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A mathematical model for post-disaster road restoration: Enabling accessibility and evacuation

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A B S T R A C T

This paper focuses on the planning of road restoration efforts during disaster response and recovery. The primary objective is to maximize network accessibility for all locations in the area during the restoration process so that survivors are evacuated and road side debris is removed as soon as possible. We propose a dynamic path based mathematical model that identifies criticality of blockages and clears them with limited resources. This model is more efficient than link based models and can solve restoration problems for realistic size networks within reasonable time. Algorithm performance is demonstrated using two instances based on districts in Istanbul.

1. Introduction and problem description

Post-disaster road restoration constitutes the first step in disaster response and recovery (FEMA, 2007). In any kind of disaster, whether hurricane or earthquake, the goal is to maximize survival rates. It is essential to be able to reach survivors and offer them relief and a possibility to evacuate the affected region during the first few days after the disaster strikes. Road network disruptions impede timely access to help and delay evacuation to shelters.

This paper addresses the issue of restoring blocked links in a road network with the goal of opening access paths for all locations as early as possible (during the first three days of response). A dynamic path based mathematical model is proposed to solve this problem. The assumptions are as follows: The operation is carried out by a limited number of equipments (denoted by D); each equipment can handle one blocked road (link) at a time; each blocked link, e_i, has an estimated restoration time, c_i. These assumptions imply that at any point in time, at most D links can be processed simultaneously by a team of D work groups.

A path p consists of an ordered sequence of links between an origin–destination (O–D) pair and it is assumed to be open when all of its links e_i are clear. Each location (node) in the network needs access to shelters or local relief distribution centers and to temporary debris dump sites (so that any debris cleared from that node can be sent out). A set of access paths are defined for each node in the network, and the union of these paths compose the total set of pre-defined access paths, P, to be cleared. Note that a link can be an element of more than one path and that some paths may already be open due to lack of damage/debris.

Given a pre-defined set of access paths, P, to be cleared, the model optimally identifies the order of blocked links, e_i, to be restored during a three-day workshift (T_{max}). The output of the model is a restoration schedule for clearing blocked links. The

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goal is to maximize the total weighted earliness of all paths' restoration completion times. A path's restoration completion time is denoted as t_p. The earliness of a path's restoration completion time is defined as the difference between the operation due date, T_{max}, and t_p. Here, a priority related weight Q_p is assigned to each path and it represents the urgency of restoring path p based on criteria such as the expected traffic flow on the path. In the objective function, each path's earliness value is multiplied by Q_p and summed over all paths, resulting in the total weighted earliness.

An earliness based goal maximizes cumulative network accessibility throughout the restoration operation. Paths that are not cleared until period T_{max} do not contribute to the objective function value. Hence, the objective function implicitly tries to maximize the number of open paths as well.

The proposed dynamic path based model is an integer program because it contains binary variables that represent the open/closed status of every blocked link and the status of every path over the time span of T_{max}. Though path based models are very compact and efficient with regard to the number of binary variables, they still involve a high complexity. In order to reduce the computational burden, a 'divide-and-conquer' strategy is adopted, i.e., we decompose the affected area into smaller zones (districts) and solve the scheduling problem for each zone under several equipment allocation scenarios. Then, we use a resource allocation model to distribute the specialized equipment among these districts equitably.

The proposed solution approach is novel in the sense that it is the first path based approach that considers maximizing dynamic network accessibility throughout the time span of the restoration process. Path based models found in the literature (e.g., see Matisziw and Murray, 2009) try to identify a given number of critical links whose failure will block a maximum number of paths. In these models, equipment limitations are not considered, there is no scheduling involved, and there is a bound on the number of links considered. Although this information is very valuable in mitigation studies, it provides little help in the response phase where the set of failed links does not overlap with the set of identified critical links. In the literature, there exist non-path based scheduling approaches involving formulations based on the multi-tour Traveling Salesman Problem (Feng and Wang, 2003), the multi-machine scheduling problem with sequence dependent travel times between restoration jobs (Chen and Tzeng, 2000) and network flow formulations (Yan and Shih, 2009). These are link based models whose complexities are so high that they can at best be solved by heuristics. On the other hand, the reduced complexity of the proposed path based model allows us to solve scheduling problems of realistic size without resorting to heuristics (Yan and Shih, 2012). However, it does not consider operational decisions such as equipment routing.

In subsequent sections, we summarize the literature related to this problem, then we describe the two mathematical models, finally we discuss the implementation of these models on two exemplary districts in the city of Istanbul (Turkey).

2. Literature survey

Phase 1 activities of disaster recovery and response involve clearing roadside debris and restoring the road network in order to open up evacuation routes and other important lifeline paths so that traffic flow is enabled in affected areas. The restoration operation can be conducted efficiently by identifying the optimal order in which critical blocked links in the road network are cleared. The goal is to maximize the overall earliness of path restoration times, which leads to maximizing cumulative network accessibility throughout the operation. The concept of network accessibility is closely linked to network vulnerability which is defined as a susceptibility to incidents that can result in considerable reductions in road network serviceability (availability for usage) (Berdica, 2002). The goal of minimizing road network vulnerability is used in both mitigation studies (reinforcing critical infrastructure) and response studies (enabling speedy network accessibility for relief). Although many models and measures are proposed to measure network vulnerability (e.g. Chen et al., 2007; Erath et al., 2010), the increase in travel time and travel distance seem to be the most common measures. Chang and Nojima (2001) define an accessibility measure based on the extension of post-disaster shortest paths between all pairs of locations in the road network. Sohn (2006) enhances this measure by weighing locations according to their populations and traffic densities. Giovinazzi and Nicholson (2010) discuss measures of post-disaster network reliability such as connectivity, travel time, capacity and accessibility. Some researchers such as Sohn (2006) and Jenelius and Mattsson (2012) identify the importance of network links/areas by evaluating accessibility measures by closing one link/area at a time and observing its impact on the whole network. However, this sequential approach does not take the combined effects of blocked links on major paths, hence, if the restoration scheduling plans are made according to such link criticality indices, the resulting plans might be suboptimal. Other studies develop commodity flow models to assess economic loss under link damages (Cho et al., 2001; Kim et al., 2002; Ham et al., 2005). These methods consider only commodity destinations.

In the area of disaster response and recovery, repair schedules for blocked links are obtained by optimization methods. For instance, Chen and Tzeng (2000) propose a two-level mathematical model for sequencing road repair tasks over time, imposing a due date. Travel times between tasks are considered but repair resources are not limited. The goal is to minimize travel weighted traffic flow. The model is quite complex, therefore, a genetic algorithm is proposed. In another study, the authors use a multiobjective GA to solve the same problem on a realistic network with 24 nodes (Chen and Tzeng, 1999).

Feng and Wang (2003) consider the following constraints in emergency road rehabilitation: limitations on dozers, manpower and a finite debris clearing capacity of 250 m^3/h for dozers. The authors consider goals that include maximizing the total length of accessible roads, the total number of cleared roads and minimizing the risk of work teams. In their model each