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A Package Reduction Approach To Modeling and Analysis of Cross-Organization Emergency Response Processes With Privacy Protected

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ABSTRACT The emergency disposals are usually charged by several geographically dispersed and logically collaborated emergency organizations. In addition, each emergency organization owns its private emergency response process and can operate independently. In this case, modeling such cross-organizational emergency response processes is really a challenging issue when considering: 1) effective collaboration and coordination among different emergency partners; and 2) reasonable privacy and security protection mechanism to maintain the sensitive information confidential and unseen by other involved partners. In this paper, we propose a package reduction-based privacy protection approach to facilitate the modeling. Specifically, a kind of workflow nets extended with time, resource, and message factors, called TRM_WF_nets for short, is first introduced to model cross-organization emergency response processes. Then, a three-layered framework is proposed to model cross-organization emergency response processes by taking into account their privacy protection and temporal performance evaluation. Next, a set of reduction rules are proposed to reduce the scale of a TRM_WF_net while keeping its external observable timing, message, and resource factors invariant. These reduction rules not only improve the efficiency of temporal performance evaluation but also protect the business privacy of each emergency organization during its collaboration and interaction with others. Finally, a real-life scenario of cross-organization fire emergency response processes is used to validate our proposed approaches.

INDEX TERMS Coarse-grained packages, cross-organization emergency response processes, Petri nets, privacy protection, reduction rules, temporal performance evaluation.

I. INTRODUCTION

Since the 9/11 terrorist attack, there have been considerable effort to improve the effectiveness and efficiency to respond to emergencies. Generally speaking, an emergency is situation that imposes immediate risk to life, property and environment, which requires urgent disposal and intervention to prevent its worsening [1]. These disposals or interventions are usually organized as a series of emergency response processes charged by one emergency command center with several subordinate emergency organizations, which are usually geographically dispersed and need to collaborate with each other to accomplish the whole emergency mission. In addition, each emergency partner owns its private emergency response process and can operate independently. In this case, modeling and analyzing such cross-organizational collaborative emergency response processes is really a complicated and time-consuming task since we have to consider: 1) effective and efficient collaboration and coordination among different emergency organizations; and 2) reasonable privacy and security protection to maintain the sensitive information confidential and unseen by other involved organizations. Traditionally, privacy usually concerns personal or sensitive data, which can be used to identify a person and its misuse may harm that person [2], [54]. This work consid-

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ers the privacy from an organizational perspective, i.e., our privacy is relevant to the sensitive information of emergency organizations, for example, its intra-organization emergency process details.

This work concentrates on the privacy protection issue of cross-organization emergency response processes. It is based on the idea that an emergency response process is quite similar to a business process, and therefore, can be modeled as a domain specific workflow [1]. A workflow is a representation of a given process that is made up of pre-defined activities, also referred to as tasks [3], [4]. In this way, cross-organization emergency response processes can be modeled like cross-organization workflows [5]–[7]. Different from existing cross-organization business processes, there is much collaboration that needs either messages sent by other organizations or resources shared with other organizations in cross-organization emergency response processes. Therefore, message and resource elements should be involved. As we aim to evaluate temporal performance of cross-organization emergency response processes, time is also considered.

The contributions of this work are twofold: 1) as a kind of workflow nets extended with time, resource, and message factors, TRM_WF_nets are proposed to model cross-organization emergency response processes; and 2) a set of reduction rules are proposed to reduce the scale of a TRM_WF_net while maintaining its external observable timing, message, and resource properties invariant.

The remainder of this paper is organized as follows. Section II discusses the related work. Section III introduces a simple fire emergency response scenario to be used as a motivating example. In Section IV, TRM_WF_net based modeling approaches are introduced. Section V addresses a three-layer framework to model cross-organization emergency response processes. Section VI gives a series of reduction rules, and their applications for privacy protection. Section VII evaluates the package reduction approaches, and Section VIII validates the proposed approach by a real-life cross-organization fire emergency case study. Finally, Section IX concludes the paper.

II. RELATED WORK

This section summarizes the work related to: 1) modeling and analysis of emergency response processes; 2) modeling and analysis of cross-organization workflows; and 3) privacy protection approaches for business processes.

A. MODELING AND ANALYSIS OF EMERGENCY RESPONSE PROCESSES

Wang [12] pioneers in an intuitive and formal approach that takes task execution time into account to support emergency response timeliness analysis, and an example of emergency healthcare is used to validate the proposed approach. A model for earthquake emergency shelter choices based on constrained optimization is provided in [13]. Its objective is to ensure that total evacuation time is the shortest by comprehensively considering the choices of evacuation routes. To lessen or avoid injury to plant personnel and citizens in a neighboring community, Tsenga *et al.* [14] show the benefits of developing an adequate emergency response plan with safety and industrial hygiene resources to deal with the effects resulting from a chlorine gas leak. Wang et al. [15] present a formal, yet intuitive, approach for the modeling and analysis of emergency response processes by taking resources into consideration. Sell and Braun [16] present a model to support the modeling, execution and management of emergency plans before and during a disaster, which supports unstructured activities and resource management.

In our previous work [1], [17], we investigate 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 are analyzed. Moreover, resource conflict detection and resolution strategies are also investigated to optimize the universal process performance. A hierarchical Petri net model, which includes a business process logic net, a business process semantic net, and a set of case models, is introduced for modeling and verification of emergency response processes in [48]. The applicability of this approach is validated by an emergency treatment process of highways under snow/ice weather conditions. More recently, we propose a top-down approach for model construction and correctness verification of cross-organization emergency response processes in [49].

B. MODELING AND ANALYSIS OF CROSS-ORGANIZATION BUSINESS PROCESSES

Van der Aalst first considers workflows distributed over a number of organizations in [5] where two important questions are well addressed: 1) the minimal requirements of cross-organization workflow, and 2) how to decide if an cross-organization workflow, modeled with Petri nets, is consistent with an interaction structure specified through a message sequence diagram. Liu et al. [18] propose a kind of interactive Petri nets to model the message channels among different process-oriented systems, and the compatibility preservation of an integrated system with message interaction is revealed. Schulz and Orlowska [19] focus on three aspects to support the execution of cross-organization workflows that have been modeled with a process view approach: 1) communication among the entities, 2) their impact on an extended workflow engine, and 3) the design of a cross-organization workflow architecture. A Petri net-based state transition approach that binds states of private workflow tasks to their adjacent workflow view is introduced. Its concepts are demonstrated by a business scenario involving two extended workflow management systems. Jiang et al. [20] describe a timed colored Petri net and process-view combined approach to construct cross-organization workflows, and a three-model framework is proposed to support the interoperability of cross-organization workflows.

In [21], we investigate the application of process mining for workflow integration based on a type of Petri nets extended with resource and message factors. A process integration approach is presented to obtain the model for a cross-organization workflow based on the model mined for each organization and the coordination patterns among different organizations. Recently, we formally define several collaboration patterns, including message interaction, resource interaction, task collaboration, and service outsourcing patterns in [7]. The modeling and correctness verification of a cross-department/organization medical workflow are effectively supported.

C. BUSINESS PROCESS PRIVACY PROTECTION

Chakraborty and Pal [22] develop a set of privacy preserving coordination mechanisms that can align the business objectives of all supply chain partners as well as optimize the overall performance of a supply chain system. A privacy-aware process-level framework for a kind of distributed mobile applications is proposed in [2]. Its main contribution is to establish a series of security constraints and based on which the Business Process Modeling Notations is extended with privacy notations to support the privacy preservation at a process level. In [23], they extend this framework to support the reasoning and enforcement of privacy constraints. Zemni et al. [24] present an initial and informal approach for business process decomposition while maintaining the privacy of sensitive information. The approach generates a fragment whose activities involve common functionalities. Following [24], they propose a novel approach to provide useful, privacy-aware, and reusable fragments in [25]. This is ensured by the proposed process decomposition mechanism that takes into account privacy constraints to avoid sensitive information inferences. Unfortunately, all these studies [2], [22]–[25] focus on the protection of users' personal data rather than the preservation of their business logic for each organization. From this point of view, Tahamtan and Johann's approach [26] is somehow similar to the approach presented in our work. They present a novel technique for the construction of process views which can be used to ensure process privacy and security. Therefore, by applying workflow views they can keep changes in a private process local such that interactions with other partners are not affected.

