Supervisory Decision Making in Emergency Response Application

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ABSTRACT

Two main causes of failure in an emergency response scenario are in communication leading to limited or delayed access to the information and delayed or poor decision making. A good choice of communication infrastructure to provide reliable and in-time delivery of information in early stage of an emergency response saves lives and money. Given that a wireless mesh is deployed or another communication infrastructure exists, the next effort is to send data from the field to decision makers off the field to improve decision making. In this paper, we use discrete event system modeling technique to illustrate how use of supervisory control solutions on on a discrete event system model can improve communication at organizational level. We present challenges and lessons learned from several real-life drills we have participated such as unclear termination or incomplete message transfer. We delineate a supervisory control solution that with higher authority and expertise can improve decision making by canceling a path and enforcing a deadlock-free path.

Keywords

decision making, supervisory control, Color Petri net

1. INTRODUCTION

Given the most effective and robust communication technology, do we have the right communication protocol at the organizational level? Does a more suitable communication infrastructure at network level solve the communication problem? Such open questions identified the need to widen our perspective on communication, information sharing, and decision making. There was no doubt that a wide range of organizational problems surrounding the emergency response scenarios impeded the collaboration at different stages. We present a systematic methodology to model, predict and analyze work flow in am emergency response to help decision makers with information flow from organizational perspectives.

Inter-organizational interactions require sharing information of various types according to the organizational communication protocols. Different organizations participate in crisis response with a variety of responsibilities and special skills. There is not a single solution to fit all scenarios, instead methodological solutions can be mapped to common problems based on real-life and what-if scenarios and situation assessment. we present our root cause analysis of several real-life scenarios in emergency response communication that we discovered. We present our event-driven supervisory model to improve decision making by predicting potential bottlenecks and enforcing expert knowledge by preventing deadlock. The term *resource* in this paper has a wide concept in the context of emergency response as it refers to humans, network resources such as bandwidth or storage capacity,and apparatus like fire trucks, radios, etc. There are limited resources at each level and communication planner, incident commander, and operations needs to be aware of the status of resources, limitations, and conflicts at all times in order to allocate resources efficiently and based on priorities. Local controller or team leaders have control to their resources and a supervisor with higher authority has a higher-level control over the overall objective. Organization of the rest of the paper is as following: Section 2 describes a drill scenario and several lessons learned from participation and interviewing first responders. Section 3 presents our motivation to use Petri nets to analyze work flow. Section 4 delineates complexity reduction techniques. Section 5 presents supervisory control solutions developed based on real scenario to minimize dependency and prevent deadlock and finally section 6 concludes the paper.

2. LESSONS LEARNED

In this section, we present lessons learned and our analysis on the cause of communication failure at several drills that we were involved [3].

Silver Bullet drill was a unique large scale, multi-incident multi-location drill that we participated which simulated a bomb explosion inside an amphitheater followed by gas spill [1]. The two locations represent two different cities in the exercise. Different organizations participated to practice and improve their speed of response, collaboration and resource allocation within a unified command including Police, Sheriff, fire department, Emergency Medical Service (EMS) paramedics from multiple agencies; HAZardous MATerials (HAZMAT), Special Forces such as bomb squads, and FBI.

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An Area Command was activated to oversee the management of multiple incidents that was each managed by a separate incident command center. There were about a hundred victims and patients consisting of volunteers who received instructions on their mock injuries and what they needed to do. The practice started with the explosion followed by an emergency phone call. A few local police officers, present at the site for general safety during the amphitheater event, attended the contaminated hot zone to help with very primary safety goals and to secure the victims from possible second incident. The police officers, contaminated after entering the hot zone, could not leave hot zone after this point. However, they communicated with dispatchers to provide information from the site. It approximately took over an hour until HAZMAT and Bomb Squad arrived at the site and took even longer until they entered the hot zone. Several factors contribute to the delay: typical city traffic to travel to to get to the site from their base locations. Upon arrival, squads needed to set up the Decontamination (Decon) facility first to make contaminated people pass through before leaving the site, and to put on the special sealed out uniforms. HAZMAT was also provided with the same protective uniforms but they were instructed to follow Special Forces to enter. After they enter the site and clear the area from chemicals and explosives, they declare the area safe and that is when the medical team can enter the hot zone to attend victims and injured people.

