A Formal Approach for Multi-occurrence Crisis Management

Hela Kadri[1,2], Simon Collart-Dutilleul[1], Philippe Bon[1] and Samir Ben Ahmed[2]
[1]*IFSTTAR/ESTAS, Université Lille nord de France, 20 rue Elisée Reclus, France*
[2]*Université de Tunis El Manar, Campus Universitaire Farhat Hached, Tunisia*

Keywords: Crises Management, Dynamic System, Formal Model, Petri Nets, Discrete Event Systems, Operating Modes, Supervisory Control Theory.

Abstract: Having observed the need from the state of the art concerning crisis management, a formal expression is proposed. In the case of neighbour crisis series, the crisis management plans (CMPs) are merged into one and the level of complexity could be increased. A formal approach to control crisis management systems (CMS) is then introduced, which is studied as a discrete event system (DES). Based on the supervisory control theory (SCT), a multi-model approach is used to define the behavior of each CMP separately as well as its different control strategies through the use of prioritized colored Petri nets (PCPN). Finally, a global CMS model is provided. It is generated using an algorithm and ensures the control of CMPs evolution thanks to the operating modes management. In addition to the simulation and the formal validation of some safety properties, the global model incorporates concepts of common operating mode and of common sub-behavior in order to be of a reasonable size.

1 INTRODUCTION

Crisis management is an important component of a resilience system (Lotter et al., 2016). Initial causes of crises vary widely (Natural disasters, terrorist attacks or sabotage, accidents, and technological disruptions), whereas a lot of challenges are common. Crisis management teams (CMT) often have no time for preparation or discussion and the team has to make fast decisions, facing unusual situations.

"*One thing for certain, crisis management, regardless of parameters, requires that strategic action be taken both to avoid or mitigate undesirable developments and to bring about a desirable resolution of the problems*" (Burnett, 1998).

Public safety agencies such as police forces, fire brigades, and emergency medical services maintain their own control organizations for day-to-day operations. Effective crisis management (CM) requires merging information from multiple sources to create actionable intelligence. Achieving this goal requires an emergency plan, which should include an accurate risk assessment, implementation of a safety and security policy, continuous training of workers on the execution plan, etc.

Extending recommendation provided by (Fines, 1985) for spokesmen to any critical actors involved into the crisis gives the following principles:

1. set a broad strategy in advance;
2. respond quickly;
3. train actors in advance;
4. seek third party support; and
5. centralize the actor's functions.

As a consequence, careful planning can mitigate the effects of confusion during crises. A single decision-maker and regular full-scale exercises help to ensure that all teams know what to do. The incidents with large-scale emergencies such as natural disasters or terrorist acts are usually characterized by a series of deadly incidents. The appointment of a single decision-maker applying an appropriate plan is expected to allow an effective response of incidents. Homogeneous information and control flow allow an efficient orchestration within and between various involved services.

The prescriptive studies have general and industry-specific applicability. In the four major questions, the following one received a consensus (Villar and Guezo, 2016): "who (else) should be involved ?". In other words, what is the dimension and the nature of the team needed to efficiently deal with the crisis. The answer to this question may vary with the occurrence of additional events, whereas the principles proposed by (Fines, 1985) remain relevant.

Kadri, H., Collart-Dutilleul, S., Bon, P. and Ahmed, S.
A Formal Approach for Multi-occurrence Crisis Management.
DOI: 10.5220/0006865606070614
In *Proceedings of the 13th International Conference on Software Technologies (ICSOFT 2018)*, pages 607-614
ISBN: 978-989-758-320-9

Critical infrastructures (CI) are infrastructures that are substantial for the well-being, even the existence of communities. Public transportation (PT) is an example for CI. It is composed of a complex network of trains, stations and tracks and plays an important role for the well-being of modern societies (Lévy-Bencheton and Darra, 2015). Because of its high relevance for the society as well as the high complexity of its network, PT should prepare for crises so that basic functions of the infrastructure are upheld, respectively re-established as quickly as possible. Thus, organizations within the sector of public transportation should establish their own crisis management especially that a vast majority of their crises have the potential for causing fatalities or injuries and/or major damage (Kadri et al., 2018).