D. SUMMARY OF EXISTING WORK

Based on this literature review, we can see that: 1) most of existing modeling and analysis work on emergency management [1], [12]–[17] are focused on time and resource perspectives, i.e., temporal performance evaluation and resource provisioning and optimization. However, no much research has concentrated on its cross-organization feature; 2) modeling and analysis of cross-organization workflows [5], [18]–[21] have drawn much attention. Because different approaches concentrate on only aspects or features of cross-organization workflows, more investigations are needed for modeling and analysis of cross-organization emergency response processes when considering different kinds of collaborations; and 3) business process privacy protection [2], [22]–[26] are becoming increasingly important in today's complex enterprise environment. Unfortunately, most of these studies, e.g., [22]–[25], focus on the protection of users' personal data only while very few emphasize the protection of their business logic for each organization, i.e., organization level business process privacy.

As a conclusion, the privacy protection of each private emergency organization in a cross-organization emergency scenario, is badly needed. To our best knowledge, no existing work has addressed these issues for the design of cross-organization emergency response processes, and this work represents the first try to do so.

III. AN EXAMPLE

Consider a fire emergency scenario. Some of the critical missions are the rescue of victims and disposal of the fire. This emergency response scenario involves three organizations: emergency command center (ECC), fire brigade and hospital. Its detailed process includes:

1) After receiving the fire emergency information, ECC first informs a hospital to perform medical rescue, and a fire brigade to conduct fire disposal.

2) The fire brigade rushes to the site upon receiving the fire rescue instruction from ECC, and conducts its specific disposal activities, and finally reports the fire disposal results.

3) The hospital personnel rushes to the site upon receiving the medical rescue instruction from ECC, and conducts its specific disposal activities, and finally reports the medical rescue results.

4) After receiving both feedback information from hospital and fire brigade, ECC makes summary and evaluation, and finally performs the file archive.

5) Finally, ECC, hospital, and fire brigade do the media coverage together.

Activities are key elements of cross-organization emergency response processes. To model them with time information, a formulation of a timed activity is needed. A timed activity is composed of activity content, required message set, sent message set, required resource set, released resource set, belonging organization, pre-activity set, and its execution time.

Definition 1: A *timed activity* is a 8-tuple *TWA*=<*AID*, *AName*, *MReq*, *MSent*, *RSet*, *Org*,*PreA*, *Etime*>, where 1) *AID* is the unified identifier; 2) *AName* represents the name; 3) *MReq* is the message set that is required when an activity starts; 4) *MSent* is the message set that is sent when an activity ends; 5) *RSet* is the set of resources that are required to execute an activity; 6) *Org* is the organization set that an activity belongs to; 7) *PreA* is the pre-activity set of an activity; and 8) *ETime* is the execution time of an activity.

According to Definition 1, activity information of *ECC*, fire brigade, and hospital are given in Table 1. Note that the pre-activities of each activity are involved, based on which the partial order relations among acvitivies are obtained.

TABLE 1. An informal description of activities.

Activity ID	Activity Name	Requied Message Set	Sent Message Set	Required Resource Set	Organizations	Pre-activities	Execution Time
t_1	*Receive the emergency information*	∅	∅	∅	{ECC}	∅	2
t_2	*inform the hospital and fire brigade*	∅	$\{p_{m3}, p_{m4}\}$	∅	{ECC}	$\{t_1\}$	3
t_3	*Emergency summary and evaluation*	$\{p_{m6}, p_{m7}\}$	∅	∅	{ECC}	$\{t_2\}$	5
t_4	*File archive*	∅	∅	∅	{ECC}	$\{t_3\}$	8
t_5	*Do media coverage*	∅	∅	∅	{ECC, Fire Brigade, Hospital}	$\{t_4, t_{10}, t_{16}\}$	3
t_6	*Rush to the site*	$\{p_{m1}\}$	∅	$\{p_r\}$	{Fire Brigade}	∅	4
t_7	*Fight the fire*	∅	∅	∅	{Fire Brigade}	$\{t_6\}$	8
t_8	*Recovery the site*	∅	∅	∅	{Fire Brigade}	$\{t_7\}$	6
t_9	*Conduct mitigation operations*	∅	∅	∅	{Fire Brigade}	$\{t_7\}$	6
t_{10}	*Report the fire rescue*	∅	$\{p_{m3}\}$	∅	{Fire Brigade}	$\{t_8, t_9\}$	2
t_{11}	*Rush to the site*	$\{p_{m2}\}$	∅	$\{p_r\}$	{Hospital}	∅	3
t_{12}	*Shunt the wounded*	∅	∅	∅	{Hospital}	$\{t_{11}\}$	4
t_{13}	*Treat the severely injured people*	∅	∅	∅	{Hospital}	$\{t_{12}\}$	8
t_{14}	*Treat the slightly injured people*	∅	∅	∅	{Hospital}	$\{t_{12}\}$	6
t_{15}	*Environmental quality detection*	∅	∅	∅	{Hospital}	$\{t_{13}, t_{14}\}$	4
t_{16}	*Report the medical rescue*	∅	$\{p_{m4}\}$	∅	{Hospital}	$\{t_{15}\}$	2

For example, activity t_{11} in Table 1 is formulated as: <"t_{11}", "*Rush to the site*", $\{p_{m2}\}$, ∅, $\{p_r\}$, {*hospital*}, ∅, 3>, which indicates that: 1) it requires message p_{m2} and resource p_r to start its execution, 2) it belongs to hospital, and 3) its execution lasts 3 time units.

We have the following explanations about Table 1.

1) This fire emergency response process is composed of three organizations: *ECC*, fire brigade and hospital, and each organization has its private business process. For example, the business of *ECC* is composed of five activities that are executed in sequence;

2) Each emergency activity contains several components. Generally speaking, an activity contains activity name, required messages, sent messages, execution time, pre-activities, and resource requirements. For example, to perform the activity "*Rush to the site*" in hospital, the message "*fire rescue instruction*" and resource "*public transportation vehicle*" are required, and its execution time is 3 time units; and

3) These emergency organizations need to collaborate to accomplish the whole emergency mission, e.g., one organization requires the message sent by the other organizations to launch or initialize its own emergency process. In addition, each organization is an autonomous entity, and its business process details cannot be revealed to other organizations. Thus, an effective privacy preservation approach is needed to maintain both intra-organization business security and cross-organization collaboration.

Table 2 describes the meaning of the involved messages and resources.

TABLE 2. Message and resource information.

Message/Resource	Meaning
p_{m1}	fire rescue instruction
p_{m2}	medical rescue instruction
p_{m3}	fire rescue results
p_{m4}	medical rescue results
p_r	public transportation vehicle

IV. MODELING APPROACHES

In this section, TRM_WF_nets are proposed to model cross-organization emergency response processes.

A. TRM_WF_net

Our work is based on Petri nets, workflow nets to be accurate. Some of the terminologies and notations of workflow nets [3] and Petri nets [8], [9]–[11], [36]–[42], [50]–[53], [60]–[61] are reviewed.

Definition 2 [9]: A *Petri net* is a 4-tuple $\Sigma = (P, T, F, M_0)$, where 1) $P = \{p_1, p_2, \ldots p_m\}$ is a finite set of places; 2) $T = \{t_1, t_2, \ldots t_n\}$ is a finite set of transitions; 3) $F \subseteq (P\times T)\cup(T\times P)$ is a finite set of arcs (flow relation); and 4) M_0: $P \rightarrow \{0, 1, 2, 3, \ldots\}$ is the initial marking; and (5) $P \cap T = \varnothing$ and $P \cup T \neq \varnothing$.