At several instances, the message was not completely transferred. Important updated information obtained by dispatchers were not relayed to responding unit in a timely manner. Disregarding organizational chart led to independent action and loss of coordination in the fire incident. At times, it was necessary to repeat the information to remove ambiguity caused by information being cut-off or lost, or organizational chart was discarded due to reachability problem or broken communication. We have identified the problem in failure to transfer message precisely and causing bottleneck as one key person turns to a single point of communication. This is similar to packet transmission over the network. Packets may get lost due to congestion and therefore a packet sequence number and acknowledgment are used so that the sender knows whether the receiver has received the packet or not. If the acknowledgment is not received before the time expires, the sender resends the packets. There are well-known send-receive packets in the network [?]. This problem can be addressed by choosing a strategically well-thought geographic location for the key person, operations or logistics, to be reachable at all times. Additionally team leaders are encouraged to stand together in the same location to facilitate horizontal communication (inter-organizational) as information will travel faster and team leaders will be able to reach each other. A supervisor must ensure that there is only one update at a time and that is received by all destinations. This is accomplished by a supervisory token that circulates among members. Only one member at a time which has access to the token can send the update. The supervisory Petri net solution is illustrated in Figure 1 [4]. We summarize a list of other challenges learned from several drill participation, interviews, and after-math incident report analysis as following: new resource or service requirements, resource reallocation as one incident develops to another incident, join

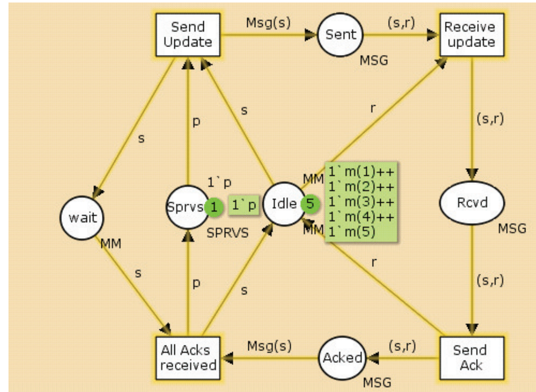

Figure 1: Petri net Model with Supervisory Token

or leave the system, unclear or ambiguity on a task termination time, waiting for an event dependent on data from another that never arrives causing deadlock or livelock. A supervisor with higher knowledge and authority can provision resources for future incidents or identify and authorize release of additional resources on a need basis.

3. PETRI NETS

Inter-organizational interactions require sharing a lot of information and the communication protocols at organizational level shape the flow of information. We use color Petri nets to decompose a system analysis to its structural and behavioral properties. Color Petri nets allow users to define different types of data to label tokens to distinct between different types of tokens [5]. For example tokens of color b in figure 5 refer to different token that tokens of type h. Structural properties refer to properties like liveness, boundedness, safeness, persistency, and structural invariants which are independent of initial marking of Petri net. Behavioral properties are based on the initial marking of Petri net and how it develops to other reachable markings. This is mainly carried out by investigating the behavioral properties mathematically including the incidence matrix and reachability tree. Reader is referred to [3] for a summary of Petri Nets and its properties.

There is not one answer that fits all scenarios but there are common problems identified in various scenarios which can be attributed to the same methods with the advantage of being re-used, and speeding up the process of decision making after several experiences.

In [2] Bammidi et al. present a Petri net that models the processes for the department of energy, Figure 2. All places in this model are one-bounded and hence the Petri net is safe. There is no deadlock. Since there is no dead transition, all the valid markings including final marking are reachable from the initial marking. However, the drawback with this model is the existence of dangling tasks (transitions) without input or output conditions (places). This leads to unclear fire time and therefore it cannot contribute to a successful completion of the task. This is the only reference to a complete work that uses color Petri nets that we we were able to find at the time of this research with similar application to emergency scenarios. The reachability tree of a bounded

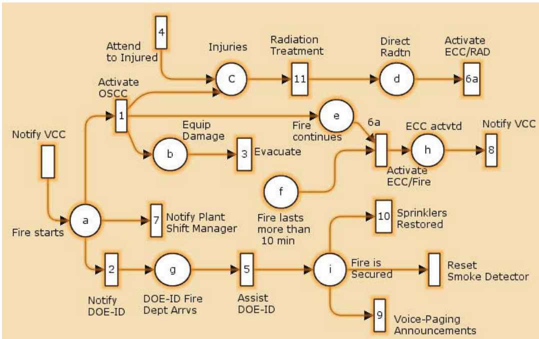

Figure 2: A Petri Net model for Department of Energy (DoE)

Petri net is finite, i.e. the number of nodes (markings) is finite [6].

