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Reliability based pre-positioning of recovery centers for resilient transportation infrastructure

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ABSTRACT

An effective and resilient transportation infrastructure is vital for the functioning of any society. Disruptions can have substantial negative effects, which are uncertain and unpredictable. One of the aspects of resiliency is prompt recovery of damage transportation infrastructure. Bridges, as one of the key components of transportation infrastructure, are highly exposed to damage by natural disasters. Efficient restoration of damaged bridges can significantly reduce the adverse impacts of a catastrophic event. Pre-positioning of recovery centers to aid in the restoration of bridges is one mechanism to increase the efficiency of the recovery process because it reduces the lead time to damaged bridges once a disaster has occurred. The objective is to cluster the bridges and locate a recovery center for each cluster by considering operational cost and system reliability. To overcome the disruption of both the recovery centers and paths, an integer programming model is developed base on reliability facility location and most reliable path. Reliability facility location determines some backup recovery centers in case of disrupted primary one, and path reliability conducts assignment based upon most reliable path instead of the shortest path. The methodology is applied on the Sioux Falls real transportation network. Results demonstrate the trade-off between operational cost and reliability and discuss how substantial improvements in reliability are often possible with minimal increases in operational cost.

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1. Introduction

The concept of resilience has been studied in a large number of fields such as engineering, psychology, sociology, ecology, business, and economics. In the engineering world, resilience has been generally defined as the ability and capacity of a system or social units to absorb, withstand, and efficiently recover from a perturbation to an acceptable level of functioning [1]. It is a characteristic of the system that indicates performance under unusual conditions, recovery speed, and the amount of outside assistance required for restoration to its original functional state [2].

Transportation network resiliency is defined as the ability of transportation systems to retain performance during and after disasters undergoing little to no loss, and their ability to return to the normal state of operation quickly after disasters. Resiliency can be construed as a four-part cycle of normalcy, breakdown, annealing, and recovery [3–5]. Annealing refers to the immediate system response to the breakdown in finding a new equilibrium for the degraded network without recovery intervention. Recovery refers to the improvements to the network in response to the disaster, such as the reopening of links necessary to return to a new normal state.

An effective disaster-related plan to reduce disaster risk and improve the resiliency of transportation infrastructure is vital to the functioning of any society. Considering the Sendai Framework, one of the priorities in disaster risk reduction is "*Enhancing disaster preparedness for effective response and to "Build Back Better" in recovery, rehabilitation and reconstruction*" [6]. The Federal Emergency Management Agency (FEMA) defines recovery as the restoration of transportation components to their condition before the event [7]. The recovery phase is characterized by activity to return life to normal or improved levels [8]. The recovery phase by timeframe for the transportation system involves major three steps:

- Initial Response: This phase involves debris removal and cleanup, Emergency, short-term repair of transportation systems and provision of interim transit services and coordination and damage assessments.

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- Mid-Term Planning: This phase involves restoration of lifeline utilities into minimum operational service level. The service is restored to a basic level with partial or complete repair of the disrupted facilities whichever is possible.
- Long-Term Reconstruction: This involves complete rebuilding and restoration of disrupted transportation systems and may take months to several years, which depend on the level of damage and speed of reconstruction and restoration of transportation systems.

Disaster mitigation strategies have traditionally overlooked the importance of transportation in mitigation and post-earthquake efforts. From previous researches, it is evident that disaster damage to certain component of network, along important and non-redundant links, will have a greater impact on transportation performance [9–11]. Due to the limited alternative roads for bridges, their deficiency deteriorates transportation network performance considerably. Bridges collapse interrupts the connectivity, restrict the accessibility, and disrupt traffic flows, which in turn affect the economy of region, post-disaster emergency response, and reconstruction operations [12]. Therefore, efficient restoration of damaged bridges can substantially help in preventing economic loss as well as rapid relief in the rescue process.