Given $x \in P \cup T$, ${}^\bullet x = \{y | y \in P \cup T \wedge (y, x) \in F\}$ is called its pre-set, and $x^\bullet = \{y | y \in P \cup T \wedge (x, y) \in F\}$ is its post-set. p is marked by M iff $M(p) > 0$. A transition $t \in T$ is enabled under M, if and only if $\forall p \in^\bullet t$: $M(p) > 0$, denoted as $M[t >$. If $M[t >$ holds, t may fire, resulting in a new marking M', denoted as $M[t > M'$, such that $M'(p) = M(p)-1$ if $\forall p \in^\bullet t \backslash t^\bullet$, $M'(p) = M(p) + 1$ if $\forall p \in t^\bullet \backslash^\bullet t$, and otherwise $M'(p) = M(p)$. An initial marking is denoted by M_0.

A Petri net that models a workflow is called a workflow net whose definition is briefly reviewed due to [3].

Definition 3 [3]: A *Petri net* $\Sigma = (P, T, F, M_0)$ is a WF-net if: 1) there is one source place $p_s \in P$ such that $^\bullet p_s = \varnothing$; 2) there is one sink place $p_e \in P$ such that $p_e^\bullet = \varnothing$; 3) each node $x \in P \cup T$ is on a path from p_s to p_e; and 4) $\forall p \in P$, $M_0(p) = 1$ if $p = p_s$, and otherwise $M_0(p) = 0$.

In a WF-net, the transition set T is used to represent the activities, the place set P is used to represent logic connection relation of activities, and source place and sink place specially represent the start and end of the process respectively. We propose a TRM_WF_net by extending a WF-net with time, resource and message information

Let R be the set of non-negative real numbers, and Z be the set of positive integer numbers.

Definition 4: A 5-*tuple* $\Sigma_{TRM} = (P, T, F, \gamma, M_0)$ is a *TRM_WF_net* if:

1) $P = P_L \cup P_R \cup P_M$, $P_L \cap P_R = \varnothing$, $P_R \cap P_M = \varnothing$, and $P_L \cap P_M = \varnothing$; P_L represents the logic place set, P_M represents the message place set, and P_R represents resource place set in Σ_{TRM};

2) $\gamma: T \to R$. $\forall t \in T$, $\gamma(t) \geq 0$ is the execution (or firing) time of transition t;

3) $F = F_L \cup F_R \cup F_M$, where 1) $F_L = (P_L \times T) \cup (T \times P_L)$ represents the logical structure of the model; 3.2) $F_R = (P_R \times T) \cup (T \times P_R)$ represents the required resource relations; and 3.3) $F_M = (P_M \times T) \cup (T \times P_M)$ represents the required and sent message relations; and

4) $\forall p \in P$, $M_0(p) = 1$ if $p \in P_R$ or $^\bullet p = \varnothing$, and otherwise $M_0(p) = 0$.

The firing rule of a TRM_WF_net is same as that of a WF-net. Given a marking M, $\forall t \in T$, t is enabled under M if $\forall p \in^\bullet t, M(p) \geq 1$. Firing an enabled t removes a token from each place in $^\bullet t$ and deposits one to each place in $t^\bullet$. All properties, e.g., as reachability and boundedness are defined similarly. The main differences between a TRM_WF_net and a WF-net are: 1) the former is a special kind of WF-nets extended with resource place set (P_R) and message place set (P_M); and 2) a transition in the former is associated with a time function to represent its execution time.

B. TRM_WF_net BASED MODELING OF INTRA-ORGANIZATION EMERGENCY RESPONSE PROCESS

Modeling approaches for a single organization emergency response process involves the following three steps: 1) modeling activities with TRM_WF_net; 2) modeling control structure with TRM_WF_net; and 3) integration of control structure model with those activity models.

In a TRM_WF_net, an activity is represented by a transition which has input and output logic places representing the start and end states. In addition, to represent the involved resources and messages, the corresponding places are added with flow relations. Its execution time is labeled with γ. An activity model in TRM_WF_net is illustrated in Fig. 1, where p_{ready} is a ready place, p_{end} is an end place, p_r is a resource place, $p_{messageReq}$ and $p_{messageSent}$ are the corresponding message places, and γ is its execution time. Graphically, a logic place is drawn with a normal circle, a double circle with full line is used to represent a resource place, and a circle with dash line is used to represent a message place, a rectangle with full line is used to represent an activity, and a shaded rectangle is used to represent a shared activity (i.e., an activity that belongs to multiple organizations. E.g., t_5). It is worth mentioning that we consider a kind of reusable resource in this work, and more discussions on reusable and consumable resources are included in [1].

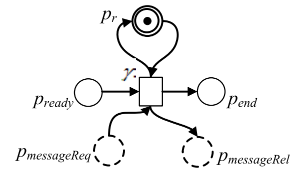
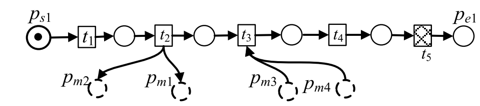
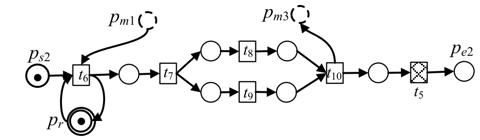
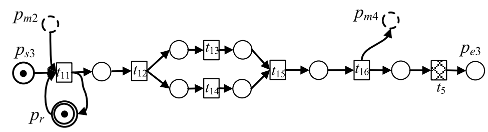


FIGURE 1. Activity model in TRM_WF_net.

TABLE 3. TRM_WF_net of each organization.

Organization	TRM_WF_net
Emergency Command Center	
Fire Brigade	
Hospital	

In this section, activity dependencies (i.e., the pre-activity relations) within an organization are first investigated to build a block-structured control-flow structure. The control structure of a TRM_WF_net, denoted as $(P_L, T, F_L, M_0|_L)$ where $M_0|_L$ is the projection of M_0 on P_L, is a standard WF-net. Based on the modeling approaches of basic control-flow routes as introduced in [1], a WF-net model to express the activities dependencies is constructed. Then, we integrate the activity model with this WF-net by adding resource places, message places and corresponding flow relations. Finally, TRM_WF_nets are contructed. Note that the message interaction and resource sharing relations are only modeled for activities among different emergency organizations.

According to the above-mentioned constructs, the intra-organization TRM_WF_net models of *ECC*, fire brigade, and hospital are obtained as shown in Table 3. Note that t_5 is a synchronization activity which is shouldered by these organizations together. To distinguish it from normal activities, we use rectangle with grid to represent it.

C. TRM_WF_net BASED MODELING OF CROSS-ORGANIZATION EMERGENCY RESPONSE PROCESSES

Next, the integrated model of cross-organization emergency response processes is obtained. To facilitate the integration of these intra-organization models, we give the following definition.

Definition 5: Let $\Sigma_{TRMi} = (P_i, T_i, F_i, \gamma_i, M_{0i})$ $(i \in \{1,2,\ldots n\}$ and $n \in Z)$ be the TRM_WF_net of n organizations, where $P_i = P_{Li} \cup P_{Ri} \cup P_{Mi}$. $\Sigma_{TRM} = (P, T, F, \gamma, M_0)$ is defined as the integrated model of Σ_{TRMi} $(i \in \{1,2,\ldots n\}$ and $n \in Z)$, such that 1) $P = P_1 \cup P_2 \cup \ldots P_n$, 2) $T = T_1 \cup T_2 \cup \ldots T_n$, 3) $F = F_1 \cup F_2 \cup \ldots F_n$, 4) $\gamma = \gamma_1 \cup \gamma_2 \cup \ldots \gamma_n$, and 5) $M_0 = M_{01} \cup M_{02} \cup \ldots M_{0n}$.

