sigma_2 = (P_2, T_2, F_2, M_{02})$ be the RMPNs of the two emergency organizations. Resource

TABLE 1: A fragment of the fire emergency drilling event log.

Emergency organization	Event	# _{case}	# _{act}	# _{mR}	# _{mS}	# _{rR}	# _{time}
*Police station	e_1	1	t_1	\emptyset	\emptyset	\emptyset	14:20 Jan 02 2014
	e_2	1	t_2	\emptyset	$\{p_{m1}\}$	\emptyset	14:21 Jan 02 2014
	e_3	1	t_3	\emptyset	\emptyset	\emptyset	14:26 Jan 02 2014
	e_4	1	t_4	\emptyset	\emptyset	\emptyset	14:30 Jan 02 2014
	e_5	1	t_5	\emptyset	\emptyset	\emptyset	14:32 Jan 02 2014
	e_6	1	t_6	\emptyset	\emptyset	\emptyset	14:32 Jan 02 2014
	e_7	1	t_7	\emptyset	$\{p_{m2}\}$	\emptyset	14:35 Jan 02 2014
	e_8	1	t_8	\emptyset	\emptyset	\emptyset	14:45 Jan 02 2014
*ECC	e_9	1	t_9	$\{p_{m1}\}$	\emptyset	\emptyset	14:23 Jan 02 2014
	e_{10}	1	t_{10}	$\{p_{m2}\}$	$\{p_{m3}, p_{m4}, p_{m5}\}$	\emptyset	14:36 Jan 02 2014
	e_{11}	1	t_{11}	$\{p_{m6}, p_{m7}, p_{m8}\}$	\emptyset	\emptyset	17:05 Jan 02 2014
	e_{12}	1	t_{12}	\emptyset	\emptyset	\emptyset	17:10 Jan 02 2014
	e_{13}	1	t_{13}	\emptyset	\emptyset	\emptyset	17:20 Jan 02 2014
	e_{14}	1	t_{14}	\emptyset	\emptyset	\emptyset	17:25 Jan 02 2014
*EOD team	e_{15}	1	t_{15}	$\{p_{m3}\}$	\emptyset	$\{p_r\}$	14:38 Jan 02 2014
	e_{16}	1	t_{16}	\emptyset	\emptyset	\emptyset	14:43 Jan 02 2014
	e_{17}	1	t_{17}	\emptyset	$\{p_{m6}\}$	\emptyset	15:00 Jan 02 2014
*Fire brigade	e_{18}	1	t_{18}	$\{p_{m4}\}$	\emptyset	$\{p_r\}$	14:37 Jan 02 2014
	e_{19}	1	t_{19}	\emptyset	\emptyset	\emptyset	15:30 Jan 02 2014
	e_{20}	1	t_{20}	\emptyset	\emptyset	\emptyset	16:40 Jan 02 2014
	e_{21}	1	t_{21}	\emptyset	\emptyset	\emptyset	16:40 Jan 02 2014
	e_{22}	1	t_{22}	\emptyset	$\{p_{m7}\}$	\emptyset	17:00 Jan 02 2014
	e_{23}	1	t_{14}	\emptyset	\emptyset	\emptyset	17:25 Jan 02 2014
*Hospital	e_{24}	1	t_{23}	$\{p_{m5}\}$	\emptyset	$\{p_r\}$	14:39 Jan 02 2014
	e_{25}	1	t_{24}	\emptyset	\emptyset	\emptyset	14:55 Jan 02 2014
	e_{26}	1	t_{25}	\emptyset	\emptyset	\emptyset	15:50 Jan 02 2014
	e_{27}	1	t_{26}	\emptyset	\emptyset	\emptyset	15:50 Jan 02 2014
	e_{28}	1	t_{27}	\emptyset	\emptyset	\emptyset	16:40 Jan 02 2014
	e_{29}	1	t_{28}	\emptyset	$\{p_{m8}\}$	\emptyset	17:00 Jan 02 2014
	e_{30}	1	t_{14}	\emptyset	\emptyset	\emptyset	17:25 Jan 02 2014