Definition 3.1. *Coverability Tree- For an infinite reachability tree, the tree may expand with a pattern such that succeeding markings is similar to the preceding one where the only difference is the incremented number of tokens in a place in the marking. In such cases, the place is not bounded and the number of tokens is incrementing and represented by a parameter called ω. Hence instead of dealing with infinite reachability tree, we can build up a coverability tree which is a finite representation of the same system utilizing ω to replace the incrementing number of tokens in one place. ω represents infinite number of tokens in a place and therefore a tree that contains ω is not bounded.*

A system can be uniquely represented either by its Petri net or by its reachability tree if the system holds certain properties discussed in theorem 3.1.

Theorem 3.1. *For a given reachability tree, there exists only one corresponding Petri net model if the Petri net holds the properties of connectedness, absence of dead transition, boundedness and persistency. This implies that the two representations are equivalent only if all the above properties hold true.*

Proof- The proof is achieved by contradiction. We assume there is more than one Petri net corresponding to a given reachability tree holding the properties mentioned above and then see how this contradicts the assumptions. For the same reachability tree, based on definition of the reachability tree for Petri nets [6], μ_0, Ψ, and μ are the same. Hence there has to be at least one place which does not appear in the marking (nodes of the tree) or a transition which does not appear on the edges of the reachability tree. The former indicates the existence of at least one place that never has a token and never receives one while the latter indicates the existence of a transition that never fires. In either case, one or more of the following properties does not hold true: connectedness, deadlock free, or persistency. A place that never receives a token is either located after a dead transition or it is not connected to the rest of the model. Similarly a transition that never fires is an enabled transition that becomes disabled for the lack of persistency property or it is not connected to the rest of the model (never becomes enabled). Two Petri nets with different number of arcs between a place and a transition have the same reachability tree with parameter ω, definition 3.1, abstracting out the specific number of connections. The two Petri nets are not bounded by the same integer number. Therefore with the properties of connectedness, deadlock free, persistency and boundedness, there is a unique Petri net model corresponding to any given reachability tree.

This allows us to uniquely analyze such Petri nets based on the reachability tree in stochastic modeling of the systems to identify the probability and the cost of reaching one state within certain number of steps as described in section 5.

4. COMPLEXITY REDUCTION

In this section we present structural complexity reduction techniques to reduce the complexity of a large Petri net. In one prototype, a large Petri net with logical OR merge can be transformed into a simpler Petri net by decomposing the possible paths that a token takes into a directed cascade while preserving the logical OR merge. In another prototype, a large Petri net with several parallel paths between two logical OR, can be transformed to a simpler Petri Net by aggregating the logical AND and replacement of a directed transition cascade with an equivalent transition. Additional prototypes can be found in [3]. The following techniques reduce the complexity of a large Petri Net as presented in Figure 3. This Petri net represents complicated interactions between different responders at a drill which can be reduced to a simpler Petri net prior to analysis.

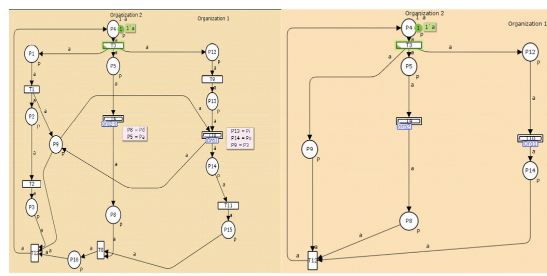

Figure 3: A Petri net System and its reduced equivalent System

Definition 4.1. *A* transition directed cascade *is a sequence of transitions and places, starting with a transition T_i and ending with transition T_n, $T_iP_jT_kP_lT_n$, such that each place or transition in the cascade is the output to the transition or place prior to it and the input to the following transition or place.*

In the above definition P_j is an output place to transition T_i and an input place to transition T_k, and similarly transition T_k is an output transition to place P_j and an input transition to place P_l.

