OPTIMIZING NETWORK ACCESSIBILITY: A CASE STUDY ON THE HAITI EARTHQUAKE

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RESUMO

A acessibilidade de uma rede urbana após uma grande catástrofe impacta fortemente o atendimento à população. Em geral, equipes de trabalho (ET) são mobilizadas para melhorar o acesso nas horas seguintes a um terremoto, removendo destroços e reparando as ruas da cidade. A eficácia da programação das ET é muito importante para as operações logísticas após desastres. Este trabalho apresenta um algoritmo capaz de lidar com grafos de grande escala e resolver instâncias reais, tais como a região central de Porto Príncipe, Haiti, após o terremoto de 2010. A rede de transportes da capital do Haiti contém milhares de vértices e arestas, e seus dados foram fornecidos pelo acordo internacional "Space and Major Disasters". O algoritmo também foi testado em instâncias simuladas para avaliar seu desempenho e eficiência. Os resultados obtidos com dados reais forneceram ideias interessantes para gestão futura.

PALAVRAS CHAVE. Logística Humanitária, Proejto de redes, Heurísticas.

Área Principal: OA - Outras aplicações em PO

ABSTRACT

The network accessibility in the aftermath of major disasters has a large impact on the response to the population. In the case of earthquakes, the access is usually improved during the hours following the quake by employing work-troops (WT) to remove debris and repair city roads. Thus, the efficacy of the WT schedule is very important for post-disaster logistics operations. We present an algorithm able to handle large scale graphs and solve real instances such as the central region of Port-Au-Prince, Haiti, after the 2010 earthquake. The Haiti capital road transportation network contains thousands of vertices and edges, and its data was provided by the International Charter "Space and Major Disasters". The algorithm was also tested on simulated instances to evaluate its performance and efficiency. Results obtained with real case data provided management insights for future applications.

KEYWORDS. Humanitarian logistics, Network design, Heuristics.

Main Area: OA - Other applications in OR

1. Introduction

The road network infrastructure can be strongly affected after a major earthquake like the one that stroke Port-Au-Prince, Haiti, on 12 January 2010. Several roads become partially or entirely blocked, as shown in Figure 1, preventing vehicles of accessing some regions of the city. In graph theory, it means the graph may not be strong connected anymore. Defining the roads repairing priority becomes a significant issue, since the road network is essential to provide relief to the population.

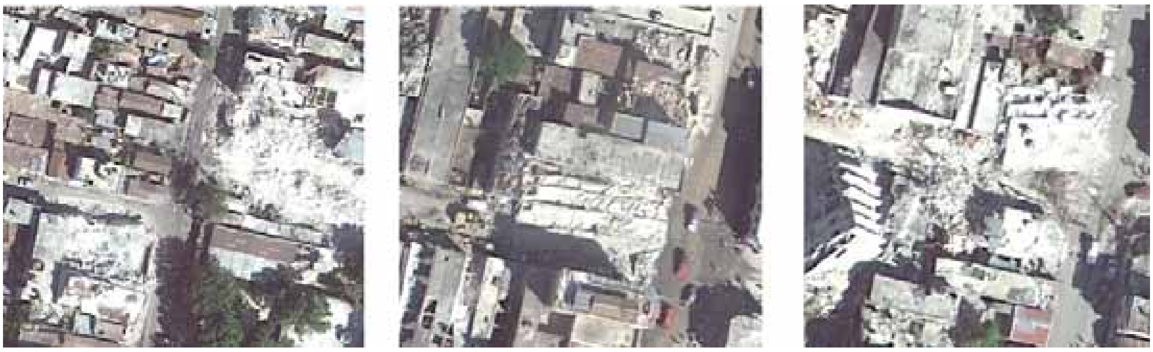
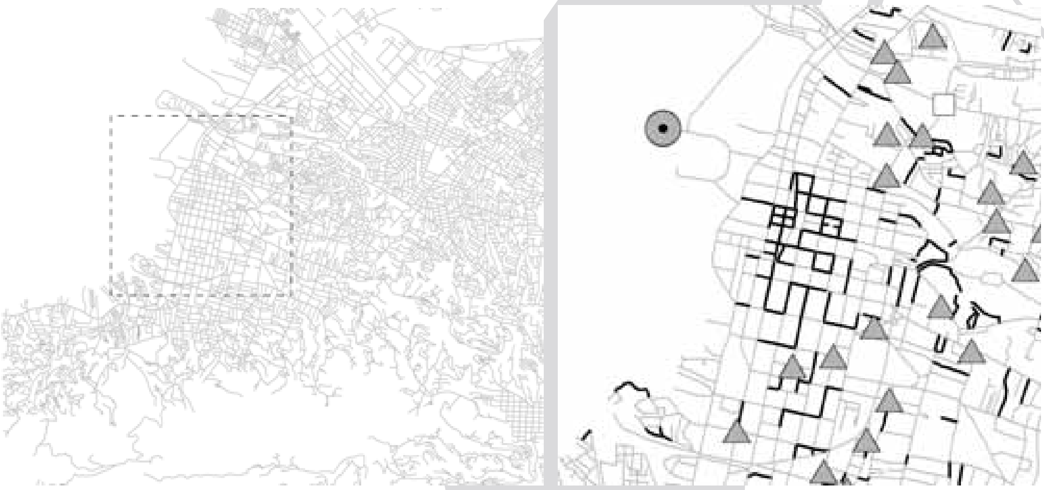