(i) INPUT: event log of a single emergency organization
(ii) OUTPUT: IERP model $\Sigma = (P, T, F, M_0)$
(1) $P \leftarrow \emptyset, P_L \leftarrow \emptyset, P_R \leftarrow \emptyset, P_M \leftarrow \emptyset, F \leftarrow \emptyset, F_L \leftarrow \emptyset, F_R \leftarrow \emptyset, F_M \leftarrow \emptyset, T \leftarrow \emptyset, M_0 \leftarrow \emptyset$; //initialization
(2) $(P_L, T, F_L) \leftarrow \text{inductive miner}(L)$; //mining the control flow
(3) For each $t \in T$
(4) For each $\sigma \in L$
(5) For each $e \in \sigma$
(6) If $t = \#_{\text{act}}(e)$
(7) If $\#_{mS}(e) \neq \emptyset$; //mining sending message places
(8) $P_M \leftarrow P_M \cup \{\#_{mS}(e)\}$;
(9) $F_M \leftarrow F_M \cup \{t, \#_{mS}(e)\}$;
(10) End if
(11) If $\#_{mR}(e) \neq \emptyset$; //mining receiving message places
(12) $P_M \leftarrow P_M \cup \{\#_{mR}(e)\}$;
(13) $F_M \leftarrow F_M \cup \{\#_{mR}(e), t\}$;
(14) End if
(15) If $\#_{rR}(e) \neq \emptyset$; //mining resource places
(16) $P_R \leftarrow P_R \cup \{\#_{rR}(e)\}$
(17) $F_R \leftarrow F_R \cup \{\#_{rR}(e), t\}, (t, \#_{rR}(e))\}$
(18) End if
(19) End if
(20) End for
(21) End for
(22) End for
(23) $P \leftarrow P_R \cup P_L \cup P_M, F \leftarrow F_R \cup F_L \cup F_M, M_0 \leftarrow \{i\} \cup P_R$;
(24) Return $\Sigma = (P, T, F, M_0)$. //output the RMPN.

TABLE 2: Discovered RMPN of each emergency organization.

Emergency organization	Discovered RMPN
Police station	
ECC	
EOD team	
Fire brigade	
Hospital	

sharing pattern exists between them if (1) $P_{L1} \cap P_{L2} = \emptyset$; (2) $P_{M1} \cap P_{M2} = \emptyset$; (3) $P_{R1} \cap P_{R2} \neq \emptyset$; and (4) $T_1 \cap T_2 = \emptyset$.

Definition 8 (task synchronization pattern). Let $\Sigma_1 = (P_1, T_1, F_1, M_{01})$ and $\Sigma_2 = (P_2, T_2, F_2, M_{02})$ be the RMPNs of two emergency organizations. Task synchronization pattern exists between them: (1) $P_1 \cap P_2 = \emptyset$; (2) $T_1 \cap T_2 \neq \emptyset$.

Then, Algorithm 2 is presented to discover collaboration patterns between any two arbitrary organizations. Algorithm 2 takes as input RMPNs of two emergency organizations and returns all collaborations patterns between them. All collaboration patterns involved in the fire emergency response process are discovered and shown in Table 3. For example, there exists message exchange pattern between the police station and the ECC via message places p_{m1} and p_{m2} .

5.4. Cross-Organization Emergency Response Process Model Mining. After mining IERP models and collaboration patterns among different emergency organizations, the whole CERP model comes into reach. In general, the CERP model is obtained by merging all IERP models and the collaboration patterns based on Petri net composition technique. Detailed steps are shown in Algorithm 3.

By taking as input the IERP models in Table 2 and the collaboration patterns in Table 3, the CERP model of the

cross-organization fire emergency response process model is obtained and shown in Figure 2.

Note that the model discovered by our approach is correct, and therefore, it can be used for further conformance checking, e.g., fitness and precision measure. However, the approach does not guarantee that all discovered models by our approach are correct. Actually, we are working on extending existing correctness verification and correction techniques, such as [26, 27], to be applicable for the discovered cross-organization process models by our approach.

6. Comparative Evaluation

In this section, we compare the quality of existing process mining approaches with our approach to discover the CERP model using the firelog. A laptop with a 2.40 GHz CPU, Windows 8.1, and Java SE 1.7.0 67 (64 bit) with 16 GB of allocated RAM is used.