Definition 4.2. *A* place directed cascade *is a sequence of places and transitions, starting with a place P_i and ending with a place P_n, $P_iT_jP_kT_lP_n$, such that each transition or place is the output to the place or transition preceding it and the input to the place or transition following it.*

In the above definition P_k is an output place to transition T_j and an input place to transition T_l, and similarly transition T_j is an output transition to place P_i and an input transition to place P_k.

In Figure 4,we present a real scenario where lack of a clear termination causes problems when the entry team (tactical law enforcement and special forces) are to declare the hot zone safe for the rest of the responders to enter the site. Communication has failed in such scenarios where an unclear signal has either delayed the entry or has put the other first responder's team in danger. The sink place represents the termination of a process where there are two input transitions, $T2$ and $T3$, for one place, $P5$. The first transition that fires, sends a token to the sink place and when the other enabled transition fires, it sends another token to the sink place and creates a second termination time. This creates ambiguity on the initiation of another task which is dependent on precise termination of this process. We change the design of the system to the one shown on the right hand side where the output of place $P3$ connects to transition $T2$. This model illustrates a reduction that corrects the structure of the Petri net model where an AND split is followed by an AND merge and the task completes only when both teams have completed their processes and there is one single point of termination. Attention needs to be paid in reduction

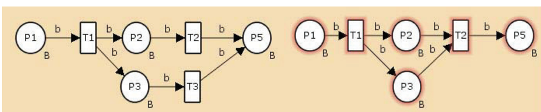

Figure 4: A Petri net with Multiple Termination Time

models that require a choice as in replacement of a directed transition or place cascade by an equivalent transition or place, the order of real execution of tasks or boundedness property or safeness in special case might be changed.

5. SUPERVISORY CONTROL

In this section, we present supervisory control solutions to reduce dependency and prevent deadlock. The reachability tree of a Petri net can be transformed into a state transition diagram where the states are the markings of the Petri net and connecting arcs represent costs or probabilities of moving to the next state. A supervisor can avoid communication problems if early symptoms such as exceeding the number of tokens in a place or number of firings of a transition are detected. The number of states in a state transition diagram is equal to the number of reachable markings in the reachability tree. The model reaches its final state through one of several possible paths. A supervisor can facilitate communication and improve performance by knowing real path costs in advance. If those costs are not known, they are assumed to be equal. Since communication may break unexpectedly or an entity may suddenly become unreachable, liveness is achieved if a supervisor can enforce a new path by placing a token in a place or by preventing an event from happening by introducing a condition to prevent a path from entering deadlock.

Consider a medical scenario where a nurse or a doctor visits two patients, and takes turn in providing care to them. It is also applicable to the scenarios where victims are brought to DECON by two different organizations such as Bomb Squads and Police. Priority for organization one has been implemented such that T_2 always fires before T_5 in Figure 5. When organization 1 releases the resource, the resource

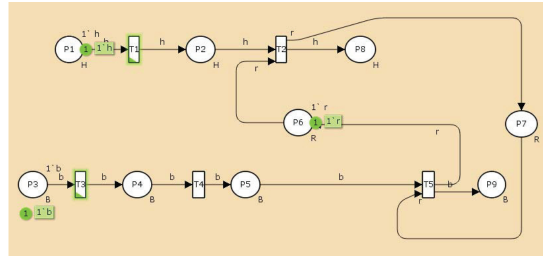

Figure 5: A Petri net model

(token) becomes available for organization two to execute T_5. Similarly as T_5 fires, the resource token becomes available to organization one. This system has one input place and one output place at each one of the parallel branches. Starting from input place the system always ends at the output place and therefore there is no dangling task or event. The reachability tree is presented in Figure 6 and the cor-

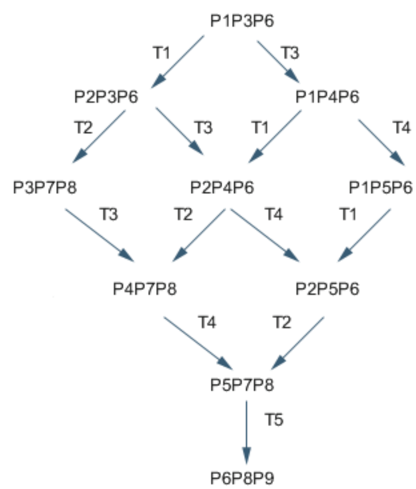

Figure 6: Reachability tree of the Petri net model

responding state transition diagram is illustrated in Figure 7. The transition matrix is derived from the state transition diagram of Figure 7:

