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Network repair crew scheduling and routing for emergency relief distribution problem

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ABSTRACT

Every year, hundreds of thousands of people are affected by natural disasters. The number of casualties is usually increased by lack of clean water, food, shelter, and adequate medical care during the aftermath. One of the main problems influencing relief distribution is the state of the post-disaster road network. In this paper, we consider the problem of scheduling the emergency repair of a rural road network that has been damaged by the occurrence of a natural disaster. This problem, which we call the Network Repair Crew Scheduling and Routing Problem addresses the scheduling and routing of a repair crew optimizing accessibility to the towns and villages that demand humanitarian relief by repairing roads. We develop both an exact dynamic programming (DP) algorithm and an iterated greedy-randomized constructive procedure to solve the problem and compare the performance of both approaches on small- to medium-scale instances. Our numerical analysis of the solution structure validates the optimization model and provides managerial insights into the problem and its solutions.

1. Introduction

Every year, hundreds of thousands of people are affected by natural disasters such as floods and earthquakes, especially in less developed regions of the planet (Guha-Sapir, Vos, Below, & Ponserre, 2011). An important observation, however, is that the number of casualties is usually increased by lack of clean water, food, shelter, and adequate medical care during the aftermath (PAHO, 2000). An adequate logistics reply to a disaster is therefore crucial. It has been conjectured that 80 percent of the disaster relief effort consists of logistics (Trunick, 2005). To a first approximation, therefore, disaster relief *is* logistics.

One of the main problems influencing the delivery of food, shelter, and medical supplies to affected regions is the state of the road network. In many situations, it is not a lack of supplies that kills people, but the impossibility to get those supplies to the people that need it. In Haiti, for example, extensive media coverage of the 2010 earthquake resulted in a large excess stock of relief supplies. However, distributing those supplies to the affected villages proved far more difficult as road infrastructure had been damaged or destroyed (Pedraza Martinez, Stapleton, & Van Wassenhove, 2010; Van Wassenhove, Martinez, & Stapleton, 2010). Further complicating the repair of the road network is the often limited availability of road repair capacity, especially in impoverished regions of the world. Therefore, it is crucial that road repair is planned and executed in the most efficient way possible.

In this paper, we consider the problem of scheduling and routing the emergency repair crew of a rural road network that has been damaged by the occurrence of a natural disaster. We call this problem the *Network Repair Crew Scheduling and Routing Problem*, abbreviated as NRCSRP. The NRCSRP addresses the scheduling and routing of a single repair crew, starting from a single depot, while optimizing accessibility to the towns and villages that demand humanitarian relief. Extending this work to more than one repair crew and more than one depot is left for future research.

The problem is defined on an undirected and connected graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ of which the nodes ($\mathcal{V}$) are either *demand* nodes ($\mathcal{V}_d$) or damaged nodes requiring *repair* ($\mathcal{V}_r$). (Note that without loss of generality, we represent a damaged road link by a node located in the middle of the corresponding edge. Therefore, repairing a road connection is equivalent to repairing a node, and we use the two terms interchangeably.) There is one supply node that corresponds to the location in which the relief supplies are positioned and from which the repair crew initially departs. This node is called the *depot*. Demand nodes correspond to locations (usually villages) that

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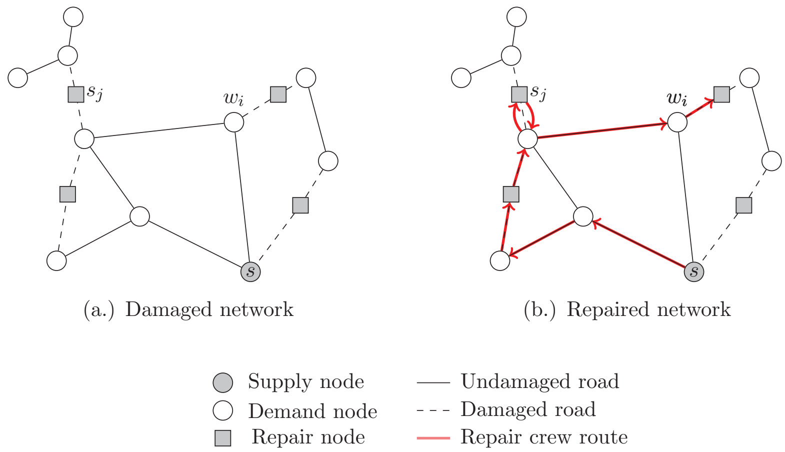

Fig. 1. Example of a damaged network and repair crew route for NRCSRP.

demand humanitarian relief. The importance of a village (node i) is represented by a *demand*, i.e., a weight factor w_i, that might, e.g., correspond to the number of inhabitants. Damaged (repair) nodes represent the locations where the work of the repair crew is needed. Such nodes have a *repair time* s_j (for node j) that represents the time the repair crew spends on its first visit. Without loss of generality, we do not distinguish between demand nodes and transshipment nodes, i.e., cross points where two or more roads come together, since such nodes can be modeled as demand nodes with zero demand. Each edge $e_{ij} \in \mathcal{E}$ represents a road that connects two nodes $i, j \in \mathcal{V}$. A travel time t_{ij} is defined for each edge e_{ij} to represent the time it takes the repair crew to traverse it.