6.1. Setup. The following three mining approaches are compared.

- (i) By taking as input the whole firelog, the inductive miner that is known as the state-of-the-art process discovery technique is directly used. This approach is denoted as A1.

```

INPUT: two RMPNs  $\Sigma_1 = (P_1, T_1, F_1, M_{01})$  and  $\Sigma_2 = (P_2, T_2, F_2, M_{02})$ 
OUTPUT: collaboration pattern model  $\Sigma = (P, T, F, M_0)$ 
(1)  $P \leftarrow \emptyset, P_L \leftarrow \emptyset, P_R \leftarrow \emptyset, P_M \leftarrow \emptyset, F \leftarrow \emptyset, F_L \leftarrow \emptyset, F_R \leftarrow \emptyset, F_M \leftarrow \emptyset, T \leftarrow \emptyset, M_0 \leftarrow \emptyset$ ; //initialization
(2) If  $P_{M1} \cap P_{M2} \neq \emptyset$  //mining messages exchange pattern
(3)   For each  $p \in P_{M1} \cap P_{M2}$ 
(4)      $P_M \leftarrow P_M \cup \{p\}$ ;
(5)     If  $p^* \neq \emptyset$ 
(6)        $T \leftarrow T \cup p^*$ ;
(7)       For each  $t \in p^*$ 
(8)          $F_M \leftarrow F_M \cup \{(p, t)\}$ ;
(9)       End for
(10)    End if
(11)    If  ${}^*p \neq \emptyset$ 
(12)       $T \leftarrow T \cup {}^*p$ ;
(13)      For each  $t \in {}^*p$ 
(14)         $F_M \leftarrow F_M \cup \{(t, p)\}$ ;
(15)      End for
(16)    End if
(17)  End for
(18) End if
(19) If  $P_{R1} \cap P_{R2} \neq \emptyset$  //mining resource sharing pattern
(20)   For each  $p \in P_{R1} \cap P_{R2}$ 
(21)      $P_R \leftarrow P_R \cup \{p\}$ ;
(22)      $T \leftarrow T \cup p^* \cup {}^*p$ ;
(23)     For each  $t \in p^* \cup {}^*p$ 
(24)        $F_M \leftarrow F_M \cup \{(p, t), (t, p)\}$ ;
(25)     End for
(26)   End for
(27) End if
(28) If  $T_1 \cap T_2 \neq \emptyset$  //mining task synchronization pattern
(29)    $T \leftarrow T \cup (T_1 \cap T_2)$ ;
(30) End if
(31)  $P \leftarrow P_R \cup P_L \cup P_M, F \leftarrow F_R \cup F_L \cup F_M, M_0 \leftarrow P_R$ ;
(32) Return  $\Sigma = (P, T, F, M_0)$ . //return mined collaboration patterns

```

ALGORITHM 2: Collaboration patterns mining.

(ii) By taking as input the whole firelog, we first project the whole log to each emergency organization based on the organization attribute in the firelog. Then, the inductive miner is used to discover a submodel for each organization. Finally, all discovered submodels are merged in a parallel manner. This approach is denoted as A2. In addition, the model discovered by approach A2 is essentially a workflow net-like structure with dedicate source and sink places and transitions.

(iii) Our proposed CERP model discovery approach is applied on the firelog. This approach is denoted as A3.

To quantify the effectiveness of different approaches, the well-defined metrics, e.g., fitness and precision, are applied to measure the quality of the discovered CERP models with respect to input firelog.

Fitness quantifies the extent to which the discovered model can accurately reproduce the traces recorded in the event log. Low fitness indicates that the event log allows for much more behaviour that is not allowed by the model. The paper applies the fitness defined in [28]. Precision quantifies

the fraction of the behavior allowed by the model which is not seen in the event log. Low precision means that the model allows for much more behaviour compared to the event log. The paper applies the precision defined in [29].

