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A PETRI-NET APPROACH FOR MODELING BOTTLENECKS IN THE RESTORATION AND/OR RESTRUCTURING PROCESS OF MULTIPLEX DISASTER-DAMAGED URBAN INFRASTRUCTURE SYSTEMS

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ABSTRACT

The Hyogoken-nambu (Hanshin-Awaji) Earthquake, which struck Japan on 17 January 1995, was a typical large-scale multiplex disaster which brought the functions of the urban infrastructure systems to a complete halt. The region was beset by deadlocks in the restoration and/or restructuring process of the urban infrastructure systems which were damaged in this disaster.

We propose a Petri-net model that describes visually the parallel dynamic relations between urban infrastructure facilities and social activities, including restoration and restructuring activities. With this method we analyzed the bottlenecks which cause deadlocks in the social dynamic process using the reachability tree of the Petri-net model. We also developed some appropriate restoration and/or restructuring processes for disaster damage.

1. INTRODUCTION: MULTIPLEX DISASTER-DAMAGE TO URBAN INFRASTRUCTURE SYSTEMS

The Hyogoken-nambu Earthquake (also referred to as the Hanshin-Awaji Earthquake) that struck the unprepared Hanshin region, of central Japan, in the early morning of January 17, 1995, was one which had a probability of taking place once in five or ten centuries. One of the most modern regions in Japan revealed its vulnerability to such a devastating earthquake. The citizens and governments of this earthquake-stricken region have since endeavored to restore and restructure its damaged cities, including Kobe, one of the ten largest cities in Japan.

Rescue and restoration activities were immediately demanded throughout the region, however most of the urban infrastructure systems (roads, ports, water supply, telecommunications, etc.) were badly damaged, as were many private buildings in the region. Thus on that day and in the days immediately-following, rescue and restoration activities could not be fully executed because the remaining, operable infrastructure system was drastically congested. Moreover, several days after the earthquake, business activities, including commuter traffic, added to the congestion.

Much of the transportation system remained paralyzed because of the catastrophic damage done to its component facilities, coupled with an amount of traffic that was beyond its capacity. As a consequence, activities, including restoration and restructuring, were delayed. If this kind of deadlock in the restoration and restructuring processes of the urban infrastructure systems could have been avoided, more lives would have been saved and the costs of restructuring would have

KEY WORDS: Earthquake Disaster, Infrastructure Planning, Petri Net Theory

been lessened.

At present, there is no way to prevent the occurrence of an earthquake, and it is extremely difficult to predict its scale and any resulting damage a priori.. Even so, can we at least, not do our best to prevent secondary disasters that result from deadlocks? Actually, it was the social seriousness of such secondary disasters (which compounded the damage) that characterized this unprecedented metropolitan earthquake in Japan. We have called this type of complex disaster, a "multiplex disaster". The Japanese media pointed out the lack of preparation for and protection against such multiplex disasters with respect to infrastructure planning. However, how can a city arrange its infrastructure system against such an earthquake in advance? Experts in the field of reliability engineering say that we should make a city's infrastructure system more "fail-safe". The notion of "redundancy" is claimed to be an effective device for a fail-safe system. The question is how can we make a system more redundant, given the catastrophic situations that took place during the Hanshin Earthquake? Our primary purpose is to present an analytical tool that answers this question.

To begin with, it is necessary to understand the dynamic structure of the restoration and restructuring processes of infrastructure facilities because deadlocks are part of the sequence of events in this process. That is, a deadlock does not appear until a particular event occurs.

We analyze and discuss the mechanism of deadlock in the restoration and restructuring processes of urban infrastructure systems. The process is undertaken by several agents, some of whom are directly engaged in the restoration activities that occur along with work and the everyday life in the city, but no one agent can control all of the activities at once. What becomes necessary is an appropriate measure that describes such a dynamic process. The Petri Net Theory [1][2] satisfies this requirement because it is used to model the concurrent, asynchronous, and undeterministic discrete dynamic process. This theory has already been used in software engineering and information technology. Our group [3] has used Petri-net modeling for the concurrent processing of the planning process for an urban renewal project. In addition to this, an analysis of the process in order to develop strategies to prevent deadlock is desirable. The reachability tree of the Petri Net is particularly useful for informing us of bottlenecks which would cause a deadlock in the process, and its resolution as well.

Hereafter, we present the Petri Net Theory and apply it to the basic description of the relation between urban activities and urban infrastructure systems, including the port and harbor system. We then establish a model that describes the actual restoration and restructuring process that occurred after the Hanshin Earthquake. Lastly we identify possible bottlenecks using the reachability tree and draw conclusion.