The aim of this problem is to determine the optimal sequence in which the crew should traverse the graph, starting from the depot node. Every time it encounters a damaged node that it has not visited before, it repairs the node and incurs the *repair time* of this node. On subsequent visits the crew can pass that node without incurring any additional time. When damaged nodes are repaired, demand nodes can become *accessible*. A demand node i is called accessible if there exists a path connecting this node to the depot that contains only undamaged and/or repaired nodes, and is not longer than a certain maximum distance D_i. The maximum distance D_i is node-specific and can be computed based on pre-disaster conditions (e.g., the distance between a demand node and the depot should not be more than twice the distance it was before the disaster). Thus, in addition to the travel time t_{ij}, each edge e_{ij} has a distance measure, denoted d_{ij}, that is used to evaluate nodes' accessibility.

For each demand node, the schedule of the crew determines the moment in time at which this node becomes accessible. The objective function of the problem is the sum of the moments at which each demand node becomes accessible weighted by the node demand w_i. The objective of the network repair problem is to determine the schedule and route of the repair crew that minimizes this objective function. In general, it is not necessary for the repair crew to visit all damaged nodes. Fig. 1 illustrates an example problem and solution for the NRCSRP with four damaged nodes.

The NRCSRP captures the most important aspects of the problem of routing a road repair crew in order to restore accessibility to demand points affected by damaged roads. To solve this problem, we develop two very different approaches. A dynamic programming (DP) model is able to find optimal solutions to small and medium-sized instances and provides insight into the fundamental structure of the problem. An efficient iterated greedy-randomized constructive procedure (IGRCP) is able to solve medium- to large-scale instances in very small computing times. A comparison of the performance of both approaches yields interesting insight into the underlying problem structure.

The problem of scheduling the repair operations in a post-disaster situation can be modeled in many different ways and the exact formulation of the NRCSRP is the result of several design choices. As mentioned, one of the main causes of human casualties is the fact that a disaster tends to disconnect remote population centers from the main supply hub. In poorer countries around the world, people are usually dependent on a very limited number of economic centers (usually larger cities) for sustenance. The demand nodes in the NRCSRP may therefore represent small villages or settlements, temporary medical facilities, shelters, or food distribution points. The supply node on the other hand will represent a city, an airport, or a port area where the relief goods arrive. When these demand points can no longer be reached by road from the supply point, the results are often dramatic. This is especially the case in rural areas, that lack the redundancy in the road network that characterizes cities. For this reason, the NRCSRP is explicitly defined on *sparse* networks, that are more common in rural than in urban situations, and the graphs underlying all generated test instances are sparse.

By explicitly considering the routing of the repair crew, the NRCSRP —unlike most previous contributions— adds a crucial time component that makes the problem more realistic and more suitable for real-life post-disaster situations. Like in real life, roads cannot be repaired until they can be reached by a repair crew. As mentioned, the objective function of the NRCSRP minimizes the demand-weighted moment in time at which all the demand nodes are connected to the supply node. The demand assigned to each demand node should be interpreted as a function of the importance of connecting this node, e.g., its population size. The objective function also takes the urgency of connecting the nodes into account, as even less important demand nodes (with small demand) may cause a large objective function increase when ignored for too long. In a sense, the NRCSRP models aspects of both the immediate response (routing of the repair crew) and the recovery (connecting the demand nodes as soon as possible) phases.

In a post-disaster immediate response situation, budget constraints are not usually a predominant issue, and the focus is on restoring connectivity of the affected regions with the limited physical means available. Nevertheless, an in-depth analysis of solutions produced by our solution approaches for the NRCSRP reveal interesting managerial results with considerable implications for further budgetary analysis. More specifically, our analysis shows that only a limited number of damaged nodes (around 30 percent) needs to be repaired in order to restore full accessibility. Additionally, when studying the optimal or best-known solutions, we observe that the repair operations have, on average, a diminishing rate of return, connecting a lot of demand in the beginning and much less demand at the end. However, this simple observation hides a large amount of