In order to establish command and control organization for crisis management, this paper studies CMS as a discrete event system (DES) and proposes a formal model applying the concept of operating modes management. This concept allows switching between the different modes according to the user input and safety requirements. Each operating mode in the crisis management system is an activated plan applied in the face of an incident. It can be transformed into a wider one in terms of area coverage or merged with another triggered in a coverage area. Figure 1 graphically describes the breakdown of a crisis management system into operating modes.

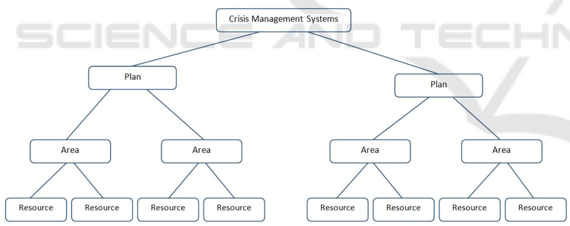

Figure 1: Proposed hierarchical structure of a crisis management system.

In the following sections, we present the developed work in its different stages and aspects.

2 BACKGROUND

2.1 Operating Mode Management

There are many theories proposing DESs control such as the supervisory control theory (SCT). This theory, initiated by (Ramadge and Wonham, 1989), is distinguished from other ones by its formal methods to ensure the safe operation without extensive use of validation and verification. Among its methods are operating modes management which is characterised by the definition of different control strategies for each operating mode. It also aims to provide switching between the different modes according to the user input and safety requirements.

In the literature pertaining to operating mode management for DES, a set of works can be mentioned such as (Nourelfath, 1997), (Hamani et al., 2004), (Kamach et al., 2003), (Kadri et al., 2013) and (Kadri et al., 2014). These authors propose a decomposition approach and a system characterization according to the resources state. This approach allows to represent a complex system by a set of operating modes. (Nourelfath, 1997) is the first to propose the use of the SCT for the nominal mode study taking into account the admissible behaviors of the system after a need of reconfiguration due to a failure of one of its components. They define therefore a switching mode. However there are no formal validation of the switching mechanism and no deadlock avoidance. This work, based on automata, makes it possible to study only two operating modes. (Hamani et al., 2004) define a switching mode, however, there is no formal validation of the switching mechanism and no deadlock avoidance. Using a multi-model approach for managing operating modes, (Kamach et al., 2003) have associated an automaton with each operating mode and have defined a switching mechanism inducing trace memorization. (Kadri et al., 2013) and (Kadri et al., 2014) have presented the behavior description of each model by a colored Petri net.

According to the two last works, we adopt the multi-model approach that allows to associate a PCPN model to each mode of operation.

2.2 Basics of PCPN

Prioritized colored Petri nets (PCPNs) are an extension of basic Petri nets (Desel et al., 1998). They allow a concise representation in a unified structure both of the static and the dynamic aspects of the considered system, thanks to its twofold representation - graphical and mathematical. The graphical aspect enables a concise way to design and verify the model, while the mathematical aspect allows formal modeling of these interactions and analysis of the modeled system properties.
In the following, we remind some basic notions of PCPNs found in the literature. A PCPN is a 8-tuple $< P, T, C, Pre, Post, G, M, \Pi >$, where

1. P is a set of places,
2. T is a set of transitions,
3. $P \cap T = \emptyset, P \cup T \neq \emptyset$,

4. C is a color function defined from $P \cup T$ into finite and non-empty sets,
5. $Pre, Post$ are the backward and forward incidence functions, respectively. They are defined on $P \times T \rightarrow I\!N$ such that $Pre(p,t), Post(p,t) \in [C(t) \rightarrow \mathbf{N}]_{MS} \forall (p,t) \in P \times T$,
6. G is a guard function. It is a Boolean expression attached to a transition $t \in T$. By default $G(t)$ is evaluated to true,
7. M is a function defined on P describing the initial marking, such that $M(p) \in C(p)_{MS}, \forall p \in P$.
8. Π is a priority function that maps transitions into non-negative natural numbers representing their priority level.