Note that there is a trade off between fitness and precision [30]. Therefore, we introduce the *F*-measure. The *F*-measure is defined as the harmonic mean of the fitness and precision metrics as shown in the following equation:

$$F - \text{measure} = \frac{2 \times \text{fitness} \times \text{precision}}{\text{fitness} + \text{precision}}. \quad (1)$$

6.2. Experimental Results. By taking as input the firelog, **A1** is first applied. This approach does not consider the organization information and collaboration patterns and only discovers the control flow of all emergency tasks directly by the inductive miner. The discovered CERP model represented as a classical Petri net is shown in Figure 3. Then, by taking as input the firelog and discovered model, the fitness, precision, and *F*-measure values are obtained and depicted in Table 4.

TABLE 3: Discovered collaboration patterns.

Emergency organization	Discovered collaboration patterns
Police station and ECC	
EOD team and ECC	
Fire brigade and ECC	
Hospital and ECC	
Fire brigade and EOD team	
Hospital and EOD team	
Hospital and fire brigade	

Then, by taking as input the firelog, **A2** is applied. This approach first projects the whole log to each emergency organization based on the organization attribute in the firelog. Then, the inductive miner is used to discover a submodel for each organization. Finally, all discovered submodels are merged in a parallel manner. The discovered CERP model is shown in Figure 4 where two transitions colored as black form the parallel relation among all organizations. By taking as input the firelog and discovered model, the fitness, precision, and F -measure values are

obtained and depicted in Table 4. Note that the organization information is supported by **A2**, but the collaboration patterns are not discovered.

Finally, by taking as input the firelog, our proposed approach, denoted as **A3**, is applied. This approach first projects the whole log to each emergency organization based on the organization attribute. This step is same to **A2**. Then, Algorithm 1 is applied to perform IERP mining where an RMPN is used to represent the discovered IERP model. Next, collaboration patterns are discovered using

INPUT: $\Xi = \{\Sigma_x | \Sigma_x \text{ is the RMP Noforganization } x\}$, $\Psi = \Sigma_{x,y} | \Sigma_{x,y} \text{ is the collaboration model between organizations } x \text{ and } y\}$
 OUTPUT: CERP model $\Sigma = (P, T, F, M_0)$

- (1) $P \leftarrow \emptyset, P_L \leftarrow \emptyset, P_R \leftarrow \emptyset, P_M \leftarrow \emptyset, F \leftarrow \emptyset, F_L \leftarrow \emptyset, F_R \leftarrow \emptyset, F_M \leftarrow \emptyset, T \leftarrow \emptyset, M_0 \leftarrow \emptyset, P_s \leftarrow \emptyset;$
 //initialize the integration model
- (2) For each $\Sigma_x \in \Xi$ //merging RMPN model
- (3) $P_M \leftarrow P_M \cup P_{Mx};$
- (4) $P_R \leftarrow P_R \cup P_{Rx};$
- (5) $P_L \leftarrow P_L \cup P_{Lx};$
- (6) For each $p \in P_{Lx}$
- (7) If $*p == \emptyset$
- (8) $P_s \leftarrow P_s \cup p;$
- (9) End if
- (10) End for
- (11) $F_L \leftarrow F_L \cup F_{Lx};$
- (12) $F_M \leftarrow F_M \cup F_{Mx};$
- (13) $F_R \leftarrow F_R \cup F_{Rx};$
- (14) $T \leftarrow T \cup T_x;$
- (15) End for
- (16) For each $\Sigma_{x,y} \in \Psi$ //merging collaboration patterns
- (17) $P_M \leftarrow P_M \cup P_{Mx,y};$
- (18) $P_R \leftarrow P_R \cup P_{Rx,y};$
- (19) $P_L \leftarrow P_L \cup P_{Lx,y};$
- (20) $F_L \leftarrow F_L \cup F_{Lx,y};$
- (21) $F_M \leftarrow F_M \cup F_{Mx,y};$
- (22) $F_R \leftarrow F_R \cup F_{Rx,y};$
- (23) $T \leftarrow T \cup T_{x,y};$
- (24) End for
- (25) $P \leftarrow P_R \cup P_L \cup P_M, F \leftarrow F_R \cup F_L \cup F_M, M_0 \leftarrow P_s \cup P_R;$
- (26) Return $\Sigma = (P, T, F, M_0).$ //output the integrated RMPN

ALGORITHM 3: CERP model mining.