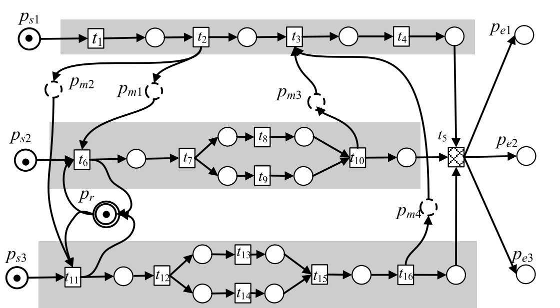


FIGURE 2. **TRM_CWF_net model of the cross-organization emergency response processes.**

By integrating the TRM_WF_nets of *ECC*, fire brigade, and hospital in Table 3, the integrated TRM_WF_net of the example cross-organization emergency response processes are obtained as shown in Fig. 2. Fig. 2 provides a global view of the cross-organization emergency response processes, based on which we can conduct temporal performance evaluation, correctness verification, etc.

In the following, we conduct temporal performance analysis of a TRM_CWF_net. The earliest time to start an activity t, which is denoted by $T_e(t)$, is computed as follows: $T_e(t) = 0$ if $^\bullet(^\bullet t) = \varnothing$; $T_e(t) = max\{T_e(t') + \gamma(t') | t' \in ^\bullet(^\bullet t)\}$ otherwise.

Take Fig. 2 as input, and $T_e(t)$ of each activity is shown in Table 4. Then, the execution duration of cross-organization emergency response processes can be obtained as $T_e(t_5) + \gamma(t_5) = 39 + 3 = 42$. In this way, we can obtain that it takes 42 time units to finish the whole cross-organization emergency response processes.

V. A THREE-LAYED FRAMEWORK FOR PRIVACY PROTECTION

In real-life scenarios, all emergency organizations are not interested in to do such integration as defined in Section 4 because their private emergency response processes are totally exposed to other emergency organizations.

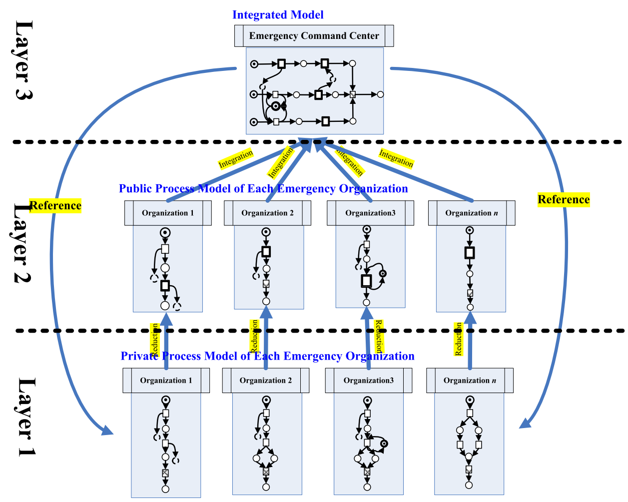


FIGURE 3. **A three-layered framework.**

To ensure the privacy protection of each emergency organization, we present a three-layered framework as shown in Fig. 3:

Layer 1: Each emergency organization establishes its private emergency response process with respect to the emergency requirements. At this stage, the processes are relatively detailed and contain many sensitive information of their organization privacy. Therefore, these models are not directly submitted to ECC for integration.

Layer 2: Each emergency organization constructs their public emergency response processes with respect to their private processes using a set of reduction rules. The reduction approach transforms TRM_CWF_net fragments to *coarse grained packages* (*CGPs*) while maintaining its external observable timing, message, and resource properties. In this way, *CGP* benefits at least the following aspects: 1) it can preserve the emergency business details unseen by other organizations; 2) it keeps the collaboration among different organizations invariant; and 3) it reduces the model scale.

Layer 3: Each emergency organization submits its public emergency response process to *ECC* for further integration and evaluation. If the integrated model is evaluated to be reasonable, *ECC* sends a copy of the integrated one to each sub-ordinate emergency organization for execution reference. By referring to this integrated model, each organization is aware of its collaboration partners and tracks the execution of the global emergency response processes.

Based on the three-layered framework, the model as shown in Fig. 2 is no longer available. Instead, a model of the cross-organization emergency response processes that protect the privacy of each organization's business detail is obtained. In the next section, we introduce a set of package reduction rules that support the transformation in *Layer* 2.

VI. PACKAGE REDUCTION RULES FOR TRM_CWF_nets

Based on the modeling approaches in Section 4, an integrated TRM_CWF_net model can be constructed to describe cross-organization emergency response processes. However, the

TABLE 4. Earliest start time of each activity in Fig. 2.

Activity	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9	t_{10}	t_{11}	t_{12}	t_{13}	t_{14}	t_{15}	t_{16}
$T_e(t)$	0	2	26	31	39	5	9	17	17	23	5	8	12	12	20	24

detailed business logics of each organization are directly exposed to their partners, which may cause leakage of its organization privacy. In addition, it may contain excessive places and transitions which can lead to inefficient analysis and performance evaluation. To overcome these limitations, we propose a set of reduction rules to reduce the scale of the model while maintaining timing constraints and business logic invariant. Moreover, the reduction can help the privacy preservation of each emergency organization by merging several emergency activities into one *CGP*. As the reduction aims to simplify a TRM_CWF_net and preserve organization privacy, they are only applicable for intra-organization emergency response processes.

There are many reduction techniques for general Petri nets [27], [28] and time Petri nets [29]–[31], [43]–[45]. However, not too much attention has been paid to timed Petri nets [32], [33], [46], [47] and their reduction techniques. Moreover, only the timing property equivalence is maintained during traditional reduction processes while no attention is focused on the preservation of resource and message-based collaborations. In this section, we propose a set of reduction rules to reduce a TRM_CWF_net. The structure, time, resource and message constraints are kept invariant. To save space, we only introduce a set of atomic reduction rules. Some advanced composite reduction rules can be realized based on them.

Rule 1: If $t_i, t_j \in T$ are two sequential activities where $t_i^\bullet = {}^\bullet t_j$, ${}^\bullet t_i \cap (P_R \cup P_M) = \varnothing$, $t_j^\bullet \cap (P_R \cup P_M) = \varnothing$, and their timing constraints are $\gamma(t_i)$ and $\gamma(t_j)$, then they can be merged to a new one t_{ij} where ${}^\bullet t_{ij} = {}^\bullet t_i$, $t_{ij}^\bullet = t_j^\bullet$, and $\gamma(t_{ij}) = \gamma(t_i) + \gamma(t_j)$.

Rule 1 shows the reduction rule for sequential activities that do not require any messages and resources, and an example of Rule 1 is illustrated in Table 5 where t_i and t_j are merged to t_{ij}.