2. MODELING THE DYNAMIC RELATIONS BETWEEN SOCIAL ACTIVITIES AND URBAN INFRASTRUCTURE SYSTEMS

The dynamic relations between the activities, the facilities, and the damage they undergo are described. A discrete dynamic process can be modeled using the Petri Net Theory. Petri-net models have a discrete graph structure with which to outline the state of the process concerned. The graph structure is formed by two kinds of node; a transition node and a place node, and the arcs that connect them. A transition node represents the opportunity for an event to happen and is symbolized by a square. A place node represents the situation and condition before, or after, an event and is symbolized by a circle. When an event happens, we say "the transition (representing the event) fires." The dynamic but discrete process that an event occurs is expressed by the movement of a token, which is symbolized by a black ball that runs from one place node to other place nodes through a transition node. The place nodes before a transition node are called "input place nodes (to the transition)" and those after it are called "output place nodes". In the

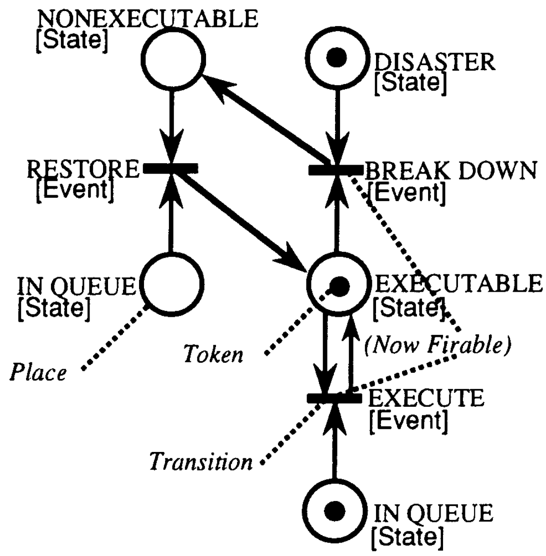

Fig. 1. Basic Petri-net Model Use and Damage to a Facility

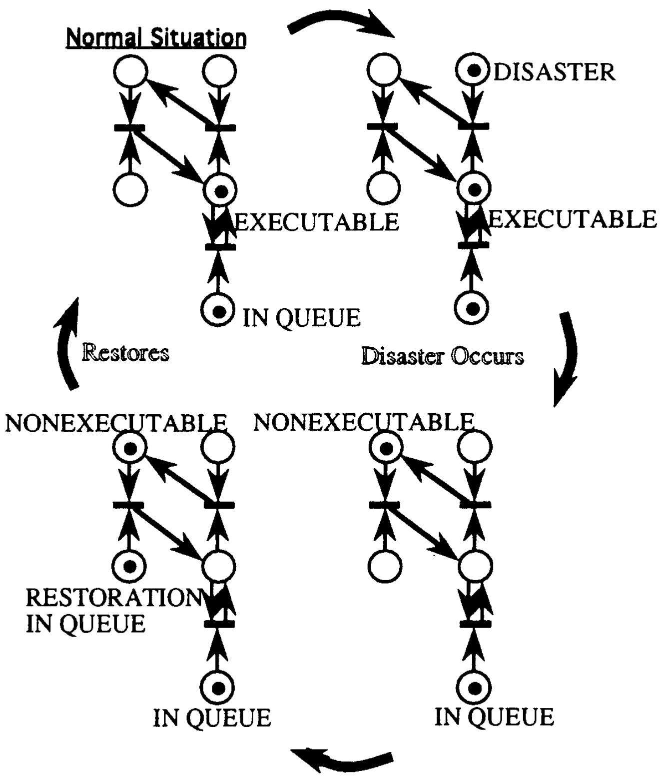

Fig. 2. Sequence of the Basiz Model

common Petri Net Theory, the rule for the occurrence of an event is that it can only occur ("the transition is firable"), if all the input place nodes are filled by tokens.

The basic structure of the restoration process of an infrastructure system is shown in Figure 1. Ordinarily an activity is executed repeatedly in the infrastructure system, as indicated by the two opposite arcs between the transition 'EXECUTE' and the place of 'Activity IN QUEUE' (Figure 1). When a fatal disaster such as a large scale earthquake (the place of 'DISASTER') occurs, the system may not function, and the activities may not be executable. There

