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A practical vehicle routing problem with desynchronized arrivals to depot

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ABSTRACT

The transportation of biomedical samples is a key component of healthcare supply chains. The samples are collected, consolidated into cooler boxes, and then transported to be analyzed in a specialized laboratory. Since many hospitals and samples' collection points are assigned to the same laboratory, it is important to manage the flow of samples arriving to the laboratory to avoid congestion. In other words, it is preferable to try to desynchronize the samples' arrivals by managing the vehicles' departure times and the routes ordering. We propose a mathematical model and a multi-start heuristic to minimize the route duration times and the maximum number of samples' boxes arriving at the laboratory within a given time period. Based on real data, we demonstrated that both the model and the heuristic are very efficient in solving real size instances.

1. Introduction

Vehicle routing and scheduling are key components of the efficiency of modern supply chains, where quantities of goods and raw materials should be continuously exchanged in the seamless way possible. In its most common version, the *vehicle routing problem* (VRP) is used to plan the distribution of goods from a depot to a set of customers, (Koç, Bektas, Jabali, & Laporte, 2016, Laporte, 2009, Semet, Toth, & Vigo, 2014) and subject to some constraints, like time windows (Bräysy & Gendreau, 2005a, 2005b), vehicle restrictions (Semet, 1995) and many other practical and industrial considerations (Coelho, Renaud, & Laporte, 2016). In other situations, products are exchanged between the customers, which leads to the pickup and delivery VRP (Berbeglia, Cordeau, & Laporte, 2010, Gschwind, 2015; Berbeglia, Cordeau, Gribkovskaia, & Laporte, 2007). Vehicles can also be used to bring back the customers' goods to a central depot, or consolidation point, like in the waste collection problem (Ghiani, Laganà, Manni, Musmanno, & Vigo, 2014). These practical routing problems deal with many real-world constraints and are often referred as *rich* VRP (Lahyani, Khemakhem, & Semet, 2015).

In this article, we focus on a situation arising in the healthcare supply chain context which corresponds to the daily transportation of biomedical samples from hospitals or clinics, which will be referred to as *collection points* (CP), to a single *laboratory* (Lab) where they will be analyzed. Transportation is done by a fleet of vehicles performing multiple routes during the day. As the lifespan of these samples is limited, CPs often require multiple collection requests on a given day, and each collection request is generally bounded by a time window. Samples are consolidated in cold boxes that, once collected, must arrive to the Lab within a limited specified time to preserve samples' integrity. The boxes are opened at the Lab, and each sample is manually registered in the system and bar-coded for tracking purposes during the analysis process. These manual tasks are time consuming and according to our partner's experts, the Quebec's *Ministère de la santé et des services sociaux* (Ministry of Health and Social Services – MSSS), they constitute a bottleneck of the samples' supply chain. In fact, if too many boxes arrive in a short period of time, samples are queued and may suffer long wait, which might exceed their remaining lifetime making them unsuitable to be analyzed. Our observations on the ground confirmed that some days or periods are more popular for sample collection. Thereby, reducing the maximum number of samples boxes arriving within a time period is desirable in order to normalize the Lab workload and minimize sample losses. Thus, the objective of

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this *vehicle routing problem with desynchronized arrivals* at the depot (VRP-DA) can be defined as minimizing the sum of the routes' traveling time as well as the maximum number of boxes arriving at the Lab within any time period of the considered planning day. This work is motivated by the reengineering of the health supply chain performed by the Quebec's government under the name of the Optilab project (MSSS, 2012). One of the first objective was to centralize the transportation needs of the collection points to obtain better tariffs from the carriers (Anaya Arenas, Chabot, Renaud, & Ruiz, 2016). Now the MSSS seeks at reducing the number of laboratories in order to better use the strategic ones. In order to do so, it clearly appears that a good management of samples arriving to the Lab would be an important issue. To the best of our knowledge, our contribution is the first one considering desynchronizing the vehicles' arrivals to the depot as this is closely related to samples' limited lifetime, which is not the case for most of classical or industrial goods.

Instead of regularizing the arrivals, many works have tried to balance the vehicles' workload. Jozefowiez, Semet, and Talbi (2009) considered a bi-objective VRP which minimized the total length of routes and the balance of routes, which is defined as the difference between the maximal route length and the minimal route length. Kritikos and Ioannou (2010) studied a VRP with time windows (VRPTW) where they balanced the load carried by each active vehicle. Baños, Ortega, Gil, Márquez, and de Toro (2013) also considered a multi-objective VRPTW with both distance and load imbalances. López-Sánchez, Hernández-Díaz, Vigo, Caballero, and Molina (2014) solved a balanced open VRP where the maximum time spent on the vehicle must be minimized. We note that, if all vehicles depart at the same time, balancing the routes will indeed concentrate the vehicle arrival times at the depot.