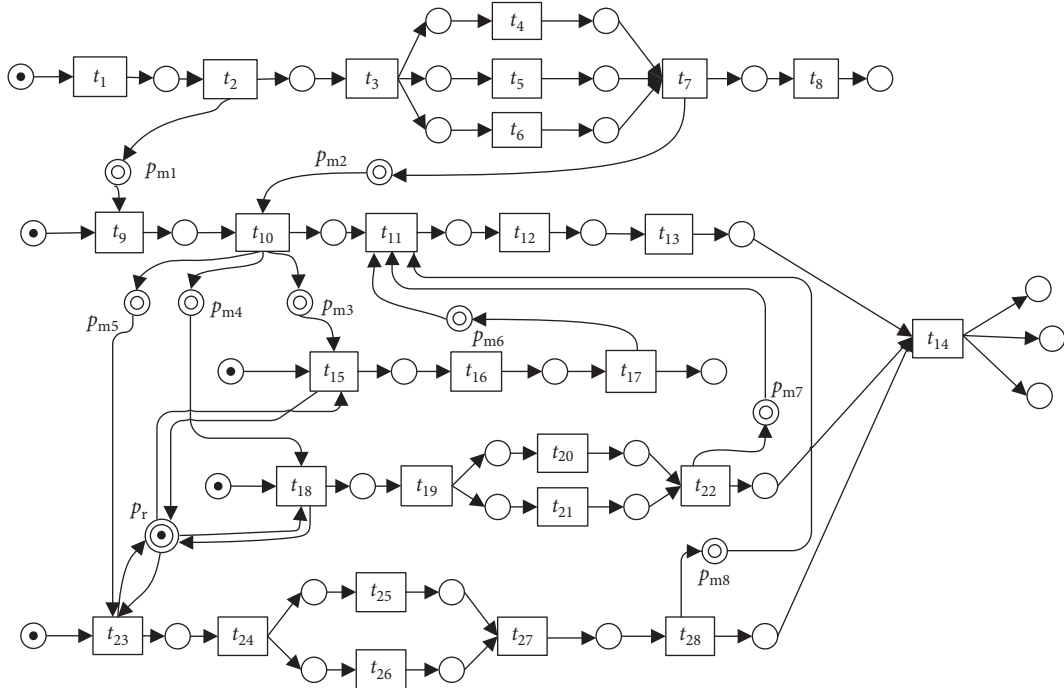


FIGURE 2: CERP model discovered by our approach.

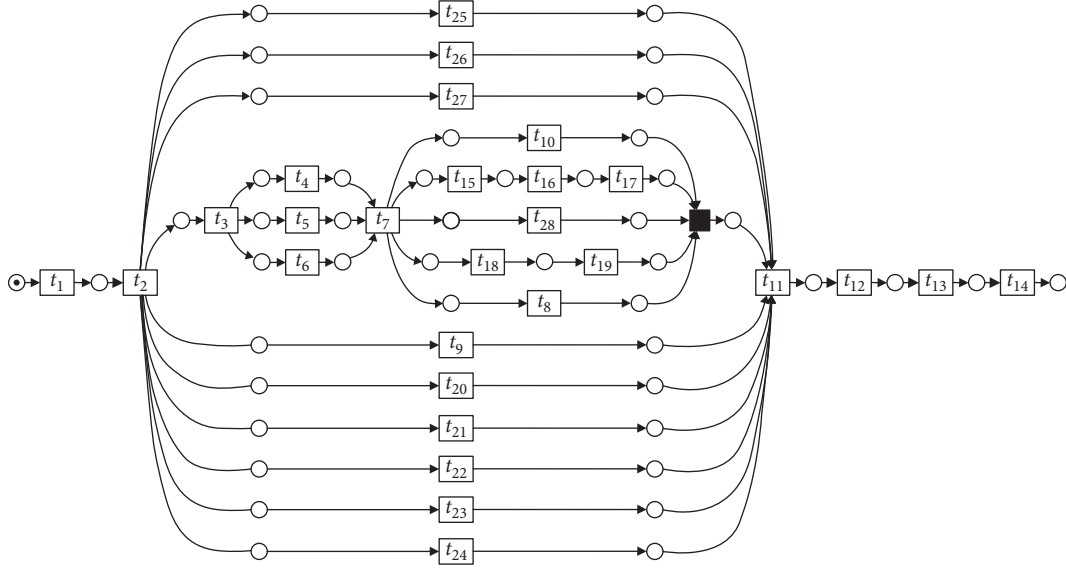


FIGURE 3: CERP model discovered by A1.