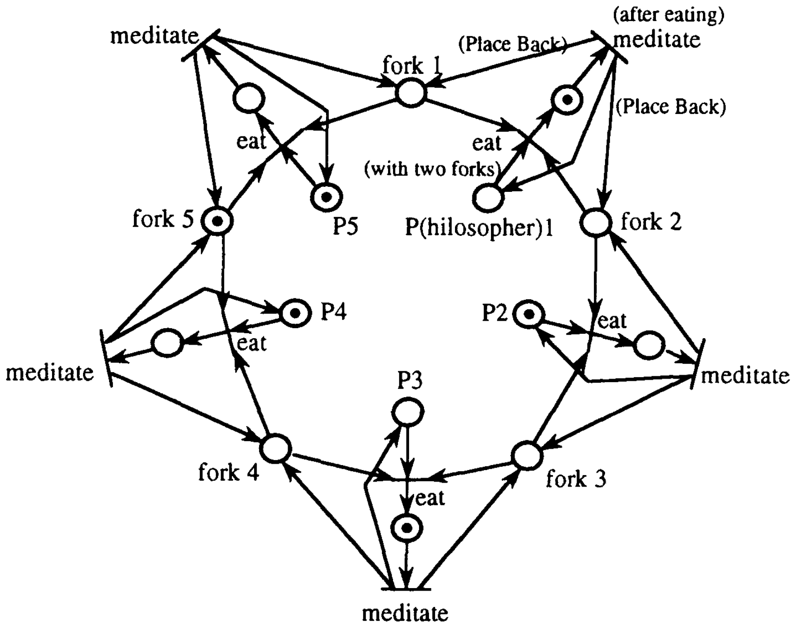

Fig. 3. The Philosophers'Table

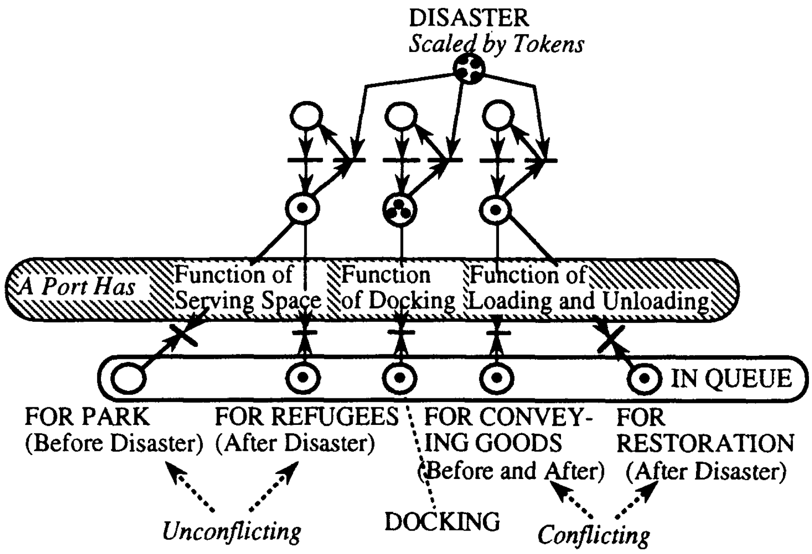

Fig. 4. Able to Describe
- Scale of Disaster
- Multiplexity of Functions
- Conflict of Activities

are three possible events in the process: an activity could use the infrastructure system, the disaster could damage the system, or some agent could restore the system. The sequence of the dynamic process in the basic model is explained in Figure 2. The states 'EXECUTABLE (Before Disaster)', 'NONEXECUTABLE', 'RESTORATION IN QUEUE' and 'EXECUTABLE (Restored)' constitute a cyclic process, as is true of any infrastructure system.

A Petri-net model shows the occurrence of a deadlock in the process. A famous model, called the Philosophers' Table, provides a simple example of deadlocking (Figure 3). In this process, five philosophers have only five forks on the table, and they are troubled because of the condition that each must eat with two forks at the same time, leaving some or all of the philosophers hungry. This suggests that the deadlock is caused by particular factors. For example, if they had a sufficient number of forks, they would not be troubled. Other options include changing the conditions so that they may eat asynchronously or use only one fork. Of course these countermeasures also can be described by Petri-net models.

Figure 4 extends the description of the basic model as follows:(i) The scale of a disaster is indicated by the number of tokens placed at the site of the disaster.(ii) The multiple functions of a facility are introduced to provide some transitions for an activity
which 'executes' in the facility.(iii) Conflict occurs among the events. Some activities are in need of the same token, which means that activities are executable on the system. Such situations are referred to as being "in conflict". It is possible for the conflict between activities to become a bottleneck in the process.

3. ILLUSTRATION BASED ON THE HANSHIN EARTHQUAKE

During the Hanshin Earthquake, we observed an actual deadlock in the restoration and restructuring process of Kobe City. Figure 5 shows the congestion of activities in the urban infrastructure systems in and around the harbor and its hinterland. Chronologically:

1. The marine transportation system (MTS) undergoes a breakdown and is rendered useless.
2. Goods in warehouses are moved to other warehouses by trucks via road.
3. The movement of these goods causes traffic jams on the roads.
4. Restructuring and restoration activities are completely obstructed.

We have extended the basic model to one illustrates this actual process. The design of the model follows the above sequence and is comprised of the four parts (Figures 6–9). In Figure 6, the process of the breakdown of the MTS is illustrated. In Figure 7, goods in warehouses near the port are moved to roads which have not suffered much damage. In Figure 8, the token in the place 'EXECUTABLE' of the road has been consumed by the extra traffic moved from the

