Integrated School Bell Time Adjustment and Vehicle Routing for Paratransit Optimization

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1 Introduction

In many countries, access to transportation for people with disabilities has become a major equity and inclusion issue. Medical and Social Institutions (MSI) and specialized schools for students with disabilities use specialized transport services every day. As a result, paratransit represents one of the main costs for specialized schools and is also expensive for public authorities (ANAP, 2016, Tellez *et al.*, 2020, Bertsimas & Yan, 2020). To reduce the cost of transport, it is possible to use a pooling approach between neighboring schools, i.e. to group users from the same area in a common vehicle, even if they have different destinations. We investigate a practical case from France, where these establishments typically have around 80 % of their users benefiting from a specialized transportation service. In this study, the considered MSI and specialized schools (called *schools* in the remaining of this abstract) are interested in studying the benefits of pooling their transport. The organization of such transport systems requires solving a Dial-a-Ride Problem (DARP) to design the best possible routes for vehicles that pick up their passengers at home and drop them off at their destination, provided they can share part of their route. In the case of people with disabilities, transports are usually performed by a heterogeneous fleet of vehicles, including wheelchair accessible minibuses. Particular attention is paid to the quality of the service to passengers, with constraints on passenger's ride times or waiting times at destination.

When several schools have similar start times, it is hard to design feasible routes that can pick up passengers living in the same area and going to separate schools. Hence, modifying the schools' start times, which is known as School Bell time Adjustment (SBA) in school bus routing (Park & Kim, 2010), facilitates transportation pooling. To address the optimization problem which consists of simultaneously determining the school start times and vehicle routes:

1. We introduce and model the Dial-A-Ride Problem with School Bell time Adjustment (DARP-SBA).
2. We integrate operational constraints, including vehicles which can differ in their cost, size and inner configuration (number of seats and wheelchair spaces).
3. To solve this problem, we present a matheuristic which combines a Large Neighborhood Search (LNS) and a route-based model solved with a solver.

4. The numerical experiments rely on instances generated from a set of 575 users and around 100 vehicles provided by the Synergihp Rhône-Alpes company in the area of Lyon, France. On average, we show that in addition to the 10% of saving that can be expected by sharing vehicle routes between schools, 7% of additional savings can be achieved by school bell time adjustment. This cost saving also decreases user ride times and the number of vehicles required, creating longer routes which are more attractive for driver services.

2 The Dial-A-Ride Problem with School Bell Time Adjustment

We consider a set of schools denoted by $\mathcal{E}$. The set of users is denoted by $\mathcal{U}$. Each user $u \in \mathcal{U}$ has a transportation request from a pickup node p_u to a delivery node d_u. This request is associated with a maximal ride time R_u and loads q_u^S and q_u^W which represent the number of seats and wheelchairs needed to transport the user in a vehicle, respectively. We denote by $\mathcal{P} = \{p_u | u \in \mathcal{U}\}$ the set of pickup nodes and $\mathcal{D} = \{d_u | u \in \mathcal{U}\}$ the set of delivery nodes. According to this notation, deliveries at the same school are represented by separate nodes in $\mathcal{D}$. The set of nodes that model a delivery at school $e \in \mathcal{E}$ is denoted by $\mathcal{D}_e$. The depot is modeled by nodes o^+ and o^-, which represent the departure and return of all vehicle routes, respectively. The set $\mathcal{N}$ of all nodes is defined as $\mathcal{N} = \mathcal{P} \cup \mathcal{D} \cup \{o^+, o^-\}$.

Without loss of generality, we only present the case of morning transport. In practice, a similar problem must be solved for return trips at the end of the day. Each school $e \in \mathcal{E}$ has a *morning interval* $[a_e, b_e]$ during which all deliveries can be scheduled. Deliveries occur within a so-called *dynamic time window* (Gschwind & Irnich, 2015) of width W_e that ends at the school start time. For practical reasons, the morning interval is discretized using a discretization step δ_e. This means that the bell time H_e at school e has to be chosen within the set $\{a_e + \kappa \times \delta_e | \kappa \in \mathbb{N}, a_e + \kappa \times \delta_e \leq b_e\}$. A vehicle may arrive before the actual opening of a school time window. In this case, it has to wait for the opening of the school before any user can leave the vehicle.