Figure 1: From the left to the right: example of lightly, moderately and heavily blocked roads.

During the first days that followed the 7.0 magnitude Port-Au-Prince earthquake, a large part of the population gathered in camps established at some points of the city, according to the information provided by satellite images. Together with a pre-existing database, the treatment of these images allowed mapping the central and most affected part of the city, as shown in Figure 2. Figure 2a presents the whole network map, with the marked area detailed in Figure 2b. The circle, triangles and black edges represent the port, population gathering places and blocked roads, respectively.



(a) (b)

Figure 2: Port-Au-Prince map after the earthquake

Let us consider Work-Troops (WT) as teams composed of bulldozers, excavators and dump trucks, initially available at some points of the network and deployed to unblock and repair damaged roads after earthquakes (in the case of Port-Au-Prince, there were over 500 roads requiring intervention). We defined the Work-troops Scheduling Problem (WSP) as generating a multi-period scheduling to allocate the WT to repair blocked edges in order to improve as fast as possible the accessibility of the population to the relief teams. The accessibility is measured in terms of the shortest traversable path from some origin points, from where WT and relief teams depart, to destination points, i.e., population gathering areas, weighted by the population in these last points. We considered that WT require an unblocked path to reach any point of the network, and that they can work together on the same blocked road depending on its width, proportionally decreasing the time necessary to repair it.

Works closely related to the WSP are provided in Table 1. The two first columns of the table presents the authors and classifies the works in static (S) or dynamic (D). Static approaches regard only which edges WT should repair at a pre-determined time instant, while dynamic ones consider the sequence of repairs along time. The following columns present other characteristics of each work: the objection function (OF) considered, the method used and the cities where the study was applied. GRASP, VND and B&B correspond to the Greedy Randomized Adaptive Search Procedure and Variable Neighborhood Descent metaheuristics, and to the Branch-and-Bound method, respectively. The matheuristics are methods that combine heuristics with linear programming. Readers interested in crisis management are referred to the surveys provided by Caunhye *et al.* (2012), Diaz *et al.* (2013) and Leiras *et al.* (2014).

Author(s)	Type	OF	Method	Application
Feng e Wang (2003)	S	accessibility + lives saved + risk	complete enumeration	Chi-chi, Taiwan
Yan e Shih (2007)	D	time to repair	matheuristic	Chi-chi, Taiwan
Yan e Shih (2009)	D	time to repair + distribute relief	matheuristic	Chi-chi, Taiwan
Duque e Sorensen (2011)	D	weighted shortest paths	metaheuristic (GRASP + VND)	Port-Au-Prince, Haiti
Yan *et al.* (2012)	D	time to repair + supplies delivery	matheuristic	Chi-chi, Taiwan
Fiondella (2013)	D	vulnerability	heuristic	USA cities
Aksu e Ozdamar (2014)	S	weighted earliness	CPLEX (B&B)	Istanbul, Turkey
Yan *et al.* (2014)	D	time to repair	metaheuristic (ant colony)	Chi-chi, Taiwan

Table 1: Classification of previous works on the WSP.

It is important to note that although all works presented in this section had applications to real cases, they use simplified network versions with at most a few hundred vertices. Our research is applied to the detailed map of the central region of Port-Au-Prince, containing more than ten thousand vertices and edges. The main goal of this study is to connect theory and practice by applying an optimization model and algorithms to solve the problem, providing a detailed solution in a reasonable time for a decision maker. For this purpose, an efficient algorithm is proposed and tested on simulated and real instances.