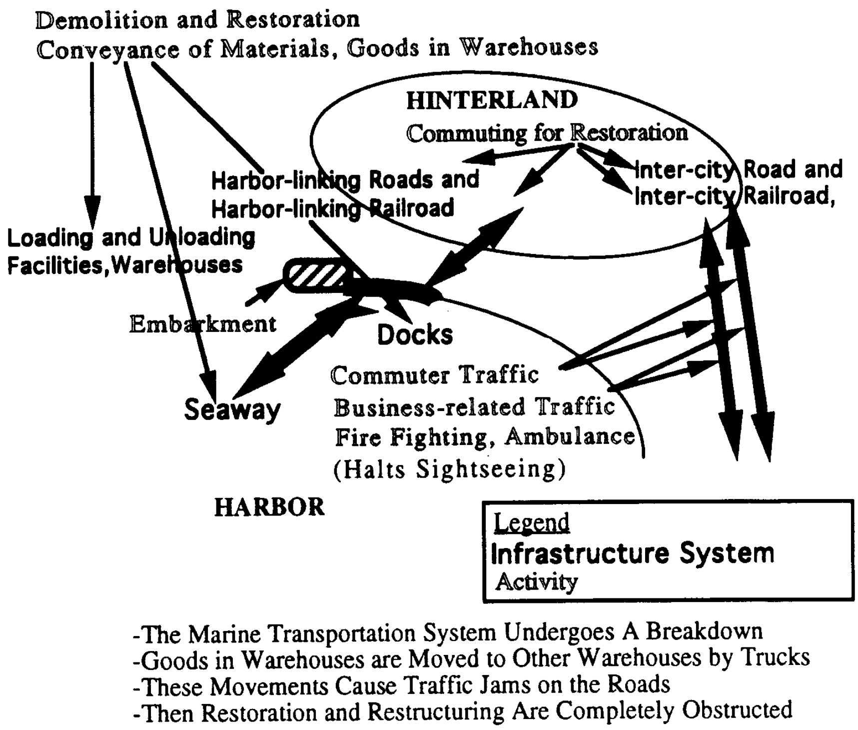

Fig. 5. Congestion of Activities in Infrastructure Systems

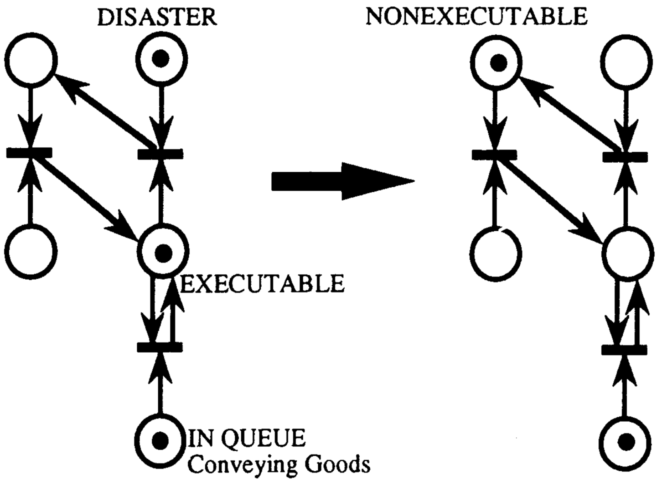

Fig. 6. The Marine Transportation System Undergoes A Breakdown (Docks, Loading and Unloading Facilities, Warehouses)

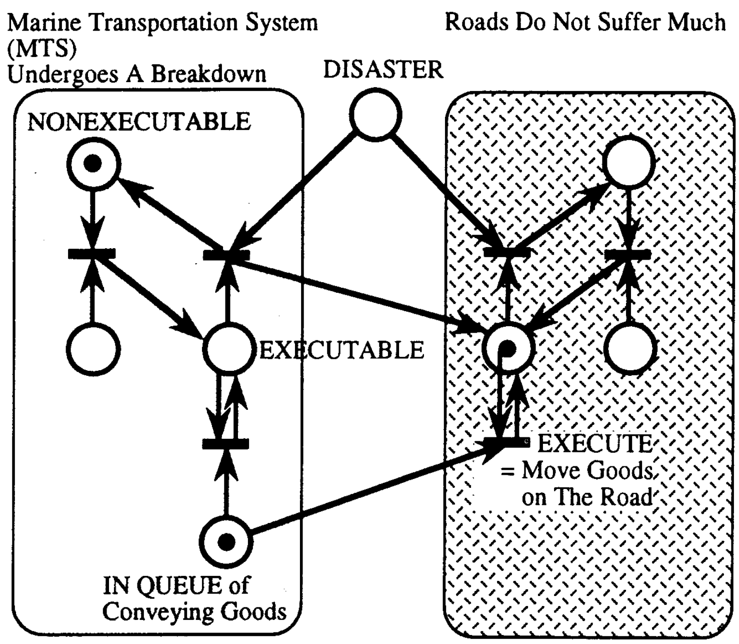

Fig. 7. Goods in Warehouse are Moved to Other Warehouses by Trucks via Road

MTS, and the other activities, including rescue, are stagnant. The trouble in Figure 9 is that the roads become nonexecutable, even though they are mandatory for all the restoration and restructuring activities.

4. STRATEGIC ANALYSIS

Previously we focused on describing the states of the activities executed and the disaster damage done to urban infrastructure systems. We now identify the bottlenecks in the modeled process and redesign the process to be a redundant one. The Petri Net Theory provides an effective tool for discussing the failure of a process system, called the reachability tree. By "reachability", we mean the possibility that a situation occurs in the process. The order of the firing of transitions varies for different event sequences. Some results of these sequences are unfavorable for the system. The concept of redundancy is used to prevent unfavorable results.