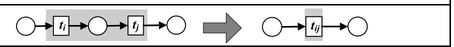
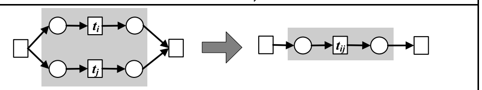
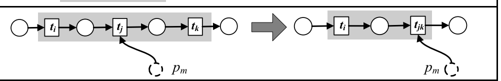
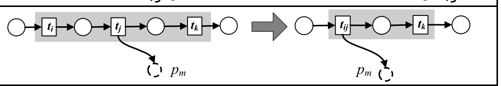
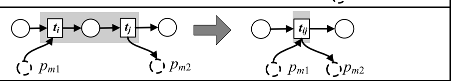
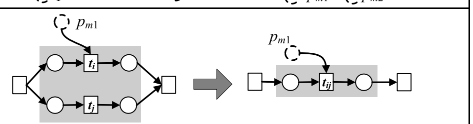
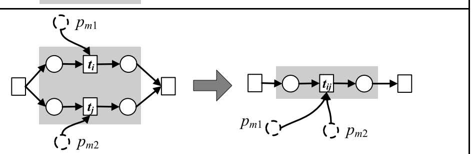
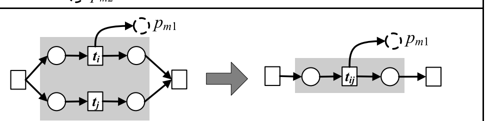
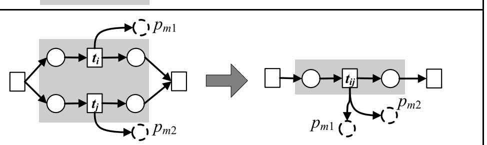
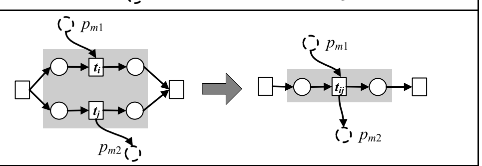
Rule 2: If $t_i, t_j \in T$ are two concurrent activities where ${}^\bullet t_i \cap (P_R \cup P_M) = \varnothing$, $t_i^\bullet \cap (P_R \cup P_M) = \varnothing$, ${}^\bullet t_j \cap (P_R \cup P_M) = \varnothing$ and $t_j^\bullet \cap (P_R \cup P_M) = \varnothing$, and their timing constraints are $\gamma(t_i)$ and $\gamma(t_j)$, then they can be merged to a new transition t_{ij} such that $\gamma(t_{ij}) = max\{\gamma(t_i), \gamma(t_j)\}$.

Rule 2 shows the reduction rule for concurrent activities that do not require any messages and resources, and an example of Rule 2 is illustrated in Table 5 where t_i and t_j are replaced by t_{ij}.

Rule 3: If $t_j, t_k \in T$ are two sequential activities where $t_j^\bullet = {}^\bullet t_k$, and ${}^\bullet t_j \cap P_M \neq \varnothing$, and their timing constraints are $\gamma(t_j)$ and $\gamma(t_k)$, then they can be merged to a new transition t_{jk} such that ${}^\bullet t_{jk} = {}^\bullet t_j$, $t_{jk}^\bullet = t_k^\bullet$, and $\gamma(t_{jk}) = \gamma(t_j) + \gamma(t_k)$.

Rule 3 shows the reduction rule for sequential activities that require messages, and an example of Rule 3 is illustrated in Table 5 where t_j and t_k are reduced to t_{jk}.

TABLE 5. Reduction rules and corresponding examples.

Reduction Rule	Reduction Example
Rule 1	
Rule 2	
Rule 3	
Rule 4	
Rules 3-4	
Rule 5 (a)	
Rule 5 (b)	
Rule 6	
Rule 7	
Rules 5-7	

Rule 4: If $t_i, t_j \in T$ are two sequential activities where $t_i^\bullet = {}^\bullet t_j$, and $t_j^\bullet \cap P_M \neq \varnothing$, and their timing constraints are $\gamma(t_i)$ and $\gamma(t_j)$, then they can be merged to a new transition t_{ij} such that ${}^\bullet t_{ij} = {}^\bullet t_i$, $t_{ij}^\bullet = t_j^\bullet$, and $\gamma(t_{ij}) = \gamma(t_i) + \gamma(t_j)$.

Rule 4 shows the reduction rule for sequential activities that send messages, and an example of Rule 4 is illustrated in Table 5 where t_j and t_k are merged to t_{jk}.

Rules 3-4 show the reduction for sequential activities that send or receive messages, based on which we can imply an advanced rule for sequential activities that both first receive and then send messages as illustrated in Table 5. Because it is not a basic rule, we do not define it in a formal way.

Rule 5: If $t_i, t_j \in T$ are two concurrent activities where (1) ${}^\bullet t_i \cap P_M \neq \varnothing$, in Table 5 Rule 5(a); or (2) ${}^\bullet t_i \cap P_M \neq \varnothing$

and ${}^{\bullet}t_j \cap P_M \neq \varnothing$, in Table 5 Rule 5 (b), and their timing constraints are $\gamma(t_i)$ and $\gamma(t_j)$, then they can be merged to a new transition t_{ij} such that $\gamma(t_{ij})=max\{\gamma(t_i),\gamma(t_j)\}$.

Rule 5 shows the reduction rule for two concurrent activities that require messages, and two example cases of Rule 5 are illustrated in Table 5 where t_i and t_j are reduced to t_{ij}.

Rule 6: t_i, $t_j \in T$ are two concurrent activities where $t_i^{\bullet} \cap P_M \neq \varnothing$, and $t_j^{\bullet} \cap P_M = \varnothing$, and their timing constraints are $\gamma(t_i)$ and $\gamma(t_j)$. If $\gamma(t_i) > \gamma(t_j)$, then they can be merged to a new transition t_{ij} such that $\gamma(t_{ij}) = \gamma(t_i)$,.

Rule 6 shows the reduction rule for concurrent activities where only one of them sends messages, and an example of Rule 6 is illustrated in Table 5 where t_i and t_j are replaced by t_{ij}. Note that this rule can only be applied when $\gamma(t_i) > \gamma(t_j)$.

Rule 7: t_i, $t_j \in T$ are two concurrent activities where $t_i^{\bullet} \cap P_M \neq \varnothing$, and $t_j^{\bullet} \cap P_M \neq \varnothing$, and their timing constraints are $\gamma(t_i)$ and $\gamma(t_j)$. If $\gamma(t_i) = \gamma(t_j)$, then they can be merged to a new transition t_{ij} such that $\gamma(t_{ij}) = \gamma(t_i)$ or $\gamma(t_{ij}) = \gamma(t_j)$.

Rule 7 shows the reduction rule for concurrent activities where both of them send messages, and an example of Rule 7 is illustrated in Table 5 where t_i and t_j are reduced to t_{ij}.

Rules 5-7 show the reduction rules for concurrent activities that send or receive messages, based on which we can obtain an advanced rule for concurrent activities that both receive and send messages as illustrated in Table 5. Because it is not a basic rule, we do not define formally. It is worth noting that this only works when $\gamma(t_j) > \gamma(t_i)$, and thus $\gamma(t_{ij}) = \gamma(t_j)$.

We have the following explanations for reduction rules: 1) we only introduce the atomic reduction rules, and some advanced composite rules, such as those in Rules 3-4 and Rules 5-7 in Table 5, can be realized on top of these basic ones; 2) the activities that are involved in a synchronization pattern cannot be merged with other activities because, if so, the collaboration information is to be concealed; 3) we only introduce rules that suit the sequence and concurrent structures, while choice and loop structures are not considered because their reduction results are usually not deterministic and can cause property changes compared with the original model; and 4) the firing rule of a transition obtained by reduction is same as that of a traditional one, i.e., the firing rule of a reduced TRM_WF_net is same as a Petri net.

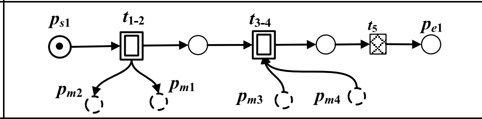
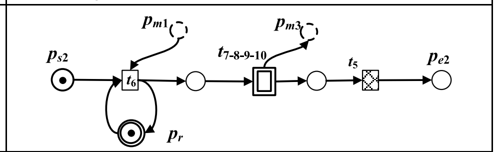
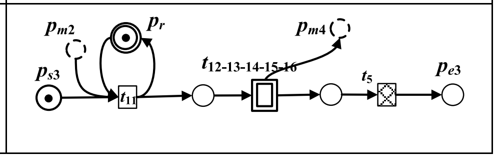
VII. EVALUATION OF THE PACKAGE REDUCTION APPROACH

In this section, we evaluate our package reduction approach from the following two perspectives: 1) the scale of the reduced model is smaller than the original one; and 2) the temporal performance before and after reduction stay invariant, based on which we prove its effectiveness.