$$T_p = \begin{bmatrix} 0 & \frac{1}{2} & \frac{1}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{2} & \frac{1}{2} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{2} & \frac{1}{2} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{2} & \frac{1}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\{1 \to 2 \to 4 \to 7\} = \left(\frac{1}{2} \times \frac{1}{2} \times 1\right) = \frac{1}{4}$$
$$\{1 \to 2 \to 5 \to 7\} = \left(\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2}\right) = \frac{1}{8}$$
$$\{1 \to 2 \to 5 \to 8\} = \left(\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2}\right) = \frac{1}{8}$$
$$\{1 \to 3 \to 5 \to 7\} = \left(\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2}\right) = \frac{1}{8}$$
$$\{1 \to 3 \to 5 \to 8\} = \left(\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2}\right) = \frac{1}{8}$$
$$\{1 \to 3 \to 6 \to 8\} = \left(\frac{1}{2} \times \frac{1}{2} \times 1\right) = \frac{1}{4}$$

The system is sound and hence it is deadlock and livelock

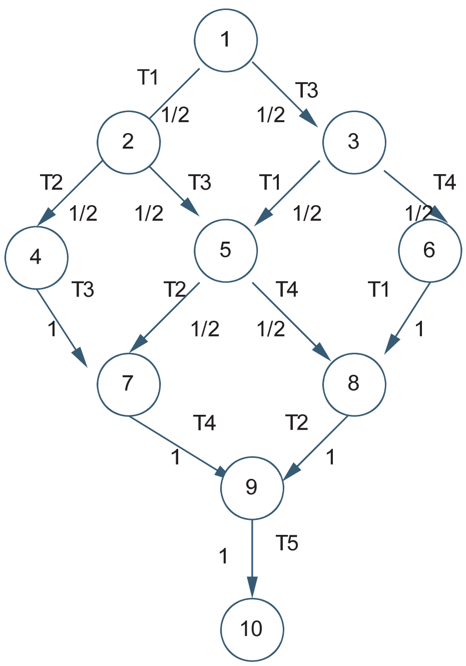

Figure 7: State transition diagram for the reachability tree of Figure 5

free [5]. The final state is reachable in five hops. The state transition diagram for this Petri net is presented in Figure 7. This system always reaches states 7 or 8 in three hops before complexity reduction and from any of these states, the system will be absorbed in final state, i.e. state 10. The last two hops to reach final state are equal to one. If the path costs are not known in advance, they are assumed equally likely and therefore the final cost to reach final state through any of those paths is as following:

The corresponding element of transition matrix to the power of *five*, $p_{1,10}$ of matrix T_p^5 is equal to 1 which verifies that the final marking is reachable in *five hops*.

$$T_p^5 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

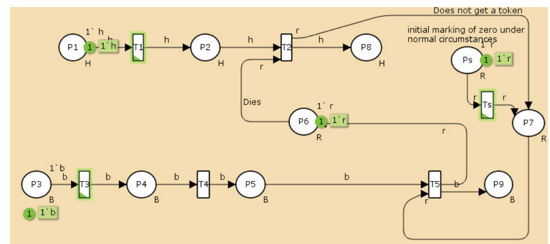

Figure 8: The Petri net model with supervisory solution

$$\{1 \to 2 \to 4 \to 6 \to 7\} = \left(\frac{1}{2} \times \frac{1}{2} \times 1 \times 1\right) = \frac{1}{4}$$
$$\{1 \to 2 \to 5 \to 6 \to 7\} = \left(\frac{1}{2} \times \frac{1}{2} \times 1 \times 1\right) = \frac{1}{4}$$
$$\{1 \to 3 \to 5 \to 6 \to 7\} = \left(\frac{1}{2} \times 1 \times 1 \times 1\right) = \frac{1}{2}$$