Definition 1. *(Multi-set MS) A multi-set m, over a non-empty set S, is a function $m \in [S \mapsto \mathbf{N}_0]$. The non-negative integer $m(s) \in \mathbf{N}_0$ is the number of appearances of the element s in the multi-set m.*

The next section details the CMS formalisation in DES framework.

3 OPERATING MODE MANAGEMENT FOR CRISIS MANAGEMENT

Although every crisis situation is unique, the responses share common elements. So, several pre-set plans can be applied in function of crises type and many other factors as the number of injured, severity of injuries, material damage, etc. Figure 2 represents a class diagram that describes the structure of a crisis management system by showing the relationships among its constituents.

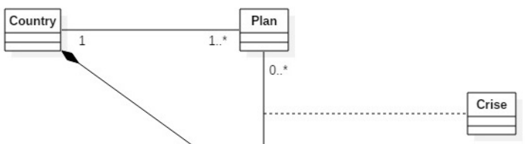

Figure 2: Class diagram of crisis management system.

An operating mode represents an activated plan. It defines its geographical scope, manages its resources and organizes the communication with all participants. However, if a series of crises occurs in the same area, the decision-maker can then change the activated plan by another one covering more areas. Also, if a new crisis triggers a plan in an area affected by another crisis plan, then these two crises will be treated by one new plan. This new plan is the merger of the first two and takes into consideration all areas concerned by the first two crises. This dynamic is ensured by the operating mode management, which allows CMS to switch from one operating mode to another one without having to stop.

Furthermore, the multi-model approach is used to allow, in context of SCT, to associate a PCPN model with each operating mode. First, let $Pl = \{pl_1, pl_2, ..., pl_{|Pl|}\}$, where $|Pl| \geq 1$ be the set of plans and let $A = \{a_1, a_2, ..., a_{|A|}\}$, where $|A| \geq 1$ be its set of the areas. Also, let $A_{i,j}, \forall i \in \{1..|A|\}, \forall j \in \{1..|Pl|\}$ be the set of the areas concerned by the crisis in a_i and the plan pl_j.
Let PL the set of all CMS operating modes where

$$\begin{array}{ccc} A \times Pl & \longrightarrow & PL \\ (a_i, pl_j) & \longmapsto & PL_{i,j} \end{array}$$

be a mapping such that $PL_{i,j}$ indicates the operating mode associated to the crisis area a_i and to the plan pl_j.
For each operating mode $PL_{i,j}$, where $i \in 1..|A|$ and $j \in 1..|Pl|$, we associate a PCPN $< P_{i,j}, T_{i,j}, C_{i,j}, Pre_{i,j}, Post_{i,j}, G_{i,j}, M_{i,j}, \Pi_{i,j} >$.
For reasons of simplicity, the same identity of each PL mode is given to its associated PCPN.

3.1 Common Operating Mode in CMS

Each plan can be applied in one or more areas throughout a country. These areas are subject to the same degree of action. Therefore, the same functioning process appears for crises activating the same plan, which leads us to define the common operating mode concept.

Formally, two operating modes of two different crisis areas are common if and only if they are modeled by the same PCPN model except tokens.

