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Transportation in disaster response operations

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ABSTRACT

Disasters are extraordinary situations that require significant logistical deployment to transport equipment and humanitarian goods in order to help and provide relief to victims. An efficient response helps to reduce the social, economic and environmental impacts. In this paper, we define and formulate a practical transportation problem often encountered by crisis managers in emergency situations. Since optimal solutions to such a formulation may be achieved only for very small-size instances, we developed an efficient genetic algorithm to deal with realistic situations. This algorithm produces near optimal solutions in relatively short computation times and is fast enough to be used interactively in a decision-support system, providing high-quality transportation plans to emergency managers.

1. Introduction

Disasters, be they anthropogenic or natural, have always affected humans. Today, with the progress in information technology, disasters are followed live throughout the planet. The accumulation of risks associated with such factors as increasing urbanization, dependence on critical infrastructure, terrorism, climate change and variability, and animal and human diseases, as well as the greater mobility of people and goods around the world, have increased the potential for various types of disasters. These disasters (e.g., floods, earthquakes, chemical spills, plant explosions) require significant logistical deployment in order to provide relief to victims and to transport equipment and humanitarian goods.

According to Altay and Green [1], who reviewed OR/MS research in disaster operations management, there is increasing recognition of the need for research in this area. Though the field is not yet well established, *emergency logistics* can be defined as "a process of planning, managing and controlling the efficient flows of relief, information, and services from the points of origin to the points of destination to meet the urgent needs of the affected people under emergency conditions" [28,29]. Emergency management is divided into four main phases: mitigation, preparedness, response and recovery [1,12]. *Mitigation* is defined as sustained action to reduce or eliminate the risk to people and property from hazards and their effects. *Preparedness* is the set of measures taken to avoid the negative consequences associated with a threat, which includes actions taken to prepare efficient response during a crisis or emergency. *Response* is using resources and emergency procedures as dictated by emergency plans to preserve life, property, the environment, and the community's social, economic, and political structure. *Recovery* involves the long-term actions taken to stabilize the community and to restore normalcy after the disaster's immediate impact has passed. Again, according to Altay and Green [1], nearly half of the research concerned mitigation.

In this paper, we focus on one of the most important aspects of the response phase: the transportation of humanitarian aid (e.g., water, food, medical goods and survival equipment) to people at fixed distribution points. To this end, we propose a formal definition and a mathematical model for the *Transportation Problem in Disaster Response Operations* (TP-DRO). Three solution approaches are proposed to solve this problem. The first approach uses the classic branch-and-bound procedure of the commercial solver CPLEX applied to our mathematical model with a heuristic stopping criterion. The second approach consists of a fast construction heuristic to generate a set of feasible solutions. The third approach is based on a genetic algorithm that uses some of the solutions output by the second approach.

The motivation for this research dates back to January 1998, when the province of Québec in eastern Canada faced its first major disaster ever. From January 5th to 9th, three successive storms left from 85 mm to 100 mm of rain, freezing rain, hail and snow in the region south of Montreal. The accumulation of ice caused a technological disaster, as over 300 electrical towers fell down, resulting in an interruption of the electricity supply over a wide area. More than 700 municipalities – nearly half of Quebec's population of six million – were affected by power outages during the cold month of January. In addition, nearly 1.4 million subscribers in Quebec were

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completely without power, which was the most important consequence of the ice storm.

Establishing a technological climate disaster, this incident also caused a major malfunction of critical infrastructure: the telecommunications, banking and financial systems, as well as the health, water, computer, heating and lighting networks were all affected. A "black triangle" – extending from St. Hyacinthe in the north, Granby to the east and Saint-Jean-sur-Richelieu to the west – disrupted the daily lives of 41,000 inhabitants. Inside this black triangle, the complete failure of the electrical power grid lasted for more than five weeks. The economic impact of the ice storm has been estimated at over one billion Canadian dollars. Since many areas had to suspend their activities for several days, Canada's economic output in January 1998 decreased by 0.7%. For Quebec, the gross domestic product decreased by 1.9% [22].

This disaster demonstrated that the political system was not ready to handle such a situation. In response, the Civil Protection Act was adopted by the Quebec government and went into effect on December 20, 2001. Now, each municipality must develop and update its own emergency preparedness plan, which includes all topics related to emergency logistics. As these requirements are relatively new, there are almost no tools or software to help and train municipality emergency managers. This led us to develop a complete decision-support system (DSS) for emergency logistics [27], which includes a database, a location and transportation optimization module and a resource allocation module. In this article, we describe the transportation module.