Pickup or depot nodes $i \in \mathcal{P} \cup \{o^+, o^-\}$ have a time window $[a_i, b_i]$. By abuse of notation, we also consider that a node $i \in \mathcal{D}$ that models a delivery at a school $e \in \mathcal{E}$, has a time window $[a_i, b_i] = [a_e, b_e]$. The service duration at any node $i \in \mathcal{N}$ is denoted by s_i.

We consider a heterogeneous fleet of vehicles in which the number of vehicles of each type is not limited. Vehicles have one or several *configurations* characterized by a number of seats and a number of wheelchairs. These configurations can easily be changed en-route by folding or unfolding some seats. Each vehicle type has a given fixed cost for its use, a traveling cost associated with the distance traveled, and a cost per hour. Although the fleet is heterogeneous, all vehicles are considered to have similar speeds. Accordingly, the driving time from a node $i \in \mathcal{N}$ to $j \in \mathcal{N}$ is denoted by t_{ij} for all vehicle types.

The DARP-SBA consists in determining a start time H_e for each school $e \in \mathcal{E}$ within its morning interval, selecting a set of vehicles and designing the route of each selected vehicle such that: all transportation requests are served; all maximum ride times, pickup and depot time windows are satisfied; all users can be dropped off at their school within its time window; the capacities of the vehicles are satisfied; and the overall vehicle, traveling and route duration costs are minimized.

Figure 1 gives a graphical representation of a solution with two routes ω_1 and ω_2 visiting a school e. Note that nodes d_1, d_2, d_3, d_5 and d_6 represent the same physical location. One of the key challenges of this problem is that routes should be synchronized at schools, where a dynamic time window is fixed in time when determining the school bell time.

3 Matheuristic approach

To solve the DARP-SBA, we propose a matheuristic which iterates over the following steps until a time limit TL is reached:

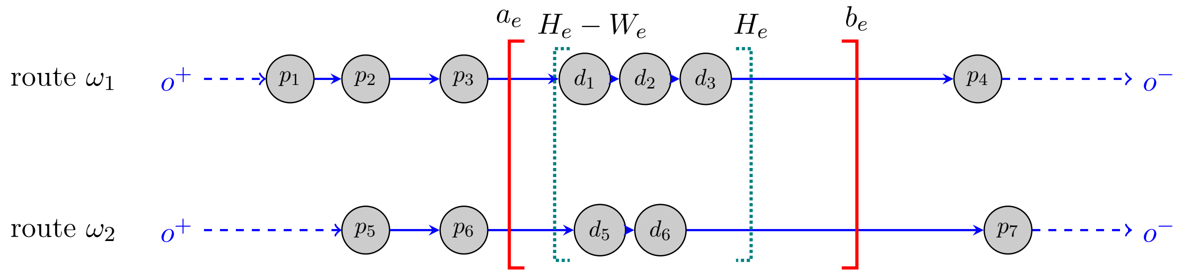

Figure 1 – *Partial time space representation of two routes* ω_1 *and* ω_2 *visiting a school* e*.* H_e *denotes the school bell time to be determined.* $[a_e, b_e]$ *is the morning interval of school* e *and* $[H_e - W_e, H_e]$ *is the dynamic time window induced by* H_e*.*