TABLE 4: Evaluation results.

Approach	Fitness	Precision	<i>F</i> -measure
A1	1	0.39	0.56
A2	1	0.44	0.58
A3	1	0.62	0.76

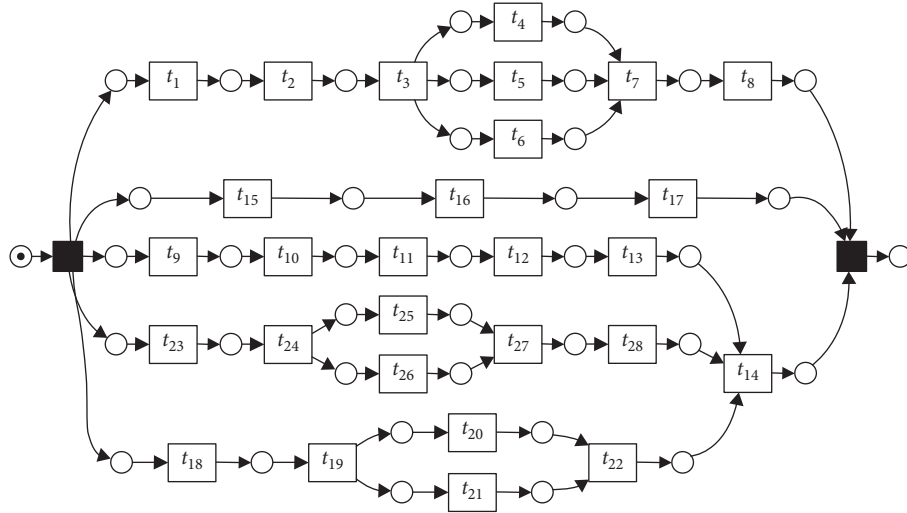


FIGURE 4: CERP model discovered by A2.

Algorithm 2. Finally, all discovered IERP models and collaboration patterns are merged according to Algorithm 3. The discovered CERP model is shown in Figure 2. By taking as input the firelog and discovered model, the fitness, precision, and *F*-measure values are obtained and depicted in Table 4. Note that both the organization information and collaboration patterns are properly discovered.

According to Table 4, we can see that (1) all three approaches can guarantee that the discovered CERP model with perfect fitness. The rationale behind is that they all rely

on the inductive miner that guarantees fitness is 1; (2) the precision of the CERP model discovered by **A3** is the highest while the precision of the CERP model discovered by that the **A1** is the lowest. A high precision value normally indicates the discovered model is more precise than that with a low precision value. This is because both **A2** and **A3** use the organization information to localize the discovery scope within a single organization, and therefore, its precision is higher than **A1**. Different from **A2** that simply connects all submodels in a parallel way, **A3** can discover collaboration

patterns that indicate cross-organization task dependencies; and (3) the F -measure of the CERP model discovered by **A3** is the highest, which indicates that the quality of the CERP model discovered by **A3** is better than that discovered by **A1** and **A2**.

As a conclusion, our proposed approach (**A3**) can discover more precise cross-organization emergency response process models compared with existing approaches.

7. Conclusion

This paper proposes a cross-organization emergency response process model mining method to support effective emergency disposal process construction. More specifically, we first extend classical Petri nets with resource and message attributes, known as RMPN. Then, IERP models are discovered as RMPNs. Next, collaboration patterns among emergency organizations are formally defined and discovered. Finally, CERP models are obtained by merging IERP models and the collaboration patterns. Through the comparative evaluation using the fire emergency drilling event log, we illustrate that the proposed approach facilitates the discovery of the high-quality CERP model than existing approaches.