2. Problem definition and statements

We define the WSP over a connected graph $G = (V, E)$, where V and E are the sets of vertices and edges, respectively. The edges correspond to city roads, and the vertices can represent road intersections or specific network points, classified into origin and destination points. The subset of origins $O \subset V$ contains the points from where WT and relief teams depart: ports, airports and other network entrance points, as large roads connecting it to neighbor areas. We consider that $q_i \in \mathbb{N}^*$ WT are available at each origin $i \in O$, with the total number of available WT being $Q = \sum_{i \in O} q_i$. The population gathering points are represented by the destinations subset $D \subset V$, for which a population of $p_i \in \mathbb{N}^*$ is estimated to be camped at each $i \in D$. N.b. that $O \cap D = \oslash$.

To approach the problem dynamically, it is necessary to define a time measure unit. We consider as one *time period* the amount of time usually necessary to repair the lightest blocked (but still non-traversable) road, making it traversable. The maximum number of time periods considered in the schedule is T.

Each edge is associated with three values: a distance, a repair and a width. The first one, defined as $d_{ij} \in \mathbb{R}_+^*$, corresponds to the edge length. The repair $r_{ij} \in \mathbb{N}$ is a measure of the effort necessary to make the edge traversable in terms of time periods. Since we assume WT can work together to repair the same road simultaneously, an edge with $r_{ij} = 6$ could be repaired in six time periods by only one WT, or even in one time period by three WT working on each of its extremities, whenever the road width allows it. The third parameter $u_{ij} \in \mathbb{N}^*$ represents not a road width in meters, but an upper bound on the number of WT that can work simultaneously at each extremity of edge $[i, j]$. The set of blocked edges (i.e., edges for which $r_{ij} > 0$) is defined as B. Thus, the WSP consists in deciding where and when sending WT to repair routes in order to improve the network accessibility to destination points. This problem has been mathematical defined in Sakuraba *et al.* (2015), where the OF is the minimization of the sum, for all time periods, of the shortest paths to all destinations weighted by its population.

3. Proposed heuristic

Immediately after an earthquake, the first edges to be repaired are the ones in the paths from origins to destinations. The proposed heuristic prioritize such edges regarding if they are in paths to destinations that can be reached from an origin or not, allocating as many WT as possible to priority edges. The objective is to create a traversable path for unreachable destinations as soon as possible, while for already reachable ones the priority is to unblock shorter paths, improving their accessibility.

Relevant edges are first classified into two sets, S1 and S2, according to the criteria described before. S1 and S2 contains edges in paths to unreachable and reachable destinations, respectively. Dijkstra's shortest path algorithm (Dijkstra, 1959) is used to determine the edges belonging to each set. First, the shortest paths (SP) from origins to destinations are determined considering edge traversing costs as $t_{ij} = \lceil r_{ij}/u_{ij} \rceil M + d_{ij}$, where M is a large integer number. Blocked edges in SP with a cost larger than M (i.e., blocked SP) are kept in S1. Then, SP are recalculated using $t_{ij} = d_{ij}$, i.e, regardless if edges are blocked or not, and blocked edges in each SP are kept in S2. Edges in both sets are kept separated by destination, and in the same order they appear in the SP.

To allocate WT at each time period, the heuristic searches both sets starting from S1. The search is made by destination, in non-increasing order of its population. Each WT is allocated to the first workable edge found, i.e., the first edge $[i, j]$ that can be reached from the origin where the WT departs and that has still less than u_{ij} WT working on it in the current period. If there is no workable edge for a WT in neither of the sets, an edge is randomly allocated to it.

The heuristic general structure is presented in Algorithm 1. Lines 2 to 5 classify relevant blocked edges into S1 and S2, calculating also their accessibility from each origin. Then, to allocate each WT to every time period, S1 is scanned, keeping the first workable edge as described before. If no such edge is found, S2 is inspected likewise. The WT is allocated randomly if no workable edge was found in any of the sets. After allocating all WT in a time period, the SP are updated with the completely repaired edges (lines 18 to 20). This update is done efficiently by calculating the SP to each repaired edge extremities. The OF value is updated by adding the weighted sum of SP at the end of each time period (line 21).