Definition 2. *Let $PL_{i,j} = (P_{i,j}, T_{i,j}, C_{i,j}, Pre_{i,j}, Post_{i,j}, G_{i,j}, M_{i,j}, \Pi_{i,j})$ and $PL_{k,j} = (P_{k,j}, T_{k,j}, C_{k,j}, Pre_{k,j}, Post_{k,j}, G_{k,j}, M_{k,j}, \Pi_{k,j})$ be two operating modes such as $i \neq k$. $PL_{i,j}$ and $PL_{k,j}$ are common, if and only if $(P_{i,j}, T_{i,j}, C_{i,j}, Pre_{i,j}, Post_{i,j}, G_{i,j}, \Pi_{i,j}) = (P_{k,j}, T_{k,j}, C_{k,j}, Pre_{k,j}, Post_{k,j}, G_{k,j}, \Pi_{k,j})$.*

3.2 Common Sub-behavior in CMS

For each plan level, the associated public safety agencies such as police, fire brigades, and emergency medical services are made available to the decision-maker. Thus, some similar behaviors between operating modes of different level plans can be underlined and in order to minimize the global model size, a concept common Sub-behavior is defined.

Formally, a common Sub-behavior is a part of a PCPN related to one or more operating modes. It can be a set of places, a set of transitions and/or a set of tokens.

Definition 3. *Let PL be the set of operating modes.* $\forall (PL_{i,j}, PL_{k,l}) \in PL \times PL$ *such as* $i \neq k$ *and* $j \neq l$, *if* $\exists c =< P_c, T_c, C_c, Pre_c, Post_c, G_c, M_c, \Pi_c >$ *such as* $(P_c = (P_{i,j} \cap P_{k,l}) \neq \emptyset)$ *or* $(T_c = (T_{i,j} \cap T_{k,l}) \neq \emptyset)$ *or* $(M_c = (M_{i,j} \cap M_{k,l}) \neq \emptyset)$ *then c is a common Sub-behavior for the two modes* $PL_{i,j}$ *and* $PL_{k,l}$.

Remark 1. *Common operating mode and common Sub-behavior are defined when the same name of PCPN components is given in different model.*

3.3 Switching Mechanism

A switching event triggers between two operating modes under decision-maker request or between three in the case of merging activated plans. It causes the deactivation of the current operating mode and the activation of another mode.

The switching mechanism is modeled by specific PCPN transitions in a given mode. To distinguish such transitions, a mapping is defined which role is to provide the information for the next mode.

Definition 4. *Let* $PL_{i,j}$ *be an operating mode and* $T'_{i,j} \subset T_{i,j}$ *be the set of switching transitions.*
Let $Next\_plan : T'_{i,j} \rightarrow PL$ *be a mapping such that* $Next\_plan(t)$ *indicates the active operating mode after firing t* $(\forall t \in T'_{i,j})$.

Merging Operating Modes. As stated above, merging operating modes is triggered automatically when a new plan is activated in an area concerned by another crisis via fusion transitions. These transitions are switching transitions with a higher priority than others.
Formally,

Definition 5. *Let* $PL_{i,j}$, $i \in \{1..|A|\}, j \in \{1..|Pl|\}$ *and* $PL_{k,l}$, $k \in \{1..|A|\}, l \in \{1..|Pl|\}$ *two operating modes. If* $a_k \in A_{i,j}$, *then* $PL_{i,j}$ *and* $PL_{k,l}$ *are replaced by a new operating modes* $PL_{m,n}$ *such as* $PL_{m,n}$ *is the concatenation of* $PL_{i,j}$ *and* $PL_{k,l}$ *and* $A_{m,n} = A_{i,j} \cup A_{k,l}$.

3.4 System Model

On the basis of the previous concept definitions, we are able now to model the CMS based on the operating modes management. Let the place containing all the areas concerned by the different crises called $ActivatedPlans$ with tokens that have the structure $((a_i, pl_j), A_{i,j})$.
The associate PCPN is a tuple

$$< P, T, C, Pre, Post, G, M, \Pi >$$

Where

$P = \cup_{(i=1..|A|, j=1..|Pl|)} P_{i,j}$;

$T = \cup_{(i=1..|A|, j=1..|Pl|)} T_{i,j}$;

$C = \cup_{(i=1..|A|, j=1..|Pl|)} C_{i,j}$;