This paper also opens the door for the following research area that needs to be investigated in our future work. (1) More complex collaboration patterns, e.g., business outsourcing, need to be explored for more accurate process discovery. (2) Evaluation techniques to quantify the quality of the mined CERP model against the input emergency drilling event logs are urgently required to consider not only control-flow conformance but also message and resource conformance. (3) Considering the volume of emergency response process event logs, log sampling techniques, e.g., [31, 32], maybe useful for efficient mining.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported in part by the National Natural Science Foundation of China under grant no. 61902222, Taishan Scholars Program of Shandong Province under grant nos. ts20190936 and tsqn201909109, and Engineering and Technology R&D Center of IIOT in Colleges of Shandong Province (QingDao Technical College under grant no. KF2019002).

References

- [1] C. Liu, Q. Zeng, H. Duan, M. Zhou, F. Lu, and J. Cheng, "E-net modeling and analysis of emergency response processes constrained by resources and uncertain durations," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 45, no. 1, pp. 84–96, 2017.
- [2] C. Liu and F. Zhang, "Petri net based modeling and correctness verification of collaborative emergency response processes," *Cybernetics and Information Technologies*, vol. 16, no. 3, pp. 122–136, 2016.
- [3] Z. He, Q. Wu, L. Wen, and G. Fu, "A process mining approach to improve emergency rescue processes of fatal gas explosion accidents in Chinese coal mines," *Safety Science*, vol. 111, pp. 154–166, 2019.
- [4] W. Van der Aalst, T. Weijters, and L. Maruster, "Workflow mining: discovering process models from event logs," *IEEE Transactions on Knowledge & Data Engineering*, vol. 16, no. 9, pp. 1128–1142, 2004.
- [5] Q. Zeng, S. X. Sun, H. Duan, C. Liu, and H. Wang, "Cross-organizational collaborative workflow mining from a multi-source log," *Decision Support Systems*, vol. 54, no. 3, pp. 1280–1301, 2013.
- [6] W. M. P. V. D. Aalst, "Interorganizational workflows: an approach based on message sequence charts and petri nets," *Systems Analysis Modelling Simulation*, vol. 34, no. 3, 1999.
- [7] Q. Mo, F. Dai, R. Zhu, and T. Li, "Parallel modeling for cross-organization business process," *Computer Integrated Manufacturing Systems*, vol. 21, no. 4, pp. 1051–1062, 2015.
- [8] H. Liu, K. Wang, and S. Yang, "Modeling and analysis for cross-organizational workflow: an overview," *Chinese Journal of Management*, vol. 7, no. 3, pp. 468–493, 2010.
- [9] P. Jiang, X. Shao, H. Qiu, and P. Li, "Interoperability of cross-organizational workflows based on process-view for collaborative product development," *Concurrent Engineering*, vol. 16, no. 1, pp. 73–87, 2008.
- [10] Q. Zeng, F. Lu, C. Liu, H. Duan, and C. Zhou, "Modeling and verification for cross-department collaborative business processes using extended petri nets," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 45, no. 2, pp. 349–362, 2014.
- [11] D. Liu, C. Huang, J. Ni, X. Lin, and X. S. Shen, "Blockchain-based smart advertising network with privacy-preserving accountability," *IEEE Transactions on Network Science and Engineering*, vol. 99, p. 1, 2020.
- [12] W. Van Der Aalst, *Process Mining: Discovery, Conformance and Enhancement of Business Processes*, Springer Science & Business Media, Berlin, Germany, 2011.
- [13] C. W. Günther and W. M. Van Der Aalst, "Fuzzy mining—adaptive process simplification based on multi-perspective metrics," in *Proceedings of International Conference on Business Process Management*, pp. 328–343, Springer, Berlin, Germany, September 2007.
- [14] S. J. Leemans, D. Fahland, and W. M. van der Aalst, "Discovering block-structured process models from event logs—a constructive approach," in *Proceedings of International Conference on Applications and Theory of Petri Nets and Concurrency*, pp. 311–329, Springer, Berlin, Germany, June 2013.
- [15] Q. Li, Y. Deng, C. Liu, Q. Zeng, and Y. Lu, "Modeling and analysis of subway fire emergency response: an empirical study," *Safety Science*, vol. 84, pp. 171–180, 2016.
- [16] Q. Zeng, H. Duan, and C. Liu, "Top-down process mining from multi-source running logs based on refinement of petri nets," *IEEE Access*, vol. 8, pp. 61355–61369, 2020.