1. In each iteration, solutions are generated by running N iterations of an LNS algorithm derived from Tellez *et al.* (2018). In this LNS implementation: the repair operator solves a DARP in which the schools time windows have been filtered thanks to a *necessary condition* to remove values that cannot lead to routes that are correctly synchronized at schools. The complete timing problem is solved by a MILP solver only for complete and promising solutions to validate their feasibility. All routes found in this process are collected in the set Ω', called *route pool.*
2. A relaxed, restricted route based model of the DARP-SBA is then solved with a MILP solver on this route pool with a time limit T^{SCP} ($T^{SCP} \ll TL$). It selects and combines routes generated at different LNS iterations. In this model: (i) the service time at each vertex of a route can be adjusted to find synchronized solutions, and (ii) the dynamic time windows at schools are relaxed and their violation is penalized to allow unfeasible solutions to be explored.
3. If solution S^* has been improved by the MILP solver, then the current solution is updated. Otherwise, the current solution is re-used as a starting point at the next iteration. When the model is solved to optimality twice in a row by the solver, the number N of LNS iterations is increased geometrically by a factor of ε. If, on the contrary, the solver has not certified the optimality of the solution and has not improved the solution S^* twice consecutively, the number of LNS iterations performed between each model solving is decreased geometrically by a factor of ε.

To intensify the search for synchronized solutions that are close to the best known solution, a mechanism progressively shrinks the arrival time windows at each school. More precisely, the school morning intervals are shrunk R times in this algorithm at regular run-time intervals.

4 Experiments

Our experimental study considers a set of 34 schools in the area of Lyon and the 575 users transported to these schools. Based on this data set, three types of instances have been produced: Small, Medium and Large instances (S,M,L) are based on a division of the data set in eight, four and two sub-problems, respectively. We also consider two fleets of vehicles (*heterogeneous* and *homogeneous*).

The matheuristic components were thoroughly evaluated and tuned. The resulting matheuristic is competitive with a state-of-the-art meta-heuristic to solve static instances of the DARP.

To evaluate the potential impact of SBA and its role in the pooling of transportation between several schools, we have considered four scenarios. In scenario 0, vehicles cannot visit more than one school. This corresponds to the situation where there is no transportation pooling between school. Scenarios 20 and 60 correspond to DARP instances where the delivery time windows are

[8:20, 8:40] and [8:00, 9:00], respectively. Finally, scenario 20/60 corresponds to the DARP-SBA with a dynamic time window of width $W_e = 20$ minutes and a morning interval $[a_e, b_e] =$ [8:00, 9:00] for each school $e \in \mathcal{E}$. Table 1 shows the results of all scenarios aggregated by instance types.

	Impact of SBA (cost)				Gap to scenario 20 (%)		
	0	20	20/60	60	0	20/60	60
Heterogeneous fleet							
S	9,223	8,485	8,040	7,582	8.70	-5.25	-10.65
M	9,223	8,336	7,743	7,333	10.64	-7.11	-12.03
L	9,223	8,290	7,571	7,076	11.25	-8.68	-14.64
Avg.	9,223	8,370	7,784	7,330	10.20	-7.01	-12.44
Homogeneous fleet							
S	9,973	8,920	8,377	7,918	11.81	-6.09	-11.23
M	9,973	8,706	8,031	7,619	14.56	-7.75	-12.48
L	9,973	8,683	7,928	7,332	14.86	-8.69	-15.56
Avg.	9,973	8,770	8,112	7,623	13.74	-7.51	-13.09
Average					*11.97*	*-7.26*	*-12.76*

Table 1 – *Impact of SBA on transportation cost*

From this table, a first observation is that the greatest savings can be achieved by pooling transports between schools. Indeed, comparing scenarios 0 and 20, pooling achieve around 10% savings on routing costs in the case of a heterogeneous fleet and up to 14% with a homogeneous fleet. The current practice of having a heterogeneous fleet of vehicles is validated with respect to the cost of a standard eight-seater vehicle. Comparing lines S, M and L where schools are gathered in clusters of increasing sizes, we see that mixed loads allow for greater savings in instances with large clusters. Second, scenario 20/60 shows that adjusting school bell times enables additional cost reduction by 7% on average. This is also a non-negligible potential saving for daily transportation operations. Finally we find that the unrealistic scenario 60 allows for only 5.5% of additional savings with respect to SBA.

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