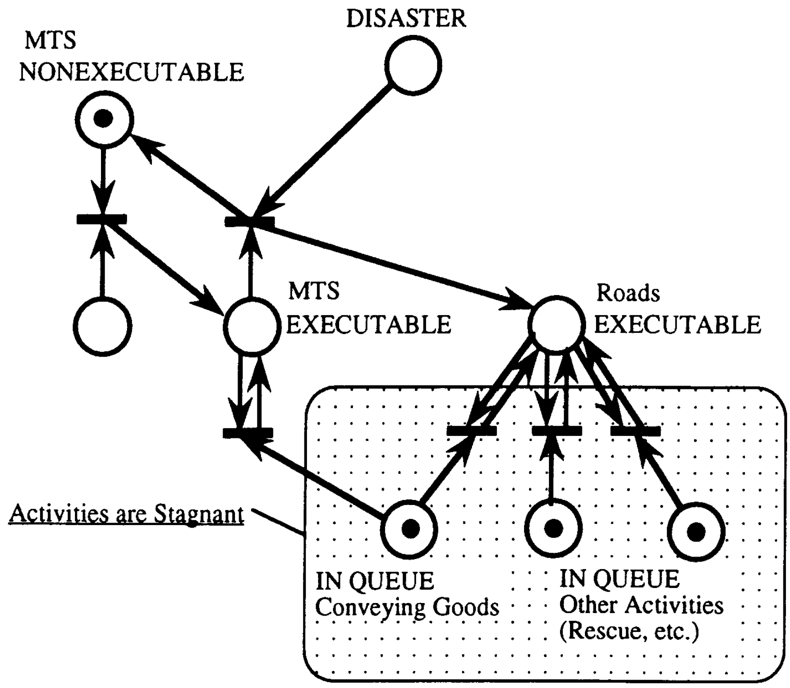

Fig. 8. Movement of Goods Causes Traffic Jams on the Roads

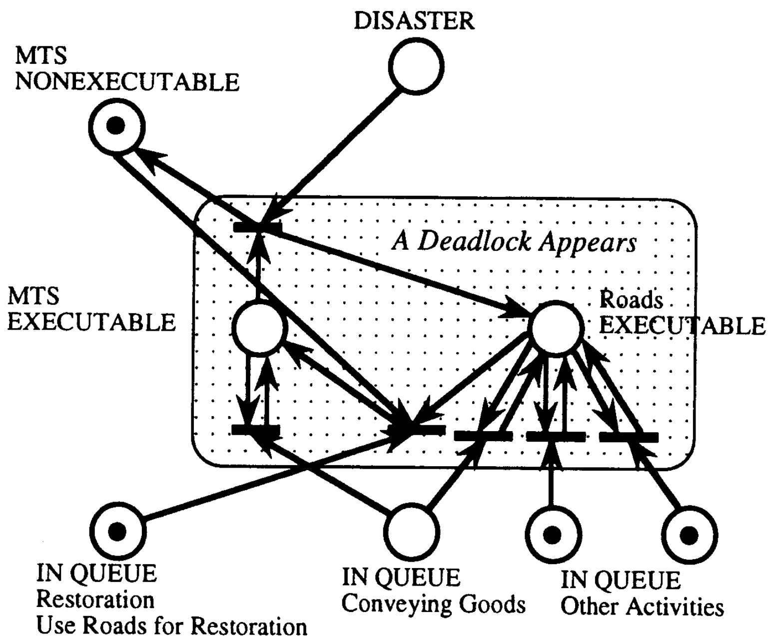

Fig. 9. Restoration and Restructuring Activities are Completely Obstructed

The initial state of the model of the actual restoration and restructuring process (Figures 6 – 9, Section 3) in Figure 10. The reachability tree in Figure 11 shows the seven reachable states of this model:

State 1. No disaster has occurred.
The MTS (Marine Transportation System) is restored or available.
No goods have been conveyed elsewhere.

State 2. No disaster has occurred.
The MTS is restored or available.