A. MODEL SCALE EVALUATION

Each reduction rule transforms several components to a smaller structure while maintaining external observable timing, message, and resource properties. Here, we name the obtained transition as a *coarse grained package*, *CGP* for short, as it is the abstraction of a set of transitions and can be used to protect the business details.

TABLE 6. TRM_WF_net of each organization after reduction.

Organizatio n	Reduced TRM_WF_net
Emergency Command Center	
Fire Brigade	
Hospital	

In the following, we show how to use our reduction rules for TRM_CWF_net simplification and privacy protection. As we have mentioned in the previous section, the reduction rules are applicable to intra-organization response processes only. Considering for example the fire emergency scenario in Section 3, we have the TRM_WF_net models of *ECC*, fire brigade, and hospital as shown in Table 3. We can apply our reduction rules to them. The reduced TRM_WF_net of *ECC* is shown in Table 6. Graphically, a *CGP* is represent by a double rectangle with full line. Specifically, *CGP* $t_{1\text{-}2}$ is obtained by merging t_1 and t_2 via Rule 4 such that $\gamma(t_{1\text{-}2}) = \gamma(t_1) + \gamma(t_2) = 2 + 3 = 5$. *CGP* $t_{3\text{-}4}$ is obtained by merging t_3 and t_4 via Rule 3 such that $\gamma(t_{3\text{-}4}) = \gamma(t_3) + \gamma(t_4) = 5 + 8 = 13$. The reduced TRM_WF_net of fire brigade is shown in Table 6. *CGP* $t_{7\text{-}8\text{-}9\text{-}10}$ is obtained by 1) merging t_8 and t_9 via Rule 2 to obtain an intermediate *CGP* $t_{8\text{-}9}$ such that $\gamma(t_{8\text{-}9})=max\{\gamma(t_1), \gamma(t_2)\}=max\{6, 6\}=6$; and 2) merging t_7, t_{10} and $t_{8\text{-}9}$ via Rule 4 such that $\gamma(t_{7\text{-}8\text{-}9\text{-}10}) = \gamma(t_7)+\gamma(t_{10})+\gamma(t_{8\text{-}9}) = 8 + 2 + 6 = 16$. The reduced TRM_WF_net of hospital is shown in Table 6. *CGP* $t_{12\text{-}13\text{-}14\text{-}15\text{-}16}$ is obtained by 1) merging t_{13} and t_{14} via Rule 2 to obtain an intermediate *CGP* $t_{13\text{-}14}$ such that $\gamma(t_{13\text{-}14}) = max\{\gamma(t_{13})$, and $\gamma(t_{14})\} = max\{8, 6\} = 8$; and 2) merging t_{12}, t_{15}, t_{16} and $t_{13\text{-}14}$ to obtain *CGP* $t_{12\text{-}13\text{-}14\text{-}15\text{-}16}$ via Rule 4 such that $\gamma(t_{12\text{-}13\text{-}14\text{-}15\text{-}16}) = \gamma(t_{12}) + \gamma(t_{15}) + \gamma(t_{16}) + \gamma(t_{13\text{-}14}) = 4 + 4 + 2 + 8 = 18$.

Finally, by integrating the reduced TRM_WF_nets of the *ECC*, fire brigade, and hospital in Table 6 according to Definition 5, the reduced TRM_WF_net model of cross-organization emergency response processes is obtained as shown in Fig. 4.

Table 7 gives the number of transitions, logic places, resource places and message places of the TRM_CWF_net before and after reduction. The comparison leads to the

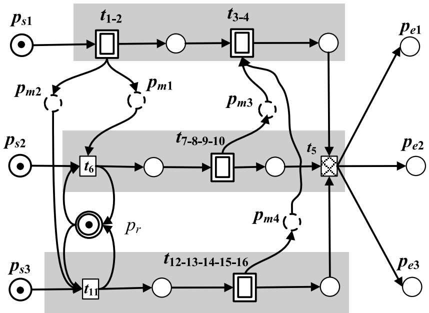


FIGURE 4. TRM_CWF_net model of the cross-organization emergency response processes after reduction.

TABLE 7. Scale comparison of the net before and after reduction.

Item	Before Reduction	After Reduction
Number of Transitions	14	7
Number of Logic Places	23	11
Numer of Message Places	4	4
Number of Resource Places	1	1

TABLE 8. Earliest start time of each activity in Fig. 4.

Activity	$t_{1\text{-}2}$	$t_{3\text{-}4}$	t_5	t_6	$t_{7\text{-}8\text{-}9\text{-}10}$	t_{11}	$t_{12\text{-}13\text{-}14\text{-}15\text{-}16}$
$T_e(t)$	0	26	39	5	9	5	8

conclusion that 1) its scale (in terms of the number of transitions and logic places) is much smaller; and 2) the collaboration elements in terms of message and resource places stay invariant.

B. TEMPORAL PERFORMANCE EVALUATION

By taking the TRM_CWF_net model after reduction in Fig. 4 as input, we get the earliest start time of each activity as shown in Table 8. Then, the execution time of the cross-organization emergency processes can be obtained as $T_e(t_5) + \gamma(t_5) = 39 + 3 = 42$.

According to Tables 4 and 8, we can see that: 1) the temporal performance before and after reduction stays invariant; 2) the time information of those activities which are maintained during the reduction process, such as t_5 and t_6, stays invariant; and 3) as the net scale is much smaller, the cost to compute the temporal performance is lower.

We have the following remarks on a TRM_CWF_net model after reduction: 1) each reduction rule transforms several TRM_CWF_net elements (places and transitions) to a transition while maintaining its external observable timing, message, and resource properties, i.e., the collaborations among different emergency organizations are not changed. Moreover, temporal performance of the reduced model is the same as that of the original one, and thereby we can conduct the performance evaluation by using the reduced one whose scale is smaller than the original one's; and 2) organizational level business privacy is properly protected after model reduction. The *CGP* is the abstraction of a fragment of process activities, based on which the internal emergency organization business logics are hidden and unseen to other partners.

VIII. A RUNNING CASE EVALUATION

For large-scale emergency cases, more organizations, such as police station and explosive ordnance disposal, are involved. Next, we apply our three-layered framework to such a case.

A. A TYPICAL SCENARIO

A typical scenario of cross-organization collaborative fire emergency response processes involves the following organizations: police station, emergency command center (ECC), explosive ordnance disposal (EOD) team, fire brigade, and hospital. It includes the following steps:

1) The police station first receives the fire emergency call, and then reports the emergency information to ECC.

2) The police rush to the emergency site to perform its detailed disposal missions, and then reports the site conditions to ECC.

3) After receiving the emergency information, ECC first establishes a temporary emergency command group, and then makes and issues emergency plans to its collaborative organizations, i.e., medical rescue instruction to a hospital, search EOD instruction to an EOD team, and fire rescue instruction to the fire brigade.

4) The EOD team rushes to the site upon receiving the search EOD instruction from ECC, and conduct its specific disposal activities according to its emergency handling requirements, and finally reports the EOD search results to ECC.

5) The fire brigade rushes to the site upon receiving the fire rescue instruction from ECC, and conducts its specific disposal activities according to its emergency handling requirements, and finally reports the fire rescue results to ECC.

6) The hospital personnel rushes to the site upon receiving the medical rescue instruction from ECC, and conducts its specific disposal activities according to its emergency handling requirements, and finally reports the medical rescue results to ECC.

7) After receiving all the feedback information from the hospital, EOD team, and fire brigade, ECC makes emergency summary and evaluation, and finally does the file archive.

8) ECC arranges the media coverage for the whole emergency response, and finally, ECC, fire brigade, and hospital do the media coverage together.

According to the above emergency response descriptions, we first give the activity information of the police station, ECC, EOD team, fire brigade, and hospital as shown in Table 9. Table 10 explains the meaning of the involved message and resource symbols.