$Pre, Post$:

- $\forall PL_{i,j} \in PL, \forall (p,t) \in P_{i,j} \times T_{i,j}$,
  $Pre(p,t) = Pre_{i,j}(p,t)$,
  $Post(p,t) = Post_{i,j}(p,t)$;
- $\forall (PL_{i,j}, PL_{k,l}) \in PL \times PL (i \neq k), \forall (p,t) \in P_{i,j} \times T_{k,l} / p \notin P_{k,l}$ and $t \notin T_{i,j}$,
  $Pre(p,t) = Post(p,t) = 0$;
- $\forall PL_{i,j} \in PL, \forall t \in T'_{k,l}$,
  $Post(ActivatedPlans, t) = Next\_plan(t)$;
  where $T'_{i,j}$ is the set of switching transitions such as $T'_{i,j} \subset T_{i,j}$.

$G : \forall PL_{i,j} \in PL, \forall t \in T_{i,j}, \quad G(t) = G_{i,j}(t)$;

$M : \forall (PL_{i,j}, PL_{k,l}) \in PL \times PL (i \neq k)$

- if $j = l, \quad M(p) = M_{i,j}(p) \cup M_{k,l}(p)$;
- if $j \neq l$, if $M_{i,j}(p) \in M_c(p)$, $M(p) = M_c(p)$; else $M(p) = M_{i,j}(p)$.

$\Pi : \forall PL_{i,j} \in PL, \forall t \in T_{i,j}, \quad \Pi(p) = \Pi_{i,j}(p)$.

3.5 Generation Algorithm

Let us present the algorithm generating the CMS model from a set CM operating modes.

Definition 1. *Generating the CMS model*

Input
- the set A of Areas
- the set Pl of plans
- the set PL of operating modes
- the mapping Next_plan

Output
a global CP-net

$$G =< P, T, C, Pre, Post, G, M, \Pi >$$

Initially
$P = \varnothing; T = \varnothing; C = \varnothing;$

For every operating mode (i, j) $i = 1..|A|, j = 1..|Pl|$ *do* */*include a new mode*/*

$P = P \cup P_{i,j}; \quad T = T \cup T_{i,j}; \quad C = C \cup C_{i,j};$
$\forall (p,t) \in P_{i,j} \times T_{i,j},$ */*defining internal $PL_{i,j}$ arcs */*
$Pre(p,t) = Pre_{i,j}(p,t);$
$Post(p,t) = Post_{i,j}(p,t);$
$\forall t \in T'_{i,j},$ */*defining the new arcs*/*
$Post(ActivatedPlans, t) = Next\_plan(t);$
$\forall t \in T_{i,j},$ */*adding guards*/*
$G(t) = G_{i,j}(t);$
$\forall p \in P_{i,j},$ */*defining initial marking*/*
$M(p) = M(p) \cup M_{i,j}(p);$
$\forall t \in T_{i,j},$ */*defining priorities*/*
$\Pi(t) = \Pi_{i,j}(t);$
For every mode $(k,l), k = 1 \ldots (i-1), l = 1 \ldots (j-1)$ *do* */*already included modes defining inexistent arcs*/*
$\forall (p,t) \in P_{i,j} \times T_{k,l},\ p \notin P_{k,l}$ *and* $t \notin T_{i,j},$
$Pre(p,t) = Post_{i,j}(p,t) = 0;$
enddo
enddo.

4 CASE STUDY

The example below is developed using the environment CPN Tools (Ratzer et al., 2003). It is a free software for editing, simulating, and analyzing Colored Petri nets.

