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Arc routing problems to restore connectivity of a road network

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ABSTRACT

After a disaster, restoring accessibility in the affected area is critical for response operations. We study two arc routing problems for clearing blocked roads. The first problem minimizes the time to reconnect the road network, while the second maximizes the total benefit gained by reconnecting network components within a time limit. For each problem, we develop a mixed integer programming formulation and two versions of a heuristic algorithm. We conduct computational experiments on Istanbul data and instances adapted from the literature. The heuristics achieve near-optimal or optimal solutions quickly in most of the tested instances.

1. Introduction

Transportation network disruptions occur after many natural disasters. These incidents cause the road networks to be disconnected due to damaged/closed roads and impede accessibility to casualties, hospitals, those in need of relief aid and critical supply locations. For instance, in the 1999 Kocaeli Earthquake in Northwest Turkey, some highway sections were severely damaged and many roads in urban areas were blocked by building debris and displaced cars. After Japan's devastating 2011 earthquake and tsunami, the debris accumulated in the downtown of Kamaishi City caused the community to be isolated from search-and-rescue efforts. In the 2015 Nepal earthquake, some road segments near the epicenter of the earthquake became impassable, and a significant number of villages were isolated for days.

To facilitate emergency transportation in the immediate disaster response phase, blocked roads should be either rapidly cleared or repaired; and if that is not possible, bypassed by alternative modes such as helicopters. Road clearing teams should be dispatched to the affected areas to restore accessibility in the shortest time. These teams may be equipped with heavy machinery, bulldozers, lighting vehicles, drainage pump vehicles, and satellite communication vehicles, etc., and consist of their operators and other required personnel.

The main purpose of this research is to provide an efficient method to decide which problematic roads to open, and in which order they should be opened, so that in the first critical hours and the following time frame search and rescue teams can reach the affected regions, casualties can be transported to emergency care units, victims can evacuate the region, and emergency relief supplies are distributed. We study two arc routing problems that involve these decisions and aim to optimize the route of a road clearance team. We consider the situation that the post-disaster road network is separated into several connected components and the goal is to regain the connectivity of the road network in shortest time. We represent the

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network by a graph and note that a disconnected graph has nodes unreachable from each other. Our goal is to make the graph connected by re-opening some of the blocked roads (edges) so that there exists at least a path between every pair of nodes.

We model the response goal of reaching the most number of people in shortest time with two objectives. The first objective is to minimize the completion time of the last unblocking task that enables the road network to be connected. This leads to the problem of both selecting the blocked edges to open in order to ensure network connectivity and designing a walk for the team (referred to as the vehicle in the remainder) starting at the depot that does not need to go back to the depot. The walk includes all selected open and blocked edges both inside and outside of the connected components as necessary. The objective is to minimize the total time of this open walk. This objective ensures that every node is connected to every other node, hence it provides full accessibility. However, one disadvantage is that the time to clear certain road segments may take too long depending on the damage level, and in the meanwhile some victims would be waiting to get connected. To avoid this, we introduce a second problem by assigning prizes to each isolated network component such that a prize is collected when the component is reconnected. The objective is to maximize the total collected prize within an imposed time limit. Among the alternative solutions, one that minimizes the makespan, that is the completion time of the last task, is selected. The prize of a component represents the benefit from providing accessibility. It could be set to, for instance, the number of people in the isolated component. Also, higher prizes can be assigned to those components containing critical facilities such as airports, ports, hospitals, and relief supply points. Thus, by means of prizes we give incentives to provide accessibility to the most number of people or the most important locations. This second problem can be solved back-to-back over a response time frame such that the decisions are implemented over time.

The first problem we study is called the *Arc Routing for Connectivity Problem* (ARCP), which is the single vehicle and undirected version of the problem defined in Kibar (2013). We name the second problem the *Prize Collecting Arc Routing for Connectivity Problem* (PC-ARCP), and define it for the first time in this study. We show that both problems are NP-hard. We first provide a mixed integer programming (MIP) model for each problem. To obtain near-optimal solutions consistently in short time, we develop a heuristic consisting of a feasible solution construction step and local search steps embedded in a Variable Neighborhood Search framework. We next provide a faster randomized version of the heuristic for each problem. We test the performance of the heuristics by computational tests on two sets of instances. The first set consists of instances based on the Istanbul city road network under various disaster scenarios. The second set is adapted from the Rural Postman Problem (RPP) instances in the literature. We also propose a rigorous method to generate road restoration times with respect to several physical and uncertain factors, and use this method to generate our test instances.

The paper continues as follows. First, we review the literature related to our problems in Section 2. Section 3 defines the problems and proves their NP-hardness. Then, the MIP models are presented in Section 4. After describing the proposed heuristic algorithms in Section 5, we discuss data generation in Section 6. We compare the MIP and heuristic solutions in Section 7, and discuss the use of the two problems in post-disaster decision support in Section 8. Finally, concluding remarks are presented in Section 9.

2. Literature review

Within the last two decades a considerable amount of effort has focused on developing optimization models and solution algorithms to support disaster response operations. Anaya-Arenas et al. (2014) and Özdamar and Ertem (2015) are recent surveys including discussions of such studies. The focus of our study is on post-disaster road clearance operations. Therefore, we mainly discuss here studies that address this subject as well as the most related arc routing problems, and compare them to our study.

2.1. Road clearance problems

The highway emergency rehabilitation problem within the critical 72-h-period after an earthquake has been studied by Feng and Wang (2003). They develop a multi-objective scheduling model with objectives of maximizing the length of the accessible roads, maximizing the number of life savings and minimizing the risks of working in sensitive areas. Furuta et al. (2008) address the problem of post-disaster restoration of lifeline systems in an uncertain environment. The decisions include assigning teams to disaster regions and finding the best restoration order. Sources of uncertainty are liquefaction, delay in moves, being unable to restore a lifeline and increase of damages because of aftershocks. They improve an existing genetic algorithm proposed for this problem. Liberatore et al. (2014) develop a model for the optimization of recovery and distribution operations in a coordinated manner and solve it on the Haiti hurricane disaster case study. In this hierarchical model, they plan for recovering the damaged roads while considering the consequent distribution to the affected areas. The criteria include helping the highest number of people, cost, delivery time, security and reliability. Via the case study, they show the importance of cooperation among agents by comparing the solutions to the coordinated and sequential optimization models. Duque and Sörensen (2011) develop a model to improve accessibility after a disaster. A number of roads need to be repaired under a budget constraint in order to minimize the weighted sum of travel time from each rural town to its closest regional center. Depending on the importance of the rural towns, weights are assigned to the nodes of the representative network. The authors propose a solution method based on the GRASP metaheuristic.