Closer to our context, Doerner, Gronalt, Hartl, Kiechle, and Reimann (2008) and Doerner and Hartl (2008) studied a blood collection problem which shares some characteristics with our problem. However, in their study they considered that the blood deterioration process begins right after the donation, and they used interdependent time windows. They also did not consider arrival times at the depot. Liu, Xie, Augusto, and Rodríguez (2013) considered the pickup and delivery of four demand types in a home health care system. They dealt with many specific constraints, but they did not consider a time limit for the samples' delivery to the depot, nor did they manage vehicles' arrival times. Şahinyazan, Kara, and Taner (2015) studied a system composed of bloodmobiles and shuttles which brought the collected blood to the depot to prevent spoilage. In order to maximize the collected blood and minimize the transportation cost, they managed the activities of the bloodmobiles and shuttles over a time horizon. However, they did not consider a time limit for the blood's return to the depot. Finally, and as stated before, this particular context was introduced by Anaya Arenas et al. (2016) which minimized traveling distance, but did not consider desynchronizing the arrivals at the Lab.

The remainder of this article is as follows. In Section 2 we propose the problem formulation and some valid inequalities designed to improve its solvability. A multi-start heuristic is developed in Section 3. The efficiency of this formulation and of the heuristic and the impact of desynchronized arrivals are evaluated in Section 4, based on a set of real instances obtained from the MSSS of Quebec, Canada. We also demonstrate how this new formulation and heuristic improve upon those of Anaya Arenas et al. (2016), where desynchronized arrivals were not considered. Our conclusions are presented in Section 5.

2. Problem definition and formulation

In order to formulate the vehicle routing problem with desynchronized arrivals, we need to identify both the locations of the CPs and the collections requests. The n CPs are represented by $V' = \{v'_1, \ldots, v'_n\}$ and each CP l requires Q_l collection requests, leading to a total of $p = \sum_{l=1}^{n} Q_l$ requests. Each request is composed of one box that contains several samples. Then we define a complete graph $G = \{V, A\}$, where $V = \{v_0, v_1, \ldots, v_p, v_{p+1}\}$ is the set of nodes in the network, which includes the laboratory as nodes $\{v_0,\ v_{p+1}\}$ where every route must start and end, and the set $P = \{v_1, v_2, \ldots, v_p\}$, being the p transportation requests. Also, we note P_l as the set of request nodes in V which corresponds to the same CP location. We consider the arc set $A = \{(v_i, v_j) :\ v_i, v_j \in V,\ i \neq j,\ i = 0, \ldots,\ p,\ j = 1, \ldots p+1\}$ and a travel time (t_{ij}) and a travel distance (d_{ij}) are assigned to each arc (v_i, v_j). Clearly, t_{ij} and d_{ij} are equal to zero for every (v_i, v_j) if i and $j \in P_l$ (i.e., i and j correspond to two requests from the same CP). In addition, each request needs to be served within a time window $[a_j, b_j]$. Finally, any two requests related to the same collection point cannot be on the same route.

K uncapacited vehicles are available for satisfying the transportation requests, and each vehicle can perform multiple routes $(r = 1, \ldots, R)$ within a work shift, but a limit on the length of the working day (T_k) must be respected. In addition, we need to consider a loading time (τ_i) for each transportation request, as well as the vehicle's unloading time (τ_0) at the Lab before a new route can be started. Furthermore, let T^i_{max} be the maximal transportation time for the samples associated to request i. The objective is to minimize the total traveling time of the vehicle, including the waiting times, plus a weighted penalty θ associated to the maximum number of boxes arriving at the depot during the most visited time period. In the following sections we present the VRP-DA formulation followed by some valid inequalities to strengthen it.

2.1. VRP-DA formulation

The following decision variables are needed to define the VRP-DA:

- x_{ijkr} — Binary variable equal to 1 if vehicle k travels from request i to request j in its route r; 0 otherwise.
- u_{ikr} — Continuous variable that indicates the visit time (start of loading) of transportation request i by vehicle k in route r.
- y_{itkr} — Binary variable equal to 1 if the request i performed by the r^{th} route of the vehicle k, arrives at the Lab within the t^{th} time period; 0 otherwise.
- w — Highest number of boxes arriving to the Lab within any given time period (the busiest one).

The model VRP-DA reads as follows.

$$Min \sum_{k=1}^{K}\sum_{r=1}^{R}\left(u_{p+1kr} - u_{0kr}\right) + \theta w \tag{1}$$

Subject to:

$$\sum_{k=1}^{K}\sum_{r=1}^{R}\sum_{i=0}^{p} x_{ijkr} = 1 \quad j = 1, \ldots,\ p \tag{2}$$

$$\sum_{j\ \in\ P_l}\sum_{i=0}^{p} x_{ijkr} \leq 1 \quad l = 1, \ldots, n;\ k = 1, \ldots, K;\ r = 1, \ldots, R \tag{3}$$

$$\sum_{i=0}^{p} x_{ijkr} - \sum_{l=1}^{p+1} x_{jlkr} = 0 \quad j = 1, \ldots, p;\ k = 1, \ldots, K;\ r = 1, \ldots, R \tag{4}$$

$$\sum_{j=1}^{p} x_{0jkr} \leq 1 \qquad k = 1, \ldots, K; \quad r = 1, \ldots, R \tag{5}$$