- [17] Q. Zeng, C. Liu, and H. Duan, "Resource conflict detection and removal strategy for nondeterministic emergency response processes using petri nets," *Enterprise Information Systems*, vol. 10, no. 7, pp. 729–750, 2016.
- [18] F. Lu, Q. Zeng, Y. Bao, and H. Duan, "Hierarchy modeling and formal verification of emergency treatment processes," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 44, no. 2, pp. 220–234, 2013.
- [19] H. Duan, C. Liu, Q. Zeng, and M. Zhou, "Refinement-based hierarchical modeling and correctness verification of cross-organization collaborative emergency response processes," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 50, no. 8, pp. 2548–2559, 2020.
- [20] Q. Zeng, C. Liu, H. Duan, and M. Zhou, "Resource conflict checking and resolution controller design for cross-organization emergency response processes," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 50, no. 10, pp. 3685–3700, 2020.
- [21] W. Reisig, *Petri Nets: An Introduction*, Springer-Verlag, Berlin, Germany, 2012.
- [22] Q. Hu, Y. Du, and S. Yu, "Service net algebra based on logic petri nets," *Information Sciences*, vol. 268, pp. 271–289, 2014.
- [23] H. Qiang, L. Minghua, Z. Zhen, and D. Junwei, "A path detecting method to analyze the interactive compatibility of service processes based on ws-bpel," *Concurrency & Computation Practice & Experience*, vol. 30, no. 19, p. e4699–, 2018.
- [24] Q. Hu and J. Shen, "A Cluster and Process Collaboration-Aware Method to Achieve Service Substitution in Cloud Service Processes," *Scientific Programming*, vol. 2020, Article ID 1298513, 12 pages, 2020.
- [25] V. D. Aalst, "The application of petri nets to workflow management," *Journal of Circuits Systems & Computers*, vol. 08, no. 01, pp. 21–66, 1998.
- [26] W. M. P. Van Der Aalst and A. H. M. Ter Hofstede, "Verification of workflow task structures: a petri-net-based approach," *Information Systems*, vol. 25, no. 1, pp. 43–69, 2000.
- [27] W. M. Van Der Aalst, "Workflow verification: finding control-flow errors using petri-net-based techniques," in *Proceedings of Business Process Management, Models, Techniques, and Empirical Studies*, pp. 161–183, Springer, Berlin, Germany, January 2000.
- [28] A. Adriansyah, B. F. van Dongen, and W. M. van der Aalst, "Conformance checking using cost-based fitness analysis," in *Proceedings of Enterprise Distributed Object Computing Conference (EDOC)*, pp. 55–64, IEEE, Helsinki, Finland, August 2011.
- [29] A. Adriansyah, J. Munoz-Gama, J. Carmona, B. F. van Dongen, and W. M. P. van der Aalst, "Alignment based precision checking," in *Proceedings of International Conference On Business Process Management*, pp. 137–149, Springer, Tallinn, Estonia, September 2012.
- [30] J. De Weerd, M. De Backer, J. Vanthienen, and B. Baesens, "A robust f-measure for evaluating discovered process models," in *Proceedings of IEEE Symposium On Computational Intelligence And Data Mining (CIDM-2011)*, pp. 148–155, IEEE, Paris, France, April 2011.
- [31] C. Liu, Y. Pei, and L. Cheng, "Sampling business process event logs using graph-based ranking model," *Concurrency and Computation: Practice and Experience*, no. XX, pp. 1–15, 2020.
- [32] C. Liu, Y. Pei, Q. Zeng, and H. Duan, "Logrank: an approach to sample business process event log for efficient discovery," in *Proceedings of International Conference On Knowledge Science, Engineering And Management*, pp. 415–425, Springer, Cham, Switzerland, 2018.