Emergency Reaction of a Resource Redistribution System to Shock Events Depending on its Topology

Vasily Lubashevskiy, Taro Kanno, and Kazuo Furuta

Graduate School of Engineering, The University of Tokyo, Japan

1 Introduction

In recent years the problem of disaster mitigation has attracted much attention. We consider this problem for a socio-technological system comprising many cities connected with one another via transport network. The system is supposed to be comparable in size with a prefecture in Japan or a State in US. It has been partly affected by a large scale disaster, e.g., earthquake, tsunami, volcano eruption, etc.; the evacuation process and the transport network destruction cause increased demand for the vital resources (pure water, medical drugs, warm clothes, fuel, and so on). As a result, in some part of the system the demand becomes higher than the normal amount of such lifelines and the situation becomes critical. So there should be some mechanism of resource redistribution enabling to mitigate the disaster aftermath and to supply the affected or involved regions with the required resources at least up to the level of their stable functioning.

There are currently a family of relative notions, such as resilience, flexibility, survivability, agility, used in describing the disaster mitigation (for review see, e.g., [1]). Following [2] the term resilience has various definitions and it can be used differently. In particular, first, the system performs under abnormal and external influence [2] and the pre-disaster functioning cannot be implemented because of the system partial destruction [3]. Second, the system behavior is determined by contribution of a large number of its elements or/and subsystems different in size and structure. The second feature enables us to classify the mitigation of disaster consequences in these systems as an emergent phenomenon. A similar point of view can be found in discussing helicopter system functioning [4] and general problems in reliability engineering [5]. Relative discussion with respect the seismic resilience can be found in [6].

The choice of a prefecture and state as characteristic examples of a given system is based on the following. First, such administrative units interact with one another as whole entities. Second, internal resources available in such structure are great enough for mitigating disasters individually. Third, being complex in structure and containing large number of subsystems differece of scales in such a unit governs the functioning of its elements as well as their interaction directly.

The purpose of the present work is to analyze the emergency reaction of the system depending on the topology of resource stock network. We examine two types of this topology, the centralized one, where the stocks are located at some main nodes of the system, and the distributed one, where the stocks with low capacity are located at all the nodes. To simulate the dynamics of the resource redistribution we adopt the following assumptions. The intensity of the required resource redistribution is limited by the rate of uploading source materials from stocks to vehicles. This limitation is caused by the fact that the number of uploading places and the rate of special uploading vehicles is not high. Resources are taken from the nearest to the affected territory node, which should send requiring amount of resorces, only minimal volume of vital resources could be kept.

2 Characteristic stages

To quantify the states of the system elements let us introduce the following characteristics of the cities. The first one is the critical amount $Q_{c,i}$ of resources in city i required for its residents and evacuees to survive. Then the value Q_i^{aff} stands for the current amount of the vital resources in the affected city i, with the inequality

$$Q_i^{\text{aff}} < Q_{c,i}$$

being assumed to hold. In addition we will use the value Q_i to describe the current resource amount in city i. To compare the state criticality of the cities with one another we also introduce the quantity

$$\theta_i = \frac{Q_i - Q_{c,i}}{Q_{c,i}},$$

which may be regarded as the measure of the proximity to the critical state ascribed to one resident in city i.

From our point of view there could be singled out three characteristic stages in the resource redistribution. The first one is the emergency reaction stage. The system is in this stage while there are cities where $Q_i < Q_{c,i}$ and, thus, the lives of their residents are in danger. Therefore the crucial point of the emergency reaction stage is its fastest implementation.

The main goal of the second stage is to form a new supplying network instead of the previous one broken by the disaster and to localize the area involved into the resource redistribution process. During the third stage the formed networks have to provide external resource flow to the affected region to recover the broken parts of the system.