B. TRM_WF_net BASED MODELING, REDUCTION AND INTEGRATION

According to Table 9, TRM_WF_nets of the police station, ECC, *EOD* team, fire brigade and hospital are obtained as shown in Table 11. Unfortunately, the current TRM_WF_net of each emergency organization has the following limitations: 1) the scale of this model is large, i.e., excessive nodes

TABLE 9. An informal description of activities.

Activity ID	Activity Name	Required Message Set	Sent Message Set	Required Resouce Set	Organizations	Pre-Activities	Execution Time
t_1	*Alarm receipt*	∅	∅	∅	{Police Station}	∅	2
t_2	*Report emergency information*	∅	$\{p_{m1}\}$	∅	{Police Station}	$\{t_1\}$	3
t_3	*Rush to the site*	∅	∅	∅	{Police Station}	$\{t_2\}$	4
t_4	*Deal with the scene*	∅	∅	∅	{Police Station}	$\{t_3\}$	5
t_5	*Evacuation*	∅	∅	∅	{Police Station}	$\{t_3\}$	6
t_6	*Rescue the wounded*	∅	∅	∅	{Police Station}	$\{t_3\}$	8
t_7	*Alarm receipt*	∅	$\{p_{m2}\}$	∅	{Police Station}	$\{t_4, t_5, t_6\}$	5
t_8	*Search the suspect*	∅	∅	∅	{Police Station}	$\{t_7\}$	6
t_9	*Establish temporary emergency center*	$\{p_{m1}\}$	∅	∅	{ECC}	∅	2
t_{10}	*Make and issue emergency plans*	$\{p_{m2}\}$	$\{p_{m3}, p_{m4}, p_{m5}\}$	∅	{ECC}	$\{t_9\}$	3
t_{11}	*Emergency summary and evaluation*	$\{p_{m6}, p_{m7}, p_{m8}\}$	∅	∅	{ECC}	$\{t_{10}\}$	5
t_{12}	*File archive*	∅	∅	∅	{ECC}	$\{t_{11}\}$	8
t_{13}	*Arranges media coverage*	∅	∅	∅	{ECC}	$\{t_{12}\}$	2
t_{14}	*Do media coverage*	∅	∅	∅	{ECC, Fire Brigade, Hospital}	$\{t_{13}, t_{22}, t_{28}\}$	3
t_{15}	*Rush to the site*	$\{p_{m3}\}$	∅	$\{p_r\}$	{EOD Team}	∅	4
t_{16}	*Search the EOD*	∅	∅	∅	{EOD Team}	$\{t_{15}\}$	8
t_{17}	*Report the EOD search results*	∅	$\{p_{m6}\}$	∅	{EOD Team}	$\{t_{16}\}$	2
t_{18}	*Rush to the site*	$\{p_{m4}\}$	∅	$\{p_r\}$	{Fire Brigade}	{∅}	4
t_{19}	*Fight the fire*	∅	∅	∅	{Fire Brigade}	$\{t_{18}\}$	8
t_{20}	*Recovery the site*	∅	∅	∅	{Fire Brigade}	$\{t_{19}\}$	6
t_{21}	*Conduct mitigation operations*	∅	∅	∅	{Fire Brigade}	$\{t_{19}\}$	6
t_{22}	*Report the fire rescue*	∅	$\{p_{m7}\}$	∅	{Fire Brigade}	$\{t_{20}, t_{21}\}$	2
t_{23}	*Rush to the site*	$\{p_{m5}\}$	∅	$\{p_r\}$	{Hospital}	∅	3
t_{24}	*Shunt the wounded*	∅	∅	∅	{Hospital}	$\{t_{23}\}$	4
t_{25}	*Treat the severely injured people*	∅	∅	∅	{Hospital}	$\{t_{24}\}$	8
t_{26}	*Treat the slightly injured people*	∅	∅	∅	{Hospital}	$\{t_{24}\}$	6
t_{27}	*Environmental quality detection*	∅	∅	∅	{Hospital}	$\{t_{25}, t_{26}\}$	4
t_{28}	*Report the medical rescue*	∅	$\{p_{m8}\}$	∅	{Hospital}	$\{t_{27}\}$	2

are used to represent an emergency response process which causes inefficiency of analysis and verification; and 2) the business details of each private emergency organization are exposed and shared among others, which may cause the leakage of internal privacy. To cope with these limitations, we reduce the TRM_WF_net of each emergency response process. In the following, we show how to use our reduction rules to obtain *a* reduced model such that the organization level privacy is protected. The reduced models are all shown in Table 11.

Specifically, *CGP* $t_{1\text{-}2}$ is obtained by merging t_1 and t_2 using Rule 4. *CGP* $t_{3\text{-}4\text{-}5\text{-}6\text{-}7}$ is obtained by 1) merging t_4-t_6 using Rule 2 to obtain *CGP* $t_{4\text{-}5\text{-}6}$ such that $\gamma(t_{4\text{-}5\text{-}6}) = \max\{\gamma(t_4), \gamma(t_5), \gamma(t_6)\} = \max\{5, 6, 8\} = 8$; and 2) merging t_3, t_7 and $t_{4\text{-}5\text{-}6}$ with Rule 4 such that $\gamma(t_{3\text{-}4\text{-}5\text{-}6\text{-}7}) = \gamma(t_3) + \gamma(t_7) + \gamma(t_{4\text{-}5\text{-}6}) = 4 + 5 + 8 = 17$.

CGP $t_{9\text{-}10}$ is obtained by merging t_9 and t_{10} using an advanced rule by combining Rules 3-4 such that $\gamma(t_{9\text{-}10}) = \gamma(t_9) + \gamma(t_{10}) = 2 + 3 = 5$. *CGP* $t_{11\text{-}12\text{-}13}$ is obtained by merging $t_{11} - t_{13}$ using Rule 3 such that $\gamma(t_{11\text{-}12\text{-}13}) = \gamma(t_{11}) + \gamma(t_{12}) + \gamma(t_{13}) = 5 + 8 + 2 = 15$.

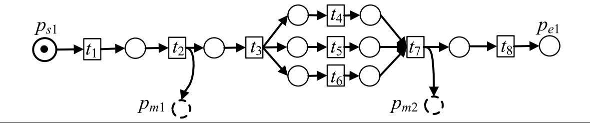
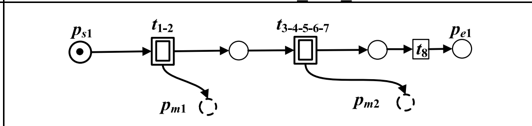
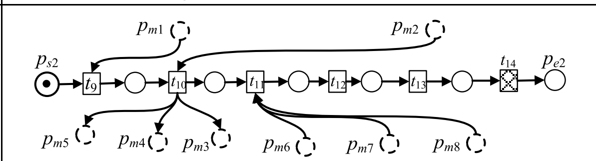
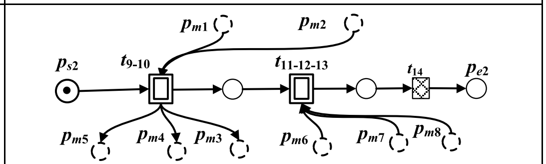
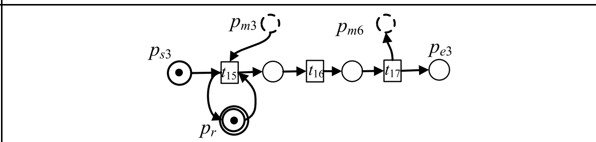
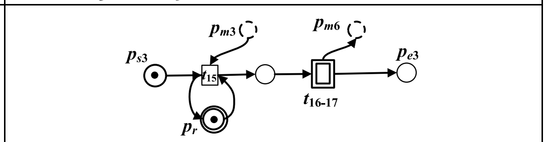
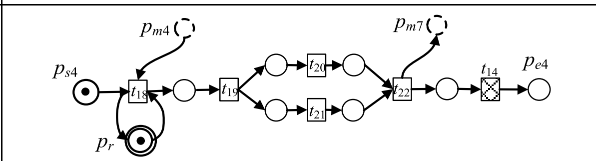
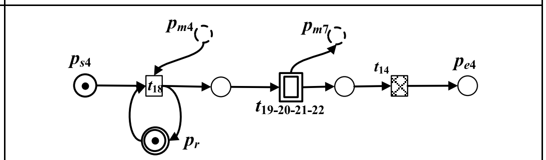
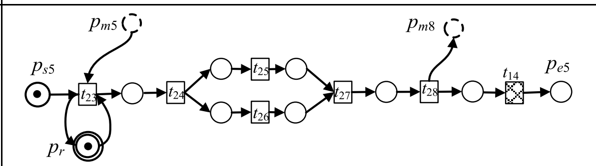
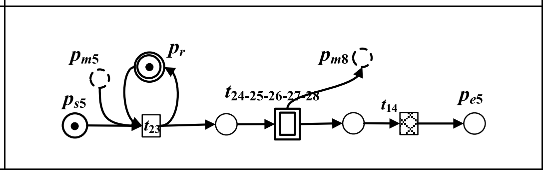
TABLE 10. Message and resource information.