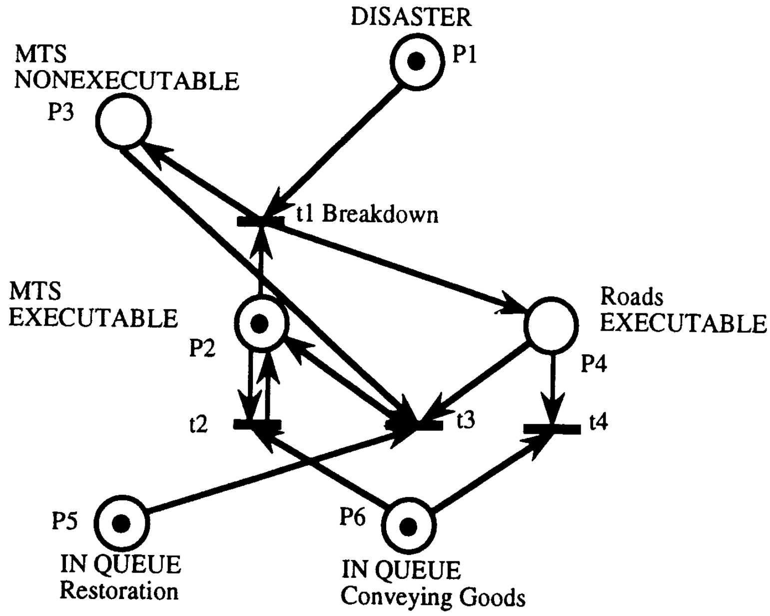

Fig. 10. Initial Marking, Just Prior to an Earthquake

	Goods have been conveyed elsewhere.
State 3.	A disaster has occurred.
	The MTS is restored or available.
	Goods have been conveyed elsewhere.
State 4.	A disaster has occurred.
	The MTS is not restored or is unavailable.
	No goods have been conveyed elsewhere.
State 5.	A disaster has occurred.
	The MTS is restored or available.
	No goods have been conveyed elsewhere.
State 6.	No disaster has occurred.
	The MTS is restored or available.
	Goods have been conveyed elsewhere.
State 7.	A disaster has occurred.
	The MTS is not restored or unavailable.
	Goods have been conveyed elsewhere.

Note that reachable States 6 and 7 terminate the restoration and restructuring process. State 6 is satisfactory because the MTS is restored after restoration and restructuring activities have been completed. State 7, however, is unsatisfactory because no transportation systems are executable, even though restoration of the MTS requires roads. A deadlock consequently occurs.

The process should be guided to a favorable result. The dynamic structure of the process should characteristically be "redundant" to prevent any deadlocks. Let us look at this point more closely.

We want to create some remedies for deadlocks in the process using the Petri-net model. Redesigning the model generally leads to the development of a remedy. This involves the reduction, addition, or movement of elements in the model. Four types of remedies are considered, together with their (changing) elements (the transition, place, arc, and token) in a Petri

Net. They are

To change a place	(P-Remedy)	(Figure 12)
To change an arc	(A-Remedy)	(Figure 13)
To change a token	(T-Remedy)	(Figure 14)
To change a combination of these three factors	(PAT-Remedy)	(Figure 15)

