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Innovative Applications of O.R.

A column generation approach for locating roadside clinics in Africa based on effectiveness and equity

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ABSTRACT

Long distance truck drivers in Sub-Saharan Africa are extremely vulnerable to HIV and other infectious diseases. The NGO North Star Alliance aims to alleviate this situation by placing the so-called Roadside Wellness Centers (RWCs) at busy truck stops along major truck routes. Currently, locations for new RWCs are chosen so as to maximize the expected patient volume and to ensure continuity of access along the routes. As North Star's network grows larger, the objective to provide equal access to healthcare along the different truck routes gains importance. This paper considers the problem to locate a fixed number of RWCs based on these effectiveness and equity objectives. We come up with a novel, set-partitioning type of formulation for the problem and propose a column generation algorithm to solve it. Additionally, we propose and analyze several state-of-the-art acceleration techniques, including dual stabilization, column pool management, and accelerated pricing, which solves the pricing problem as a sequence of shortest path problems. Though the facility location problem is strongly $\mathcal{NP}$-hard, our algorithm yields near-optimal solutions to large randomly generated problem instances within an acceptable amount of time. We use a real life case study on the North South Corridor Network to analyze the impact of including the equity criterion into the location problem. The results show that significant improvements in terms of equity can be achieved at marginal loss in terms of North Star's current objectives.

1. Introduction

Long distance truck drivers in Sub-Saharan Africa are extremely vulnerable to HIV and other infectious diseases (Apostolopoulos & Sönmez, 2007). The underlying determinants seem to be loneliness, long separation from home, monotony, and stress, which make them engage in high-risk sexual behaviors (Morris & Ferguson, 2007). This context thereby brings about huge health (and thereby social and economic) risks to this population, and seems to fuel the spread of HIV and other infectious diseases (Gatignon & Wassenhove, 2008).

Providing long distance truck drivers with continuous access to basic (HIV) prevention, treatment, and care services is therefore believed to be an effective way to combat HIV and its consequences. Traditional healthcare facilities, however, are generally incapable of delivering these services. The main reasons are that truck drivers do not have time or permission to deviate from their routes, that these facilities cannot be accessed by truck, and that the opening hours are inconvenient to the drivers (Ferguson & Morris, 2007; Gatignon & Wassenhove, 2008).

Non-governmental organization North Star Alliance (North Star) aims to fill this gap by placing the so-called Roadside Wellness Centers (RWCs) at busy truck stops along major truck routes in Sub-Saharan Africa. These RWCs provide basic healthcare services, such as clinical services, HIV testing and counseling, and behavior change communication to truck drivers and surrounding populations. North Star's current network consists of 35 RWCs, and will expand considerably in the next couple of years. This is expected to bring about large health benefits to truck drivers and surrounding populations. In the first place, by placing new RWCs at busy truck stops, North Star makes sure that many truck drivers are provided with (at least a basic level of) access to the most needed health services when they spend the night there. In addition, establishing a dense network of RWCs ensures that many truck drivers also have continuous access to the needed health services. That is, they are sufficiently close to an RWC at every moment during their trip, which De Vries, Van de Klundert, and Wagelmans (2014a) argue to be a requirement for several health services to be effective.

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Choosing the locations of a given number of new RWCs presents novel and complex optimization problems. Decision makers face a huge number of possible location decisions, and have to balance multiple objectives. De Vries, Van de Klundert, and Wagelmans (2014b) propose a mixed-integer programming (MIP) formulation for the problem to locate a given number of new RWCs and to decide on the set of health services to be offered by these RWCs. The objectives are to maximize the impact of the new RWCs in terms of the patient volume served and in terms of health service effectiveness, as determined by the extent to which the truck drivers have continuous access to these services. Numerical and analytical results suggest that the model potentially yields significant improvement for the location decisions taken by North Star.

In spite of that, further improvement of the model is needed in two directions. First, as many other non-profit organizations, North Star operates in a complex environment that is characterized by many different objectives and stakeholders. As North Star's network grows larger, a third objective is gaining importance among them: to provide equitable access to healthcare. More specifically, inequalities in access among truck drivers using different truck routes are to be minimized, both for ethical reasons, as inspired by the right to health (Nations, 1946), as well as for medical and financial reasons.

The second direction for improvement deals with the complexity of the location problem. De Vries et al. (2014b) show that the location problem is strongly $\mathcal{NP}$-complete, and numerical experiments show that solving large problem instances becomes extremely difficult. Moreover, the complexity of the problem will be increased considerably by including an equity criterion. Alternative model formulations and solution methods are required to deal with this.