4.1 System Description

To start with we suppose that in the country of the studied example, there are 3 levels of plans:

- Plan1 is for limited crises which will not seriously affect the functional capacity of the concerned area and will not exceed the available resources in that area but nevertheless require some degree of action;
- Plan2 is for emergency or disaster which may be severe and cause damage, fatalities or injuries and/or interruption to the concerned area operations and it may develop from incidents beginning at the Plan1. The resources of the area concerned and those of the neighboring areas are made available to the decision-maker;
- Plan3 is for major crisis such as natural disasters and can be caused by incidents beginning at the Plan2. In this plan, the resources of the concerned area, of all its neighbors and of the neighbors of the neighbors are made available to the decision-maker.

The example represents a series of coordinated explosions in two passenger trains. Such blasts kill people and leave many others critically injured. We suppose that the blasts of the train in area $A1$ happened a few minutes before the second one. Plan2 is triggered in $A1$ then the same plan is also triggered in $A7$ with the incident of the second train. In such a situation of plans overlapping and in order to respond effectively, a new plan is created by merging the two previous modes: the decision-maker of the first incident becomes also the one for the second. Their plans' areas are merged. Figure 3 shows a situation map of the example where the yellow color represents the areas concerned by the new plan.

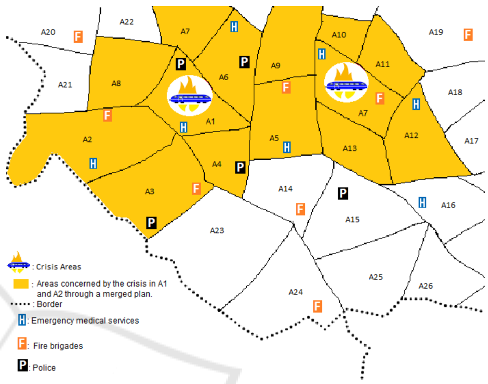

Figure 3: Situation map.

4.2 PCPN Models

To better understand the global model, we begin by describing each common operation mode that corresponds to each plan level in distinct PCPN models. This generic study allows to understand any operating mode triggered in any plan level.
In the studied example, there are 4 common operating mode: $\{Plan1, Plan2, Plan3, MergedPlans\}$.

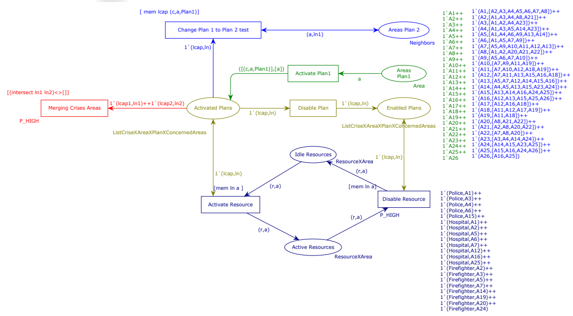

Figure 4: Plan1 model.

Figure 4 represents the CMS behavior in the $Plan1$ as well as the management of allocate resources , it may be stated:

- The triggering / shutting down of $Plan1$ is represented by the state machine made up of places

$\{ActivatedPlans, EnabledPlans, AreasPlan1\}$, transitions $\{ActivatePlan1, DisablePlan\}$ and the arcs that interconnect them.

- Each token of $\{ActivatedPlans, EnabledPlans\}$ is a couple of lists. The first list contains a couple of values: the crisis area and the activated plan. The second list contains areas concerned by the activated plan.
- The behavior of the use/release of permitted resources is represented by the places $\{IdleResources, ActiveResources\}$ and their related arcs.
- Transitions $ChangePlan1toPlan2$ and $MergingCrisesAreas$ are switching transitions (i.e. $Next\_plan(Change\ Plan1toPlan2) = Plan2$ and $Next\_plan(MergingCrisesAreas) = MergedPlans$). Moreover, the transition $MergingCrisesAreas$ is a high-priority transition and it implies the merging plans in the situation of overlapping areas.