Algorithm 1 Proposed heuristic

Input parameters: $G = (V, E), O, D, B$
for `each origin` **do**
  Calculate SP and accessibility to all vertices using t_{ij} values to build S1
end for
Calculate SP from origins to destinations using d_{ij} values to build S2
for `each time period` **do**
  for `each WT` **do**
    if `there is an unreachable destination` **then**
      allocate the WT to the first workable blocked edge in S1
    end if
    if `WT still not allocated` **then**
      allocate the WT to the first workable blocked edge in S2
    end if
    if `WT still not allocated` **then**
      allocate the WT randomly to a workable blocked edge
    end if
  end for
  for `each` $[i, j] \in B$ `fully repaired` **do**
    Update SP and accessibility from origins to all vertices
  end for
  Update OF value
end for
return WT schedule and OF value

4. Computational experiments

Experiments for the WSP were addressed to check the proposed heuristic performance. A set of 80 simulated instances and the graph of Port-Au-Prince obtained hours after the 2010 earthquake were used, for which we assumed $q_i = 2, \forall i \in O$. Tests were performed on an Intel Core i7-4600M CPU with 2.90 GHz and 16 GB of RAM. The heuristic was implemented in C ANSI and CPLEX 12.6 was used to solve the simulated instances to optimality.

The simulated instances were randomly generated over a graph with $n = 10, m = 20, |O| = 2$ and $|D| = 3$. Ten different blocked edge configurations were generated for each value of $|B| = \{5, 10, 15, 20\}$. For each configuration, two instances were generated with $R = \sum_{[i,j] \in B} r_{ij} = 40$ and 45. The determination of T required preliminary tests to guarantee the feasibility of all instances. T was set to 13 to all simulated instances, the smallest value for which all of them are feasible.

Table 2 summarizes the results obtained on these instances by CPLEX within a time limit of two hours and by the proposed heuristic. Each line in the table corresponds to a set of 10 instances, representing a combination of R and $|B|$ parameters previously defined. The three first columns "inst. set #", "R" and "$|B|$", present respectively the instance set number and the values of the two parameters. The results obtained by CPLEX are shown in the three following columns, where "TLE", "t(s)" and "nb nodes" correspond to the number of instances in each set that had the two hours Time Limit Exceeded, and the time in seconds and number of nodes visited in the CPLEX B&B average values, respectively. The two last columns show the number of optimal solutions ("nb opt.") found by the heuristic and its average relative deviation ("diff. %") to the optimal or best solution found by CPLEX solver for the 10 instances.

90% of the instances were solved by CPLEX to optimality, and the experiments suggest instances with 10 or 15 blocked edges are somehow difficult for CPLEX to handle. The heuristic

inst. set #	R	$\|B\|$	CPLEX TLE	t (s)	nb nodes	Heuristic nb opt.	diff. %
1	40	5	0	12.63	9,090.5	9	0.21
2		10	1	882.92	160,058.1	4	5.27
3		15	1	936.65	72,434.9	5	8.73
4		20	0	83.65	14,348.0	8	2.49
5	45	5	0	23.30	11,980.7	9	0.09
6		10	2	1,518.22	223,138.5	5	2.72
7		15	3	2,277.90	108,982.0	5	0.57
8		20	1	818.18	39,447.4	8	1.87

Table 2: Results obtained by CPLEX and BCH on simulated instances.

was able to obtain the optimal solution for approximately two thirds of the instances (53 out of 80), and for 85% of the instances with $|B| = 5$ or 20. Besides, for 79 out of 80 instances, the accessibility of the solutions, i.e., the first time period from which all destinations become reachable, was the same one found by CPLEX. If we consider only instances for which the heuristic solutions are different from CPLEX, the average relative deviation is about 8.1%. Regarding the heuristic performance on all instances, the same deviation is around 2.7%.

The Port-Au-Prince graph after the 2010 earthquake has the following parameters: $|V| = 16,657, |E| = 19,558, |O| = 4, |D| = 62, |B| = 536$ and $R = 842$. T was set to $\lceil R/Q \rceil = 106$ time periods, guaranteeing that all edges could be repaired with $Q = 8$ WT. Edge repair values r_j were estimated based on satellite images as the ones in Figure 1.

The solution obtained by the heuristic reduces the value of the weighted SP to all destinations from 333 to 94 thousand by the end of the first period (i.e., from $t = 0$ to $t = 1$). From the second period, the changes in this value per time period are very small (less than 0.03%). It consumes 25 seconds to finish the first time period allocation, and 4 minutes to handle all 106 time periods. It is important to mention that the time to allocate WT in the first time period plays a key role in real situations, since the algorithm has a whole time period to find the next period allocation once WT are sent.