3 Implementation algorithm of the emergency reaction stage

The consequences of real disasters practically cannot been predicted. That is why a mechanism of the resource redistribution should be based on a certain algorithm rather than be of the form of a plan prepared beforehand. We will use a "step-by-step" algorithm and thus are to determine a certain time step Δt. Let us specify it as the time necessary to load up one vehicle. Then, the unit of the resource amount h should be set equal to the vehicle capacity. In this way we can ascribe to each stock the number of volume units and number of units that can be sent by one time step. Suppose that information about current transport ways is known and we have a possibility to send the vehicles to all the affected cities.

The algorithm uses the list $\{i_k\}$ of the cities ordered according to the value θ_i, which determines the city i_{worst} with the worst situation. Then we seek for the nearest city j such that $Q_j > Q_{c,j}+h$ and add the unit resource amount h to the queue $\Delta Q_{j\to i}$ to be sent to the affected citites at the next system update event. Then we check whether the virtual situation in the affected city i_{worst} remains the same and if so the procedure is repeated. Otherwise, the list $\{i_k\}$ is updated and actually the same procedure is repeated with respect to the new city i_{worst}. The procedure runs until the load capacities of all the stocks are exhausted. When the number of planned parcels becomes equal to possible number of loaded vehicles per unit of time, Δt, parcels are sent, which is implemented in the system update procedure, $t \to t + \Delta t$ and for the affected cities

$$Q_i\big|_{t+\Delta t} = Q_i\big|_t + \sum_j \Delta Q_{j\to i} - \text{r.c.}\,,$$

for the involved cities

$$Q_j\big|_{t+\Delta t} = Q_j\big|_t - \sum_i \Delta Q_{j\to i} - \text{r.c.}\,,$$

for the not-involved cities

$$Q_k\big|_{t+\Delta t} = Q_k\big|_t - \text{r.c.}\,,$$

where the symbol "r.c." stands for the resource consumption. This implementation of the emergency reaction stage is terminated when the condition $Q_j > Q_{c,j}$ holds for all the cities.

4 The dynamics of the emergency reaction stage depending on the resource network topology

The dynamics of the emergency reaction stage and the formation of the region involved into the corresponding resource redistribution process depends substantially on the details of the stock arrangement in the system including their spatial distribution as well as their difference in capacity. In the present work we confine ourselves to the study of the simplest situation matching the limit cases. Namely, we assume the resource stocks to be located in a few cities only so they capacities should be rather high or the large number of low capacity stocks to be distributed uniformly over the whole area under consideration.

Using the model described in the previous section we justify the following scenario of the disaster mitigation.

When a few stocks are located at the main nodes of the system and have a large volume of resources, they individually determine the values $\{Q_i\}$ in cities located in large parts of the area under consideration before and after the disaster. They form a stable pattern of resource flow from the stocks to the affected region. However, when one of these stocks is damaged by the disaster, not only the region affected directly but also all the cities supplied previously by the damaged stock arrive under the critical conditions because of resource consumption and the absence of local stocks in their vicinity.

In the case of uniform distribution of relatively small stocks over the whole area a stable quasi-centralized supplying network does not arise but such distribution is more stable with respect to different disaster consequences and is faster in implementation. In this case there can be singled out two regions different in properties. The first one which may be categorized as involved region containing cities with $\{Q_i\}$ gradually decreasing in the direction towards the affected region. The second one surrounding the first region comprises the cities with pre-disaster conditions.

5 Conclusion

This work has presented the mechanism of emergency reaction of a resource redistribution system to a large scale disaster which functioning can be regarded as an emergent process. A certain concept of the full recovering of a region after a shock event has been constructed and three main stages of this recovering has been singled out.

The main attention of the work is focused on the initial stage called the emergency reaction stage. Its main goal is to recover the affected region up to the minimal survival conditions as fast as possible. A simple algorithm implementing this stage is considered. To be specific and to demonstrate its efficiency two limit cases are studied in detail. Namely, the first one is determined by a uniform distribution of relatively small resource stocks over the area under consideration. The second case matches a few large stocks located at main cities distant from one another. The developed mathematical model justifies the results meeting also the general argumentation, which enables us to expect the model to be efficient in studying complex situations characterized multi-scale distributions of resource stocks.

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