Message/Resource	Meaning
p_{m1}	emergency information
p_{m2}	site conditions
p_{m3}	medical rescue instruction
p_{m4}	fire rescue instruction
p_{m5}	search EOD instruction
p_{m6}	EOD search results
p_{m7}	fire rescue results
p_{m8}	medical rescue results
p_r	public transportation vehicle

CGP $t_{16\text{-}17}$ is obtained by merging t_{16} and t_{17} using Rule 4 such that $\gamma(t_{16\text{-}17}) = \gamma(t_{16}) + \gamma(t_{17}) = 8 + 2 = 10$. TRM_WF_net of the *EOD* team is shown in Table 11.

CGP $t_{19\text{-}20\text{-}21\text{-}22}$ is obtained by 1) merging t_{19} and t_{20} using Rule 2 to obtain *CGP* $t_{20\text{-}21}$ such that $\gamma(t_{20\text{-}21}) = max\{\gamma(t_{20}), \gamma(t_{21})\} = max\{6, 6\} = 6$; and 2) merging t_{19}, t_{22} and $t_{20\text{-}21}$

TABLE 11. TRM_WF_net of each emergency organization before and after reduction.

Organization	TRM_WF_net	Reduced TRM_WF_net
Police Station		
ECC		
EOD team		
Fire Brigades		
Hospital		

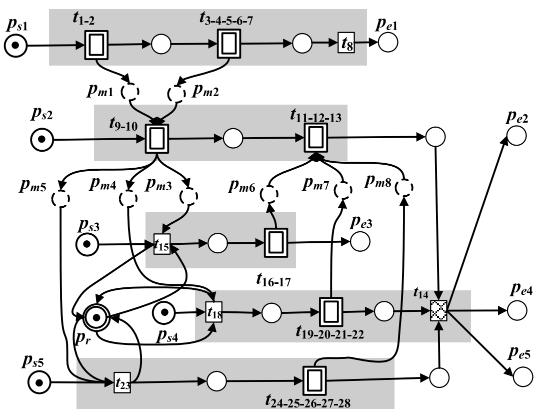


FIGURE 5. TRM_WF_net of the cross-organization fire emergency response process after reduction.

with Rule 4 such that $\gamma(t_{19\text{-}20\text{-}21\text{-}22}) = \gamma(t_{19}) + \gamma(t_{22}) + \gamma(t_{20\text{-}21}) = 8 + 2 + 6 = 16$.

CGP $t_{24\text{-}25\text{-}26\text{-}27\text{-}28}$ is obtained by 1) merging t_{25} and t_{26} using Rule 2 to obtain *CGP* $t_{25\text{-}26}$ such that $\gamma(t_{25\text{-}26}) = max\{\gamma(t_{25}),$ and $\gamma(t_{26})\} = max\{8, 6\} = 8$; and 2) merging t_{24}, t_{27}, t_{28} and $t_{25\text{-}26}$ to obtain *CGP* $t_{24\text{-}25\text{-}26\text{-}27\text{-}28}$ with Rule 4 such that $\gamma(t_{24\text{-}25\text{-}26\text{-}27\text{-}28}) = \gamma(t_{24})+\gamma(t_{27})+\gamma(t_{28})+\gamma(t_{25\text{-}26}) = 4+4+2+8 = 18$.

By integrating the reduced TRM_WF_nets in Table 11, the reduced TRM_WF_net model of cross-organization emergency response processes is obtained as shown in Fig. 5.

TABLE 12. Scale comparison of the net before and after reduction.

Item	Before Reduction	After Reduction
Number of Transitions	28	12
Number of Logic Places	39	19
Numer of Message Places	8	8
Number of Resource Places	1	1

C. PERFORMANCE EVALUATION

Table 12 gives the number of transitions, logic places, resource places and message places of the TRM_CWF_net before and after reduction. Clearly, its scale after reduction is much smaller while the collaboration elements stay invariant.

In the following, we conduct the temporal performance evaluation of the global cross-organization emergency response processes. To do so, we need to compute the start time of 28 transitions when using the TRM_CWF_net without reduction. If we lay our computation on the reduced TRM_CWF_net, we only need to compute the start time of 14 transitions. Take the TRM_CWF_net model in Fig. 5 as input, the earliest time to start each emergency activity is obtained and illustrated in Table 13. Then, the execution time of the cross-organization emergency response processes can be obtained as $T_e(t_{14}) + \gamma(t_{14}) = 71 + 3 = 74$.

As a conclusion, the reduced TRM_WF_net has benefits in the following aspects: 1) because *CGP* is the abstraction of a fragment of an emergency process, based on which the internal emergency organization business logics are hidden

TABLE 13. Earliest start time of each activity in Fig. 5.

Activity	$t_{1\text{-}2}$	$t_{3\text{-}4\text{-}5\text{-}6\text{-}7}$	t_8	$t_{9\text{-}10}$	$t_{11\text{-}12\text{-}13}$	t_{14}	t_{15}	$t_{16\text{-}17}$	t_{18}	$t_{19\text{-}20\text{-}21\text{-}22}$	t_{23}	$t_{24\text{-}25\text{-}26\text{-}27\text{-}28}$
$T_e(t)$	0	5	22	22	56	71	27	31	27	35	27	38

and unseen to other partners. In this way, it effectively preserves the business privacy of each emergency organization; 2) it keeps the collaborations among different emergency organizations invariant; and 3) it is convenient to conduct the temporal performance evaluation on the reduced model owning its smaller scale than the original one's.

IX. CONCLUSION

In this paper, we focus on a package reduction-based privacy protection approach for the modeling and performance evaluation of cross-organization emergency response processes. The main results of this work include: 1) a kind of WF-nets extended with time, resource, and message information (TRM_WF_net) is proposed to model the cross-organization emergency response processes; 2) a set of reduction rules are proposed to reduce the scale of our TRM_WF_net by maintaining its external observable timing, message, and resource properties invariant. These reduction rules not only improve the efficiency of temporal performance evaluation, but also protect the business privacy of each emergency organization while keeping the collaborations among different emergency organizations invariant; and 3) a three-layered framework is proposed to model and analyze cross-organization emergency response processes.

In the future, we aim to extend the package reduction-based privacy protection modeling approach in the following two directions. First, we plan to address the correctness verification of an integrated model. In this way, the structural correctness preservation relation during a reduction process need to be investigated. Secondly, the temporal performance is evaluated in a relatively rough manner, and the resource conflicts are not fully addressed in this work. More efforts are needed to investigate resource conflict detection and resolution strategies [11], [17], [34], [35] when a complex cross-organization emergency response emerges. Thirdly, with the development of IoT-based and sensor-based technologies, real-time monitoring and anlaysis of cross-organization emergency response processes are highly desired [51]–[52].

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