This paper considers these two directions in the context of the problem of *locating a given number of RWCs* (i.e., we do not consider the decisions on the health services to offer at the RWCs). Our contributions are fourfold. First, we introduce and motivate the equity criterion, and propose several measures for (in)equality in access to healthcare among mobile patient populations. Second, we propose and analyze a novel set partitioning type of formulation for this type of facility location problem. The strengths of this formulation are that it allows for a variety of objective functions (e.g., maximizing patient volume, ensuring continuous access, and providing equity), and that the integrality gap is very small. Third, to deal with the exponential number of variables our formulation brings about, we propose and analyze a column generation approach to solve it. Moreover, we investigate several strategies to speed up our algorithm, including dual stabilization, column pool management, and accelerated pricing. The latter solves the pricing problem to near-optimality as a sequence of shortest path problems. Last, we numerically assess the trade-off between the equity criterion and North Star's current criteria (patient volume and continuous access) based on randomly generated instances. Our results suggest that solutions that are close to optimal with respect to each of the optimization criteria are attainable.

Though we specifically focus on the problem to select locations for a given number of RWCs, these contributions also apply to the extension in which decisions on the health services to offer are considered. Additionally, our contributions are also applicable to a variety of related facility location problems that deal with moving demand units. Examples include the positioning of refueling stations, billboards, detection or inspection stations, convenience stores, and ambulances.

The remainder of this paper is organized as follows. Section 2 gives an overview of the relevant literature. Section 3 describes the problem and the optimization criteria in detail. Next, we present the set partitioning type of formulation in Section 4. Section 5 describes our basic column generation approach. After this, we describe our acceleration techniques in Section 6. Section 7 presents our results. This is followed by Section 8, which investigates the trade-off between equity and North Star's current objectives using a real life case study about the North South Corridor Network. Finally, in Section 9 we draw some conclusions and discuss possible directions for future research.

2. Literature review

2.1. Equity

Equity involves the comparison of two or more populations (or individuals) along some dimension. To account for the equity criteria in facility location decisions, one needs to clarify the exact meaning of equity. Though the literature on equity stresses the importance of the subject, particularly in a resource allocation context, there is no consensus on its definition (Waters, 2000). Young (1995) classifies resource allocation rules based on three equity concepts: parity (claimants should be treated equally), proportionality (goods should be divided into proportion to differences among claimants), and priority (the person with the greatest claim to the good should get it). Depending on the weights assigned to these concepts, many views on equity are possible, ranging from a totally egalitarian perspective (inequalities are unacceptable) to a Marxist perspective (inequalities should represent differences in need) to a Rawlsian perspective (inequality is only allowed if it benefits those least advantaged) (Williams & Cookson, 2000).

Equity measures compare *effects* of actions on different groups, and possibly weigh such effects based on the characteristics of a group (e.g., needs or size). An abundance of literature proposing and analyzing such measures is available. Marsh and Schilling (1994) provide a list of 20 equity measures that have been developed in the facility location context. Though each of these measures prefers a completely equitable distribution over any other distribution, they differ in their valuations of inequitable distributions. More specifically, they assign different weights to the concepts of parity, proportionality, and priority. Ogryczak (2000) studies the trade-off between effectiveness and equity corresponding to several equity metrics for location problems. In a later paper, Ogryczak (2009) investigates how to include equity measures while avoiding inferior solutions in terms of effectiveness (e.g. distances).

The literature reveals a wide variety of concepts and variables that are used in studies on equity. Concepts that are being used to compare the service or utility a health system provides to different populations include health status, distribution of resources, expenditures, utilization, and access (Culyer & Wagstaff, 1993; Goddard & Smith, 2001; Musgrove, 1986). For example, Cardoso, Oliveira, Barbosa-Póvoa, and Nickel (2016) incorporate *equity of access, geographical equity, and socioeconomic equity* in long-term care and network design decisions. Griffin (2012) analyzes allocation strategies that aim at achieving equity in *health improvement* among different communities. McCoy and Lee (2014) consider equitable allocation strategies for *motor cycle trips* facilitating access to healthcare in rural areas. Besides the variety in concepts and variables, there also exist differences in the methods to include them in a model. For example, Cardoso et al. (2016) incorporate equity by enforcing targets to be met whereas Cardoso, Oliveira, Barbosa-Póvoa, and Nickel (2015) incorporate equity measures in the objective function.

Given the amount of literature on equity, we can conclude that equity is a frequently applied and highly relevant optimization criterion. Ongoing discussions on the definition and measurement of equity have yielded in a wide variety of ways to incorporate this concept in optimization models, some of which we will discuss in the next section.