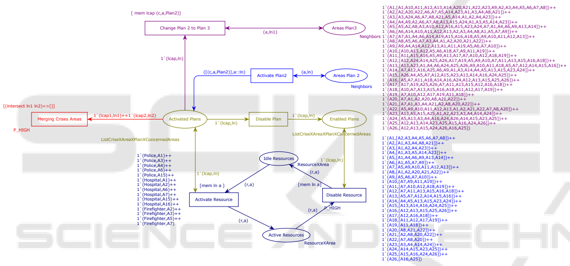

Figure 5: Plan2 model.

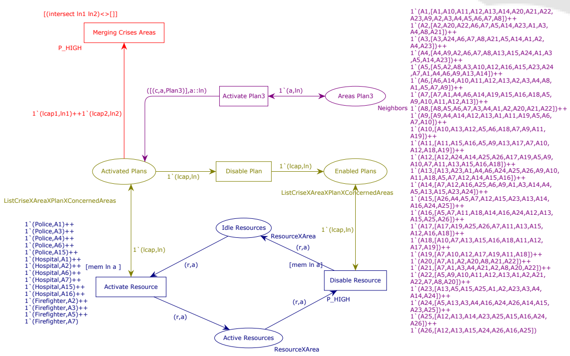

Figure 6: Plan3 model.

Figure 5 (resp. Figure 6) describes the behavior of the functioning in the $Plan2$ (resp. $Plan3$). We can note the following points:

- The activation of a crisis in the $Plan2$ (resp. $Plan3$) is represented by the transition $ActivatePlan2$ (resp. $ActivatePlan3$). The place $AreasPlan2$ (resp. $AreasPlan3$) represents the area of crisis, its neighbors areas concerned by the crisis when $Plan2$ (resp.$Plan3$) is applied.
- A common sub-behavior between the models appears through the places $\{IdleResources$, $ActiveResources$, Activated Plans,$EnabledPlans\}$ and transitions $\{Activate\ Resource$, $DisableResource$, $DisablePlan$, $MergingCrisesAreas\}$. In fact, they keep the same name. Their internal arcs are the same also.
- Transition $ChangePlan2toPlan3$ is a switching transition that allows the system to change $Plan2$ to $Plan3$ of a current crisis (i.e. $Next\_plan(Change-\ Plan2toPlan3) = Plan3$).

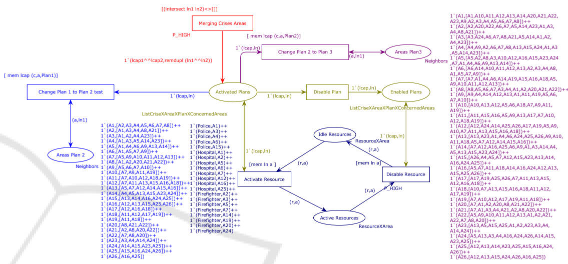

Figure 7: Models of merged plans.

The functioning of the mode $Merged plans$, modeled in Figure 7, is similar to the other plans with the ability to switch the plans for each crisis that compose the merged crisis to another coverage plan of larger areas.

Figure 8 presents the global PCPN describing the operating modes management for the crisis management. In this model, all places, transitions, arcs and tokens of the four common operating modes are presented without duplicating the common sub-behavior. Moreover, new arcs are added in order to express the mode management:

- The place $AreasPlan2$ (resp. $AreasPlan3$) is connected to the transition $ChangePlan1toPlan2$ (resp. $ChangePlan2toPlan3$) by a bidirectional arc labeled by $(a, ln1)$.
- The transition $ChangePlan1toPlan2$ (resp. $ChangePlan2toPlan3$) is connected to the place $ActivatedPlans$ by an arc labeled by $1`((a, Plan2) :: (rm(a, Plan1)lcap), remdupl(ln1\text{dln}))(resp.$ 1`((a,Plan3)::(rm (a,Plan2) lcap), remdupl (ln1dln))) allowing the replacement of the plan by a new one and updating the list of the concerned areas crisis.
- The transition $MergingCrisesAreas$ is connected