Figure 3 illustrates some changes in SP after the first period repairs. In the figure, the circle corresponds to the port (origin point) and triangles to destination points. Gray and dark paths correspond to the original ones and to the new paths obtained after the reparation of the crossed edges, respectively.

5. Concluding remarks

In this work, we presented a heuristic to deal with real instances of the Work-troops Scheduling Problem, whose solution has a large impact on the relief distribution after a major earthquake. Despite of its simplicity, computational experiments show that the proposed heuristic has a good overall performance when compared to CPLEX, with practically the same accessibility and an average relative deviation of less than 3% for randomly generated instances with 10 vertices and 20 edges. It also performed well for the real instance corresponding to the graph of Port-Au-Prince after the 2010 earthquake, obtaining in a few seconds a first-period WT allocation that reduces the sum of weighted shortest paths to population gathering zones to less than one third of its original value.

The Port-Au-Prince case study showed that the development of efficient tools guarantees accessibility improvements as fast as possible, which is crucial for relief operations. Even in cases when the population is reachable from the beginning, the reduction of the travel distances have

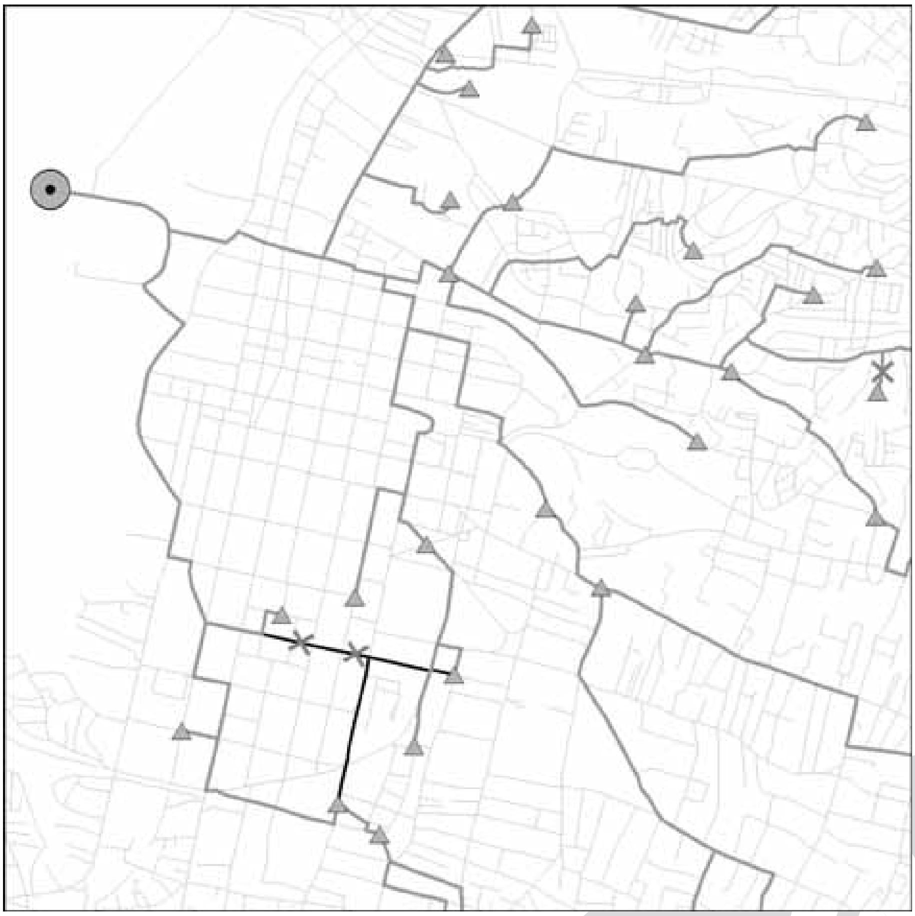


Figure 3: Changes in SP to destinations after the first period repairs.

a large impact on the efficiency of rescue teams, that are required to move slowly inside a risk environment.

The next steps include the development of relief distributing algorithms associated with the road repairing schedule. Also, long term road network and city structures rehabilitation are intended to be investigated as optimization problems applied to real situations, where a good planning may significantly reduce the time to reestablish a city struck by a major disaster. We also intend to approach other real case applications, making real contributions to post-disaster operations. By the time this paper was submitted, the data from the Gorkha earthquake, occurred in Nepal on 25 April 2015, was expected to be received.

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