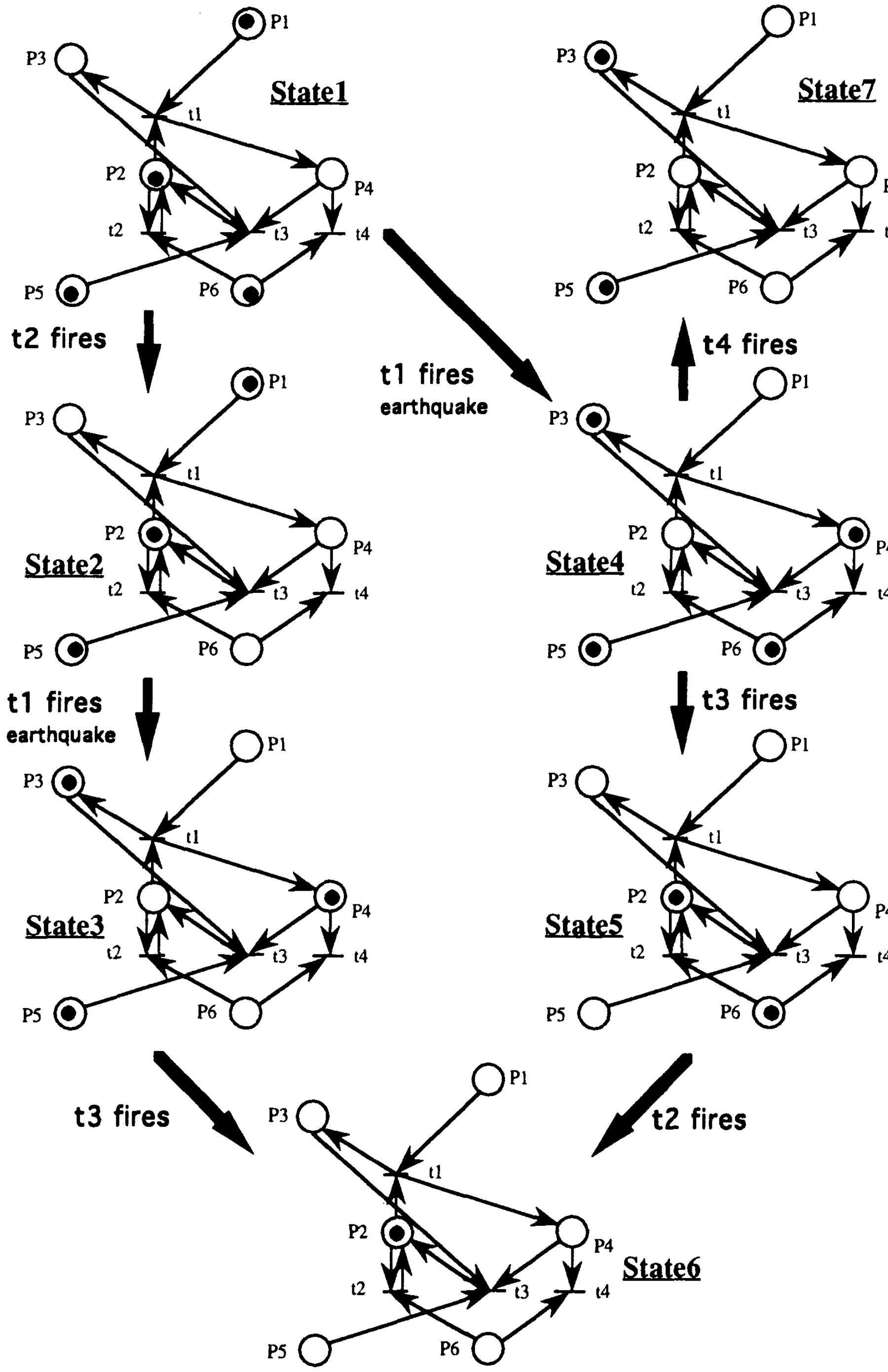

Fig. 11. Reachability Tree

The reachability tree in Figure 11 shows that we should resolve the deadlock before advancing to the problem in State 7. We redesign the model to enable the process to reach the state that in which the MTS is restored to the available condition. One strategy is to enable t3 to fire even

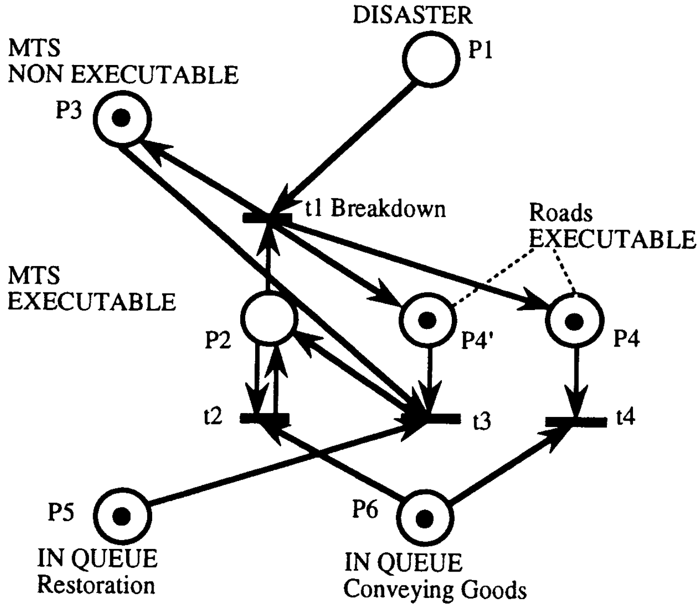

Fig. 12. P-Remedy: Add A Place substituting P4

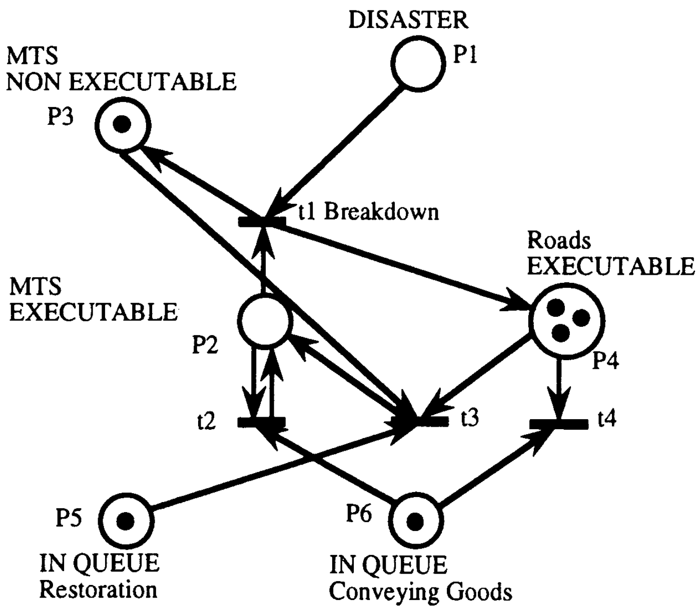

Fig. 13. T-Remedy: Add Some Tokens in P4

if t4 is firable at State 4, which may come out just before State 7. This strategy is obtained by the following four types of remedies:1. Add a place for the restoration separated from Place 4. (a P-Remedy) This means that traffic for the restoration of the MTS should not share the road with traffic conveying private goods. Other special transportation measures should be prepared for activities for the restoration of the MTS after a disaster. 2. Reduce an arc, making P4 unnecessary for the firing of t3. (an A-Remedy) This means that the MTS should be self-restorable. For example, strong, earthquake-proof docks are constructed in advance, and traffic related to the restoration is executed within the MTS.3. Add some tokens in Place 4. (a T-Remedy) For example, a road administrator should prepare a temporary road to be used only after a disaster. Such roads can be used as open spaces for recreational and other social activities at all other times. 4. Give the firing order between t3 before t4. (a PAT-Remedy) In particular,