However when transition T_2 does not fire, organization two cannot proceed and this is when a supervisor can enforce liveness by preventing system from entering deadlock. The solution is illustrated in Figure 8 where a supervisor enforces a new path by placing a token in place p_s. The supervisory control place does not have a token under normal circumstances but when event T_2 does not fire, the supervisor places one control token there so that organization two can proceed. The reachability tree of the Petri net with supervisory solution is shown in Figure 9 where $*$ represents place p_1 or place p_2. The state transition diagram is presented in Figure 10. The system will be absorbed in final state in four hops: To conclude the results, if supervisory event fires first, the process will be only dependent on organization two internal delays. If supervisor provides a faster response by setting the firing time of transition T_s smaller than the events in organization two, the final state is achieved in such order with a higher probability. In a large-scale event different organizations with their individual Petri net models collaborate to meet the overall objectives. Detailed information on inside events of an organization may not be accessible from outside of that organization for territorial reasons. A supervisor with knowledge on the system can enforce constraints to prevent deadlocks and to improve performance. We conclude this section by presenting a systematic methodology to examine structural properties of the Petri net model including conditions of liveness and the behavioral properties of the model to develop the supervisory solution. The model with supervisory control solution should be checked again for the conditions of liveness: *a*. check for conservation, boundedness, or safeness property and develop the flow matrix, *b*. verify whether the system is deadlock free or not, *c*. develop reachability tree *d*. reduce complexity of the model if possible and calculate transition matrix, *e*. find an admissible constraint or verify whether a given constraint is admissible; transform if not admissible *f*. develop supervisory control solution and check the closed loop supervisory control model to determine whether it is deadlock free or not *g*. if there is a deadlock, revise the constraint and reapply supervisory control solution.

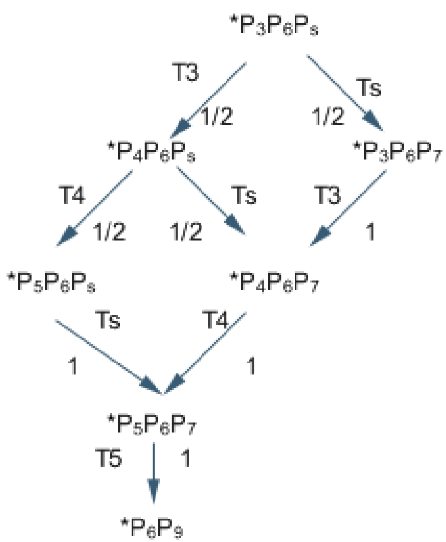

Figure 9: The reachability tree of the Petri net with supervisory solution

6. CONCLUSION AND FUTURE WORK

In this paper, we presented an event-driven modeling approach and lessons learned from real-life scenarios to investigate structural and behavioral properties of work flow in an emergency response. A supervisor can contribute to the crisis response field by reducing unnecessary complexities of interactions to achieve efficient performance in one or more of the following ways: minimizing dependencies, cancellation of an scheduled event and providing an alternative option in case of unreachability of a peer or supervisor, enforcing liveness in case of a deadlock, resource allocation and ensuring the receipt of updated message by all, to prevent the distribution of multiple copies of data and to ensure reliability. It is possible that a supervisory control solution causes deadlocks and creates more complexity and dependencies in which case, the communication protocol and interactions need to be revised and the model has to be examined again for deadlock free state. We believe that developing event-driven models for each organization and analyzing the hierarchical structure of them when they gather to respond to a disaster once, is worth the time and cost for the benefits of monitoring critical statistics and preventing potential

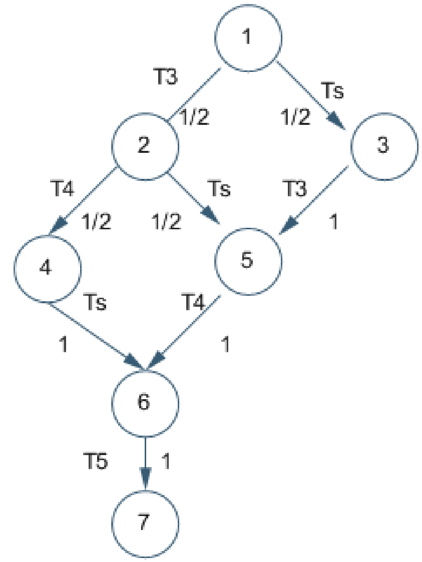

Figure 10: State transition diagram of the Petri net with supervisory solution

deadlocks. The hierarchical design allows the model to be robust to lower-level changes in each individual organization. The modeling is a one-time cost that with the mathematical foundation provides valuable insights to improve performance by predicting and preventing deadlocks, unclear termination, and supervisory control solutions.

7. ACKNOWLEDGMENTS

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