When designing the transportation algorithms, our primary objective was to produce high-quality solutions quickly (i.e., within a few seconds) so that these algorithms could be integrated in the DSS transportation module to help crisis managers efficiently deploy logistical resources. This DSS is also designed to be used to train municipal managers. The algorithms had thus to be fast enough to allow the decision-makers test and evaluate different deployment scenarios or transportation routes, for example. Moreover, as emergency situations are highly dynamic, new urgent requests may arrive at different times and must be scheduled immediately.

The main contributions of this article are the following. First, we model a practical transportation problem faced by crisis managers in emergency situations. We show that the exact branch-and-bound procedure used by CPLEX can yield optimal solutions in short computation times for very small problems with the proposed formulation. Second, we develop efficient algorithms for large problems, which produce near optimal solutions in relatively short computation times. In fact, the genetic algorithm proposed is fast enough to be used interactively in a decision-support system and provide high-quality transportation plans for emergency managers. Finally, computational results show that solutions produced by the genetic algorithm remain very close to the optimum even if demands and travel times are subject to small changes.

The remainder of the paper is organized as follows. Section 2 presents a detailed description of the *Transportation Problem in Disaster Response Operations* (TP-DRO) and its mathematical formulation. A literature review follows in Section 3. Section 4 introduces the developed algorithms. Section 5 reports our computational results, and Section 6 presents our conclusions.

2. Problem description

A disaster is a highly complex situation in which a flow of various goods must be transported to a stricken population using the vehicles available. Requested goods are generally shipped from a set of distribution centers, already open and staffed, to a set of delivery points that represent the locations where the disaster victims can go to obtain help. Since the transportation requests are numerous and heterogeneous, disaster managers often requisition almost all the available vehicles, even if some of them are not really efficient for delivering some kinds of goods or cannot be easily loaded/unloaded at some locations (e.g., school, sport center, town hall, private or public warehouse).

2.1. Problem definition and assumptions

The *Transportation Problem in Disaster Response Operations* (TP-DRO) can be formally defined as follows. Let u be the number of distribution centers (DC), indexed $l = 1,\ldots,u$, from which the humanitarian products are shipped. The number and the location of these distribution centers are assumed to be already determined (by the location module of the DSS, for example). Let n represent the number of delivery or distribution points, $i = 1,\ldots,n$, where people can go to obtain help (e.g., a refugee camp or a dormitory). Let p denote the total number of products types (or groups of humanitarian goods), $j = 1,\ldots,p$, needed for people relief. The nature of these products is closely related to the type of disaster (e.g., earthquake, chemical spill). The quantity of product j available at DC l is denoted as p_{jl}, and the quantity of product j required at delivery point i is denoted as d_{ij}. Throughout the paper, the total quantity available at DCs for each product type j is assumed to be sufficient to cover the demand of all delivery points for this product type (i.e., $\sum_{i=1}^{n} d_{ij} \le \sum_{l=1}^{u} p_{jl}$).

In addition, at each distribution center l, it is assumed that there are m_l vehicle types, $h = 1,\ldots,m_l$, and u_{hl} vehicles of each type h. Since all distribution centers may not be equally equipped for receiving a particular vehicle type, different docking times, τ_{hl}, are considered, one for each vehicle type h and the corresponding DC, l. Similarly, some vehicles may have certain handling equipment that makes them more efficient at manipulating some products. The time needed for loading and unloading one unit (i.e., a pallet) of product j into a vehicle of type h is defined as α_{jh}, where $\alpha_{jh} = \infty$ if product j cannot be loaded into a type-h vehicle.

There are also some restrictions on the total weight and the total volume associated with certain vehicles. These restrictions depend on the vehicle type used. Formally, a loaded vehicle of type h must not weigh more than Q_h weight units nor have a volume over V_h volume units. To determine the total weight (the total volume) corresponding to a given vehicle's load, the weight w_j in weight units (the volume s_j in volume units) of each product j is assumed to be known with certainty.

Finally, a maximum daily work time, L_h (in time units) for each vehicle type h is imposed. A given vehicle can perform as many trips as needed during a day as long as the corresponding work time limit is respected. In disaster situations, determining travel times is not an easy task since updated information on the state of the transportation infrastructure has to be collected in order to obtain reliable estimations (see Yuan and Wang [37] for path selection models under emergency conditions). In this study, the travel times between the different points of origin and destination are assumed to be known. The travel time between delivery point i and distribution center l is denoted as t_{il}.

As requested quantities are generally large in terms of vehicle capacity (in weight and/or volume), each vehicle trip is assumed to visit only one delivery point at a time. In other words, only back and forth trips are considered. Obviously, a delivery point may be visited many times. However, because of the maximum daily work time, the number of trips performed to delivery point i by a specific vehicle will be limited to a maximum value r. In practice, deciding on the appropriate value for r may have strong consequences on both the quality of the solutions and the solution time. For example,