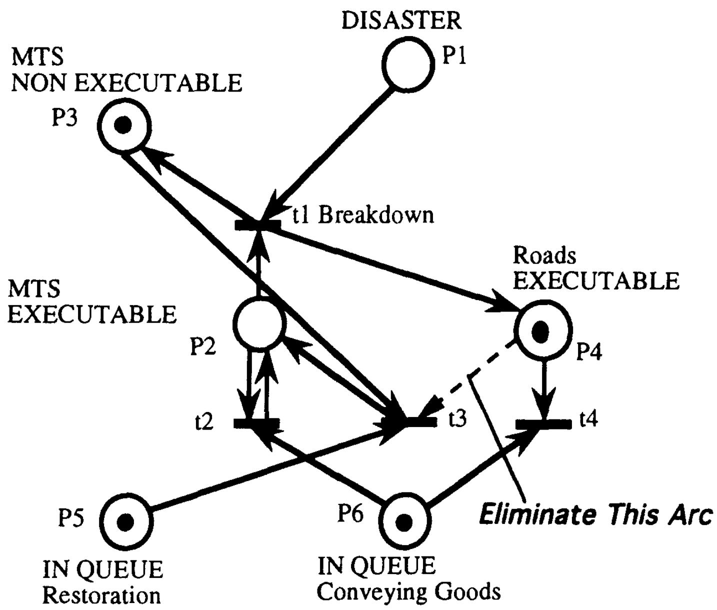

Fig. 14. A-Remedy: Eliminate the Arc from P4 to t3

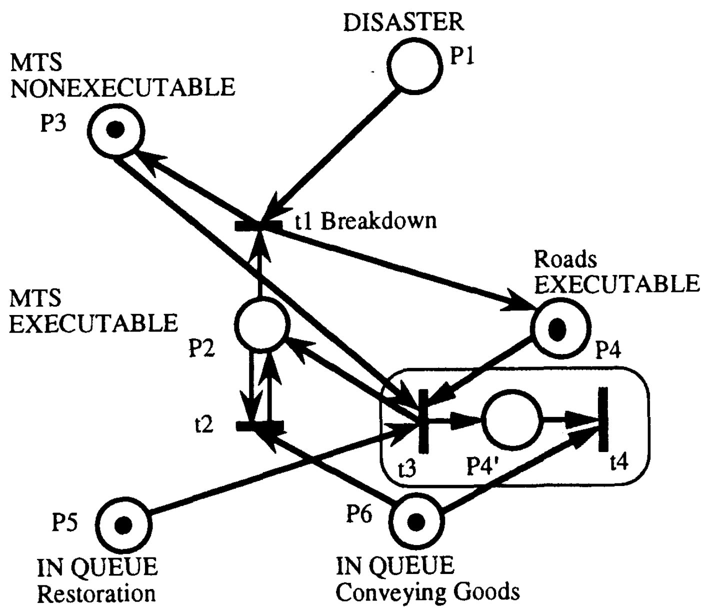

Fig. 15. PAT-Remedy: Regulate the Order of the Firings

the road administrator regulates the conveyance of private goods, before restoration of the infrastructure systems is complete.

Other strategies for preventing deadlock can be considered as well by observing the composition of the model. A different strategy, for example, is to disable t4 fire at State 4 (the conveyance of goods is forbidden just after a disaster).

In planning for disaster prevention in the infrastructure arrangement, we need to pay attention to these strategies in order that the planning will ensure deadlock-proof infrastructure systems. These strategies are not necessary for reconstructing infrastructure systems (as hardware). We need to manage all the activities that use the infrastructure system temporarily and spatially during recovery from a the breakdown immediately after a disaster. To begin with the practice of the strategies, we must gain understanding of the relationship and possible sequence of events among various (human) activities, the performances of urban infrastructure systems, and the phenomenon of the disaster itself, through the models described in this paper. We note that the restructuring process is not a simple restoration, rather it is a planning process which involves strategies that will lead to stronger infrastructure systems.

5. CONCLUSIONS

We focused on multiplex disasters triggered by a Hanshin Earthquake-like disaster and then discussed effective remedies (strategies) for reducing damage done by secondary disasters that are caused by the malfunction of the social system as a whole. An approach using Petri Net Theory has been developed. It shows that Petri-net models are very effective for identifying bottlenecks in an infrastructure system as well as efficacious remedies. Of course, the Petri-net models developed in this study can be extended in order to analyze more complicated situations of the multiplexity problems that result from such earthquakes. A future step is to discuss the process of restructuring which proceeds in parallel with restoration. Conflict occurs if the two processes are not synchronized. The Petri Net Theory may provide a powerful tool with which to analyze such conflicts.

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