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Combined location and routing problems for drug distribution

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ABSTRACT

We present a model for the optimization of logistics operations in emergency health care systems; in particular, we study the problem of efficient distribution of vaccines or drugs through the simultaneous and coordinated use of distribution centers and vehicles. We devise an exact algorithm based on column generation with three different types of columns and branch-and-bound. The pricing subproblems are solved through advanced dynamic programming techniques. In order to strengthen the dual bounds, we adapt two families of cuts from the literature and we introduce a new one. Our framework also includes primal heuristics and ad-hoc branching rules. An experimental campaign on realistic data proves our method to be effective and flexible.

1. Introduction

Mathematical programming models and algorithms have been successfully used for decades to optimize operations in distribution logistics: typical examples concern freight carriers, mail services and on-demand pick-up and delivery services.

A more recent field of investigation concerns the application of operations research techniques to the optimization of logistics operations in health care systems and emergency management. These sectors are characterized by a larger dependency on human behavior (which is often unpredictable), the need for fairness in service provision (which is not an issue in industrial logistics) and the lack of reliable historical data (because of the uniqueness of the events considered, especially in the case of emergencies). In particular in this paper we discuss the application of mathematical programming techniques to the distribution of drugs or vaccines in the case of an emergency. Such situations are hardly foreseeable and almost impossible to avoid; hence it is crucial to be able to set up an efficient response system to provide the required services in an optimized way when needed. Optimization in this case is such an essential component of a good response system that the U.S. Centers for Diseases Control and Prevention in 2007 evaluated "the timeliness of distributing antibiotics to the general public as an effective measure against a release of anthrax" [6].

Operations research techniques have already been applied to emergency drug distribution: in [20] the authors present a stochastic model for a Vehicle Routing Problem (VRP) arising in large-scale bio-terrorism emergency, in which the maximum number of citizens must be reached within a specified time limit using a heterogeneous fleet of vehicles. Such a model is then reformulated as a deterministic VRP and solved with a tabu search algorithm.

In this paper we expand the model introduced in [20], also including an additional distribution strategy based on distribution centers. This allows us to consider more realistic situations in which multiple distribution channels can be exploited at the same time. In particular, we explore the option of reaching citizens in two ways: either by delivering drugs at their homes with a heterogeneous fleet of vehicles, or by establishing distribution centers where the citizens go by their own means to receive treatments or drugs. Hence a combined Location and Routing Problem (LRP) arises. Location-routing

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is a lively research area [18]; in particular, recent exact algorithms like [3,4,8] try to cope with refined handling of limited resources. Problems with up to 200 customers and 14 potential depots for the so-called Capacitated LRP can be solved to proven optimality, even if several hours of computation might be needed. Our problem shares some features also with the Multi Depot Heterogeneous VRP [5], in which the starting point of each vehicle is part of the decision process, and for which state-of-the-art exact algorithms can solve problems with hundred customers in a few hours. Finally, for what concerns the objective of the optimization, our problem is similar to the Team Orienteering Problem (TOP) [22], being concerned in reaching the largest amount of demand with limited resources: TOP instances involving up to one hundred customers can be tackled by state-of-the-art algorithms.

To the best of our knowledge our double channel distribution problem has never been addressed before. We present an exact algorithm, which is based on dynamic column and cut generation and branch-and-bound, where the pricing subproblems are solved through advanced dynamic programming techniques.

The paper is organized as follows: in Section 2 we describe the problem and we point out its main features. A mathematical model is given in Section 3 and our solution approach is detailed in Section 4. In Sections 5 and 6 the results of our experimental campaign and some conclusions are reported.

2. Problem description

The problem we address fits into the following scenario: the population living in a given region has been partitioned into small groups and a corresponding suitable set of delivery sites, one for each group, has been identified. These sites represent the demand points, i.e. the destinations where the drugs have to be brought. We assume that once a delivery site is visited, all people assigned to it will get the drugs within a very short time. A limited number of the delivery sites can be selected as facilities where the drugs can be stored; these selected facilities are the origins of the distribution. When a facility is selected it can employ two different strategies to deliver the drugs to the sites assigned to it.

Distribution center strategy. Facilities using this strategy are called Distribution Centers (DCs). They are characterized by a capacity and a distribution range (Fig. 1(a)). The capacity is an estimate of the overall demand that the facility can satisfy. The range defines the maximum distance within which a DC can provide its services to the delivery sites assigned to it. Several distribution methods can lie behind this strategy, as the use of many small vehicles, one for every site, self-service points, or the use of the existing postal network for last-mile services.

We remark that when the capacity of a DC is less than the overall demand falling within its range, we assume that it is possible to decide which delivery sites are assigned to the DC and which of them are not.

Routing strategy. This strategy, illustrated in Fig. 1(b), is the classical VRP-like distribution method. When a facility uses this strategy it is called depot. With every depot is associated a fleet of heterogeneous vehicles with different capacities. Every vehicle can perform a single route starting from the depot, visiting some delivery sites and coming back to the same depot.

Decision variables. Fig. 1(c) shows the big picture of the logistics system with mixed distribution strategy, where the problem is to choose which facilities are to be selected and what is the most appropriate distribution strategy for each of them. Optimal routes must also be computed for the vehicles.

Constraints. The following constraints must be respected.

I No delivery site can be served multiple times by a single DC or visited more than once by a single route. Multiple assignments to different distribution centers and multiple visits by different routes are allowed but they do not increase the number of citizens served.
II No split delivery: when a delivery site is assigned to a DC or visited by a vehicle, its demand is entirely served.
III If a facility is used it can be either a depot or a DC, but not both at the same time.
IV The total number of DCs that can be opened is limited by a budget constraint.
V The overall demand of the delivery sites assigned to a DC must not exceed the capacity of the DC.
VI All delivery sites assigned to a DC must be within its range.
VII The number of available vehicles of each type is limited.
VIII Each route starts from a depot.
IX The overall demand of the sites visited by a vehicle must not exceed the capacity of the vehicle.
X Every delivery site in a route must be visited before the deadline. The deadline represents a time limit within which the pharmacological treatments are most effective. It is worth noting that is not necessary for a vehicle to be back at the depot within the time limit.

Objective function. We want to maximize the demand served within the deadline. We are aware that many other objective functions can and should be considered in the design of optimized emergency systems, e.g. equity in service provision. However we decided to concentrate our analysis on this objective for two main reasons: first of all, in the case of a pandemic outbreak it is of paramount importance to reach the largest part of the population as quickly as possible; this carries an advantage also to those who do not receive any treatment because it limits the spread of the illness. The second reason is that this is the objective function considered by Shen et al. [20] and therefore it allows for a comparison of the two algorithmic approaches.