When disaster strikes, prompting the initial response and mid-term planning are vital to the launching of disaster relief operation and minimize consequences of defected network. Since bridges play a major role in a transportation network, to minimize consequences of a degraded network on both transportation operation and relief efforts, the general purpose of this study is to propose an efficient strategy in the recovery and restoration process. During the recovery stage, damages caused by disasters on the network are maintained, obstructions are removed, and facilities are restored or replaced. The speed of recovery is dependent on the rate of flow of external resources into the system and resourcefulness. Resourcefulness can be defined as the availability of resources and technology, and ability or managerial capacity to mobilize them with a reasonable speed to repair, renovate, rehabilitate, replace, and restore the facilities and system functionality. Accordingly, it has been recognized that strategic location of depots and pre-positioning of inventory greatly facilitate the speed and efficiency of delivering supplies in the crucial days immediately after disaster strikes [13]. Therefore, to prompt bridges recovery, the proposed strategy focuses on the pre-positioning recovery centers which provide space to be equipped with the materials, tools and machines for the recovery efforts.

Pre-positioning the infrastructure recovery centers is beneficiary in both early recovery and reconstruction in long time after disasters. In short term, both the relief and recovery efforts will need to proceed in parallel. Although the immediate priority is to prevent further loss of life through public health, food, medical and shelter programs, the restoration of transportation network connectivity and accessibility to reach out to the various damaged areas is imperative, which will be expedite with support of equipped recovery centers. In long time reconstruction, it reduces the time and cost of equipment and restoration plan. Considering the study of Cho et al. [14], to reduce the cost of equipment staging and project set up, transportation agencies would be likely to repair bridges in groups that are spatially proximate. In this study, the objective is to determine the number of clusters, the boundary of each cluster, and the location of recovery center for each cluster. The model proposed assists planners during preparedness stage in the design of the logistics efforts to mitigate the risk of disruption by accelerating the recovery process. This strategy prompt bridges recovery by saving in equipping time and cost, as well as reducing the lead time in reaching the bridges that are affected by a disaster.

Both the pre-positioned recovery centers and network routes have the risk of failure. Accordingly, it is possible that bridges might not be reached from centers due to disruption in either pre-positioned recovery centers or routes from centers to bridges. To overcome these challenges, in addition to a primary recovery center for each cluster, it is considered some backup recovery centers to support bridges when the primary one fails. Furthermore, instead of considering shortest path, bridges and centers are connected based on most reliable paths.

A mathematical model is developed to cluster bridges and to find the optimum number and location of recovery centers to support bridges. The model presented in this paper chooses facility locations to maximize the probability of having a route to damaged bridges while also hedging against recovery centers within the system. The goal of this model is locating the recovery centers such a way to have a reliable system with the ability to perform well even when parts of the system (including routes and centers) have failed.

The rest of this paper is organized as follows. Section 2 provides a comprehensive literature review about different aspects of transportation network recovery. More detail explanation of the problem is presented in Section 3. The methodology for finding the most reliable paths by definition of unreliability path cost is presented in Section 4. In Section 5 the multi-objective integer programming formulation for the reliability pre-positioning problem developed. Section 6 provides an application to a real transportation network (Sioux Falls) under different probabilities of failure. Finally, in Section 7 conclusion of the study is presented.

2. Literature review

There have been several streams of research that are indirectly related to this problem. Mathematical programing and optimization have been used extensively in various fields of engineering and science [15–23], however; in this study, the review of the literature includes *Bridges importance in transportation network, Clustering* , *Pre-positioning supply,* and *Reliability facility location problems.*

2.1. Bridges importance role in transportation network

Bridges performance under various environmental condition is a fast developing concept [24,25]. Considerable importance of bridges has been demonstrated in past researches by analyzing the impact of bridges failure on transportation network performances, users behavior, and economic. Werner et al. modeled the effect of bridges failure on the post-earthquake travel time, travel distance, and the economic impact of these loss [12]. They presented the impact of disaster on indirect dollar losses to commuters and businesses, and the effects of reduced access to emergency centers and residential areas. Basöz and Kiremidjian [26] demonstrated how bridges failure deteriorates the network connectivity. Bono and Gutiérrez [27] presented the accessibility reduction following a disaster, and analyzed how urban blocks are affected and, in particular, are isolated as a consequence of road disruptions. Ardekani [28] conducted research on impacts of the 1989 Loma Prieta earthquake. He stated that due to the lack of nearby alternate routes, the impact of the Bay Bridge closure was especially significant. In perspective of users behavior, many motorists chose alternate modes of transport including Bay Area Rapid Transit (BART) and ferry. He found 40% increase in BART daily ridership after disaster. In another study, Chang and Nojima [29] developed simple post-disaster system performance measures that require only readily available data on network configuration, damage, and pre-disaster origin/destination traffic. They applied this measure in quantitatively assessing the loss of transportation service in the