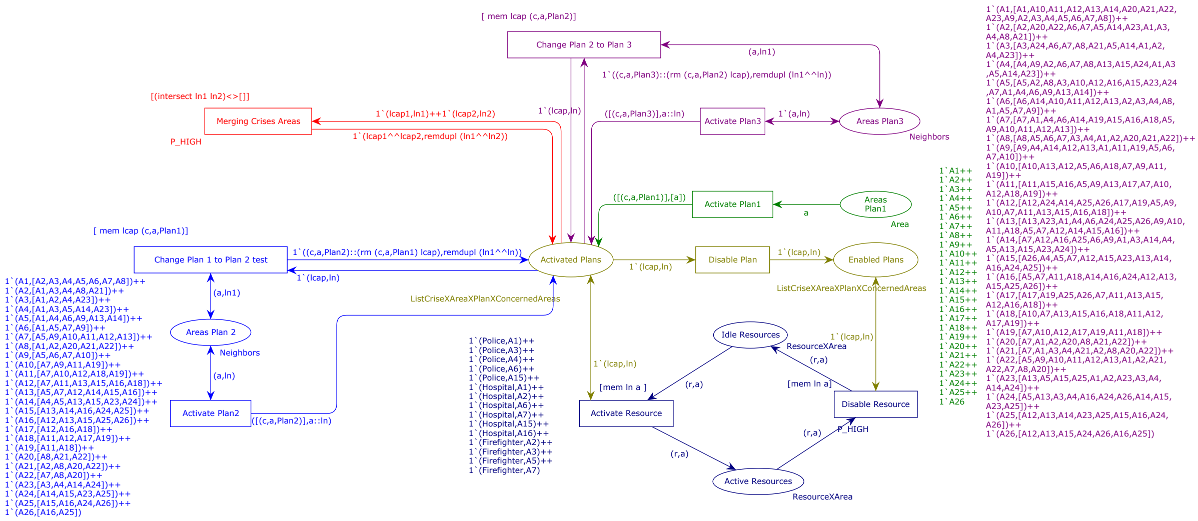

Figure 8: Global PCPN model.

to the place *ActivatedPlans* by an arc labeled by 1‘($lcap$1dlcap2,remdupl (ln1dln2)).

4.3 Simulation and Formal Validation

Simulation and formal validation of the obtained PCPN model are carried out by CPN Tools. During the simulation of the crisis management behavior, we can notably observe the change of CMPs and the crises' mergers. Such modes shifts take place when an event of plan switching, to another plan of larger coverage areas, occurs. A set of monitors can be integrated into the PCPN model to observe its simulation and produce output files which may be used for drawing curves and making statistics.

Formal validation enables the automatic detection of errors such as deadlock and the verification of some properties of the global model. The following safety properties were verified using the state space which is directly generated by CPN Tools:

- The deadlock-free states: we can be noted that any overlap between operating modes implies a merger between them, which allows to avoid deadlock states.
- At any time, only one operating mode can be activated for a given crisis area.
- At any time, any area can be concerned at most by only one activated plan.
- For each crisis, the system can switch from one operating mode to another without stopping.
- Merged plans are immediately and automatically triggered by priority transitions.

5 CONCLUSION

A formalization of the organizational needs for crisis management has been proposed within a global PCNP framework in this paper. CMS are classified as complex and dynamic systems. The operation mode management and the multimodel approach adopted allowed us to represent this studied system by a set of modes of operation and to ensure switching between modes without system stopping. Also, the definition of the common operation mode and common sub-behavior concepts allowed us to avoid the state explosion problem.

Moreover, this mathematical framework may be used to specify and check the consistency of organizational procedures and partly computerized behaviors. The problems of crisis management in inter-country areas will be proposed for future work. In this situation, the consistency problems between various rules become complex and critical. With the occurrence of crises in border areas, anticipation and preparation are crucial in order to be able to react properly.

ACKNOWLEDGEMENTS

The work is partly supported by the ANR Deufrako project named REHSTRAIN.

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